DRYING PROCESSES IN THE UNITED KINGDOM

Assessment of Industrial Energy Utilisation and Efficiency of Drying Systems and the Modelling of Drying Characteristics Using Neural Networks

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Doctor of Philosophy

THE UNIVERSITY OF ASTON IN BIRMINGHAM

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THESIS SUMMARY

Drying is an important unit operation in process industry. Results have suggested that the energy used for drying has increased from 12% in 1978 to 18% of the total energy used in 1990. A literature survey of previous studies regarding overall drying energy consumption has demonstrated that there is little continuity of methods and energy trends could not be established.

In the ceramics, timber and paper industrial sectors specific energy consumption and energy trends have been investigated by auditing drying equipment. Ceramic products examined have included tableware, tiles, sanitaryware, electrical ceramics, plasterboard, refractories, bricks, and abrasives. Data from industry has shown that drying energy has not varied significantly in the ceramics sector over the last decade, representing about 31% of the total energy consumed. Information from the timber industry has established that radical changes have occurred over the last 20 years, both in terms of equipment and energy utilisation. The energy efficiency of hardwood drying has improved by 15% since the 1970s, although no significant savings have been realised for softwood. A survey estimating the energy efficiency and operating characteristics of 192 paper dryer sections has been conducted. Drying energy was found to increase to nearly 60% of the total energy used in the early 1980s, but has fallen over the last decade, representing 23% of the total in 1993. These results have demonstrated that effective energy saving measures, such as improved pressing and heat recovery, have been successfully implemented since the 1970s.

Artificial neural networks have successfully been applied to model process characteristics of microwave and convective drying of paper coated gypsum cove. Parameters modelled have included product moisture loss, core gypsum temperature, and quality factors relating to paper burning and bubbling defects. Evaluation of thermal and dielectric properties have highlighted gypsum's heat sensitive characteristics in convective and electromagnetic regimes. Modelling experimental data has shown that the networks were capable of simulating drying process characteristics to a high degree of accuracy. Product weight and temperature was predicted to within 0.5% and 5°C of the target data respectively. Furthermore, it was demonstrated that the underlying properties of the data could be predicted through a high level of input noise.

KEYWORDS : Drying, Modelling, Neural Networks, Energy Utilisation and Efficiency.

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NOMENCLATURE

Principal Symbols

α	Heat transfer coefficient
ε''	Loss factor
ε'	Permittivity
θ, T, t	Temperature
λ_0	Free space wavelength = (speed of light/frequency)
A	Area
a	Summation of neural inputs and matrix weights
Dp	Penetration depth
E	Network error
g(a)	Function of a
h	Specific heat of evaporation
M	Mass
m	Number of hidden neural units
RH	Relative humidity
t, τ	Time
v, N	Drying rate
w	Neural network weight
x	Neural network input
x (m), U, m, M, W	Product moisture
z	Neural output

Subscript Symbols

Crit.	Critical
d	Dry
db	Dry basis
eff.	Effective
g	Gas
i	Input
lim.	Limiting
p	Product
s	Surface
wb	Wet Basis

CHAPTER 1

INTRODUCTION

Introduction

Drying is an important unit operation in the process industry. There is a great variety of drying technologies available, a variety which continues to expand through development of new techniques, products, processes and technology.

The high energy consumption associated with drying and the development of drying technologies warrant an inventory and analysis of the various types and features of drying processes. Furthermore, a comprehensive understanding of a process can lead to benefits of substantial energy reduction, improved quality and productivity resulting from the implementation of improved control systems.

General Aims and Objectives

The general aims of the study can be summarised as;

- To investigate the energy utilisation and efficiency of industrial drying processes.
- To examine energy efficient technology, previous and projected targets, and proposed schemes, measures and practices regarding the awareness of energy utilisation.
- To investigate the modelling and control of drying systems with reference to energy efficiency and utilisation.

Detailed description of the aims, objectives, methodology and potential benefit of the work can be found in Chapters 3, 8, and 9 regarding the investigation of energy utilisation and the neural network modelling of drying systems respectively.

Thesis Structure

The work undertaken can be divided into two areas;

- Energy efficiency and utilisation of industrial drying applications, &
- Modelling and control of drying systems.

The energy intensive nature of industrial drying processes has been the topic for many research projects, and results have generated a considerable concern for energy efficiency. The range of energy saving measures which can be applied in this field is large. Energy consumption varies widely depending on material and drying technique. To enable progressive implementation of new technology and the realisation of energy efficiency concepts, it is essential to assess how and where energy is used within a process.

The work is aimed at process engineers in industry, research consultants and equipment manufacturers who have a responsibility within their organisation for drying processes. The intention is to simulate ideas and introduce concepts of energy efficiency and energy targets in the industrial drying field by analysing industrial applications.

Chapters 2-7 describe work concerning energy utilisation of industrial drying processes.

Chapter 2 defines drying and introduces aspects of equipment type, design, construction and general operational principles. Additional details include investigation of the classification of dryer types and methods of dryer selection. Results of a survey of UK dryer equipment manufacturers is described highlighting types of equipment and the main product sectors where sales are focused. Results will show that a wide variety of drying systems are employed in industry.

Chapter 3 describes energy related topics with reference to drying systems. Total industrial energy consumption is examined and comments made concerning overall production. Energy efficiency, specific energy consumption and other factors governing the efficiency of a drying process are defined and comments made regarding the cost of drying and assessment of previous literature concerning dryer thermal efficiency. General energy saving measurers are addressed and past estimates of the energy consumption for drying processes examined in detail. Results of an energy update are expressed highlighting significant findings in the trends in energy usage. This research has estimated that the energy used for drying processes has increased since the 1970's and represents up to 18% of the total industrial energy consumed. Comments are made concerning the proportion of the total energy used for drying within six industrial sectors and the variation over the last decade. Using the updated information and examination of previous literature the aims and objectives of the energy study are described. The focus of the project and potential benefits of the work are introduced, relating results to industrial practices, new technologies and developments.

Chapters 4-7 each take a similar format and examine in detail drying processes within specific industrial sectors: Ceramics including sanitaryware, tableware, tiles and electrical ceramics, building materials, paper and the timber industry. In each sector the industry is described including details of production trends, equipment utilisation and product ranges. Comprehensive results of the analysis of the specific energy consumption of equipment and trends over the last decade are examined. Comparisons are made to previous studies involving energy utilisation or efficiency and comments made concerning energy targets, effectiveness of previous energy efficient measures and predicted energy demand. Significant results are noted within the timber industry, whereas findings for the paper industry show large variations in specific energy consumption over the last decade. Many case study examples of drying systems are described within the ceramics industry and demonstrate the limited application of energy saving measurers and their influence on the overall energy consumption. Recent developments in drying technologies and energy saving measures applicable to processes within the sectors are addressed. Where appropriate evaluation is made regarding energy savings and additional benefits such as productivity, quality and environmental aspects.

Modelling and Control of Drying Systems

Drying techniques have been in use since man first dried animal skins for clothing using natural methods. However, the investigation of drying processes and history of modelling dates back only to the beginning of the 19th century. Drying processes are complex involving simultaneous heat and mass transfer. Although substantial work has been conducted within this area there is still a lack of understanding of systems, material, vapour and equipment interactions during drying.

A knowledge of the characteristics of a drying system will aid the application and selection of equipment, optimisation of operating conditions and improve control of the process.

The aim of a control system is to maintain the output specifications to as near to their desired value as possible. Control is an important objective for energy efficiency. A poorly controlled process is likely to be wasteful, both in energy terms and in terms of off specification product. It is likely to result in reduced throughput, possible low equipment utilisation, reliability and energy efficiency and a product of inferior quality.

The work conducted was of a fundamental development nature. Direct application to industrial users would require further innovation and demonstration of the flexibility, costing and wide variety of benefits potentially available.

Chapters 8 and 9 describe the modelling of specific drying systems using neural networks, and the application to control principles.

Chapter 8 describes the modelling of drying processes and theoretical principles of neural networks. The history of the modelling of drying is described together with the purpose and potential benefits. Limitations and problems associated with traditional mathematical techniques using simultaneous heat and mass transfer equations are addressed. Theoretical principles of neural networks are investigated including design, development and verification procedures. Industrial applications of neural networks are described including a comprehensive review of work associated with the application of neural networks for drying process modelling. The review concludes that limited work has been conducted concerning the application of neural methods to drying systems.

Chapter 9 described the neural network modelling of microwave and convective drying characteristics. The methodology of the selection of a drying system, equipment, parameters, materials and methods of data acquisition are described. The product material has been examined to gain an understanding of the drying characteristics, including chemical and physical properties. The materials interaction in an electromagnetic field and convective drying medium has been investigated, including analysis of dielectric and thermal properties. Comments are made concerning the large variation of product and drying characteristics obtained and their interaction with the removal of moisture during heating. Results of drying trials and the methodology behind the development of a neural model are described including experimental equipment and procedures. Networks are developed including systems to model moisture loss, product temperature and quality factors during drying. Comments are made concerning the accuracy of the models produced and verification using experimental data. The significance of the results and the ability of neural networks to model the non-linearity and dynamics inherent in drying systems are discussed. This research will show that neural networks can effectively simulate drying systems and results demonstrate potential for further development and implementation in energy saving measures.

Conclusions and proposals for future development and application of the work are addressed in Chapters 10 and 11 respectively.

Conclusions

The thesis subject area has been introduced and generalised objectives of the work have been described. A brief outline of the thesis chapters are detailed showing the progressive flow of work from the analysis of literature, conceptual ideas, development and description of results and the conclusions reached. Application of the results and the potential for future work are also addressed.

CHAPTER 2

INTRODUCTION TO DRYING TECHNOLOGY

Introduction

Drying can be defined as the process whereby, through heating or a vapour pressure difference, moisture is evaporated from a solid to produce a relatively dry substance [306]. Van'l Land highlights the main reasons for drying materials to a specified moisture [368];

- Production of a free flowing material that can be transported, packed or dosed,
- Contractual limits including standards, e.g. BS 4978 Moisture Specifications for Drying Softwood,
- Quality reasons which may affect shelf life, nutritional value in food stuff, or loss of value,
- The efficiency of subsequent processes, e.g. for the milling of wheat,

Drying of industrial products can be achieved by various methods, such as mechanical means, absorption, thermal processes or dehumidification [270]. Drying in this study refers only to the removal of water from a solid or semi-solid material. While the most common solvent is water, the removal of organic solvents is often referred to as drying (e.g. spray painting). These other solvents drying applications are not covered in this report.

Fundamentals of Drying

Basics

A wide variety of literature is available describing the fundamentals of drying theory [191], [207], [234], [337], [378]. A large number of articles have been published concerning the modelling of drying and classification of theories. Treybal [356] and Lydersen [236] present expressions for heat and mass balances at the surface of a material where the drying rate is obtained from an assumed or experimental drying rate curve. Similarly, Nonhebel and Moss [267] present simplified drying theory in which the drying rate under arbitrary conditions is computed from an experimental drying rate curve. The forms of 'characteristic drying curves' are developed and analysed in several works by Keey et al [205], [207], [343], and their application to investigate drying rate profiles and the design of equipment are addressed in further papers [208], [209]. The purpose of this introduction is to briefly describe the broad basics of drying concepts. Mathematical explanation of phenomena such as heat and mass transfer, and inter-molecular material characteristics are beyond the scope of this introduction and the reader is advised to study the quoted texts for detailed information. Further information concerning the application of drying theory can be found in Chapters 8 & 9 with reference to the neural network modelling of microwave and convective drying.

Regardless of how heat is provided to the product, the drying cycle can be divided into three stages;

- Sensible heat must be added to the drying mass until the boiling point of the liquid under the given operating conditions is reached. Heat can be supplied by conduction, convection or radiation.

- Evaporation takes place at a rate related to the moisture level in the solid and can be described in terms of simultaneous heat and mass transfers. This period is commonly known as the constant drying rate period [199], [282], [342]. During this period the moisture content is very high and evaporation will occur from the surface at a constant rate so long as the ambient conditions remain constant. Product temperature will remain constant assuming an adiabatic process and the evolution of the air characteristics in the boundary layer surrounding the material will be isenthalpic i.e. the total energy will remain constant.

- As the moisture content reduces below a critical level, which depends on the type of material, the rate of evaporation becomes progressively less with decreasing moisture, being limited by the reduction of water transfer from the interior of the solid towards its surface. This stage is termed the falling drying rate period during which the menisci of the water pores fall below the evaporating surface thus impeding drying.

Figures 2.1, 2.2 and 2.3 show examples of drying curves for moisture content, rate of drying and product temperature, where x_p represents product moisture, v the drying rate and θ product temperature [191]. The three stages of drying are designated by regions I, II and III, where III is the falling rate period.

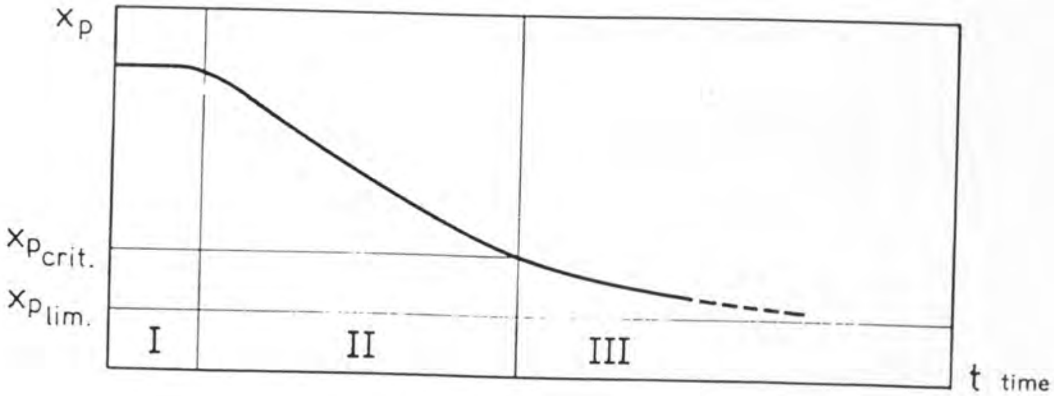


Figure 2.1 - Moisture content variation

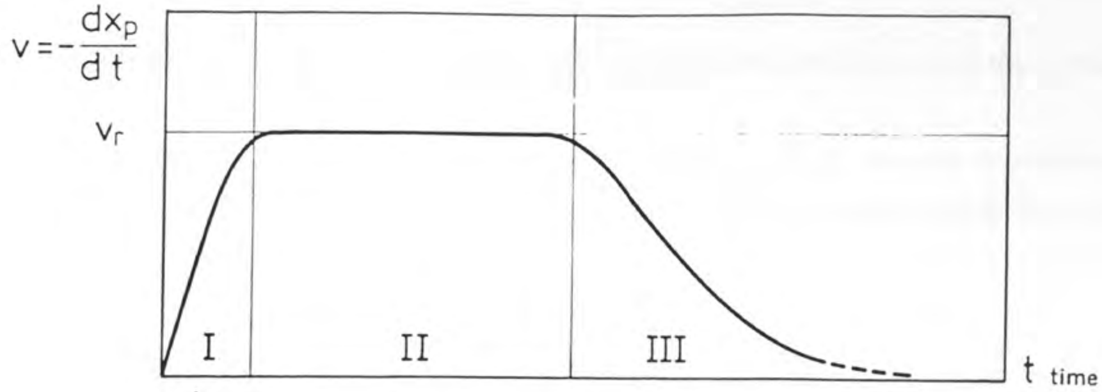


Figure 2.2 - Drying rate variation

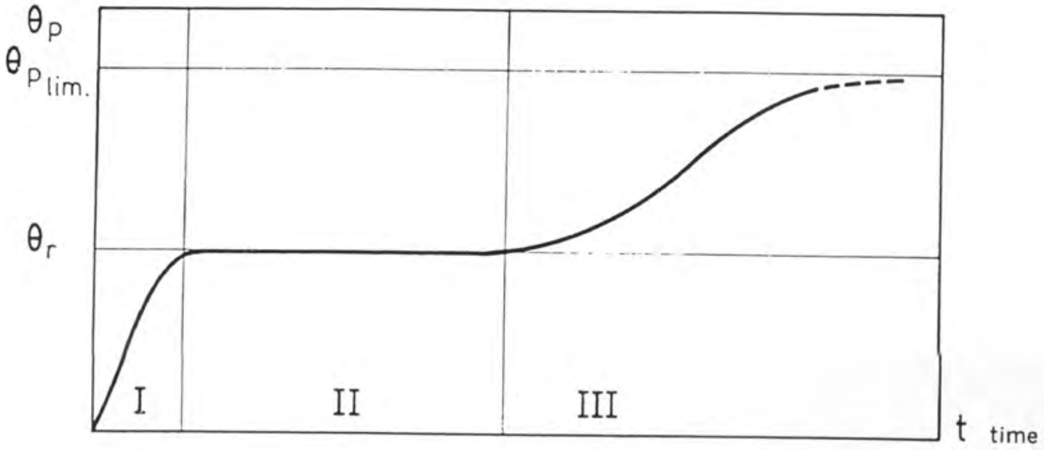


Figure 2.3 - Product temperature variation

In practice the periods of drying are not commonly well defined and transition between phases is often gradual.

Water Retention of Solids

Water within a drying mass may occur as surface, commonly termed free, mechanically bound or chemically bound moisture. Mechanically bound moisture occupies the interstices of the solid and moves to the surface through phenomena such as diffusion, capillary action, and pressure gradients [306]. Mechanically bound water may take the form of capillary bound water, or absorbed water held by Van der Waals forces. Chemically bound water often appears as water of hydration, or held by the structural reorientation of a chemical or by reaction. The heat required to release this moisture is, in addition to the heat of vaporisation, the heat of crystallisation or of reaction.

The moisture content of a product can be expressed in terms of a dry or wet weight basis [191];

Dry Weight Basis - This is the ratio between the mass of water in a material and the bone dry mass of the material.

Wet Weight Basis - This is the ratio between the mass of water in a material and the mass of the wet material.

The relationship between the two is shown in Figure 2.4 where x_{wb} and x_{db} represent the moisture content expressed on a wet and dry basis respectively. The figure demonstrates the importance of defining the exact wet or dry nature when moisture content is quoted.

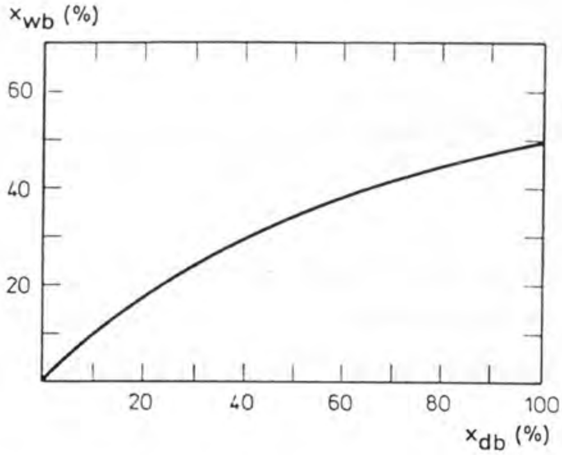


Figure 2.4 - Relationship between wet and dry weight moisture content.

Moisture Migration

Metaxas describes the fundamentals of moisture migration through a porous body in terms of capillary flow and material interaction [253]. During the constant drying rate period water is continuously supplied through capillary forces from the interior layers of the material towards the surface. Eventually a point is reached, termed the critical moisture content, where it is not possible to maintain the hot surface with moisture, resulting in the evaporating zone moving further within the interior of the solid. During the falling rate period the moisture moves towards the outer surfaces by mass flow of the liquid and vapour phases. As the solid dries out the network of capillaries ceases to be continuous introducing pockets of air which impedes the liquid migration towards the outer layer. Vapour flow is now the transfer mechanism. During this period the heat transfer rate to the interior of the solid is being slowed because of the receding boundary of the liquid. The non-wetted portion of the product thus increasing in resistance. Bories and Pourhiet [30] have analysed the mechanisms of moisture migration and Szentgyorgyi and Orvos provides a detailed description in terms of the mass and heat transfer equations [344]. A further paper by Coates and Pressburg [54] discussed the effect of drying rate changes caused by particle structure.

Drying conditions can take place at any temperature and depends on there being a vapour pressure difference between the wet body and the surrounding gas [198]. Conditions must be such as to keep the vapour pressure of evaporated liquid in the area of the dryer less than the vapour pressure of the remaining liquid. This provides a pressure differential to remove the evaporating liquid from the solids surface [306].

Liquid phase movement is related to moisture gradients and temperature, whereas in the vapour phase it is due to a partial pressure or temperature gradient [280]. Theoretical principles and postulated theories are well documented in literature, and an article by the UIE Process Heat Recovery Group provides a general background to the principles of psychrometric properties, evaporation, moisture migration and their relation to the dynamics of drying [191].

Drying Equipment

In most industrial drying operations the temperature of the body is increased to evaporate the liquid water and having a flow of heated air over the outside surface [99].

Previous studies have demonstrated that it is much more economic to remove liquid water by mechanical means than by evaporation. However, the nature of the product and final properties dictate if mechanical means can be used [198]. Mechanical processes are simple and fairly well understood including techniques of;

- Decanting,
- Filtration,
- Centrifuging, and
- Pressing using screw, roller, plate or balloon techniques.

Additional mechanical techniques include airknives, semi-permeable membranes, reverse osmosis and ultrafiltration. Only brief reference has been made to these processes and further details can be found in Chapters 4-7.

The effectiveness of a drying processes depends upon many factors including the temperature difference between the body and the drying gas, the velocity of the gas stream, the nature of the surface and the moisture and vapour transfer properties of the material [198].

Classification of Dryers

The diversity of products and the general nature of the drying process make it difficult to generalise the drying technology selection process [179]. Many factors will determine the type of drying plant to be installed. Four basic routes have been used to classify equipment; operation, type of material, scale of production and special factors which may be used separately or combined with other groupings.

Many attempts have been made to classify drying equipment. McCormick catorgorized units from the users perspective [282]. Sloan identified 20 types of dryers [323], and Lapple and Clark [224] discussed 39 designs.

Dittman [115] observed that previous classifications were difficult to follow, and reduced the principle classes to two by focusing on the methods of heat transfer; indirect or direct. Nonhebel and Moss [267] proposed a classification technique based upon method of operation, physical form of the feed and scale of operation. A summary of equipment classifications can be found in Hulls [186].

Various articles describe the classification of materials and range from microscopic properties to physical form. Hulls [186] categorised materials into eight groups including: liquid, slurry, paste, hard, granular, fibrous, sheet and preform.

Dryer Types

There are literally hundreds of different types of dryers available to industry. The variety is due to the diversity of dried product, which dictates certain variations in dryer features. Many published articles give descriptions of dryer structure, design, construction, operation and applications [6], [97], [185], [186], [179], [191], [198], [207], [233], [241], [250], [253], [260], [265], [306], [337], [378]. Van't Land [368] provides a comprehensive description of industrial drying equipment with reference to design, selection and application.

In summary common dryer types include [179], [186], [191], [250], [276], [306];

Spray : Large capacity dryer where liquids and slurries are pumped through an atomiser at the top of the dryer with a con-current or counter-current hot air stream used as the drying medium and cyclones used for product recovery. The chamber may be a vertical cylinder or conical in shape. They operate in continuous mode and are suitable for drying a wide range of materials, particularly heat-sensitive ones.

Tray : Also known as shelf or oven dryers. Product is placed on a tray supported in a chamber through which air is passed. Trays may be solid and perforated and a variety of air flows is possible using baffle plates and nozzle injectors. A variety of the tray dryer, commonly know as the turbo tray design, incorporates a wiper and cascades the product through radial slots on rotating tables. In this way a continuous flow of solid from the top of the dryer to the bottom is achieved.

Screw/Paddle: Comprises of a trough containing a screw or system of blades to feed the product through the dryer. Used to mix and dry paste or powder products.

Rotary : Versatile dryer used for liquids, slurries and powders. Consists of a cylinder inclined a few degrees from the horizontal, from 1-100m in length, rotating at 5-20 rpm. Heating either direct or indirect using con-current or counter-current flow. There are three main types; cascading or direct, louvre, and indirectly heated dryers commonly using steam tubes. They are usually operated in continuous mode.

Tunnel: Wet powders, pastes or solids are placed on conveyors, trays or trucks travelling through an enclosed tunnel. Can be single or multipass, with con-current, counter-current or through circulation, with the product on a perforated belt for the latter configuration.

Flash: Vertical system designed for drying wet particles and powders in a vertical shaft before separation in cyclones.

Fluid bed: Hot gasses are passed up through one or more beds of the wet powders or small solids, creating turbulent fluidization.

Drum/Cylinder: Drying heat is conducted through the walls of a drum from a hot medium (usually steam) on the inside to a liquid, slurry or sheet form on the outside. Can be configured as single units or in a battery for a moving web.

Several hybrid drying systems have evolved over the years including; spray drying incorporating a fluidised bed [63] and combined hot air and radio frequency [64]. Additional dryer types employ novel concepts such as in freeze and vacuum drying, and using super heated steam as a drying medium [129], [248], [340].

Electrical techniques involve the application of microwave, dielectric, infra-red heating, heat pump systems, induction rotary dryers and resistant element batteries. Electricity has also been applied for producing steam which is used in dryer systems. The benefits of using electrotechnologies for drying processes have been the focus of many publications [185], [186], [191], [233], [270].

Depending on current and expected fuel costs, the configuration of the dryer might include a waste heat recovery device. This would result in lower energy costs but higher capital and maintenance costs because of additional components.

Equipment Manufacturers

Richardson and Jensen [301] conducted a survey of dryer equipment manufacturers and analysed 17 dryer types in the United States. Typical ranges of operating parameters and concepts concerning heat recovery and energy efficient technologies were addressed, although no reference was made to specific products processed.

A literature search showed that little work had been conducted investigating the general nature of UK dryer equipment manufacturers. A questionnaire was sent to over 200 manufacturers covering a wide variety of companies (See Appendix A). Information was sought concerning the type of company, type of dryers manufactured, and general product sector areas where sales efforts were focused. In additional to providing an overall view of the industry contacts were established regarding energy utilisation figures, design data and detailed information concerned with the operation and application of drying processes.

A questionnaire return rate of about 35% yielded 70 replies covering a wide variety of manufacturers. Data showed that many companies were engaged in design, construction and installation of equipment. Only a few manufacturers did not install or commission their equipment. Table 2.1 shows the number of companies manufacturing equipment types.

Cylinder		Freeze	2	**Spray**	9	Stenter	6
Rotary	17	Solar	0				
Indirect	3			**Pneumatic**		**Multistage**	
Steam-tube	7	**Belt/Band**		Pneumatic		Combinations	
Cascading	5	Belt	13	conveying	7	of more than	
		Band	11	Flash	9	one dryer type	11
Shelf/Tunnel		Perforated		Spouted bed	1		
Shelf	6	band	8			**Drum**	
Rotating shelf	3	Plate	1	**Fluid Bed**		Drum	5
Turbo tray	4			Fluid bed	10	Rotary filter	1
Tunnel	22	**Paddle**		Fluid bed			
Oven	21	Double cone	3	granulator	5	**Mechanical**	
Impingement	6	Conical	3	Vibrated		Press	2
Dielectric/IR	10	Horizontal/vertical		fluid bed8		Centrifuges	7
Moving bed	5	Paddle	6	Torbed	0		
Package	0	Vertical pan	4	Centrifugal	2	**Other Dryer**	18
Filter-dryer	7						

Table 2.1 - Range of equipment produced by UK manufacturers

The most common 'Other' equipment type included dehumidifiers, and air knives. Figure 2.5 shows product group and the number of manufacturers with sales in these sectors. A large proportion of equipment manufacturers and installers were involved with the food, chemical and pharmaceutical industrial sectors. Due to the nature of equipment and/or industrial sector size, results indicated that industries such as the tobacco, paper and wood were supplied by only a small proportion of drying equipment companies.

Although the survey only reviewed a small proportion of the total number of equipment manufacturers, results reflected general trends in equipment sales and product areas where a substantial variety of drying equipment was utilised.

Selection of Dryers

The type and configuration of a particular dryer for a given application has significant product, capital and energy cost implications to the user. However, Holms et al. reflect the view of many stating that the selection process is more of an art than a science [179]. Reay [298] discusses the methodology of dryer design noting that there are inadequacies in the use of drying theory. Further comments of a similar nature were noted by van Brakel [367].

In a dryer design there are two basic points that require consideration;

- Method of material feed; either batch or continuous, &
- Method of heat transfer; either convection (direct), conduction (indirect) or radiation.

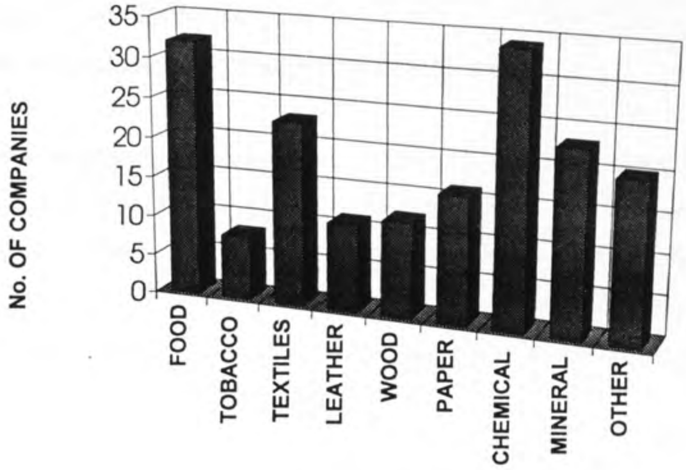


Figure 2.5 - Product sector groups and companies involved

Various characteristics require consideration before the correct dryer can be implemented including;

Properties of the material being handled: Physical characteristics wet and dry, toxicity, corrosiveness, particle size, abrasiveness, and explosiveness,

Drying characteristics of the material: Types of moisture, initial and final moisture content, and permissible drying temperature,

Flow of material through the dryer: Flowrate, continuous or batch operation, and process prior and after dryer,

Product qualities: Shrinkage, contamination, uniformity of moisture content, decomposition, temperature, and bulk density etc.

Recovery problems: Dust, solvent and heat recovery,

Installation position: Space, temperature, humidity and cleanliness of air, fuels, noise, vibrations, dust or heat losses, source of wet feed and exhaust outlet.

The problems of dryer selection have been described by Hulls [186] and include;

- A lack of standardised laboratory tests with which to provide key data on material drying characteristics. Thus there is limited basis for discussion between equipment suppliers and users,
- Only a partial understanding of the mechanisms of water removal from a solid during drying,
- A lack of understanding of exact material equipment interactions and the problem of scaling up laboratory and pilot scale data for some equipment types,
- No agreed systematic comprehensive classification of dryer types.

There is an abundance of literature concerning the application of dryer types in various situations and the operation of equipment. The selection, sizing and cost of drying equipment has been addressed by Noden [265], while Papagiannes [276] discusses several factors worth considering in dryer selection including particle size, shape, temperature limitations, specific heat, bulk density, specific gravity, viscosity and surface tension. Thurner [352], describes dryer types and comments upon the suitability with regards to operation, material type, and throughput. Many other publications address similar criteria.

With the advent and progressive development of microprocessor systems computational aids to select dryer systems have been developed. However, many manufacturers still base selection processes on past knowledge and scaling up of laboratory testing [63].

An expert system was developed by the Electricity Council Research Centre (now EA Technology), Capenhurst, UK in the 1980s concerning the selection of electrical drying methods. The system was based upon a Leonardo expert system shell and provided the user with a broad database of electric applications and methods [64], [67]. Information concerning product type, e.g. sheet bulk etc., throughput, degree of utilisation, and value of product is input and using a rule based system an appropriate system is suggested. Feedback from users showed that the system offered limited potential due to the generalisation of data and lack of specific details concerning product properties.

A recent development is a tool produced by the Separations Process Service, Harwell, UK [91]. The package uses a wide variety of information from product properties, which can be entered from experimental trials or selected from a comprehensive database. Additional information required relates to the drying regimes. The results of the selection of drying systems are ranked in order of preference, with constructive notes enabling the user to chose the appropriate system. The system is still undergoing commissioning trials and a users perspective was unavailable.

Due to the complexity of drying processes and lack of quantitative understanding of the fundamentals of drying it is envisaged that expert systems will never completely replace experimental trials or selection based upon past experience. However, in the near future, these systems could reduce development time and the extent of experimental trials by focusing on specific equipment areas before costly investigation commences.

Drying Process Applications

A literature survey together with information from equipment manufacturers and industrial users showed that there are a very great number of drying applications in industry. Units vary from custom designs to off the shelf components [63], [65], [186], [301].

	FOOD	**TOBACCO**	**TEXTILES**	**TIMBER**	**PAPER**	**CHEMICALS**	**RUBBER AND PLASTICS**	**STONE, CLAY AND GLASS**
DIRECT - CONTINUOUS								
FLUIDISED BED						X	X	X
TUNNEL			X	X		X	X	X
THROUGH CIRCULATION		X	X			X	X	
SPRAY						X	X	X
ROTARY						X		X
CONVEYOR		X	X		X	X	X	X
SHEETING					X		X	
TRAY		X	X	X		X	X	
FLASH						X	X	
TOWER								
DIRECT - BATCH								
TRAY	X					X	X	
INDIRECT - CONTINUOUS								
CYLINDER	X				X			
ROTARY	X					X		
SCREW CONVEYING	X					X		
DRUM	X		X			X	X	
INDIRECT - BATCH								
VACUUM ROTARY	X					X		
FREEZE	X					X		
AGITATED PAN								

Table 2.2 - Typical drying applications

A review and detailed description of material processes and equipment utilised is beyond the scope of this introduction. In-depth descriptions of processes within the ceramics, paper and timber industry can be found in Chapters 4-7. A publication by the Process Heat Recovery UIE Working Group provides an excellent review of electrical drying applications [191], while sales information from equipment suppliers and trade organisations details specific equipment and case studies of installations. Table 2.2 shows a generalised classification of equipment and product area [186], [301].

CHAPTER 3

ENERGY UTILISATION FOR DRYING PROCESSES

Introduction

The two oil crises of the 1970s stimulated the need for a more rational, comprehensive and long term management of energy resources. Energy is now a key factor and will become increasingly important.

Energy is a vital commodity used widely throughout both the industrial and public domain. Many investigators have studied energy consumption for specific industrial unit operations. Drying is one such industrial unit operation and past studies have indicated that drying is widely employed in a large number of UK industries and is a major consumer of energy [16], [131], [177], [249], [251], [267], [297], [338], [380], [382]. Analysis of the trends and current consumption of energy for industrial drying is an important quantity. Figures enable two areas to be studied;

- Development of an in-depth understanding of energy utilisation within industry. Demand and supply networks can be planned and maintained to meet industrial requirements.

- Analysis of areas for potential energy conservation. These could be machine, process, sector or product specific. Results could lead to a reduction in energy costs, increased production, and a more environmentally friendly drying process.

The latter is an important factor when considering the rise of energy prices, legislation on pollution, working conditions and safety, which have become more stringent during the last decade. An estimated 820 million tonnes of CO_2 are produced annually by industry in the European Union. A reduction of 119 million tonnes per year has been proposed as achievable through improved energy efficiency in industry [132]. To meet these requirements and optimise energy consumption new thinking in drying methods and dryer design is required [338].

Energy auditing and estimations of consumption does not appear, according to a literature survey, to be a regular topic for examination. Published results have been examined and up-to-date and regular auditing does not take place. The last published estimation [380] in 1982, apart from an overall report for the chemical industry [249] and a European review of the ceramics industry [132], is now thirteen years old. Industrial energy consumption has shown a decrease during the last decade [123], [124]. These trends emphasise the need for regular estimates of energy consumption for industrial drying. According to experts within the field [91] there is no current work involving energy consumption for drying in UK industry.

Investigation of previous studies has shown that no common approach has been taken to estimate the energy consumption in industrial drying. The lack of a common methodology has led to problems of comparing data and examination of energy trends.

Overall Industrial Energy Consumption

Many sources are published regularly concerning overall energy usage both industrial and in the public sector [122], [132]. Additional texts generally comment on energy figures [117], [267], [338], [347]. Figure 3.1 shows the variation of industrial energy usage from 1970 to 1991 [122].

Energy data was taken from an audit of fourteen industrial sectors;

- Iron and steel,
- Chemical,
- Petrochemical,
- Non-ferrous metal,
- Non-metallic mineral,
- Transport equipment industry,
- Machinery industry,
- Mining Industry,
- Food and tobacco,
- Paper and pulp,
- Wood industry,
- Construction,
- Textile and leather, &
- Non-specific industry.

These industrial components were selected due to their large energy consumption. Others were considered negligible.

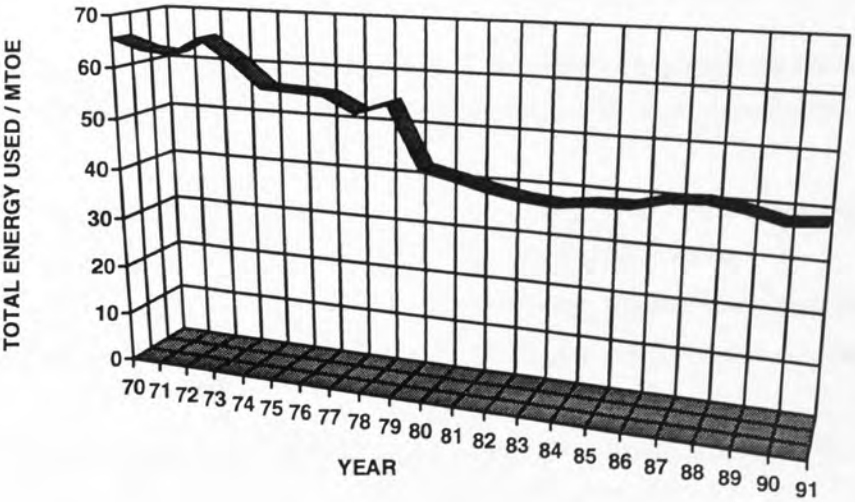


Figure 3.1 - UK Industrial energy consumption 1970 - 1991

Figures show a trend of decreasing consumption within the industrial sector (65.61 million tonnes of oil equivalent in 1970 to 41.47 MTOE in 1991 [122]). Figure 3.2 shows the production index and ratio of industrial energy consumption to production. Although the production index has risen over the last two decades, the decrease in the ratio is not proportional. Thus, the amount of energy consumed by industry has declined, although overall production has increased. i.e. more effective energy efficient production methods are being employed.

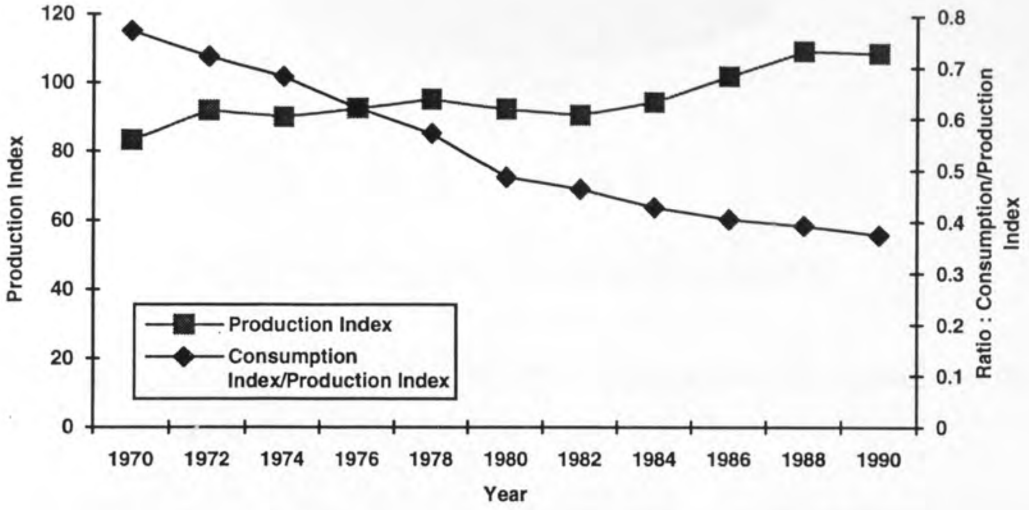


Figure 3.2 - Production index and the ratio of industrial energy consumption index to production index [122]

Energy Consumption for Drying Processes

Background

The thermal efficiency of a dryer is expressed as the ratio of heat required to provide the necessary latent heat of vaporisation to the heat actually used. The energy demand of an industrial dryer can be divided into [338];

- Energy required for evaporation of moisture,
- Energy lost in exit air stream,
- Energy lost through wall of dryer,
- Energy lost through sensible heating of product,
- Energy required to heat dryer structure and enclosed air volume,
- Energy required to move product through dryer,
- Energy required for air circulation.

Clegg presents an energy audit for a typical convection dryer [53]. Figure 3.3 shows the estimated energy balance.

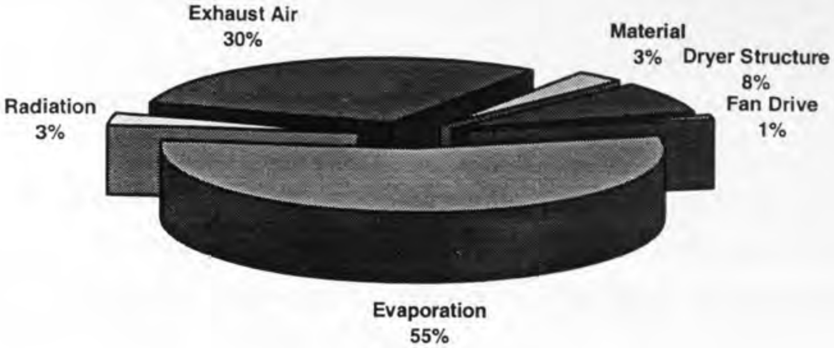


Figure 3.3 - Energy utilisation in a convection dryer [53]

Figure 3.3 demonstrates that most of the energy used within a drying system is for evaporation of the moisture. Energy lost through exhaust gas venting is also significant.

Energy efficiency, also commonly termed thermal or operating efficiency, is a phrase for describing the concept of economic efficiency of energy utilisation [124]. When applied to a machine it is the ratio of the output energy, i.e. the energy utilised, to the input energy. The energy supplied can be based upon thermal heat into the material or dryer, or calculated on a fuel basis. The latter takes into account burner efficiencies etc.. Figures for energy efficiency are widely stated in industry, although the base is not always defined. In an industrial process there may not be an output energy, and energy efficiency must be related to a theoretical minimum or absolute standard. Figures calculated in this thesis are based upon the thermal energy supplied to the dryer and theoretical heat required to remove the resident water unless stated otherwise. A common term used is the specific energy consumption (SEC). SEC is the quantity of delivered energy used to process a unit mass of product. Alternatively, the energy consumption is related to the quantity of water removed. SEC values allow comparison of a specific product or process. Thermal efficiency (thermal energy basis) of a dryer has been described in terms of the dryer dry-bulb inlet and outlet temperatures (T_{in} and T_{out}) and the ambient air temperature (T_{amb}) according to the expression [171], [177];

$$Efficiency = \frac{T_{in} - T_{out}}{T_{in} - T_{amb}} \tag{3.1}$$

Similar equations have been derived to account for partial air recirculation [177], [220]. However, Equation 3.1 is only suitable for the assessment of low temperature, low humidity drying [11]. Ashworth presented results concerning the energy efficiency of direct convective drying of solids expanding Equation 3.1 to include terms of energy mass transfer defined using dimensionless potentials [11]. Comments were made concerning the relationship between parameters on the efficiency of the system. However, many of the parameters formulated cannot normally be determined in an industrial situation without extensive laboratory trials in controlled conditions. Cook and DuMont assessed the influence on energy efficiency by varying drying parameters using a spread sheet technique and experimental dryer data [96]. Information was based upon generalised machine auditing and limited the study to a specific machine type, processing a single product.

Thermal Efficiency of Drying Processes

The capital costs of equipment, together with the influence on product quality and productivity are the fundamental factors assessed when considering the implementation of new technology for drying processes. Energy consumption commonly takes a low priority. However, over the lifetime of machine operation the fuel costs are very significant as illustrated in Figure 3.4 [15].

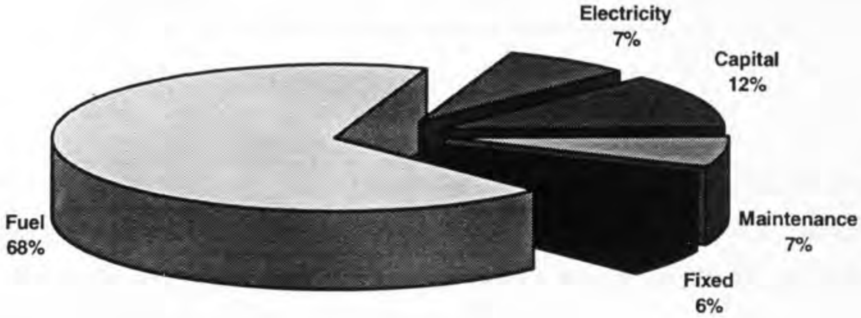


Figure 3.4 - Typical life-time costs for a rotary dryer

Including electrical consumption energy represents approximately 80% of the total costs incurred over the equipment lifetime. Implementation of energy efficient measures could result in significant cost and environmental savings.

Much of the equipment used for drying operations in the UK was designed and built during a period of comparatively low energy prices [131] and industrial dryers are frequently operated at thermal efficiencies well below their potential [15]. Reay suggested that the energy efficiency of drying equipment was certainly less that 50%, and could be as low as 25% or 20%, although using modern techniques efficiencies up to 80% could be achievable[295], [296], [297]. Stratton [336] reported that it was rare for energy consumption to be less that 3 kg steam per kg of water evaporated for dryers operating under atmospheric pressure, i.e. an energy efficiency of about 25% thermal basis. Strumillo and Lopez-Cacicedo suggest that the energy efficiency of continuous dryers ranges from 25 to 75% [338] while Pratt [291] stated that the energy efficiency of industrial direct-contact dryers is often about 30%. However, in the above cases a base for energy efficiency calculations was not defined thus hindering comparison of efficiency figures. Richardson and Jensen describe details of a comprehensive survey of drying equipment performed in 1976 [301]. Thermal efficiencies of 17 dryer types were analysed using equipment manufacturers data. Thermal efficiencies ranged from between 20% for a tower dryer, to 92% for an indirect cylinder dryer. Table 3.1 summaries their findings. Information from equipment users was not examined and the application of the results to industrial applications is questionable as only commissioning and design data was assessed. A base for efficiency calculations was not stated but figures suggest a thermal basis.

DRYER TYPE	THERMAL EFFICIENCY (%)
Pneumatic	20 - 75
Spray	50
Tunnel	35 - 40
Fluidised bed	40 - 80
Rotary	75 - 90
Cylinder	90 - 92
Infra - red	30 - 60
Dielectric	60

Table 3.1 - Thermal efficiency of dryer types [301]

Care is required when analysing efficiency values due to the exclusion of additional factors such as burner efficiency, steam distribution system etc. Several studies have published proposals for a standard production index for specific equipment types [17]. However, figures of this nature are not commonly used due to the cost of field testing, and the lack of standardisation on testing procedures.

Mercer describes details of the range of energy efficiency of drying equipment [250]. However, no reference is made to exact processes or materials. Table 3.2 summarises range of efficiencies.

DRYER TYPE	TYPICAL SEC (MJ/kg water)
Rotary	3.0 - 12.0
Band tray and Tunnel	3.5 - 16.0
Drum	3.0 - 12.0
Fluidised bed	3.5 - 8.0
Spray	3.5 - 10.0
Stenter	5.0 - 12.0

Table 3.2 - Variation of thermal efficiency [250]

Energy consumption varies considerably depending on the material and drying technique used [250]. Analysis of previous studies has demonstrated that the thermal efficiency of equipment is dependant upon criteria such as machine type, operating conditions, nature of product, age and condition of the equipment. Many studies have quoted efficiencies of equipment without any reference these influencing factors.

General Energy Saving Measures

The scope of improved energy conservation in process plant has been described in detail in the literature [12], [13], [14], [15], [16], [117], [163], [171], [218], [220], [223], [257], [263], [264], [266], [285], [295], [296], [297], [301], [335]. A text by Mercer provides a detailed introduction to energy efficient measures. Technologies are discussed including case study examples of industrial practices, comments on operational experiences, and economic benefits [250].

Many of the issues addressed by previous studies include; good housekeeping measures, heat recovery, insulation, improved control and production scheduling, reducing feed stock moisture content, utilisation of direct heating, air recirculation, maximising the temperature drop across the dryer system, alternative fuel resources, stage and combination dryer systems, and the analysis of burner efficiencies. Further articles have described details of performing energy audits on drying systems with the aim of reducing energy consumption and improve throughput, quality and environmental emissions [12], [13]. The study was confined to thermal drying. However, many sources suggest that thermal efficiency can be increased by employing mechanical dewatering methods such as; filter presses, vacuum filters, centrifuges, reverse osmosis and electrokinetics which require substantially lower amounts of energy [338].

Previous Studies Relating to Industrial Energy Consumption for Drying Processes

A literature survey showed that many studies have been conducted concerning energy utilisation for drying processes. To provide a basic background to energy consumption past studies were examined in detail and comments made concerning methodology and accuracy of results. A comparison of previous studies was also performed to examine trends in energy usage.

The work of Hodgett [177] is widely referenced, and quoted by many industrialists. Hodgett estimated the energy usage in industrial drying by selecting 14 product areas. The water removed was calculated by examining the typical change in moisture content during drying and relating this value to the annual production. Table 3.3 shows the results. An estimated 17.4 million tonnes of water was removed. However, due to assumptions made 20 or 30 million tonnes was suggested as more appropriate. A thermal efficiency of 50% was assumed yielding an energy consumption of 148 million GJ, or 6% of all prime energy used by the industries in question in 1976. The methodology used induced many inaccuracies. Limited materials were considered and the whole of the chemical, pharmaceutical and foodstuff industrial sectors were not included. It is common knowledge that drying is a major energy consumer within these sectors [124], [249]. Results were increased in order to cover these sectors, however, the method of increase is not justified, and the author states that it is an 'approximate guess'. The accuracy of the moisture content drop is questionable. Even for the same product, the moisture content before and after drying will vary enormously depending upon production methods and drying technique used. A constant thermal efficiency of 50% was used throughout the estimation. This is a very general assumption, although the variation is addressed. It was noted that the estimation does not include energy for motive power or for devices such as pumps, motors and fans etc.

MATERIAL	ANNUAL PRODUCTION Million tonnes	AVERAGE MOISTURE CONTENT DROP %	WATER REMOVED Million tonnes
Paper and Board	4.6	200	9.2
Bricks	15.7	15	2.4
Milk, dried	0.21	900	1.85
Milk, condensed	0.17	500	0.85
Gypsum	3.7	20	0.74
Plaster and plasterboard	2.3	45	1.0
Textiles	1.4	30	0.4
China clay	3.5	10	0.35
Fertiliser	4.0	3	0.12
Timber, softwoods	0.27	45	0.12
Timber, hardwoods	0.24	20	0.05
Dyestuffs	0.1	50	0.05
Vitrified clay pipes	0.75	15	0.11
Tiles, pottery and sanitary ware	1.0	15	0.15
Total of 14 Materials	▨	▨	**17.4**

Table 3.3 - Water removed in 14 industrial product groups

Baker and Reay published details of a survey of industrial drying in 1982 [16]. Energy data was combined from the Department of Trade and Industry Thrift and Audit reports, the US Department of Energy targets and the Digest of UK Energy Statistics. Six selected industries were analysed, relating production levels of specific products to values of specific energy consumption and hence annual energy figures. Data was verified by discussions with research associations, the Energy Technology Support Unit (ETSU), National Engineering Laboratory, and the Electricity Council. Table 3.4 summaries the results.

INDUSTRY SECTOR	ENERGY CONSUMPTION (Million GJ/year)	
	DRYING	TOTAL SECTOR ENERGY USE
Food and Agriculture	35	286
Chemicals	23	390
Textiles	7	128
Paper	45	137
Ceramics and building material	14	127
Timber	4	35
Total	**128**	**1103**

Table 3.4 - Summary of drying and total energy usage in selected UK industries.

Results concluded that drying accounted for 11.6% of the total energy consumption in the sectors investigated.

The estimation states energy data on a gross basis. Thus losses and inefficiencies of equipment were included within the figures. No breakdown or method of drying efficiency relating to specific product/process was described. Furthermore, methodology for the calculation of specific energy consumption was not disclosed. World-wide data was used for the analysis of some products, and may not truly reflect the situation in the UK. Although a vast quantity of products were analysed for each industrial sector error would have arisen due to exclusions. The authors estimated the percentage of the total product range covered by the survey within each sector and compensated for insufficient analysis by increasing the energy figures. However, little justification to the methodology applied was described.

PRODUCT	WATER REMOVED (kt)
Sugar	14400
Paper and board	6800
Clay bricks	1097
Timber	250
Skimmed milk	230
Condensed milk	145
Raw clay	120
Compound fertiliser	112
Dust for tile making	108
Instant coffee	92
Shaped refractioners	91
Cotton	84
Drystuffs/pigments	72
Gelatine	65
Fullers earth	64
Cellulosics	57
Electrical porcelain	6
Wool	53
Vegetables	42
Condensed sweetened milk	33
Tableware etc.	31
Nylon	25
Polyester	23
Whey	19
Tiles	19
Tobacco	18
Sanitary ware	18
Acrylica	17
Potatoes	13
Plaster moulds	2
Instant tea	1.7
Whole egg	1.5
Glazed ceramics	1

Table 3.5 - Water removed for various products.

A similar analysis to that of Hodgett [177], using product moisture changes during drying, was the basis to a survey conducted by Witt of the Electricity Council Marketing Department [382]. The survey included an estimation of the weight of water removed for a selection of products and described details of typical machine operating characteristics. Table 3.5 shows the results. An estimated 24.1 million tonnes of water was removed by drying in 1978. Little information regarding the energy efficiency of equipment was described. The lack of product detail and exclusion of product groups will have caused error.

ETSU [131] published details of a study investigating drying, evaporation and distillation in twelve industrial sectors in 1985, although much of the data was based upon information from the late 1970s and early 1980s. The choice of sectors was limited to those that consumed in excess of 2×10^{15} J a year for drying. Various techniques were employed to estimate the energy usage in each sector. Production levels were used in conjunction with information from trade organisations, producers, audits of manufacturers and data from the large scale Energy

Thrift Schemes conducted during the late seventies. Specific energy consumption per unit produced were linked to recent production figures. Table 3.6 shows the findings of the survey.

PRODUCT	ENERGY USED FOR DRYING. MILLION GJ PER YEAR
Malt	5.4
Whisky by-products	n.a.
Milk powder	2.2
Sugar (beet)	4.0
Beet sugar by-products	4.5
Pottery	3.4
Bricks	8.9
Timber	3.1
Textiles	9.3
Laundries	6.3
Dry cleaning	n.a.
Paper and board	38.6
Chemicals	18.1
Total	**103.8**

Notes n.a. means data not available.

Table 3.6 - National energy use for drying, 1981.

A total drying energy consumption of 103.8 million GJ/annum was estimated, i.e. about 6% of the total industrial energy consumed in 1981. Errors due to limited product/sector analysis will have occurred. Moreover, there was little indication of exactly where figures had originated from, their accuracy or validation, or what aspects of the energy utilisation they covered. The inclusion of energy used for motive power, fans, drives etc. was not apparent.

The work of Wilmshurst added to the study conducted by ETSU [131], [380]. Wilmshurst carried out an estimation of the energy usage in industrial drying for the year 1981. Figures were taken from ETSU reports [131] and the Industrial Energy Thrift Schemes (IETS) were combined. Additional product sectors were analysed and data obtained from IETS reports, trade organisations, and by directly contacting the producers. In some sectors energy consumption was linked to production levels. Findings are shown in Table 3.7.

Total industrial energy usage for drying was estimated to be 144.1 million GJ in 1981, i.e. about 8.3% of the total energy consumed in industry that year. A machine efficiency of 35% was used throughout the analysis, although a few examples which varied significantly from this postulation were noted. As with other studies of this nature limited industrial sectors were analysed and confined to industries consuming more than 0.1 PJ/year. Furthermore energy consumed by drives, fans etc. was not included in the study.

A further literature survey uncovered numerous studies concerning the energy usage characteristics of specific machine types or the analysis of single product groups. The large amount of work conducted is beyond the scope of this general review of energy utilisation. However, reference has been made to relevant work and can be found in Chapters 4-7.

PRODUCT	ENERGY PJ
Malt	5.4
Whisky by-products	1.0
Milk powders	2.2
Beet sugar by-products	4.5
Breakfast cereals	0.5
Seed cake	0.5
Meat and bone meal	2.0
Maize starch	0.3
Gluten	0.4
Fish meal	0.4
Dried potato	0.7
Dried vegetables	0.1
Coffee	0.4
Pasta	0.1
Drystuffs	2.9
Polymers	3.2
Inorganic Chemicals and Fertilisers	14.2
Organic Chemicals	2.9
Miscellaneous chemicals	6.3

PRODUCT	ENERGY PJ
Textiles	10.3
Leather	1.2
Paper and Board	38.6
Bricks and tiles	3.0
refractories	0.5
Asbestos products	0.1
Plaster and plasterboard	4.7
Pottery	3.4
Cement	14.8
Timber	3.1
Laundries	6.3
Rubber	0.1
Salt	0.1
Road stone	7.5
China clay	4.4
Potash	0.2
Fluorspar	0.1
Ball clay	0.2
Fuller's earth	0.6
Silica sand	0.6
Limestone and dolomite	0.4
Chalk	0.7
Tobacco	0.1
Pharmaceuticals	0.5

Table 3.7 - Energy consumed for drying

Previous work was also located which examined specific industrial sectors. A large scale series of audits was conducted in the 1970s by the government and termed the Industrial Energy Thrift Scheme. The study involved substantial detailed reviews of key industrial manufacturers and included all aspects of energy utilisation and was not purely confined to drying processes. The results of these surveys are well documented in literature [124]. Two further surveys worthy of note are the analysis of energy use in the chemical sector [249], and a review of the ceramics industry [132]. The former reviewed machine usage and estimated the energy consumption of rotary, spray and band dryers. No reference to product types, or specific production processes were described. The ceramics survey covered tableware, tiles, and sanitaryware, using industrial data from trade organisations, research institutions and manufacturers. The report was based upon European data, which in some cases shadowed the overall view of the UK industry. Furthermore, no assessment of the energy used for space heat, a common mode of drying within the industry where the factory work area is heated, was made.

The following points summarise problems with previous estimates of the energy utilised for drying processes in the UK;

- All studies considered a small group of industrial sectors and limited specific products/processes within the selected sectors were investigated. Some sectors were excluded from the analysis, which could consume a substantial amount of energy.

- Many of the previous studies assumed a set machine efficiency. This study has shown that the efficiency of drying equipment varies considerably between products, processes, and is dependant upon the integration of the drying stage in the manufacturing system.

- In many cases, little information was provided on the reliability of information, comparison or variation of energy values for specific processes, and in some, the source of information.

- The energy consumed by drives, pumps and fans etc. was excluded during many studies and in others the exact components of the values stated were unclear.

Figure 3.5 shows a comparison of previous studies relating to overall UK industrial drying energy consumption.

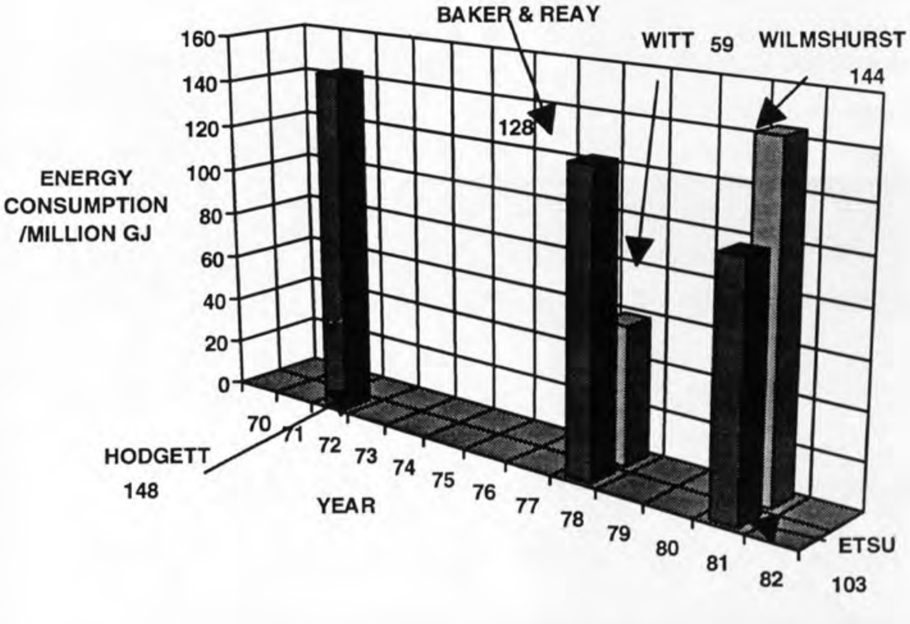


Figure 3.5 - Drying energy consumption in the UK for previous surveys studied

Comparison of previous studies, as shown in Figure 3.5, demonstrates that no defined trend can be established. Witt assumed a thermal efficiency of 100% which is technically not feasible. Investigation has shown that no common approach has been taken to estimate the energy consumption in industrial drying. Furthermore, errors could not be attributed to the methodology of the surveys conducted. The lack of product coverage and detailed information relating to specific sectors appears to be the fundamental cause of error.

Estimation of Trend in Energy Consumption for Drying

Methodology

A comprehensive review of previous literature showed that analysis of the energy utilised for drying processes was not a regular topic for examination. The last published survey was conducted in 1982 [380] and an analysis of the trends and variation of consumption could not be assessed. A decision was made to use a previous method to provide an estimated update of energy consumption.

The update survey was performed to;

- Investigate which industrial sectors consumed a large amount of energy for drying processes. Furthermore, highlight areas where the drying energy represented a large proportion of the total energy consumed,

- Analyse the general trend of energy consumption over the last decade, and compare drying energy variation to the total consumption,

Methods of using moisture changes were considered but not implemented due to the limited product range covered in these surveys. Re-examination of large scale industrial audits was considered time consuming and of little potential. The method employed by Baker and Reay [16] of using SEC and production values was selected.

Calculations using original SEC values was considered appropriate for an initial trend analysis, although this assumed that the energy efficiency of drying equipment had not changed significantly over the last 10 years. Industry was grouped into six sectors;

- Food and agriculture,
- Chemicals,
- Textiles,
- Paper,
- Ceramics and Building Material, &
- Timber.

In each sector a variety of products were selected, and production figures combined with SEC values yielding an overall figure for drying energy consumption. Baker and Reays study had been for the year 1978. A reestimation using production figures every two years was performed although availability of production data for all products limited analysis to 1990. Various sources of information were used including statistical books of production [42], [47], [113], [149], [192], and the Government Business Monitor series. Trade organisations were consulted [72], [73], [74], [75], [76], [79], [85], [87], [88], [90], [93]. Figures regarding energy consumed by the timber industry and quantity of timber dried were not available due to the original source [25] changing the category of energy sectors. The exclusion of timber from the whole trend estimate was unavoidable due to the missing data.

Results

Table 3.8 compares energy for drying with total energy usage for the sectors studied.

INDUSTRIAL SECTOR	YEAR ENERGY Million GJ							
	1978		1980		1982		1984	
	DRYING ENERGY	TOTAL ENERGY	DRYING ENERGY	TOTAL ENERGY	DRYING ENERGY	TOTAL ENERGY	DRYING ENERGY	TOTAL ENERGY
FOOD AND AGRICULT.	35.42	286.44	37.80	197.71	39.29	173.34	41.40	168.38
CHEMICALS	23.00	461.80	21.29	435.74	20.44	420.23	24.06	404.30
TEXTILES	7.30	127.77	5.96	98.33	5.18	84.51	6.00	78.40
PAPER	44.83	137.16	43.29	116.37	38.57	90.20	42.81	91.16
CERAMICS/BUILD. MAT.	10.40	127.76	8.76	114.89	7.11	99.70	7.84	100.23
TOTAL	**120.96**	**1140.94**	**117.11**	**963.04**	**110.61**	**867.99**	**122.1253**	**842.46**
DRYING % OF TOTAL	**10.60 %**		**12.16 %**		**12.74 %**		**14.49 %**	

INDUSTRIAL SECTOR	YEAR ENERGY Million GJ					
	1986		1988		1990	
	DRYING ENERGY	TOTAL ENERGY	DRYING ENERGY	TOTAL ENERGY	DRYING ENERGY	TOTAL ENERGY
FOOD AND AGRICULT.	40.79	167.86	38.89	168.49	42.06	172.82
CHEMICALS	25.34	338.15	26.62	352.3	26.62	354.60
TEXTILES	5.73	52.12	5.91	54.75	5.16	49.48
PAPER	46.15	91.80	52.55	93.90	58.92	102.44
CERAMICS/BUILD. MAT.	7.69	105.08	8.67	108.35	8.38	96.64
TOTAL	**125.72**	**755.01**	**132.65**	**777.79**	**141.15**	**778.98**
DRYING % OF TOTAL ENERGY	**16.65 %**		**17.05 %**		**18.19 %**	

Table 3.8 - Summary of drying and total energy estimation.

Figure 3.7 shows that the overall consumption of energy within industry fell dramatically during the early 1980s, reaching a plateau in about 1985. Drying energy consumption also reduced between 1980 and 1992 reaching a minimum around 1982. However, during the latter part of the 1980s drying energy consumption increased steadily, and represented approximately 18% of the total energy consumed in 1990.

Comparison of the results shown in Table 3.8 and detailed examination of specific sectors, as described in Chapters 4-7, show discrepancies. Accuracy of the updated energy study figures is questionable. Errors can be attributed to the validity of the SEC values quoted by Baker and Reay [380]. Moreover, the method does not account for any change in energy efficiency characteristics of drying equipment over the last decade. These factors and the limited product range covered within each sector will have contributed to errors. However, figures give a general impression of the magnitude of energy used within the six sectors and estimated proportion of the drying component.

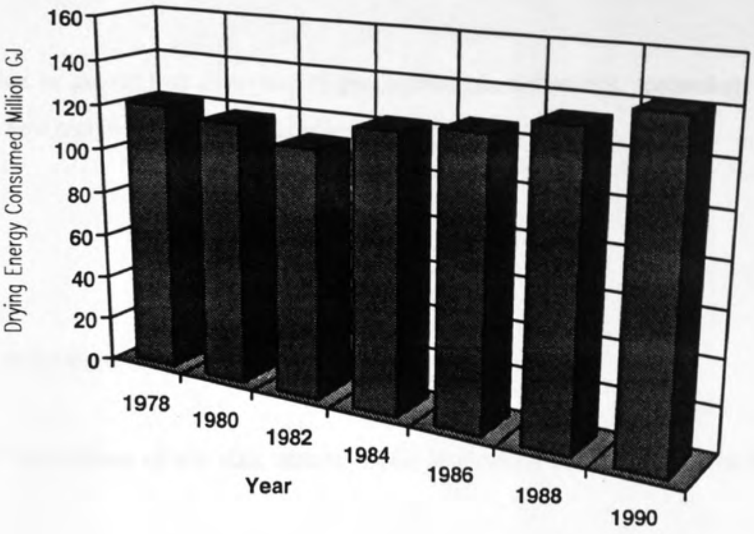


Figure 3.6 - Variation in drying energy consumption

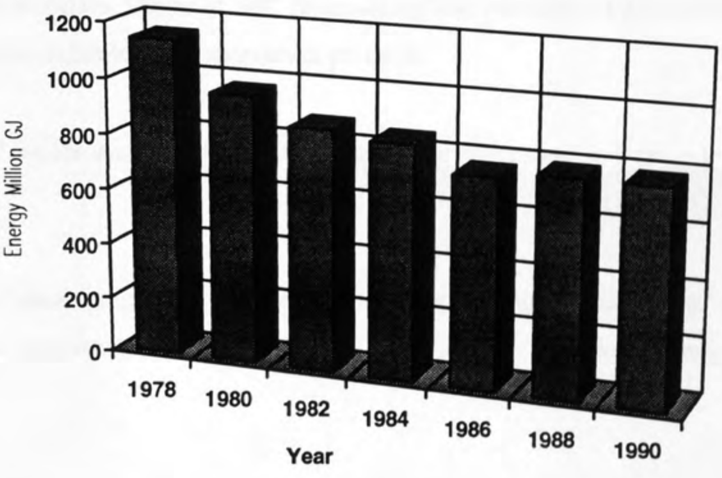


Figure 3.7 - Total industrial energy consumption.

Table 3.8 shows that the chemical, food, building materials and paper industry are large consumers of energy. Moreover, a large proportion of the total energy is used for drying within the paper, food and chemicals industry. Less energy is consumed for drying within the buildings material and textile industry, although still a significant proportion of the total.

Investigation of Drying Energy Consumption

The study was intended to provide an overview of production characteristics, technology, energy use, level of energy efficiency and new technologies in the relevant sector.

Aims and Objectives

The objectives of the study were;

- Provide a detailed description of the size, structure and production characteristics of the selected industrial sector,
- Provide a detailed breakdown of energy consumption within the sector for major processes or activities, and evaluate specific energy consumption (SEC) per unit of output,
- To comment upon the variance of SEC for drying processes within a sector, process or specified product type. To identify, if appropriate, values of SEC representing best practice and potential target values, highlighting efficient innovative technologies, processes or products,
- Estimate overall sector energy consumption for drying processes, and provide a critical comparison to previous studies,
- Describe briefly past, present and developing energy efficiency techniques, equipment and practices. Comment where appropriate on the technical potential for improving energy efficiency using these technologies,
- Investigate fully the potential aspects of the implementation of energy efficiency including operators views, technology available, and degree of utilisation of efficient systems.
- Highlight potential target areas for energy efficiency demonstration schemes, implementation of techniques, the focus of research and technical development. Including areas for optimisation and improved operating of dryers, instrumentation, dewatering techniques, and heat recovery aspects.

Selection of Industrial Sectors

Initial investigation into industrial drying processes showed that data concerning energy utilisation was commonly not available. Furthermore, many processes, especially within the chemicals and pharmaceutical industry were commercially sensitive, and information regarding processes used, products and machine operating characteristics was unavailable. Due to these problems and further restrictions placed by the time restrictions of the project the decision was made to analyse only a few industrial sectors. A detailed survey of a few sectors was considered to be more beneficial than a general overview of industry, which would involve large assumptions and be of limited industrial use.

The food and chemical industry consume a large amount of energy according to the updated estimation performed using the methods proposed originally by Baker and Reay [16]. Moreover, an estimated 24% of the total energy is used for drying processes in the food sector, although in the chemicals industry only approximately 7.5% of the total is used for drying. A large variety of products are manufactured within each sector and a substantial range of equipment and processes are used. Competitiveness was significant and initial contact with industry [65] showed that data was not readily obtainable. More co-operation with industry, research and trade organisations would be required if a detailed review of these industries is to be performed.

The update survey of this study estimated that 10% of the energy consumed by the textile industry is used for drying process. Information from companies within the industry [65] showed that monitoring of drying equipment was not performed on a regular basis. Furthermore, steam heated systems were commonly used. Collection of energy data would require substantial effort involving the installation of steam consumption monitoring equipment. Instrumentation is presently expensive and would involve disrupting the process during commissioning. The sector was not examined in detail due to the time limitations and un-willingness of industrial companies to assist in data collection.

The paper, timber and ceramics sectors were selected for analysis. An abundance of literature reported that the energy consumption for paper manufacture was very intense, with drying representing a large proportion of the total utilised. However, limited analysis of the UK industry was found during a literature survey. Little information was available concerning the timber industry and details of equipment utilisation and the quantity of timber processed was not available. Over the last decade several British Standards have become mandatory concerning the drying of timber, and the effect on the timber drying market or trend in energy use have remained to the authors knowledge unexamined in the past. The ceramics industry was selected due to the impetus placed by past literature upon the traditional nature of the manufacturing processes used. Although the general energy estimate showed that drying only represented a small proportion of the total usage, figures were considered inaccurate due to the limited product types studied. In this view the potential saving offered by the implementation of new technology within the ceramics industry was considered substantial.

Methodology of Data Acquisition

Information was gathered from equipment manufacturers, trade and research associations, consultants within the field, energy utility companies, national statistics and manufacturers. Communication with industry showed that few companies were able to fully relate their drying energy consumption to production variables. In many industries output was commonly measured in pieces, giving no indication of weight of product or water removed during drying.

In particular cases detailed figures were available through equipment monitoring by manufacturers. However, a proportion of data was assessed by examining commissioning specifications, design details, and general views from operators. Other energy values were based upon financial information, fuel prices and calorific values. The oldest data relates to 1993 and the most recent 1996.

Some data obtained described detailed product and energy information and was subject to commercial confidentially. Much of the data collected was generalised and links to specific product brands, processes, and exact equipment type in custom processes were not made.

The payback of many energy efficient technologies is largely influenced by factors other than energy savings. For example, productivity, maintenance, manning levels, product quality and environmental aspects. Associated payback times and benefits have been stated for known industrial situations, however a complete analysis of the economic reasoning of applying energy efficient concepts have not been addressed fully.

Benefits of Energy Study

A vast source of literature exists concerning previous studies relating to drying processes. Much of this information lacked clarity concerning exact definitions of drying, process under examination, and source and verification of utilisation data. This study was based upon information provided by industry, concerning only the UK market. The utilisation of industrial data enabled a realistic assessment of techniques and applications, providing practical information concerning the scope of technology and energy targets.

The results of the study will be of potential use to inform and motivate key personnel, including energy users, equipment suppliers, organisations offering services, consultants and energy suppliers. Furthermore the study will;

- Encourage manufacturers and equipment suppliers to improve their energy efficiency, conserving fuel resources and reducing emissions.

- Provide information to improve industrial competitiveness by reducing energy consumption in an increasing hostile market. Enabling planning of energy use, and providing information for proposals for implementation of energy efficiency projects. Improvements in addition to energy savings may take the form of increased throughput, better working environment, less operating problems, and better quality.

- To stimulate technology transfer between manufacturers within a sector, and throughout industry.

Energy targets, plans for the implementation of energy efficient concepts and the development of new technology cannot be realised until sufficiently accurate information exists concerning the present industrial situation. Many previous studies have provided data which is very generalised and lacking sufficient detail for practical use by industrialists, while others lacked clarity on the exact nature of figures. The study performed aimed to rectify this situation by examining the ceramics, paper and timber industry in detail. Furthermore the trends in the consumption of energy used for drying have not been fully examined in the past. The study conducted investigated detailed values and the range of SEC, total energy consumption and the proportion of the total energy utilised for drying processes.

Significant changes within the industry were identified relating to production characteristics and the implementation of new technology. Links to production were important since a declining industry naturally resulted in the closure of older inefficient plants resulting in a general decrease in the range of SEC, which may otherwise have been attributed to improved energy efficiency.

A literature review found little information regarding the variation of energy consumption for drying processes over the last decade. The study examined the present industrial situation and was able to provide a complete comparison to previous surveys conducted in the 1970s. General manufacturers views on the implementation of new technology and practices were assessed from the comparison.

Although time series operating characteristics of drying equipment was not analysed in detail, data could provide a basic fundamental backbone for the development of demand side management (DSM) techniques. The detail of the study performed would highlight areas to concentrate energy levelling and information on the type of dryer or process, either batch or continuous, would enable specific groups, processes or equipment to be targeted. ETSU suggested that electricity utilities will become more aware of energy efficient schemes and the application of results to DSM projects [132].

Conclusions

The following conclusions can be drawn from investigation of the energy utilisation of drying processes;

1. It has been emphasised that energy is an important commodity used widely throughout industry.
2. Since the 1970s the quantity of energy used in industry has reduced dramatically. However, overall production has increased indicating that more efficient processes are being implemented. This could be linked to the reduction of 'smoke stack' industry over the last decade.
3. It has been shown that an understanding of where energy is utilised and technologies available is essential before plans can be made concerning the implementation of energy efficient concepts.
4. The energy efficiency and specific energy consumption of drying equipment has been defined. Furthermore, comments have been made concerning where energy is utilised demonstrating that a large proportion is typically lost in vented exhaust gasses.
5. The economics of installing a drying system have been addressed and indicated that energy costs can represent approximately 80% of the total costs incurred over the equipment lifetime.
6. Comments have been made concerning previous estimates of the thermal efficiency of drying equipment. Efficiencies varied widely, although in general many studies fail to describe exact processes, equipment or product type, thus providing limited scope for further application in an energy estimate.
7. Energy saving measures have been briefly described highlighting many aspects from control to heat recovery systems and performance monitoring of plant.
8. Previous studies concerning the energy consumption for drying processes in the UK have been examined in detail. Methods, results and inaccuracies have been described. Results were compared demonstrating that a trend in dryer energy consumption could not be established.
9. A comprehensive literature survey and communication with experts within the field showed that the analysis of the energy utilised for drying is not a topic for regular assessment. Furthermore, a complete review of the industry has not been performed since 1982.
10. Results of an energy update using a methods proposed by Baker and Reay have been described. Points addressed included the aims of the update, selection of a methodology and details of calculations performed. Comments were made concerning total and drying energy consumption within six sectors highlighting large consumers of energy for drying and general trends over the past decade.

11. An introduction to the analysis of drying processes within industry has been presented. Details examined included aims and objectives, selection of area to focus efforts based upon results of the energy update and information from industry. Further points included the methods employed in data collection and proposed benefits of the study.

CHAPTER 4

ENERGY UTILISATION IN THE CERAMICS INDUSTRY

Introduction

The principle subsections of the ceramics industry are;

- Tableware,
- Sanitaryware,
- Tiles,
- Electrical and Engineering Ceramics.

Other products include refractories, abrasives and non-metallic mineral products such as plaster board which are described in Chapter 5.

The UK ceramics industry is diverse, with a broad range of products being made by 1500 companies, employing over 20000 people [132]. Stoke-on-Trent is the main region containing 90% of the industry. A decade ago the sector consisted mainly of small traditional style potteries, but recently has become more concentrated.

Production levels have remained fairly constant with slight increases in tableware production and decreased output from the tiles industry. The level of production is not expected to change significantly during the next decade, although stronger competition is expected from the Far East utilising cheaper fuel and labour, and modern equipment.

Production Processes

The majority of ceramic manufacturers produce their products from slip; an aqueous suspension of clay, filler and flux, with a solids content of around 70%.

Forming technologies vary significantly according to the type, size and shape of the product, but traditional craft skills are highly important [131]. A typical ceramics process flow is shown in Figure 4.1 [67], [132].

Three different forming processes have been identified;

- Drying the slip to form a powder which is pressed, commonly known as isostatic pressing,
- Squeezing water out of the slip to produce a dense plastic body which can be moulded; extruded, or shaped on plaster formers or hydraulic presses, or in the case of electrical ceramic products machined,
- Casting the slip in a plaster mould which the absorbs water from the slip, depositing a layer of clay on the inside surface of the mould.

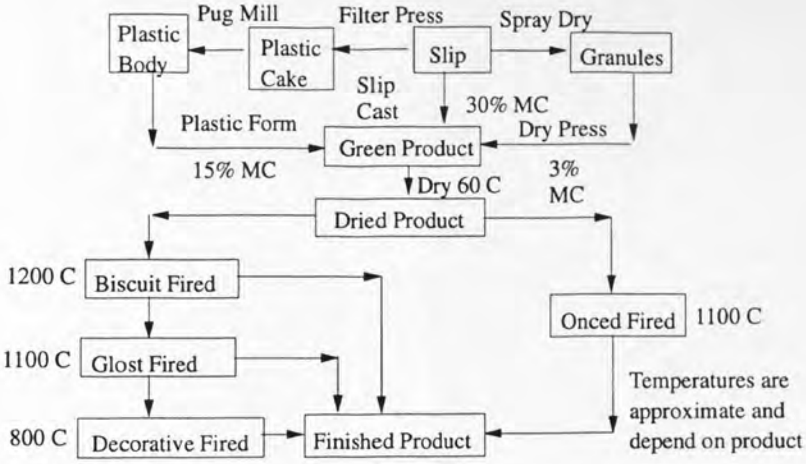


Figure 4.1 - Typical ceramic process flow

The drying of formed green products is essential to prevent damage to the articles due to moisture migration during high temperature firing. Slip cast ware contains about 20% water, plastic formed ware 12-15% and pressed granules 1.5-3%. Plaster moulds also require drying prior to reuse. Granulate pressed products which have been formed from dried slip particles require very short drying times and is often incorporated into the firing cycle. Green products formed by other routes contain too much water and separate drying operations are required. Drying time and temperature is dependant upon product moisture content and thickness. Controlled reduction of the ambient humidity to avoid cracking is essential. Drying ware in the mould presents further problems with plaster dihydrate formation limiting drying temperature. Further processes often include the drying of glazes and decoration, which is common within the tableware industry.

Dryers are generally continuous using turntables or conveyors to move the ware through a heated chamber. For larger products, such as sanitaryware, intermittent dryers are often used. In many cases open shop drying is practised in which the whole area is heated to dry the product which is left on racks. Various sources of literature [131] remark that the equipment used for drying pottery before firing is often primitive and relatively energy-inefficient, mainly because the cost of energy has traditionally been low compared with other production costs.

Sanitaryware Manufacture

Introduction

Sanitaryware products vary greatly and include fitments for bathrooms, lavatories and kitchens. Products tend to be larger and more complex than other goods produced in the ceramics industry. Products can be divided into the following groups;

- Closets,
- Systems,
- Pedestals,
- Basins.

A variety of other products such as bidets, and shower fittings are also produced.

Most sanitaryware is made from vitreous china, first introduced by Joshua Twyford in the potteries during the 17th Century [212]. A typical composition is 25% ball clay, 25 % china clay, 20% felspar, and 30% quartz [132]. The majority of products are formed by traditional slip casting techniques, although several firms contacted during this study were experimenting with pressure casting. Products can stay in the mould for up to 24 hours. Once released from the mould the product has a moisture content of approximately 18% by weight [58].

Moulds are made by mixing plaster and water and casting in a metal former. Moulds are dried in a variety of ways including the use of heat pump dehumidifiers and conditioning chambers held at 40°C.

Space heating drying techniques are widely practised in the sanitaryware sector. After mould release, products are fettled and left in the workshop, usually overnight. Room temperatures are raised to 35-45°C using electric, direct and indirect gas burners, or a steam or dehumidifier system. Empty moulds are also left over night and dried using space heat or processed in gas heated chamber. A mould typically casts 120 pieces before becoming ineffective.

Intermittent chamber dryers are commonly used, with gas or oil heating. Waste heat recovered from the kiln is used by some manufacturers for drying. Four types of dryer were identified during this survey;

- Direct fired chamber dryers,
- Heat pump dehumidifiers,
- Tunnel dryers,
- Vacuum dryers.

Chamber dryers were the most common form of drying equipment, using either gas or oil heating. Products enter the dryer with a moisture content of 11-13% and are dried to < 1% before firing. Drying temperature are dependant on product type and vary between 45-90°C. From 100 to 500 pieces are processed in each dryer load and drying times of up to 48h were reported. With the introduction of automated glazing and continuous firing manufacturers contacted during this study regarded the drying stage to be the bottle neck within the production process.

Information regarding the degree of implementation and utilisation of waste heat systems for drying has not been published and the lack of information from manufacturers has hindered the analysis of sanitaryware production.

Once dried, pieces are glazed and once fired at temperatures around 1250°C.

Industry

The industry is dominated by Armitage Shanks who represent 70-80% of the market by sales in 1991 [212]. Other main manufacturers include Caradon Twyfords, Idea Standard and Shires.

Figure 4.2 shows the variation of manufacturers sales for the UK [39], [40], [41].

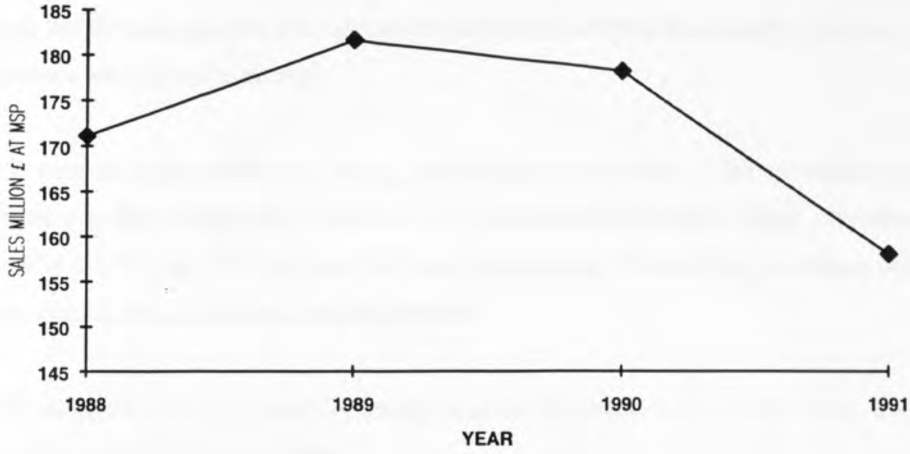


Figure 4.2 - Variation in sanitaryware sales

The demand for baths and sanitaryware grew rapidly during the 1980s, fuelled by the boom in the housing market and increasing trend towards co-ordinated bathroom suits [212]. However, in the early 1990s, the housing market declined, resulting in a 15% by volume decrease in sanitaryware sales from 1991-1992.

Energy Utilisation

A complete energy consumption survey from a major UK sanitaryware manufacture produced a total SEC figure of 15.6 GJ/tonne of finished product, of which 9.7% was from electricity [58]. Table 4.1 shows specific energy consumption (SEC) data for dryer sections investigated during this study.

DRYER TYPE	DRYING SEC GJ/tonne	THERMAL EFFICIENCY %
Space Heating	1.45	13.5
Chamber	0.79	10.7
Heat Pump	0.12	Note 1

Note 1 : Not realistic to state efficiency of heat pump system due to additional energy input from heat sink.

Table 4.1 - SEC for drying sanitaryware

Information shown in Table 4.1 was based upon manufacturers data, and for chamber and space heating drying systems with no waste heat recovery. Efficiencies for space heating drying methods did not include mould warming, space heating during day time working hours, or energy required to remove water from used moulds. Information concerning the energy utilisation of vacuum drying equipment and the energy requirements for initial mould production was not available.

Table 4.1 shows that thermal efficiencies are low with typical chamber dryers being only 10% efficient. There is thus scope for improvements in dryer efficiency through the implementation of energy saving measures. Heat pump dehumidifier systems uses considerable less energy than chamber dryers, although advantages are weighted by the greater unit cost of electricity in comparison to fossil fuels. Heat pumps are not suited for the utilisation of waste heat which has discouraged the wide spread implementation within the industry. Only a small number of dehumidifier systems were found to be used.

Drying SEC will vary according to the age of equipment, operating conditions, and the utilisation of waste heat. This study estimates a total drying SEC value of 2.25 GJ/tonne for chamber drying, representing an overall drying efficiency of 12.5%, and 0.91 GJ/tonne for heat pump system. Thus drying consumes about 14% of the total energy consumed in the manufacture of sanitaryware.

An estimated 3.7 million GJ was consumed for the manufacture of sanitaryware in 1992 [128], implying that 0.52 million GJ was consumed for drying processes.

Comparison to Previous Studies

Table 4.2 shows a comparison of SEC values from previous studies.

YEAR	TOTAL SEC GJ/tonne	DRYING SEC GJ/tonne	REFERENCE
1978	47.10	15.07 (32%)	[131]
1980	44.00	15.09 (34.3%)	[124]
1990	27.50	6.00 (21.8%)	[132]
1995	15.60	2.25 (14.4%)	This study

Note : Bracket figures represent proportion of total SEC

Table 4.2 - Comparison total and drying SEC values

It was estimated that implementation of energy saving measures could reduce the total SEC for sanitaryware manufacture from 44 GJ/tonne to 27.7 GJ/tonne by 1995 [124].

The table shows that total SEC values have reduced significantly over the last decade, reducing 67% between 1978 and 1995. Drying SEC values have halved in comparison to findings published in 1992 [132]. Figures indicate that greater savings have been achieved for drying equipment in comparison to other processes within the sanitaryware industry. The closure of inefficient older plant due to the declining market, improved monitoring, control and energy saving measures will have contributed to the trend in decreasing total SEC.

This study showed dryer thermal efficiencies of less than 13%. A drying SEC of 6 GJ/tonne as suggested in 1992 [132] represents a dryer thermal efficiency of less than 1.5% which is extremely low in comparison to other industrial drying systems. Figures of the 1990 survey were based on European data, which may not give a true perspective of the UK industry. Moreover, figures derived in 1990 did not include an assessment of space heating

Tile Manufacture

Introduction

The tile industry comprises of wall and floor tiles, and are further divided into whiteware and red tiles. This study has only examined the production of whiteware tiles.

Wall and floor tiles comprise of; 20% ball clay, 25% china clay, 15% china stone, and 40% quartz. The manufacture involves drying a slurry of raw materials to a moisture content of about 8% and pressing to shape in a semi-dry state using a hydraulic or a pneumatic system. This is followed by final drying and firing.

With the exception of hand made tiles, which represent only a small proportion of the total production, wall and floor tiles are manufactured in the UK using two techniques;

- Traditional, &
- Roller.

Traditional methods employ the use of vertical and tunnel dryers, where as roller techniques use a single layer fast dryer. Typically two dryers supply a single kiln. Drying times vary up to approximately 70 minutes using either gas or oil heating [61].

In the past drum dryers were utilised for producing materials for pressing, although spray dryers are now used exclusively in the UK. Raw material enters the spray dryer at 72% solids, and exits with a moisture content of 8% by weight. The use of waste heat for spray drying was disclosed by one major manufacturer, although this practice was not common within the industry.

Industry

The manufacture of tiles is relatively small scale in comparison to European competitors [132]. Two major companies operate in the UK; H & R Johnson and Pilkington Tiles, the former producing 60-70% of the UK output. The production of tiles is recorded in square meters, irrespective of the thickness of tile produced. Figure 4.3 shows the production of glazed and un-glazed tiles [38], [39].

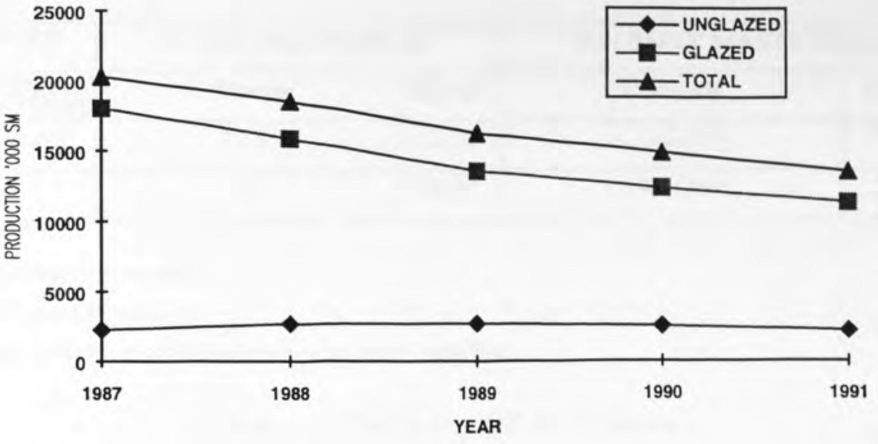


Figure 4.3 - Production of glazed and un-glazed tiles

The production of tiles has decreased since the mid 1980s, although the manufacture of unglazed tiles has remained fairly constant. In 1991 an estimated 13.65 million square meters were produced.

Energy Utilisation

An estimated 1.8 million GJ of energy was consumed for tile manufacture in the UK in 1990 [132]. 13650 thousand square meters were produced, yielding a total SEC of 0.132 GJ/m^2 or approximately 13.04 GJ/tonne of finished goods.

Table 4.3 shows energy consumption data collected during this study for drying processes.

DRYER	GJ/tonne$_{Product}$	MJ/m^2	THERMAL EFFICIENCY %
Spray	2.73 (0.86)[1]	-	23
Traditional	0.40	4.07[2]	36
Roller	0.21	2.68[3]	68

Notes :

1 - Figure in brackets represents consumption with 68% of energy supplied by waste heat

2 - Based upon 1m^2 = 10.11 kg

3 - Based upon 1m^2 = 12.5839 kg

Table 4.3 - SEC for drying

Table 4.3 shows that the energy consumption of roller dryers is nearly half that of traditional systems.

The thermal efficiency of roller dryers appears exceptionally high at nearly 70%. However, additional water lost from the application of glaze was not considered due to limited information from manufacturers. The efficiency will undoubtedly be lower than the figure stated.

Table 4.4 shows total consumptions with and without the utilisation of waste heat.

DRYER	WITH WASTE HEAT		WITHOUT WASTE HEAT	
	GJ/tonne	MJ/m^2	GJ/tonne	MJ/m^2
Traditional	1.26	12.78	3.13 (25%)[1]	31.65
Roller	1.07	10.86	2.943 (26%)	29.75

Notes

1 - Overall thermal efficiency in brackets

All MJ figures based upon 1m^2 = 10.11 kg

Assuming spray dryer operating with 68% of thermal energy from waste heat

Table 4.4 - Total drying SEC for tile drying

Table 4.4 shows that the overall drying SEC for roller dryer systems are only just lower than traditional methods. The largest proportion of the total drying energy is derived from the spray drying of raw material and dominates the low thermal efficiency of the drying process.

Figures demonstrate that the application of waste heat to spray drying raw material dramatically decreases drying SEC values. A reduction of 63 % in the total drying SEC is possible if heat recovery is used on just the spray drying component of a drying system.

Roller drying is widely used in Europe, although traditional techniques still dominate in the UK. Using production figures from manufacturers an estimated 82% of the total production of tiles are manufactured by traditional methods.

For dryers operating with no heat recovery, calculations based upon production and energy consumption figures from industry yield an overall drying consumption of 0.43 million GJ for 1991, representing an estimated 23 % of the total energy consumed. Assuming a case of all spray drying equipment operating with 68% of its energy from waste heat, drying energy consumption was 0.17 million GJ, representing 9.4 % of the total energy consumed.

Witt suggested that possible over 50% of dryer energy is supplied by waste heat in 1976 [382]. With the exception of heat recovery for spray drying of raw material, no evidence of heat recovery in tunnel dryers was uncovered during this survey. Lack of monitoring within the industry prevented an assessment of the degree of utilisation of waste heat.

Comparison to Previous studies

Table 4.5 shows a comparison of previous studies.

YEAR	TOTAL SEC GJ/tonne	DRYING SEC GJ/tonne	REFERENCE
1978	16.8	3.8 (23 %)	[131]
1980	13.7	3.9 (29 %)	[124]
1990	9.0	2.2[1] (24 %)	[132]
1995	13.0	3.1 (24%)	This study

Note : Bracket figures represent proportion of total SEC

1 - 0.5 GJ/t drying and 1.7 GJ/t grinding and spray drying

Table 4.5 - Comparison total and drying SEC values

The 1995 drying SEC may be as low as 1.22 GJ/t if 68% of dryer energy was derived from waste heat, thus representing 9 % of the total SEC. Comparison of figures for systems using no waste heat show that the total SEC has fallen only slightly since the 1980s, while drying SEC has reduced by 20% since 1980. The implementation of roller drying methods will have attributed to this trend.

Figures derived in 1990 [132] appear to be exceptionally low in comparison to the 1995 survey. The energy contribution from spray drying raw material is considerably less than those found during this survey. 1.7 GJ/t represents a drying efficiency of 37%, which will be appreciably higher due to the inclusion of energy for grinding and mixing. No details of waste heat utilisation were described in the 1990 survey.

It is suggested that the UK tile industry uses modern technology in line with the European norm [132]. However, information for UK industry suggests that only 20% of production is produced on the more efficient roller dryers.

Tableware

Introduction

The pottery industry is one of Britain's traditional industries and world famous names such as Wedgwood, Royal Doulton and Royal Worcester have been around for over 200 years [214]. Tableware consists of dinner services, tea pots, tea sets, coffee sets and mugs.

Products can be divided into [214];

- Bone China - Bone china consists of china stone, china clay and animal bone. A hard vitreous product, china derives its strength, whiteness and translucency from bone.

- Hard Porcelain - A china clay, felspar and quartz mix. Semi-translucent with a hard glaze. Porcelain is heat resistant.

- Earthenware - A composite of china clay, ball clay, flint and china stone. Must be glazed and made thicker and heavier for strength.

- Stoneware - A similar product to earthenware but contains more stone.

Dryers tend to be continuous using turntables or conveyors to move the ware through a heated chamber. Several manufacturers use a combination of chamber and tunnel dryers with gas, oil or steam heating. Several applications of dehumidifier systems were investigated during the study.

'Mangle' style dryers, where the ware is moved vertically on rotating trays through a hot air chamber, were commonly used for drying flatware. Operating temperatures ranged from 40-80°C, with drying times from 40-100 mins. This sort of dryer is used for drying ware before and after mould release [59].

Hot air chambers for drying greenware were found to be operated at temperatures between 60-100°C, for drying times upto three hours. Green vitrified products are dried at a higher temperature, typically 140-160°C for about 1.5 hours. Solid cast items are often dried in the mould with drying times being dependant on product size, e.g. solid cast cup handles have a drying time of about 3-4 hours at a temperature of 30-40°C.

A process may have several drying phases depending upon the nature of the product. For example cups are typically manufactured by spinning a plastic body onto the inside of a plaster mould, which travel through a heated oven at about 150°C. Once removed from the mould handles and glaze are applied and a further drying phase commences.

All products using a plastic body or slip casting technique use a plaster mould. Plaster moulds are cast in metal formers and removed after about a 20 minute setting time. The moulds are then dried and conditioned ready for use. Typical drying times for a flatware plate mould is about three days using a heat pump system.

Many manufacturers with intermittent kilns were found to dry ware during the kiln warm up phase. This was particularly common for products made by isostatic pressing techniques.

Industry

The UK tableware industry is very diverse comprising of approximately 770 companies, employing more than 43000 people in 1992 [36] A decade ago the sector consisted mainly of small traditional style potteries, but recently has become more concentrated. Major firms include;

- Royal Doulton - Bone china,
- Wedgwood - China and earthenware,
- Staffordshire tableware - Earthenware and stoneware,
- Churchill Tableware - Earthenware,
- John Tams Group - Earthenware and bone china,
- Royal Worcester - Bone china.

Royal Doulton accounts for more than 50% of the UK china production, Wedgwood has a 25% share of the ceramics tableware, and Staffordshire Tableware has more than half of the earthenware market [246]. Wedgwood and Royal Doulton alone represent 36.5 % of the total tableware market [214]. In 1992 the UK retail market for china and earthenware was worth £1.07 billion. Tableware and kitchenware representing 70% of the sales, and 30% from giftware.

Table 4.6 shows the sales figures for the production of pottery [39], [214].

SALES £M	1986	1987	1988	1989	1990	1991	1992
China and Porcelain	192.6	197.6	226.8	258.8	264.3	265.4	251.1
Earthenware	191.3	200.9	211.8	231.5	235.3	216.6	223.0
Other	38.9	40.3	48.8	55.8	50.4	58.8	56.8
Price Index (1985 =100)	106.2	111.8	119.1	130.1	114.5	159.9	-

Table 4.6 - Sales of tableware

Table 4.6 shows that there has been an increase in china, porcelain and other tableware sales over the last decade, although sales of earthenware have remained fairly constant. It is predicted that the tableware sales of china and earthenware is a major growth area and market sales have been forecast to rise from £1070 million in 1992 to £1427 million in 1996 [214].

In 1980 an estimated 8,658.8 tonnes of chinaware and 94,172.5 tonnes of earthenware was produced, representing a total output of 102,831 tonnes [124]. An estimated 49,966.8 tonnes of porcelain and china was produced in 1993 representing a sales value of £4.30 per kg, while 50,872.7 tonnes of stoneware, earthenware and other table was manufactured. Thus, an estimated total output of 100,839.5 tonnes in 1993 [75], [79]. Analysis of sales figures, the price index variation and discussion with industry suggested that the production of chinaware has not varied significantly over the last decade. 1993 figures for production were verified by two independent sources and were of a simular magnitude. The validity and accuracy of the 1980 chinaware figures are questionable, and production may have been underestimated.

An estimated 620000 pieces of cast earthenware are produced annually [146]. An average piece weight of 1.13 kg yields an overall production of 36431.2 tonnes in 1993. ETSU estimated that 18554 tonnes of flat earthenware are manufactured annually [139]. Thus a total of 69086 tonnes of earthenware was produced in 1993, with castware representing 66% of the total production. These figures conflict with those quoted by the Central Statistics Office. Overall energy calculations in this study were based upon production figures from the Central Statistics Office.

This survey showed that only a very small fraction of manufacturers used isostatic pressing techniques and five companies with spray drying facilities were identified [75]. Companies included the major manufacturers within the tableware sector and information received from industry showed that approximately 50% of flatware produced by these companies was formed by isostatic pressing. An estimated 18% of the total flatware production is currently made by isostatic pressing techniques based upon the production capacity of the five companies involved with granular pressing. Approximately 8994t and 9280t of china and earthenware is manufactured by pressing respectively.

Energy Utilisation

An annual census of fuel and power consumption is carried out by the British Ceramics Manufacturers Federation (BCMF) [75]. However, the report only covers a proportion of the industry, typically around 75% [124]. Moreover several major pottery manufacturers, notably Wedgwood, are not members of BCMF and figures relating to tableware production may not reflect the current UK energy consumption.

The energy consumed for tableware manufacture can vary considerably from one plant to another according to the products made and types of equipment utilised [131]. Table 4.7 shows that the thermal efficiency of the surveyed dryer sections varied from 2.2% to 45% for a direct chamber dryer and IR system respectively. Spray dryers producing clay for pressing methods were found to be typically 20-22% efficient. The implementation of waste heat for spray drying has been demonstrated in the tiles industry and could produce savings within the tableware sector [61]. The total energy consumed for producing earthenware by isostatic pressing is only slightly less than using traditional techniques, 9.5 GJ/tonne and 10.18 GJ/tonne respectively. With respect to energy savings the effectiveness of eliminating the greenware drying stage by using isostatic pressing techniques is reduced by the low efficiency of spray drying systems. However, results show that dry forming techniques can save up to 96% of the energy used for drying chinaware by traditional methods. Additional benefits of using isostatic pressing techniques included the elimination of plaster moulds and subsequent drying of used moulds.

The proportion of the total energy used for drying varied widely from 5 % for a IR system drying hotelware to 48% for the production of bone china. The large consumption for drying bone china was due to very low thermal efficiency of traditional equipment. Moreover, drying techniques for chinaware consume more energy than that for earthenware due to the more conservative drying regimes. The differences in clay properties and improved quality of the high value ware directly affect the drying conditions used. Drying processes involved with isostatic pressing of chinaware consumed an estimated 3.2% of the total energy, although additional kiln energy consumption due to an extended warming/drying phase could not be considered due to the lack of data.

POTTERY	DRYING METHOD	STAGE OF DRYING	DRYING SEC GJ/tonne (Thermal Efficiency)	TOTAL SEC GJ/tonne	PROPORTION OF TOTAL FOR DRYING %
Earthenware	Slip Casting	Mould Making	0.17	-	-
		Greenware	3.58	-	-
		TOTAL	3.75 (14 %)	10.18	36 %
	Isostatic Pressing	Spray Drying	2.73 (22 %)	9.49	38 %
Hotelware	IR System	Mould Release + Greenware	1.17 (45 %)	22.27[1]	5 %
Bone China	Isostatic Pressing	Spay drying	2.48 (20 %)	77.70[1]	3.2%
	Plastic Forming	On Mould	23.65 (3 %)	-	-
		Greenware	47.29 (2.2 %)	-	-
		TOTAL	70.94 (2.4 %)	146.19[1]	48 %

Note : 1- Based upon manufacturers data and weighted average kiln SEC [34]

Table 4.7 - SEC for drying tableware

An estimated 200 kg of plaster is consumed per tonne of flatware produced for the fabrication of moulds for plastic forming techniques. However, the study showed that energy consumption for mould dying was not commonly assessed. A thermal efficiency of 48% was recorded for a modern gas fired chamber drying moulds based on commissioning data from a flatware manufacturer. Calculations estimating the energy consumption for mould drying were hindered by the moisture content of a mould being dependant on product, cycles in use, weight and shape. Although moulds are conditioned before use, and some are dried in hot air chambers, many manufacturers commonly redry moulds using a return cycle through a mangle style dryer, or by space heating techniques. A realistic energy estimation could not be made.

The implementation of heat pump systems has increased since the 1980s, although an exact assessment of the number currently in operation was not conducted. A dehumidifier drying plaster greenware cups was found to consume 1.7 MJ/kg of water removed. Table 4.8 shows an estimation of the total energy consumed within the tableware sector based upon production and SEC values from this study. In 1993 an estimated 3.1 million GJ was consumed for drying processes for tableware production, representing 43% of the total energy consumed.

Comparison to Previous studies

Ceram Research [75], [145] suggested that conventional dryers were commonly less than 10% efficient, although modern gas fired equipment could achieve efficiencies of up to 56%. General flatware dryers consuming 6.23 GJ/tonne product (8.3% efficiency) and cup dryers consuming 8.29 GJ/tonne (6% efficiency) have been reported [75].

PRODUCT	PRODUCTION tonnes	DRYING ENERGY MILLION GJ	TOTAL ENERGY MILLION GJ
China - Traditional	40972.8	3.391	6.978
China - Pressed	8994.0	0.026	0.823
Earthenware - Traditional	41592.7	0.156	0.426
Earthenware - Pressed	9280.0	0.025	0.088
Total	100839.5	3.11 (43%)	7.2

Table 4.8 - Total energy consumption for tableware manufacture

An energy consumption of 1.72 MJ/kg water removed was suggested for the drying of plaster moulds using a dehumidifier system [145]. This figure compares well with 1.7 MJ found during this survey for drying greenware cups. The application of heat pump systems appears to offer large potential energy savings. However, the cost of electricity is considerably more than fossil alternatives, and dehumidifiers are only suited to a batch processing system.

It has been estimated that energy savings in the order of 2 GJ/t can be realised when replacing traditional methods with isostatic pressing techniques [132]. Comparison with the findings of this study showed that only about 1 GJ/t was achieved for implementation on a earthenware production line, however, savings upto 68 GJ/t could be achieved for chinaware.

Table 4.9 shows a comparison of previous studies.

YEAR	PRODUCT	TOTAL SEC GJ/tonne	DRYING SEC GJ/tonne	REFERENCE
1978	Bone China	249.0	84.6 (34%)	[131]
	Hotelware	51.1	10.2 (20%)	[131]
1980	Bone China	212.5	84.6 (40%)	[124]
	Earthenware	42.9	10.2 (24%)	[124]
1990	Bone China	69.8	20 (28%)	[132]
	Earthenware	9.8	3 (30%)	[132]
This Study	Bone China	77.7	2.48 (3%)	Isostatic pressing
		146.2	70.94 (48%)	Plastic
	Earthenware	9.5	2.7 (28%)	Isostatic pressing
		10.2	3.7 (36%)	Slip Casting
		22.3	1.2 (5%)	IR system

Note : Bracket figures represent proportion of total SEC

Table 4.9 - Comparison total and drying SEC values

Table 4.9 shows that energy savings have been achieved within the tableware sector. Total SEC have reduced from 249 GJ/t in 1978 to 146 GJ/t in 1993 for chinaware, while those of earthenware have reduced by 80%.

Drying SEC for china production have only decreased slightly over the last decade, although approximately 64% less energy per tonne is consumed for drying earthenware.

Table 4.10 shows a comparison of total energy consumption's.

YEAR	PRODUCT	TOTAL ENERGY MILLION GJ	DRYING ENERGY MILLION GJ	REFERENCE
1978	China	1.90	0.65 (34%)[1]	[131]
	Earthenware	4.20	0.84 (20%)	[131]
1980	China	1.84	0.74 (40%)	[124]
	Earthenware	4.04	0.97 (24%)	[124]
1993	China	6.68	2.93 (44%)	This Study
	Earthenware	0.51	0.18 (35%)	This Study

Note : Bracket figures represent percentage of total energy.

Table 4.10 - Comparison of total energy consumption

Comparison of figures show large discrepancies between 1980 data and that estimated in this survey. Energy estimates performed in 1978 and 1980 used a similar figure for production. Analysis of financial statistics, and communication with manufacturers suggested that production of chinaware may have been underestimated in the past. This hypothesis is reflected in the low energy figures for the drying of chinaware calculated in the 1980s. The reduction in the energy utilised for drying earthenware can be attributed to the decline in production over the last decade. Furthermore, significant implementation of energy saving measures have resulting in the reduction in SEC of earthenware drying equipment.

Due to the questionable nature of the 1978 and 1980 figures the validity of a comparison of energy data is debatable. However, results suggest that the largest proportion of savings have been achieved by improved kiln operation, as the percentage of the total energy consumed for drying has risen slightly since 1978.

Electrical Ceramics

Introduction

The electrical ceramics market is very diverse in nature and includes hollow and solid core tension insulators. Many products within this niche sector are technically very difficult to produce, and reject rates up to 70% have been reported [247].

The manufacture of electrical ceramic products can be divided into three broad techniques [60];

- Turning,
- Pressing, &
- Extrusion.

A large proportion of electrical ceramics manufactured in the UK are produced from a clay comprising of china clay, ball clay, felspar and fillers. As with tableware manufacture, two processes are used for forming;

- **Plastic Process** - Once mixed the clay is filter pressed to a moisture content of typically 20-22%. Products are shaped on plaster moulds. Up to 3% of product moisture is lost in the plaster mould.

- **Granular Pressing** - The clay is spray dried from 60-70% solids to 0.2-12% moisture content before pressing.

All ware is dried to 0.5-1% moisture before firing. Chamber dryers dominated the UK industry, with direct, indirect and dehumidifier systems being utilised. Space heating is used by some manufacturers for initial drying. Chamber temperatures ranged from 40-60°C with drying times upto 4 weeks.

Little information regarding the proportion of the total production manufactured by plastic and granular processes was located during this study. Many manufacturers used both techniques and methods varied widely depending upon product type.

Industry

The technical and electrical ceramics market is a small niche sector in comparison to tableware and sanitaryware. Seven member of the BCMF are involved with technical ceramics, estimated to represent about 60-65% of the industry [131]. Major manufacturers include; Morgan Matroc, Fairey Insulators, Taylor Tunicliff, A.G. Hackney and B.H.W. Ceramics.

An estimated 12154.2 tonnes of technical and electrical ceramics was produced in 1995 based upon sales figures from BCMF. The industry has been in steady decline over the past decade, with production estimated at 35000 t in 1975 [382], 17772.5 t in 1978 [131], and 18158 t in 1980 [124]. However, the application of advanced ceramics in microelectronics and as specialist structural components in engineering are predicted to accelerate in number, although not representing a high tonnage output [132].

European production of electrical ceramics was estimated to be of the order of 25000t in 1990 [132], thus based upon 1995 figures the UK production represented approximately 48% of the European market. In 1995 electrical/technical ceramics represented 8% of the total UK ceramics sales [75].

Energy Utilisation

An estimated 3.9 million GJ/year is consumed for the manufacture of technical and electrical ceramics in the UK [128]. However, an estimated 0.95 million GJ was consumed in 1995 [75]. The latter figure was based upon an audit of BCMF members.

ETSU estimated that average total SEC to be 50 GJ/t in 1990 and represented approximate 1% of total energy consumption in the European ceramics industry [132]. Calculations based upon data from industry and BCMF estimated that total SEC values for UK manufacture were in the order of 100 GJ/t [60], [75].

Very little information was available concerning energy utilisation for drying processes within the electrical ceramics industry due to a lack of monitoring. An energy audit was conducted on a direct gas fired chamber, operating at 75°C drying 32800 kg of wet product at 18% moisture content to less than 0.5% moisture over a 100 hour cycle. Energy consumption was 0.8 GJ/tonne of product, representing a thermal efficiency of 69%. This thermal efficiency is high in comparison to other drying installations in the ceramics sector. However, calculations were based upon detailed information from a major manufacturer and were deemed reliable.

A spray dryer system analysed during this study consumed 3.16 GJ/t for drying clay, operating at a thermal efficiency of about 16%. This figure is low in comparison to thermal efficiencies of 20-22 % found in the tableware industry. The pressing of spray dried clay is complicated further by some processes involving rewetting of the clay or mixing with other materials. Further drying using chamber systems may be necessary for these processes.

Assuming that 50% of production is manufactured by granular processes an estimated 24065.4 GJ was consumed for drying processes in 1995, representing 2.5% of the total energy consumed.

Comparison to Previous Studies

Table 4.11 shows a comparison of previous studies.

YEAR	TOTAL SEC GJ/tonne	DRYING SEC GJ/tonne	REFERENCE
1978	84.4	43.0 (51%)	[131]
1980	77.1	43.0 (56%)	[124]
1990	50.0[1]	n.a.	[132]
1995	78.3	2.0 (2.5) [2]	This Study

Note : Bracket figures represent proportion of total SEC

1: Estimated from European figures

2 : Based upon 50% of production manufactured by granular means.

Table 4.11 - Comparison total and drying SEC values

Table 4.11 shows that significant changes have occurred within the technical/electrical ceramics industry over the last decade. This study showed that total SEC have not changed significantly since the 1980s, although ETSUs estimation of 50 GJ/t was based upon an European figure and may not accurately represent the UK. Drying SEC have decreased dramatically from 43 GJ/t in 1980 to 2 GJ/t in 1995.

A drying SEC of 43 GJ/t estimated in 1978 and 1980 represents a thermal efficiency of 1.3%. This is exceptionally low in comparison to other industrial drying equipment. The introduction of granular forming techniques using spray dried material and heat pump dehumidifiers may have reduced drying SECs over the last decade. However, figures presented in this study appear exceptionally low. Drying figures were based upon limited data from industry, although an accurate audit of the equipment was performed for the data presented. Figures in Table 4.11 may not represent the average UK industry but give an indication of achievable targets.

Overall Summary of the Ceramics Industry

Table 4.12 summarises the findings of this study for energy consumed in 1994-95.

SECTOR	TOTAL ENERGY MILLION GJ	DRYING ENERGY MILLION GJ	PROPORTION OF TOTAL ENERGY FOR DRYING %
Tableware	7.2	3.11	43
Sanitaryware	3.7	0.52	14
Tiles	1.8	0.43	24
Electrical Ceramics	0.9	0.02	2
TOTAL	13.6	4.07	

Note : Limited information available for electrical ceramics

Table 4.12 - Summary of ceramics survey

Figures 4.4 and 4.5 show the proportion of the total and drying energy consumed by the product groups.

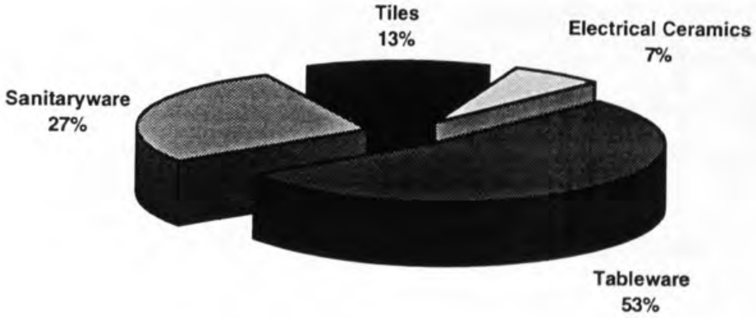


Figure 4.4 - Proportion of total energy consumed - 1995

Figures 4.4 and 4.5 show that the largest proportion of energy is consumed within the tableware sector, representing 53 % of the total and 76 % of the drying energy. The figures reflect the percentage of total energy consumed within the tableware sector for drying processes.

Largest savings could be achieved by implementing energy efficiency concepts within the tableware industry, although the potential for energy saving measurers should not be overlooked within the other sectors, especially tiles. Further investigation into electrical ceramics is required for an accurate assessment of potential savings.

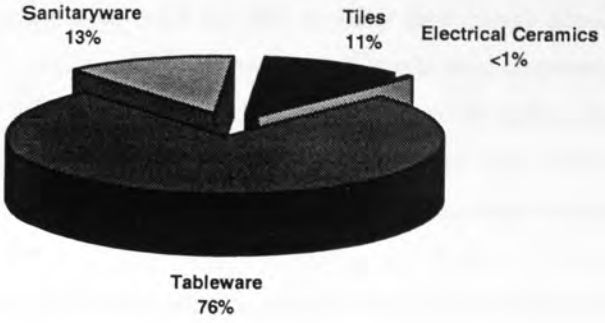


Figure 4.5 - Proportion of drying energy consumed - 1995

Table 4.13 shows a comparison of previous studies.

YEAR	TOTAL ENERGY MILLION GJ	DRYING ENERGY MILLION GJ	REFERENCE
1978	-	4.1	[16]
1978	14.8	4.5 (30.6%)	[131]
1980	14.1	4.3 (30.5%)	[124]
1990	6.9	1.5 (22%)	[132]
1995	13.6	4.1 (30%)	This Study

Note : Figures in brackets represent the proportion of the total energy

Table 4.13 - Previous studies of the ceramics industry

Table 4.13 shows that the energy consumed for ceramics production and that utilised for drying has not varied significantly over the last decade. This survey showed that 4.1 million GJ were consumed in 1995, representing 30% of the total energy.

A large proportion of industry contacted during this study were using equipment that was up to 30 years old. Many operators were not concerned with energy utilisation. Main objectives were focused on quality and productivity. New techniques such as isostatic pressing have been introduced although the proportion of the total output manufactured by these techniques is small and has had very little impact on the total energy consumed.

Energy Efficient Technologies

Many companies contacted during this study were not able to relate their energy consumption to production variables such as output tonnage or even pieces. Moreover, manufacturers were commonly only concerned with productivity and quality. It was rare for a company to measure SECs of different pieces of equipment e.g. grinding, forming, drying, firing etc. Until this situation is rectified, the introduction of energy efficient technology will be difficult for potential investors to justify since the benefits cannot be directly observed.

Manufacturers are prepared to invest in new technologies if the gains in productivity and energy efficiency give paybacks on the investment within at most five years and, more commonly, around two years. These gains are acceptable only if there is no degradation in product quality. Increases in productivity, decreases in staffing levels due to automation and environmental gains may in many cases influence the investment over energy savings.

In general improvements in energy efficiency to date are attributed to improved housekeeping, such as improving insulation and reducing air leaks, although much is due to reorganisation and sometimes closure of older plant. Improved burner design, retrofit heat recovery schemes and attempts at increasing throughput to reduce specific energy consumption have contributed to savings [131].

Efforts to reduce costs are hindered by outdated production technology and awkward factory layouts in multifloor buildings [132].

Various energy efficient technologies have been highlighted as potential ways of reducing energy consumption [124], [131];

- Use of waste heat,
- Direct heating to replace steam,
- Controlled dehumidification, &
- Fast drying (Including infra-red and microwave).

Information received from manufacturers and case study information concerning energy savings require careful examination since most figures quoted relate to a comparison of new to old equipment. In many cases the equipment replaced is often antiquated and operating at very low thermal efficiencies.

Heat Recovery

Heat recovery within the tableware sector is far less developed in comparison to the brick industry, representing less than 1% of the total energy used [75].

Recovering waste heat from the kiln cooling zone or kiln exhaust to the dryer is hindered by the complex factory layouts inherent in most manufacturers and the possibility of fouling on heat exchangers due to glaze volatile mixing with exhaust gasses. An estimated energy saving of 1.15 GJ/year could be realised if waste heat was fully utilised [131].

A UK Energy Efficiency Demonstration Scheme Project has shown that a payback time of around four years was estimated for the implementation of heat exchanger to supply waste heat from the kiln exhaust to dryers. 60% of the dryer heat was derived from waste heat [132].

Problems of control were noted by one manufacturer contacted during this study. Although waste heat was available from a continuous tunnel kiln, ineffective control have lead to product quality being effected [58].

It has been estimated that up to 50% of drying energy costs could be saved by implementing waste heat recovery in the tableware sector. Waste heat utilisation for spray drying of clay has shown that significant savings could be achieved. An operator contacted drying this study has demonstrated that an energy consumption of 0.86 GJ/t is achievable using waste heat whereas other units were typically consuming 2.5 GJ/t [61].

Slip Preparation

Experiments conducted at Centro Ceramico in Italy have demonstrated that continuous grinding techniques, which is used in the preparation of slip for spray drying, could produce significant savings in comparison to batch processing. The thixotropic nature of clay slip produced by continuous grinding has a lower moisture content than that produced in a batch process. Energy savings of up to 33% have been achieved using these continuous technique and spray dryers [132].

Dry grinding techniques are under development and initials trials have demonstrated that dry grinding and granulation is roughly 2.5 times more energy efficient than wet grinding and spray drying. These techniques are presently not used within the UK whiteware production, however are expected to play a major role within the next ten years.

Capillary Vacuum Casting

A framework is used to support capillary tubes in the mould which are connect to a vacuum system. Slip is poured into the mould and a vacuum applied to the capillaries to remove the water. Once a sufficient thickness of clay has built up on the mould the slip is drained and an internal pressure is applied to the piece and vacuum continued. Once the piece is removed the mould is immediately ready for casting. The system ensures the mould never gets wet so that it requires a separate drying step [132]. Energy saving are hard to assess due to the lack of monitoring on mould drying. However, savings of 1 GJ/t have been estimated [132].

Improved Dryer Design

Information from manufacturers and Ceram Research showed that many dryers operating in the tableware sector are over 20 years old, and were designed with productivity and capital cost in mind when energy was inexpensive in comparison. ETSU suggested that savings in the order of 30% of the current drying energy consumed could be saved by improving drying design and control [131].

An estimated energy saving of 5.1% of the total energy consumed in 1990 was suggest by improving dryer recirculation. Projects replacing steam heated dryers supplied by a centralised boiler by direct gas or electrical heating systems have demonstrated that savings are achievable. Savings depend largely on the original installation, however could range between 10 to 50% [132]. A demonstration project within the refractory industry [130] has shown that considerable savings can be made.

Electrical Energy Saving Techniques

It is highlighted in Caddett Analysis Series Report No.12 [250] that high levels of energy efficiency can be achieved with heat delivered by electromagnetic energy directly to the solid or the moisture in the solid, thereby avoiding the need to heat a stream of drying air.

The main electrotechnologies for drying applicable in the ceramics industry are;

- Infra-red,
- Radiofrequency,
- Microwave, &
- Heatpump dehumidification (including waste heat recovery).

Many sources are available describing these techniques; design and operation, and only the application within the ceramics sector and possible energy savings will be emphasised here.

The considerable non-energy benefits of electrically heated systems, particularly the vastly reduced drying times, can also be extremely valuable and give rise to short payback periods. Many of the examples quoted were situations where the electrical technique replaced an older less efficient type of dryer, which may be considerably different than those available today.

Infra-red Techniques

A combination of sources can be combined to emit a broad spectrum of infra-red radiation (IR). The oven design has to be customised to match the absorption bands of the product to optimise heating. IR radiation cannot penetrate ceramic bodies and so only the surface is heated. The core of the product is heated by conduction from the surface. The method is ideally suited to thin items such as tiles. Although gas IR units exist electric offer improved response times and eliminates problems of combustion products.

IR heating can easily be retrofitted to existing dryers by bolting on simple panel-shaped emitters at suitable points. Trials conducted by Centro Ceramico of Bologan [132] have compared fast single layer roller drying and infrared roller drying. The results are summarised in Table 4.14.

	FAST DRYER	INFRARED DRYER
CYCLE TIME (mins.)	40 to 140	5 to 10
TEMPERATURE (°C)	100 to 240	180 to 200
SEC (GJ/t product)	0.3 to 0.4	0.2 to 0.4

Table 4.14 - Comparison of fast and IR dryers for tiles

The study demonstrated that IR drying was more energy efficient and required less maintenance in comparison to conventional techniques. IR dryers are already used for tile production, although they have not penetrated UK markets. The tableware and sanitaryware sectors are potential areas for the application of IR techniques although the uptake of IR technology is limited. IR/vacuum techniques for drying sanitaryware have been demonstrated, with drying times being reduced from 24 hours to 2 hours with no detrimental effects on product quality [250]. Infra-red heating has been applied by Portmeirion Potteries for maintaining glostware at the correct handling temperatures for the application of decorative transfers. The application of this controllable form of heating has enabled quality levels to be maintained [59].

Table 4.15 shows a typical energy balance for an IR dryer and conventional fast dryer. Figures demonstrate the improvement in product heating by the direct absorption of IR energy by the material in comparison to conventional methods.

100% ENERGY INPUT	**FAST DRYER**	**IR DRYER**
EVAPORATION OF WATER	36%	35%
MATERIAL	8%	33%
EXHAUST AIR	30%	14%
HEAT DISPERSED	26%	18%

Table 4.15 - Energy balance for IR and conventional dryer

Radio Frequency and Microwave Drying

Dielectric heating is a generic term for heating with an alternating electric field of high frequency (between 1MHz and 2.45GHz). Frequencies below 300 MHz are called radio frequency (RF), and those above 300 MHz, microwaves. The two systems differ in the way the energy is applied, RF by a series of electrodes, while microwave is through a wave guide. Heat is delivered directly to the solid or to the moisture in the solid, thereby removing the need to heat a stream of drying air.

Various applications in the ceramics industry have been documented;

Oda, Woods and Foster [269] describe work involving the drying of ceramic 'green bodies'. Chabinsky and Eves [44] comment further on the drying of ceramic forms including the processing of ceramic ware in gypsum moulds during slip casting. They describe relatively new applications where the time for mould release has been cut from 24 to 7 hours by microwave treatment, increasing throughput and reducing the need for mould drying between casts.

Microwave drying of cast enamel ware has reported energy savings of 73% and a payback of only 1.3 years. The short payback is due to increased production and savings in labour costs as much as energy savings [250].

Although RF and microwave technologies are very efficient at the point of use the efficiency of generation varies. Efficiency are typically 60% for microwave heating and 50% for RF. However, microwave and RF systems offer additional benefits including; reduced drying times, fewer moulds required (and hence eliminating the energy utilised in reconditioning (drying of moulds between cycles) and production), increased mould life, reduced space heating requirements for the casting shop, and increased productivity.

A microwave/vacuum drying system has been installed at Goodson Lighting for the heating of slip in a process following drainage from the plaster mould. Microwaves are used for the initial hardening and then combined with sub-atmospheric pressure moisture removal in a second stage. After product removal the empty mould undergoes a further period of microwave/vacuum conditioning before returning to the casting station [146], [146]. Drying times were reduced from 20 hours to under 15 minutes, allowing an increase in production capacity. Due to the nature of the microwave system precise control was achieved allowing Goodson to program the heat input into every product base, improving quality and reducing energy costs. The application of reduced pressure enables the drying process to operate at lower temperatures. Consequently the life of gypsum moulds has been increased by up to five times, reducing the number of moulds required by 83%. Even working at 50% capacity an annual energy saving of 5 TJ was realised. Total benefits, including improved productivity, quality, manpower resource and energy, valued at more than £168000 and a payback within three years was achieved. Cast earthenware products in the UK amounts to approximately 620000 pieces/week [146]. The majority of these pieces are dried using open shop systems, gas heated castings and cabinet dryers. If, however, the microwave/vacuum drying technology was used, the potential energy savings on cast earthenware production alone would be 314TJ/year (or £893000/year based on natural gas at £2.84/GJ). If the total replication potential in the cast china tableware and giftware sectors of the UK industry were realised, savings of at least 1412TJ/year would be expected [146].

The application of microwave systems have been discouraged due to the high capital cost of installations, this combined with the relatively short life of magnetrons (approx. 2500 hours) has slowed the response from industry although the processes is technically feasible. Demonstrations in Italy with the drying of sanitaryware have achieved cycle times of 3 to 4 hours, incomparison with up to 48 hours for conventional methods.

A microwave system installed by a major sanitaryware manufacturer has increased productivity. Traditional slip casting techniques involved a casting time for up to 24 hours before mould release. The new technique involved a 1 hour hardening period followed by 15 minutes in a microwave system before mould release. Drying energy consumption was not improved but increased productivity has reduced overall SEC values, and quality has been improved. Fewer moulds are required thus savings in energy required to produce and redry moulds have been achieved.

Heat Pump Dehumidification

In a traditional chamber dryer, large volumes of air are heated, passed over the product and then vented. Although heat recovery systems are available to recycle energy they are not widely utilised. Dehumidification systems are more energy efficient than conventional chambers because they are totally closed. Water is removed in a refrigerated heat exchanger which cools the air below its dew point releasing its latent heat. The hot exchanger in the refrigerant cycle heats the air in the chamber.

Information from various ceramic manufacturers in the UK [58], [59], [60], [61], [67] showed that the implementation of heat pumps within the UK ceramics industry has become more wide spread than other electrotechnologies.

A heat pump dehumidification unit installed at Steelite International, a tableware manufacturer, replaced a gas fired 'in-kiln' drying process. Rejects were reduced by over 90% to under 0.5%, producing an annual saving valued at over £8000. The system was capable of handling 6000 cups overnight, removing 512 kgs of water in a 16 hour cycle. The dehumidifier enabled greater utilisation of the kiln, and reduced the floor space required when using a 'in-kiln' drying process. The introduction of dehumidifiers at Portmeirion Potteries has reduced plaster mould drying times from 72 hours to between 24 and 48 hours. This cut in drying time of up to 66% has generated annual savings valued at £30000 for an investment of only £20000. Control of the drying atmosphere using the dehumidifier resulted in the production of high quality moulds which was reflected in the reduction of rejects further down the production line. Working conditions were also improved [67].

A UK tableware manufacture has claimed that drying times have been reduced to one third with energy savings of 80%. [132]. Furthermore results published by CERAM Research suggest energy savings of 75% in comparison to direct gas-fired and steam heated chambers for plaster mould drying [131]. CADDETT studies [250] of applying heat pump dehumidification in the pottery industry has achieved cost savings of 45-50%, while reducing drying time by 20%.

A company manufacturing decorative plaster mouldings [348] have obtained a 90% reduction in drying time, 50% increase in throughput, a consistent product quality, with a pay back of only seven months by replacing their existing oven with an electric heat pump dryer. An electrical ceramic manufacturer also using heat pump drying techniques [67] has reduced drying times from four weeks to 15 days and reduced product reject rates by around 60%. Further applications include a pottery replacing an oil fired dryer with a heat pumps. Energy consumption was reduced by 45%, drying time cut by 30%, reduced rejects by 10% and production doubled.

Process integration of heat pump technology must be considered since it is fundamentally a batch process. Savings may not be achievable in continuous flow process situations, such as the tile industry.

A cost effective form of heat pump is mechanical vapour recompression (MVR). Although not applicable to most dryers, it can be used where superheated steam is used as the drying medium. In this technique the exhaust steam is adiabatically compressed, causing it to become hotter but without causing condensation. After recompression, the steam is suitable for reuse as the drying medium. No known applications are currently in operation within the UK ceramics industry, although tests have been performed drying bricks. CERAM Research/EA Technology are currently building a prototype low-pressure superheated steam dryer for the ceramics industry incorporating MVR heat recovery [129], [340].

Implementation of Energy Efficient Processes

Many studies [58], [59], [60], [61], [124], [131], [132] have revealed that few companies are able to relate fully their energy consumption to production variables such as output tonnage. This is largely because the output is traditionally measured in pieces rather than weight. Furthermore, many companies do not monitor their equipment and are hence unaware of the energy consumption characteristics of their processes.

Results summarised here emphasise that electrical drying techniques show outstanding promises in comparison to conventional methods, although their uptake within the UK ceramics industry is slow. Many barriers such as risk assessment, capital investment justification have to be assessed, together with the technical aspects of monitoring and implementation of a project which many smaller companies will not be capable of conducting. The Energy Efficiency Office offer a range of guides and projects from Energy Consumption Guides to New Practice Projects describing installations and energy efficient technologies are well documented. However further emphasis must be placed upon the need for monitoring and targeting to control energy use and plan improvements in the efficiency of the energy used. This assessment of machine operational performance will give a clearer picture of where energy is consumed within the ceramics sector, and reveal potential areas for improved efficiency and targets for the application of new technology and effective demonstration projects.

With energy utilities now looking at least cost planning/demand side management options it has been suggested [132] that in the future utilities will help finance energy efficiency investments, in particular where the investment defends their market share against competitors.

Conclusions

The following conclusions can be drawn from analysis of the ceramics industry;

For sanitaryware manufacture;

1. The production of sanitaryware products has fallen during the last five years due to a slump in the house building market.

2. Direct fired chamber dryers, heat pump systems, tunnel dryers and vacuum dryers were identified as currently being utilised. Average thermal efficiencies of chamber dryers were found to be 10%.

3. Space heating techniques for drying processes are widely practised in the sanitaryware industry. The thermal efficiency of a space-heating system was found to be about 13%. The low temperature atmosphere and loss of moisture due natural convection may have attributed to the improved efficiency of space heating methods in comparison to chamber dryers.

4. A total SEC of 15.6 GJ/t of finished product was calculated for sanitaryware, of which 9.7% was electricity.

5. An average drying SEC of 2.25 GJ/t was estimated from industrial information, representing an overall drying efficiency of 12.5%. Heat pump systems were found to consume 0.91 GJ/t.

6. Drying consumes about 14% of the energy consumed within the sanitaryware industry. An estimated 3.7 million GJ was consumed in 1992, implying that 0.52 million GJ was utilised in drying processes.

7. Comparison to other figures showed that total and drying SEC figures have decreased over the last decade. Figures indicated that greater savings have been achieved for drying equipment in comparison to other processes within the sanitaryware industry. The closure of older plant due to the declining market may have contributed to this trend.

For tile manufacture;

1. The production of tiles has decreased since the mid 1980s, and an estimated 13.65 million square meters were produced in 1991.

2. Traditional techniques of forming/drying still dominate in the UK, representing an estimated 82% of the total production.

3. An estimated 1.8 million GJ of energy was consumed for tile manufacture in 1990, yielding a total SEC of 0.132 GJ/m^2, or approximately 13.04 GJ/t.

4. Calculations based upon data from industry showed traditional drying methods consumed 3.13 GJ/t while roller methods consumed 2.94 GJ/t. Thermal efficiencies were 25% and 26% for traditional and roller methods respectively.

5. The largest proportion of the total drying energy utilised is derived from the spray drying of raw material.

6. Industrial data showed that up to 68% of the energy supplied for spray drying can be derived from waste heat which would reduce the drying SEC by 63%.

7. In 1991 an estimated 0.43 million GJ was consumed for drying, represent 23% of the total energy used. If waste heat systems on spray drying equipment were fully implemented in the industry an estimated yearly consumption of 0.17 million GJ would be realised, representing 9.4% of the total energy.

8. Comparison with previous studies showed that the total and drying SECs have fallen slightly since 1980. The implementation of roller techniques will have attributed to this trend.

For tableware manufacture;

1. An estimated total output of 100,839.5 tonnes of tableware was manufactured in 1993. Comparison has shown that there is some deviation between figures of production output from published sources. Analysis of sales figures, the price index variation and discussion with industry suggested that the production of chinaware has not varied significantly over the last decade. The validity and accuracy of the 1980 chinaware figures are questionable, and production may have been underestimated.

2. A survey of manufacturers showed that the thermal efficiency of drying equipment varied from 2.2 % to 45% for a direct chamber and IR system respectively. Spray dryers producing granular materials for pressing were found to be 20-22% efficient.

3. The total energy consumed for producing earthenware by isostatic pressing is only slightly less than using traditional techniques. However, significant energy savings of up to 96% were demonstrated for chinaware. The large consumption for the traditional drying of chinaware, and hence significant saving by pressing methods, is due to very low thermal efficiency of traditional equipment. Moreover, drying techniques for chinaware consume more energy than that for earthenware due to the more conservative drying regimes.

4. The proportion of the total energy used for drying varied from 5% for a IR system drying hotelware to 48% for the production of bone china. Isostatic pressing techniques consumed an estimated 3.2% of the total for drying. Approximately 18% of the total flatware production is manufactured by isostatic pressing techniques.

5. An assessment of energy consumed for mould drying could not be made due to the lack of industrial data.

6. In 1993 an estimated 3.1 million GJ was consumed for drying processes, representing 43% of the total energy consumed.

7. Comparison to previous studies showed that energy savings have been achieved within the tableware sector. Total SEC have reduced from 249 GJ/t in 1978 to 146 GJ/t in 1993 for chinaware, while those of earthenware have reduced by 80%. Drying SEC for chinaware production have only decreased slightly over the last decade, although approximately 64% less energy is consumed for drying earthenware.

8. The survey showed that the largest proportion of savings have been achieved by improved kiln operation.

For electrical/technical ceramics;

1. The production of electrical and technical ceramics has decreased since the 1970s, and production was estimated at 12154.2 tonnes in 1995.

2. Total SEC values were estimated at 100 GJ/t, which were considerably higher than 50 GJ/t suggested in 1990. There was considerable deviation between published sources of the estimated total energy consumption within the industry.

3. Limited data concerning the energy utilisation of drying equipment was examined due to a lack of industrial monitoring. A chamber dryer audited consumed 0.8 GJ/t, representing a thermal efficiency of 69%. A spray dryer analysed consumed 3.16 GJ/t operating with a efficiency of about 16%. Investigation of processes were complicated further due to rewetting of products, mixing and additional drying phases.

4. A study of the complete industry was not accurate due to limited information. However, equipment analysed during the study gave a good indication of achievable targets.

General conclusions;

1. An estimated 13.6 million GJ was consumed for ceramics production and 4.1 million GJ for drying processes. The largest proportion of energy is consumed within the tableware sector, representing 53% of the total and 76% of the drying energy.

2. Energy efficient technologies have been analysed describing applications and potential energy savings. Many examples in the form of case studies highlight benefits.

CHAPTER 5

ENERGY UTILISATION IN THE BRICK, ABRASIVES AND PLASTERBOARD INDUSTRY

Energy Utilisation in Clay Brick Manufacture

Introduction

Clay is the basic raw material of bricks. However, chemistry is complex and a good brick-earth is a composite compound of silica, alumina, oxides of iron, calcium, magnesium, sodium and potassium [213]. Five main types of brick are produced [124];

Facing	- Used for the outer walls of houses and have a high aesthetic standard.
Common	- Appearance is not important but their properties are as good as facing bricks.
Engineering	- Used in severe environmental conditions. They have mechanical and corrosion properties superior to other types of brick.
Pavers	- Increasing in popularly for pavements and driveway surfaces.
Specials	- Complex geometry's or irregular shapes used for architectural features and decoration.

In recent years common bricks have been widely replaced by lightweight concrete [124]. Brick types may be further divided into fletton and non-fletton bricks. Fletton bricks are made exclusively by the London Brick Company, using Oxford clay. Fletton bricks can be facings and commons. Non-fletton bricks are made from a variety of clays ranging from carboniferous shale to Weald [124].

Manufacture

A typical manufacturing process is shown in Figure 5.1. Raw clay is crushed, ground and blended with other materials as necessary to produce the clay body. Four processes are used for forming bricks, and to some extent determines the amount of energy required to dry the product before the firing stage. These processes are;

- **Stiff plastic process** - Clay with a relatively low moisture content (11-15% dry basis) is formed and dried effectively in the kiln without preliminary drying.

- **Extrusion process** - The bricks formed in this way are dried before firing. Moisture content ranges from 12-24%.

- **Soft mud process** - These bricks have a very high moisture content (19-54%) and a large amount of energy is required for drying.

- **Semidry process** - This process is used mainly for producing fletton bricks. Moisture contents of the clay is between 19-25%.

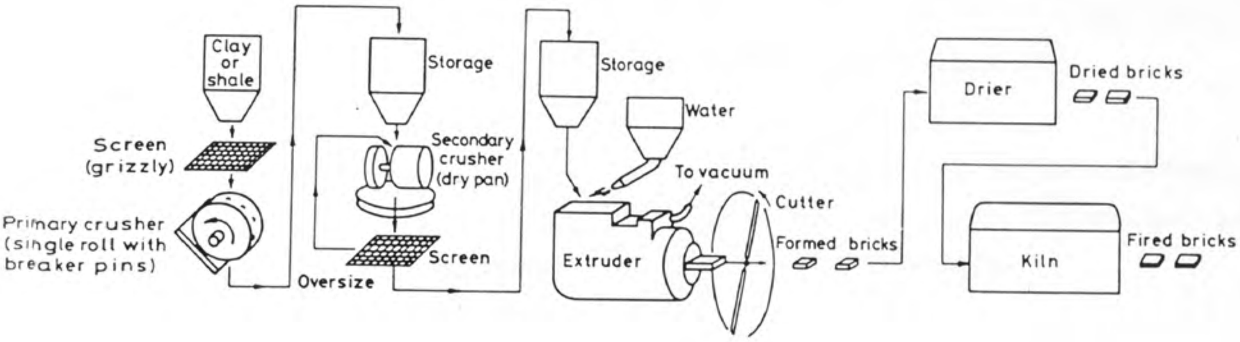


Figure 5.1 - Schematic of a brick making process

Figures 5.2 and 5.3 show a comparison of the total weight of bricks produced by forming process [20], [124].

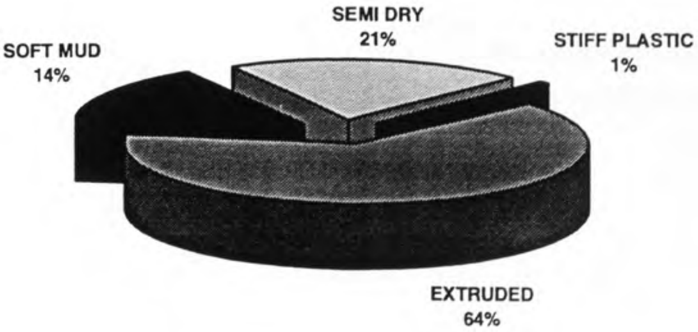


Figure 5.2 - Forming method and proportion of total weight produced - 1994

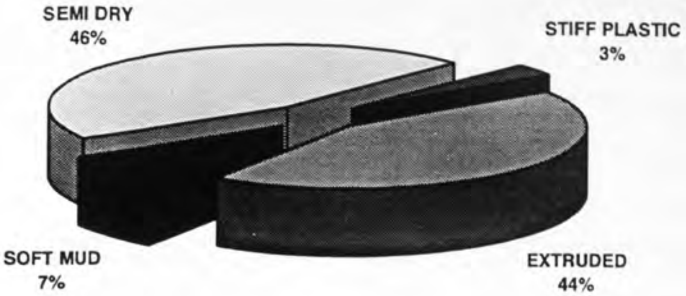


Figure 5.3 - Forming method and proportion of total weight produced - 1980

Figures 5.2 and 5.3 show that the production of bricks using stiff plastic and semi dry processes have decreased significantly over the last decade. Production methods employing extruded and soft mud techniques have increased, with the production of bricks using the soft mud processes doubling since 1980.

Industry

During the period 1954-1968 the number of companies within the brick industry more than halved, while the output per plant almost doubled [124]. In 1991 174 structural clay firms (including tiles and non-brick clay building materials) were operating [36]. A survey of the industry conducted by Ceram Research covered the Fletton industry and 100 non-fletton brick manufacturing sites, representing an estimated 90% of the industry [36].

The London Brick Company accounts for all the fletton production, representing 20% of the market by weight. Other companies include Armitage, Butterley, Crossley, Steeley, Ibstock, and Redland. Nine companies account for 90% of production [137].

Beardmore [20] revealed that the industry was declining with 6 manufacturing sites closing between 1991 and 1992. The decline in brick production is linked to the building industry, which was in recession during the late 1980s due to a slump in the house building market [213].

Production

Table 5.1 shows the production of bricks in 1994.

BRICK TYPE	METHOD/TYPE	MILLIONS	TONNES $x10^3$
Flettons	Common	56.500	108.3
	Facing	653.200	1252.1
Common	-	11.037	25.9
Facing	Extruded	1497.285	3646.8
	Soft mud	406.947	938.0
Engineering	-	178.746	482.2
Pavers	-	35.077	106.0
Specials	-	19.614	54.8
Total		***2858.406***	***6614.1***

Table 5.1 - Production of bricks - 1994

Figure 5.4 shows the variation of production over the last decade.

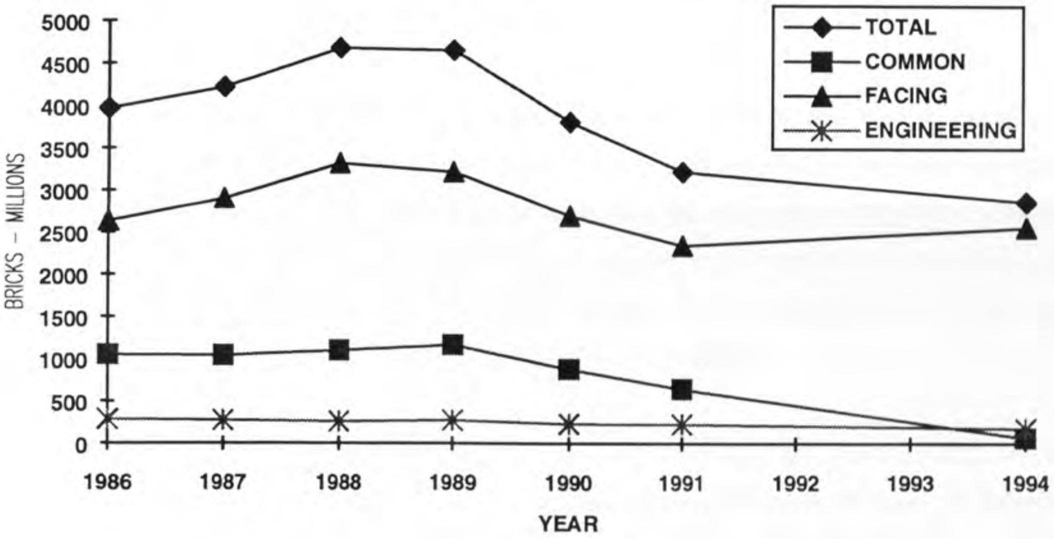


Figure 5.4 - Variation in production over the last decade

Figure 5.4 shows that there has been a decline in the production of common bricks since the 1980s, although the production of facing bricks has increased since the early 1990s. The trend in total production shows the effect of the decline of the house building market in the early 1990s.

Energy Utilisation

A survey of energy utilisation within the brick manufacturing industry is conducted annually by Ceramic Research [20]. However, a direct study of the energy consumed for drying processes is not separated from that for kilning operations.

Information from manufacturers [57] showed that little monitoring of drying equipment was conducted. Data available often combined drying plant and kiln information thus hindering direct analysis of the drying process.

The source of energy consumed in the brick making process can be [137];

- External - Conventional energy used in kilns, dryers and ancillary machinery,
- Added - Carbonaceous material added to the clay body,
- Inherent - Carbonaceous matter naturally present in the clay.

The inherent carbon content of a clay influences the energy required for the firing process. Fletton bricks have the highest inherent fuel content and thus have a significantly lower firing energy requirement than all other brick types.

TOTAL ENERGY CONSUMPTION

The energy consumed in brick production depends upon the type of dryer and kiln used, the type of brick produced, the method of manufacture and the raw materials.

Total energy requirements for drying and firing varied between 0.79-8.85 GJ/tonne in 1994, excluding inherent energy within the clay body [20]. Fletton bricks require substantially less energy per tonne produced due to inherent energy from the clay carbon content. Specials consumed the most energy. Non-fletton common bricks typically require 2.73-5.17 GJ/tonne for drying and firing, facing and engineering bricks 2.67-4.94 GJ/tonne, soft mud bricks 3.37-3.69 GJ/tonne, and pavers 3.45-5.97 GJ/tonne [20]. The utilisation of intermittent kilns significantly increases the specific energy consumption for drying and firing.

Table 5.2 shows a comparison of drying and firing specific energy consumption's. Generally the energy required for drying and firing has decreased since the 1980s. However, significant increases in specific energy consumption were noted for the manufacture of carboniferous common and hand made bricks.

In 1994 an estimated 16.6 million GJ of energy was consumed for the manufacture of 2858.4 million bricks (6614.1 x 10^3 tonnes) [20]. In 1980 21.65 million GJ was consumed to manufacture 4562 million bricks (9185 x 10^3 tonnes) [124]. Figures indicate that average specific energy consumption per weight of brick manufacture has increased since the early 1980s. These findings contradict suggestions that average SEC values have fallen by 22% over an 18 year period [137]. ETSU suggested that producers have responded to the decreasing market size by improving quality and widening their product range [124]. However, this has led to a wide range in specific energy consumption. The significant increase in the use of soft mud production methods has attributed to the increase in energy requirements per tonne produced.

BRICK TYPE	**CLAY**	**AVERAGE DRYING AND FIRING ENERGY GJ/tonne**		
		1980	**1994**	**% Change**
CONTINUOUS KILNS				
Fletton	Oxford	0.91	0.79	-13.2
Common	Carboniferous	1.17	2.97	+153.8
	Boulder	2.64	2.22	-15.9
Facing + Engineering	Carboniferous	3.07	2.61	-14.9
	Keuper Marl	3.03	2.31	-23.7
	Etruria Marl	3.05	2.96	-2.9
	Weald	3.77	2.95	-21.7
	Boulder	2.24	2.31	+3.1
INTERMITTENT KILNS				
Facing	Various	5.25	5.18	-1.3
Handmade	Various	2.97	3.62	+21.8
Blue + Brindled	Etruria Marl	6.61	4.93	-25.4

Table 5.2 - Comparison of SEC for drying and firing (excluding inherent energy)

DRYING ENERGY CONSUMPTION

Descriptions and application of drying equipment within the industry is well documented [150]. Tunnel and chamber units are the most commonly used dryers in the brick manufacturing industry. A chamber dryer consists of a series of chambers where the bricks are stacked. In a tunnel dryer the bricks move slowly though the system, with hot air flowing in a countercurrent direction to the movement of the bricks [150].

Heat for drying is usually hot air from the cooling zone of the kiln, or/and direct fired air heaters. Steam heated dryers have been developed but are uncommon. The use of combustion products from the kiln is rare due to the corrosive nature of the exhaust.

Table 5.3 shows data obtained from manufacturers relating to tunnel and chamber kiln types [57].

If the rate of moisture extraction from a brick is too high cracks will form and produce significant quality problems. The moisture extraction rate is dependant on clay type, and thus the total drying time is affected by both the moisture extraction rate and the initial moisture content. Table 5.3 shows that tunnel dryers for extruded bricks were the most energy efficient. The increase in drying time due to high initial moisture and limits of the rate of moisture extraction is reflected in the energy requirements for drying soft mud bricks. The increase in drying time results in an increase in heat losses and hence fuel efficiency is reduced. The increased operating temperature of the chamber dryer may have reduced the overall thermal efficiency, which is low in comparison to the tunnel unit, due to greater radiated thermal losses. Limited chamber insulation may have attributed to the figures obtained.

DRYER TYPE	Tunnel	Chamber	Tunnel
FORMING METHOD	Extruded	Extruded	Soft mud
MOISTURE CONTENT CHANGE (%)	18-2	17-4	25-3
TYPICAL DRYING TIME (h)	36	18-32	48
TEMPERATURE (°C)	80	100	80
WASTE HEAT (PROPORTION OF TOTAL ENERGY UTILISED) (%)	75	85	82
ENERGY (inc. waste heat) GJ/tonne	0.74	1.15	1.89
ENERGY (Gas + Elec. only) GJ/tonne	0.17	0.19	0.31
THERMAL EFFICIENCY (inc. waste heat) (%)	67.4	26.6	39.6

Table 5.3 - Energy utilisation of drying equipment - 1994

A comprehensive literature search revealed little information relating to the thermal efficiency of brick drying equipment or typical energy consumption characteristics. Data relating to the number of tunnel and chamber dryers in operation within the industry in 1994 was not available in any published format.

A thermal efficiency of 44% was assumed by Beardmore for calculations involving the drying of non-fletton bricks [20]. A figure of 1.059 GJ/tonne was suggested for the drying of extruded bricks, where as handmade and soft mud bricks required 1.928 GJ/tonne for drying processes [20]. Comparison to Table 5.3 shows that the energy consumption of drying equipment were typically lower than figures presented by Beardmore [20], extruded bricks typically requiring 0.945 GJ/tonne and soft mud bricks 1.89 GJ/tonne. Heat recovery from the kiln cooling zone is widely practised in the industry [137] thus, these figures do not represent actual energy consumption, but give an indication of the heat required to remove moisture from the bricks.

A thermal efficiency for brick drying systems is estimated at 41.25% [131], and 27-50% was proposed by Ford [150]. The efficiency of a brick drying system varies widely and is dependant on dryer type, product characteristics and dryer construction. Opportunities for improving the energy utilisation for brick drying include heat recovery, control, burner design, and use of waste heat.

TOTAL SECTOR ENERGY UTILISATION FOR DRYING PROCESSES

Average efficiency figures from Table 5.3 were used in estimating the energy consumption for drying processes within the brick industry. Table 5.4 shows drying figures relating to the energy required to remove moisture from the clay body, and the total conventional energy utilised in 1994.

PROCESS	PRODUCTION 000 tonnes	WATER REMOVED 000 tonnes	TOTAL ENERGY Million GJ	DRYING ENERGY Million GJ	PROPORTION OF TOTAL ENERGY %	DRYING ENERGY GJ/tonne
Extruded	4229.9	759.1	11.94	4.13	34.62	0.97
Semi Dry	1368.1	342.7	1.10	1.87	169.60	1.36
Stiff Plastic	62.9	8.3	0.27	0.05	16.90	0.71
Soft Mud	947.7	309.4	3.29	1.98	60.22	2.09
Total	6608.6	1419.5	16.59	8.02		

Note : No waste heat utilisation - Not including inherent energy

Table 5.4 - Drying energy consumption

Table 5.5 shows drying energy consumption and comparison to the total energy consumption including inherent fuel in the clay body.

PROCESS	PRODUCTION 000 tonnes	WATER REMOVED 000 tonnes	TOTAL ENERGY Million GJ	DRYING ENERGY Million GJ	PROPORTION OF TOTAL ENERGY %	DRYING ENERGY GJ/tonne
Extruded	4229.9	759.1	13.79	4.13	29.97	0.97
Semi Dry	1368.1	342.7	4.56	1.87	40.91	1.36
Stiff Plastic	62.9	8.3	0.29	0.05	15.58	0.71
Soft Mud	947.7	309.4	4.31	1.98	45.92	2.09
Total	6608.6	1419.5	22.95	8.02		

Note : No waste heat utilisation -Including inherent energy

Table 5.5 - Drying energy consumption

Table 5.4 shows that waste heat is utilised for drying bricks manufactured by the semi dry process since the basic drying energy requirements are greater than the conventional fuel input. Table 5.5 demonstrates that fletton bricks, representing 98% by weight of bricks manufactured by the semi dry process have a large inherent energy in the clay body. There is little change in the proportion of the total energy used for drying when comparing the effects of inherent energy for stiff pressed bricks, and to a lesser extent extruded products.

It is estimated that annual energy for drying alone accounts to 8.02 million GJ based upon no waste heat recovery, representing 48% of the total sector energy consumption. This suggests an average specific drying figure of 1.21 GJ/tonne produced.

In 1992, 6.36 million GJ was estimated for the energy required to dry non-fletton bricks, representing some 44.3% of the total energy used in non-fletton production [20]. A comparison using data calculated in this study revealed that this figure has decreased slightly to 6.16 million GJ, representing 39.7% of the total (including electricity) in 1994.

Waste Heat Recovery

Heat recovery from the kiln cooling zone to supply energy to the brick dryers is widely practised in the industry [137]. However, many sites are not suitable for heat recovery due to plant layout or insufficient utilisation Vs capital expenditure. A intensive literature survey revealed no sources relating to the degree of utilisation of heat recovery systems on drying equipment in the UK.

The lack of information relating to the overall extent of waste heat utilisation has hindered the estimation of the total drying energy consumed within the UK.

Table 5.6 shows the effects on the total energy utilisation for a dryer system supplied with 75% of its heat requirements from recovered waste heat.

PROCESS	PRODUCTION 000 tonnes	WATER REMOVED 000 tonnes	TOTAL ENERGY Million GJ	DRYING ENERGY Million GJ	PROPORTION OF TOTAL ENERGY %	DRYING ENERGY GJ/tonne
Extruded	4229.9	759.1	11.94	1.03	8.66	0.24
Semi Dry	1368.1	342.7	1.10	0.47	42.40	0.34
Stiff Plastic	62.9	8.3	0.27	0.01	4.22	0.18
Soft Mud	947.7	309.4	3.29	0.49	15.05	0.52
Total	6608.6	1419.5	16.59	2.01	-	-

Note : Not including inherent energy

Table 5.6 - Drying energy consumption - 75% waste heat

Even with 75% of the drying energy supplied by waste heat, 42% of the total energy used for semi dry processed bricks is used for drying. This implies that little energy is required for firing due to the high inherent fuel content of the clay body.

The specific energy required for drying is reduced significantly by using waste heat, and ranges from 0.18-0.52 GJ/tonne produced for the above case. These values agree with case studies from manufacturers, with figures varying from 0.17 GJ/tonne for a tunnel dryer for extruded bricks with 75% waste heat, and soft mud bricks requiring typically 0.31 GJ/tonne [57].

This work showed that in some cases up to 85% of the energy required for drying was supplied by waste heat. Using this information the energy used within the brick industry used for drying process could vary from 0.18 GJ/tonne for all systems using 85% of energy supplied from waste heat, to 1.21 GJ/t for no waste heat utilisation.

Averaging values suggest a figure of 0.69 GJ/tonne for drying processes. Thus an overall drying energy consumption of 4.6 million GJ in 1994, representing 28% of the total conventional fuel consumed within the industry.

Comparison of Energy Surveys

Table 5.8 shows a comparison of previous surveys and results from this study. Estimates of the energy consumed for drying processes within the brick industry vary widely. Information regarding the extent of implementation of heat recovery systems in the UK is essential required for an accurate assessment. ETSU [131] estimated that 66% of energy may be derived from waste heat, although there is no published evidence to back their proposal. Table 5.8 reveals no trend in drying energy consumption and inaccuracies were found in comparing studies conducted the same year.

YEAR	**ENERGY CONSUMED Million GJ**		**PERCENTAGE OF TOTAL**	**REFERENCE/ NOTE**
	DRYING	**TOTAL**	%	
1976	13.95	73.00	19	[387]/1
1976	6.37	n.a.	-	[177]/2
1978	4.30	n.a	-	[16]
1980	8.90	22.08	40	[131]/3
1980	2.90	22.08	13	[131]/4
1995	8.02	16.59	48	This study/3
1995	4.6	16.59	28	This study/5

Notes

1: Based upon 2.4 x 10^6 tonnes of water removed with a dryer efficiency of 44% (thermal). Total energy also includes that for tile manufacture.

2: Based upon 1.097 x 10^6 tonnes of water removed with a dryer efficiency of 44% (thermal).

3: Assuming no waste heat recovery.

4: Assuming 66% of energy supplied by waste heat.

5: Assuming average values of 75% waste heat recovery and no waste heat recovery.

Table 5.7 - Comparison of previous studies

Energy Efficient Technologies

Many opportunities for improving energy utilisation for brick drying in the UK are currently available and implementation may significantly reduce the energy consumed within the industry.

KILN HEAT RECOVERY

Energy losses from kilns in the form of sensible and latent heat in exhaust gasses can amount to 40-80% of the total energy input for brick manufacture [20]. Kiln exhaust gas contains moisture, sulphur and fluorine which can lead to acid corrosion due to condensation. Expensive materials could be utilised to increase the life of a heat exchange system, but dramatically increases the capital costs. Although heat recovery from continuous kilns in the non-fletton sector offers an energy saving potential of 0.43 GJ/tonne of product it is unlikely to be adopted on a large scale basis until low cost corrosive resistant heat recovery systems are available [20].

HEAT RECOVERY FROM DRYERS

It has been estimated that 80% of the non-fletton brick industry uses supplementary heat for drying, in addition to the heat recovered from kilns [131]. Further savings could be achieved from energy recovery from dryer exhausts, either by heat exchangers or heat pumps.

It has been estimated that the application of heat pumps to recover waste heat from drier exhausts could produce energy savings of about 25-50% of the primary energy used [131]. However, problems of control have been reported when utilising waste heat [32], resulting in a 10 % reject rate due to the difficulty of controlling the drying cycle. Implementation of heat recovery systems may be financially viable on sites which have a constant supply of waste heat from the kiln. However, many smaller producers will face problems of control and large capital costs if complex control systems are required due to intermittent supplies of kiln waste heat.

DEHUMIDIFICATION DRYING

Electric dehumidifier systems are used for brick drying and energy and production improvements have been reported [32], [118], [327]. Wastage of large special shaped bricks have been reduced from 50 to 5% and energy consumption has been cut by 60% in comparison to the original chamber dryers [118]. Benefits of using heat pumps for bricks drying include;

- Improved product quality,
- Lower labour cost,
- Lower unit production costs,
- Increased flexibility,
- Improved working conditions, &
- Reduced environmental pollution.

However, heat pump drying is fundamentally a batch process and implementation may not be suitable for a continuous process system such as replacing a tunnel drier.

IMPROVED DRYER CONTROL AND PROCESS INTEGRATION

Better monitoring of drying conditions should lead to efficiency improvements in various ways, ranging from more flexible control systems which will adjust for changes in dryer loading, to the correction of dryer conditions to prevent cracking or incomplete drying of bricks. Energy savings of 50% have been achieved by improving control of a brick chamber drier [131].

Energy savings of 20% have been achieved by improved process flow conditions and dryer design [33]. Optimising the mixing of drying air has resulted in more even drying and shortened drying times. A second measure has uncoupled the press machine and dryer, allowing a buffer area and implementation of an automated transport system. This arrangement has allowed utilisation of waste heat from the kiln in the drying chambers.

AIRLESS DRYING

An airless drying system has been developed which uses a steam medium for drying. Waste heat is recovered using a mechanical vapour recompression unit, or is utilised by another process requiring low grade heat or hot water. Although fundamentally a batch system, plans have been unveiled for a continuous dryer [340].

Airless drying has been shown to increase the speed of drying and produce significant energy savings [129]. The technique is in the development phase and if trials are successful may produce large savings for drying processes within the brick industry.

Energy Utilisation in Refractory Manufacture

Introduction

Refractory materials can withstand high temperature while remaining dimensionally and chemically stable [124]. Products are based on oxides of aluminium, silicon, magnesium, calcium and chromium.

The industry produces shaped products such as bricks for furnace lining and powders which may be used as cement, mouldables or castables.

Manufacture

Figure 5.5 shows the main production route for refractories [124]. After raw products are mixed and ground, the material may be sold as an unshaped product or shaped, dried and fired for sale. Many products (mainly non-fireclay) are shaped in hydraulic presses from material containing 4-5% moisture. However, fireclay materials have higher levels of water, typically around 16%. Drying to <1% moisture content is carried out before firing.

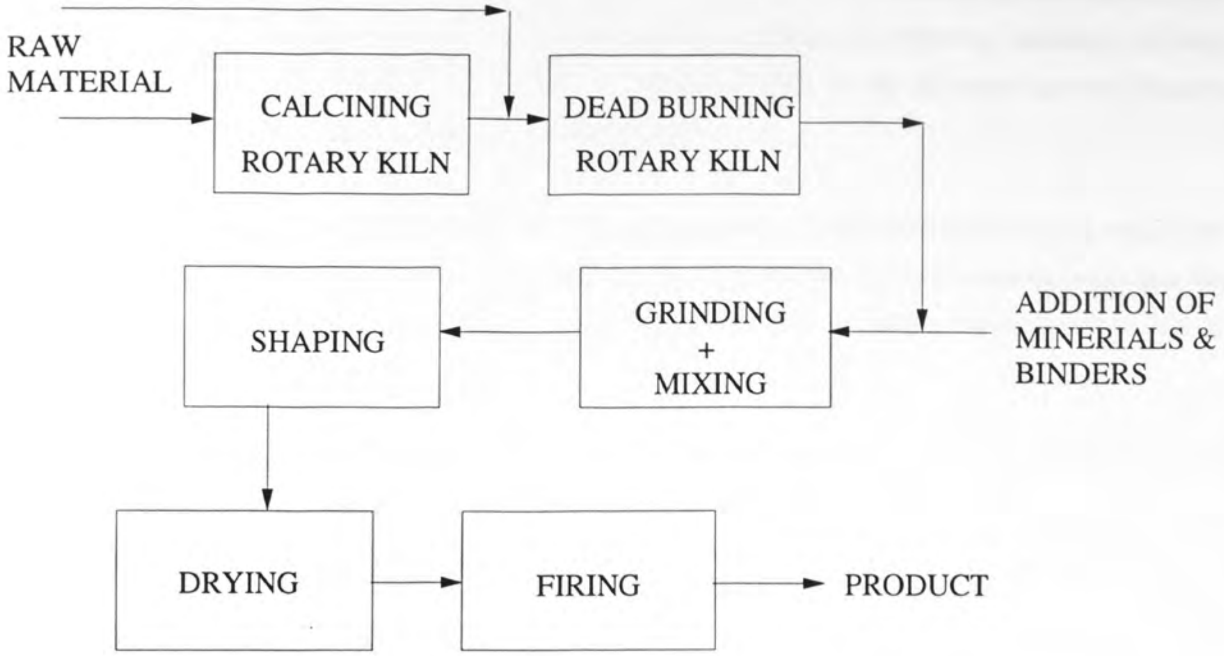


Figure 5.5 - Schematic of refractory manufacture

Industry

Annual production statistics are collected from the major manufacturers within the refractory sector, although there is considerable delay between collection and publication of data [255]. This study was based upon 1990 production data.

Figure 5.6 shows the variation of production and the number of companies over the last decade.

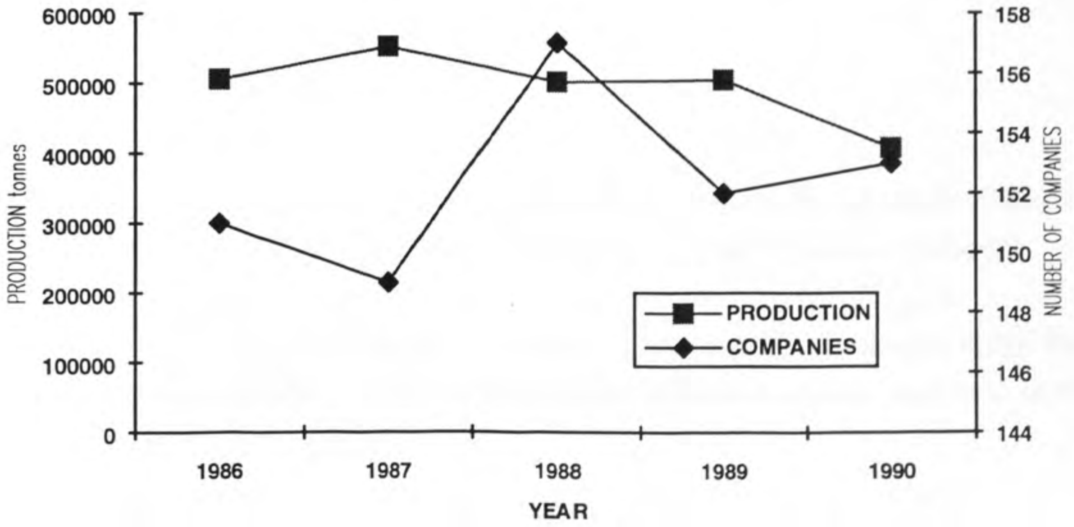


Figure 5.6 - Variation of production and number of companies [36], [255]

The production of refractory products has fallen dramatically since the 1970s, reducing by 69% between 1978 and 1990. A large part of the refractories output is used by the metals manufacturing industries and large cutbacks in production of these industries has led to a significant effect on the refractory industry. However production only reduced slightly during the period 1985 to 1990.

Figure 5.6 shows that there has been a slight increase in the number of companies manufacturing refractories during the late 1980s. Consultation with Ceram Research [75] suggested that the figures may be misleading due to the inclusion of non-manufacturing companies who market products. In 1978 a survey reported only 30 companies manufacturing refractories [124].

Energy Utilisation

TOTAL ENERGY CONSUMPTION

A literature survey has shown that a detailed energy analysis of the refractory industry has not been conducted since 1978.

The specific energy requirement for refractory manufacture can vary widely due to differences in raw materials, the types of product and the equipment in use. In 1978 an estimated 90% of the energy used within the refractory industry was used for drying and firing, representing 12.0 GJ/tonne [121], [124], [138].

In 1990 408 kt of refractory products were manufactured, consuming an estimated 5.275 million GJ of energy [75], [255]. Thus a mean specific energy consumption of 12.94 GJ/tonne. Comparison with data from the 1978 survey shows that the average total SEC for refractory manufacture has increased slightly since the 1970s. It has been suggested that the mean SEC has increased mainly because of a shift by users to higher performance products [124]. Low utilisation of equipment due to reduced production may have also attributed to this trend.

DRYING ENERGY CONSUMPTION

Tunnel and chamber dryers are common within the industry, with typical drying temperatures ranging from 50-90°C. Drying times vary according to product and dryer type and can range up to several weeks [70].

Calculations based on confidential information from industry has produced an estimated drying SEC of 4 GJ/tonne [70]. Thermal efficiencies of drying equipment vary widely but typically were about 24%. An estimated 3% of the total energy was from electricity.

In 1978 an energy audit of the refractory industry reported a drying energy figure of 2 GJ/tonne [380], and Baker and Reay based their calculations on 0.68 GJ/tonne [16].

Comparison of previous values of drying SEC has shown that figures vary up to 3 times for estimates conducted the same year. The degree of accuracy of previous studies is thus questionable.

Using 1990 production data and SEC values, an estimated 1.664 million GJ was consumed for drying processes, representing 31.5% of the total energy consumed [70].

Comparison of total and drying SEC figures demonstrates that the proportion of the total energy used for drying process has increased since 1978. Running drying equipment at reduced capacity due to a declining market may have influenced this figure.

Energy Efficient Technologies

Information from refractory manufacturers showed that waste heat was recovered from kilns and intermittently used for drying [70]. Information provided showed that not all companies utilised waste heat, although other manufacturers derived up to 90% of the heat energy for drying using heat exchanger systems.

Future energy saving have been assessed and concepts include [124];

- Heat recovery from kilns,
- Heat recovery from afterburner exhaust,
- Improved insulation, &
- Improved process control.

It has been suggested that 5% of the total energy consumption could have been saved by implementing energy efficiency measures by 1995 [124]. Results of this study demonstrate that that savings have been achieved for kiln operation, however, drying SEC has nearly doubled since 1978.

Energy Utilisation for Plasterboard Manufacture

Introduction

Plasterboard is a flat sheet which consists of a core containing gypsum hemihydrate plaster, sandwiched between two sheets of heavy paper known as plasterboard liner. In the UK the most common thickness of plasterboard are 9.5 mm and 12.5 mm, although upto a 19 mm board is produced [176].

Plasterboard is used extensively in the building industry, typically for internal lining for walls, internal partitions within buildings, ceiling material and as roof lining material.

Production

The manufacture of plasterboard is relatively simple, involving the production of a plaster slurry which is sandwiched between two sheets of paper, cut to length and dried [66].

Plaster is made either from natural gypsum or from gypsum produced as a by-product of some other process. The latter is most commonly from flue-gas desulphurisation (FGD).

Natural gypsum is delivered to the factory in the form of crushed rock which requires milling to a fine powder. DSG is already in powder form. The gypsum is then calcinated by heating in a direct submerged gas jet or oil fired vessel at approximately 120-160°C. This process removes a proportion of the water of crystallisation leaving calcium sulphate hemihydrate, commonly known as plaster. The calcination is not considered as a drying process. Plaster is sold to both commercial and domestic customers for various applications including the building trade, and manufacture of plaster moulds.

Plaster is mixed with water to form the di-hydrate, and excess is added to yield a workable slurry. Various additives are added to improve the porosity and structure of the finished material including; foam, silicone and fibre. The mixture is then housed between two layers of paper which travels on a continuous flat bed processing line typically 200 - 400m long. The paper edges are sealed, and a setting phase occurs during which an exothermic reaction occurs within the board and gypsum crystals grow. The board is then cut into lengths which vary according to the batch.

The boards are automatically transferred to the drying line which usually runs parallel to, and in the reverse direction to, the forming line. They then pass through a large oven, usually with eight to twelve decks, which typically accept two 1200 mm wide boards abreast. The dryers are direct gas fired, although oil is sometimes used if the economics are justified.

A problem commonly encountered during the drying stage is overdrying, resulting in calcination. Calcination often occurs at the interface between the gypsum and paper interface, causing separation of the paper and rendering the board unfit for use. Edge over heating is also a common problem. To prevent overdrying the ovens are divided into several heating zones at decreasing air inlet temperatures. Most of the moisture removal occurs in the first zone, at temperatures of approximately 170°C.

The application of tempering air jets at the sides of the oven help to reduce edge calcination. Counter current air flow is used in the first drying zone, where as co-current flow is used is subsequent sections. A modern dryer typically utilises waste heat and much of the energy input to the final dryer section is supplied by air/air heat exchangers from former zones [66]. Once dried the boards are trimmed to length and stored ready for use.

Industry

There are four main manufacturers of plasterboard in the UK; BPB, RPL, Knauf and Eternit. BPB produces 76% of the UK output on nine plasterboard lines [176].

Figure 5.7 shows the production variation of plasterboard over the last decade. Production of plasterboard is commonly measured in surface area regardless of thickness, a basis of measurement termed 'superficial' within the trade. In this study figures are related to 9.5 mm board.

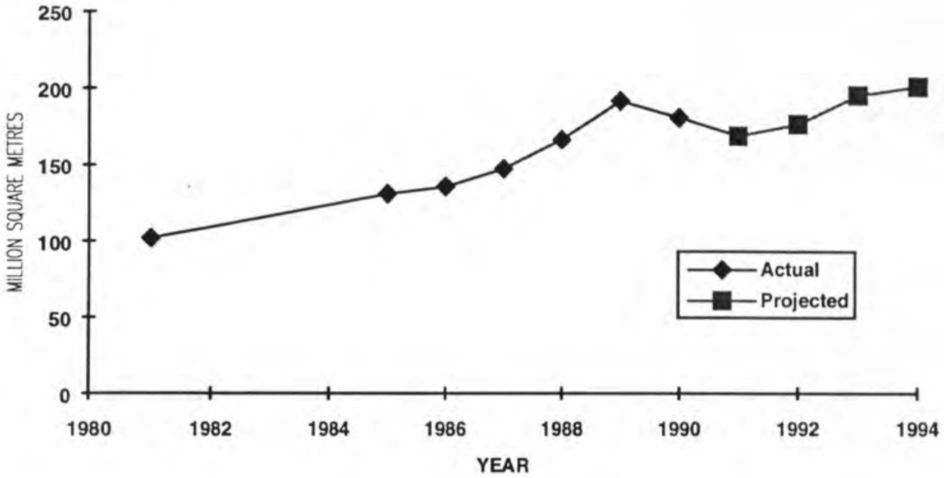


Figure 5.7 - Production of plasterboard - 1985-1991 [176]

In 1991 an estimated 170 million square meters of plasterboard was manufactured, with an increasing production trend projected for the early 1990s. Only 69.7% of the total installed UK capacity was utilised in 1990.

The decrease in production during the late 1980s is probably linked to the slump in the house building market [213].

Energy Utilisation

The production of plasterboard from gypsum is a very energy intensive process requiring over 22.7 MJ/m^2 [294].

A literature search showed that analysis of energy utilisation for plasterboard manufacture is not a regular topic for examination. Overall energy consumption figures for the UK plasterboard industry are not published.

All raw materials, either mined gypsum or by products from FGD require drying before processing. However, this study found that energy consumption for drying of raw material was not monitored. Contacts within UK industry suggested that drying raw materials consumed an insignificant amount of energy incomparison to the drying of plasterboard. Figures from the United States Gypsum Company [294] suggest that 1.13 MJ/m^2 of board produced is used for initial raw material drying.

Plasterboard enters the drying oven with an initial moisture of approximately 30% by weight. Drying time is dependant on board thickness ranging from 60 mins for 9.5 mm board to 85 mins for 19 mm board. Final moisture is 1.5-2% by weight.

Calculations performed using information from industry showed that 2847 kJ of thermal energy was required to remove 1 kg of water, with a further 106.3 kJ/kg consumed for motive and fan power. Thus an estimated energy consumption of 2953 kJ/kg water removed is utilised for the drying of plasterboard, representing a machine thermal efficiency of 71% [66].

Typically, 3.5 kg/m^2 of water is removed during the drying phase for a 9.5 mm board. Hence an estimated 11.46 MJ/m^2 is consumed (including 1.13 MJ/m^2 for drying raw material [294]) for drying plasterboard.

Table 5.8 shows estimated drying energy figures.

In 1994 an estimated 2.33 million GJ was used for drying process, representing 50.5% of the total energy consumed. Energy for crushing, calcination and material transportation represents a large proportion of the non drying energy.

YEAR	PRODUCTION Million m^2	TOTAL ENERGY CONSUMPTION Million GJ	DRYING ENERGY CONSUMPTION Million GJ	PROPORTION OF TOTAL ENERGY FOR DRYING %
1980	102	2.31	2.70	-
1991	170	3.86	1.95	50.5
1994	203	4.61	2.33	50.5

Note : Total energy based upon 22.7 Million GJ/m^2 [294].

1980 figures from Wilmshurst [380]. 1994 energy figures based upon forecast production figures.

Table 5.8 - Total and drying energy consumption

Wilmshurst [380] examined the production of plasterboard in 1981. An estimated 2.7 million GJ was consumed for the production of 102 million square meters in the UK. Thus representing a drying energy of 26.5 MJ/m^2. Calculations were based upon the water added to the raw plaster to produce slurry and the requirements for hydration. A dryer thermal efficiency of 35% was also assumed. The plaster setting phase before drying is exothermic and water would be lost during this time. Wilmshurst did not account for this water and estimated energy figures may have inaccuracies. Comparison to an estimation of the total energy consumption based upon figures from the United States Gypsum Company [294] suggest that an assumed efficiency of 35% may not truly represent the equipment utilised.

Comparison of previous figures and those derived in this study has shown that there has been improvements in dryer energy consumption over the last decade.

Discussion with key manufacturing personnel suggested the following have attributed to dryer energy savings;

- Improved burner design,
- Improved dryer control,
- Use of cooling air jets to allow oven temperatures to be maintained without affecting product quality or reducing productivity,
- The application of IR temperature monitoring equipment to ensure the dryer is operating at a critical level between product overheating, causing calcination, and reducing productivity due to lower oven temperatures,
- On-line monitoring of fuel utilisation and productivity.

Cove Manufacture

Various forms of decorative cove are produced using a similar process as plasterboard. Products range from paper coated cove to plaster with added glass fibre and setting agents.

Special high value products such as the glass fibre impregnated cove are dried in a RF/microwave/impingement jet tunnel unit from about 50% moisture by weight to <1%. The other types of cove are processes using a fossil fuel fired tunnel dryer which resembles a small scale plasterboard oven.

A cove dryer analysed during this study consisted of a six layer hot air tunnel unit. The system was less efficient than that calculated for a plasterboard oven, operating at about 3265.7 kJ/kg of water removed, yielding a thermal efficiency of 65%.

Figures relating to the UK production of cove are not published and have limited an analysis of the energy consumed. Based upon energy requirements for plasterboard production, the energy consumed for cove manufacture in the UK may be significant.

Heat Recovery On Drying Equipment.

The application of heat recovery is practised within the industry, mainly using air/air heat exchangers to recover heat from the initial drying zones to feed the latter stages of the dryer.

A dryer thermal efficiency of 71% estimated in this study is extremely good in comparison to other industrial drying equipment and demonstrates the energy savings permissible from the implementation of heat recovery systems. Further improvements may not be fundamentally possible, although all drying units within the plasterboard industry may not be achieving efficiencies of this magnitude.

Other Technologies for Plasterboard Manufacture

A direct resistance drying system has been installed in Canada for the drying of plasterboard [191]. The original gas or fuel oil fired burners were replaced by two electric resistance banks rated at 9 and 7.5 megawatts. Main advantages reported were;

- Energy savings of about 12%,
- Production increase by 3-5%,
- Better product quality,
- Maintenance simplified,
- Better reliability,
- Improved environment, less noise, and fumes.

The system gave a payback time of 2 years.

Although the use of electric heating offers outstanding benefits in comparison to fossil fuelled systems, the cost of electricity in the UK would make the implementation of this form of heating uneconomical on a large scale.

Work conducted by the Centre for Materials Fabrication [294] has analysed the technical and economic aspects of using radio frequency (RF) heating for drying plasterboard. Results showed that RF energy was a technically viable approach for heating and drying gypsum wallboard, having the distinct advantage of being self regulating. It offered the potential for 0% free moisture in the plasterboard without calcination. However, economically the use of RF was not practical. The potential quality and production gains were not sufficient to overcome the higher running and capital investment costs.

RF heating is applied in the UK for the drying of high value glass fibre impregnated decorative cove. Figures relating to operating costs and energy utilisation were not available. However, total energy consumed was considered to represent only a small proportion of the total due to the limited application of RF techniques.

Microwave systems have been analysed [66], but there has been a lack of uptake of this technically feasible application due to high capital costs.

Energy Utilisation in Abrasive Manufacture

Introduction

Abrasive materials can be divided into three product groups;

- Bonded/Vitrified grinding wheels,
- Coated material commonly using a paper or fabric backing,
- Shot and grit for blast cleaning and wire sawing.

The energy utilisation for the manufacture of abrasive powders and grains was not investigated during this survey.

BONDED/VITRIFIED ABRASIVES

Bonded abrasives are manufactured by mixing abrasive grit, water based binder and bond powder. A typical mix contains 1000 parts abrasive, 150 parts bond and 20-60 parts binder. The bond powder and grit is commonly dried using a attritor, from a moisture content of 18% - 3%, prior to mixing. The abrasive wheel is then pressed into shape, dried and fired. Products range from 25 to 140 cm diameter and 0.1mm to 70 cm thick [55].

This study showed that chamber dryers are commonly used within the industry and many of the drying systems in operation are over 30 years old [55]. Products are dried from a moisture content of 3-8% by weight to <0.5% using either steam, electricity or direct fired oil or gas. The drying time and temperature depends upon the chemical composition and dimensions of the wheel. Temperature ranged from 40-180°C with drying times from 0.5-18 days. Some dryers are operated in batches and run continuously even when they are only partially filled or not used.

Some manufacturers use space heating techniques to dry small products. Direct gas or dehumidifier heating is commonly used.

Microwave techniques have been applied to a limited extent for the drying of grinding wheels. A number of magnetrons allow the power level to be varied according to the load. Abrasives have been successfully dried using microwave powers up to 50 kW, with product loads up to 1400 kg in weight. Drying times vary from minutes to 4 hours. However, the chemical composition, dimensions of the abrasive and weight restrict the permissible microwave power, and thus the application of this method of drying to the whole range of abrasives manufactured has limitations.

COATED ABRASIVES

An abrasive grit is coated with a water based adhesive and spread onto a paper or material backing. Alternative production methods involve coating the backing material with binder and electrostatically applying the abrasive grit. The product is then dried and cured in a hot air oven. The survey showed that tunnel dryers were most common within the industry as the production process are typically continuous. Drying times of about 20 minutes were recorded with dryer temperature ranging from 50-110°C. Between 64-224 grams of water is removed per square meter of coated abrasive depending upon the grit size.

Industry

In 1991 73 companies in the UK were involved with the sale of abrasives [37]. Only a small proportion of these manufacture abrasives in the UK, with the remainder involved with the converting industry or importing. Major manufacturers of vitrified abrasives include Universal Abrasives, Carboradom, Consort Ltd and Abrafract Ltd. Coated abrasive manufacturers include 3M United Kingdom, English Abrasives, J.G. Naylor, and Action & Boardman Ltd.

An estimated 12.87 million m^2 of coated abrasive was manufactured in the UK in 1995 [71] and 10273 tonnes of coated/vitrified abrasives were manufactured in 1990 [255]. The production of bonded abrasives is deemed not to have changed significantly over the last five years [71].

Energy Utilisation

Analysis of the total energy consumption within the industry is not a regular topic for examination and a literature survey revealed little sources of reference. Table 5.9 shows SEC figures for drying as derived in this study.

ABRASIVE TYPE	FIRING/CURING SEC	DRYING SEC	THERMAL EFFICIENCY %
Bonded/Vitrified - Convection	11.6 GJ/t[5]	0.85 GJ/tonne (7.3%)[3]	20[1]
Bonded/Vitrified - Microwave	11.6 GJ/t	0.21 - 0.24 GJ/tonne[2] (2%)[2]	70-79
Coated[2]	0.71 MJ/m^2[4]	48.63 kJ/m^2 (6.8%)[3]	14

NOTES :

1 : Estimated from commissioning data from industry due to lack of dryer instrumentation in industry.

2 : Figure based upon data for a direct gas fired tunnel dryer using an average grit size and water based adhesive.

3 : Proportion of total energy consumed for drying and curing (excluding mixing and cutting).

4 : Energy for drying and curing.

5 : Based upon industrial data for an average firing cycle.

Table 5.9 - Drying SEC for abrasives

The drying of raw materials was not consistent and varied according to the raw supply and mixture require for wheel pressing. No evidence of monitoring of raw material dryers was found during this survey of the industry.

The proportion of the total production of vitrified grinding wheels dried by microwaves is small in comparison to traditional drying techniques. Table 5.9 shows that microwave drying systems for vitrified abrasives consume about 70% less energy than conventional methods. Accounting for the higher cost unit of electricity in comparison to fossil fuels, microwave drying is more economic than traditional techniques.

Table 5.10 shows an estimation of the energy used for drying processes in the abrasives industry for 1995.

PRODUCT	PRODUCTION	TOTAL ENERGY GJ	DRYING ENERGY GJ
Coated	12.87 million m^2	9200.7	625.87 (6.8%)
Bonded/Vitrified	10273 tonnes	119166.8	8732.05 (7.3%)
Total	-	128367.5	9357.9 (7.3%)

Note : Bracket figures relate to proportion of total energy used for drying.

Table 5.10 - Drying energy consumption

Table 5.10 shows that an estimated 9.35 TJ was consumed for drying processes within the abrasives industry, representing 7.3 % of the total energy consumed within the sector.

Unlike other ceramics sectors such as tableware, tiles and sanitaryware, the drying of abrasives only represents a small proportion of the total energy consumed for abrasive manufacture. The low drying energy consumption is reflected in the low initial moisture content of material entering the drying phase.

Wilmshurst examined the abrasives sector and suggested that 10 TJ was consumed for drying processes within the industry in 1981 [380]. Comparison to the findings of this survey show that the energy consumption for drying has not changed significantly over the last decade. A large proportion of the drying facilities utilised in the industry were over 30 years old, and many manufacturers were unaware of new technologies or best practice guidelines for reducing drying energy consumption.

Energy Efficient Technologies

The study has shown that many dryers within the abrasive industry are old and relatively energy in-efficient. Significant savings could be achieved by 'good house keeping techniques', utilisation of waste heat and improved dryer design.

The study has shown that microwave energy is efficient for drying bonded/vitrified abrasives and savings can be achieved in comparison to traditional techniques. Savings in the order of 6420 GJ/year could be realised, representing a reduction of 73% incomparison to traditional techniques, if microwave systems were fully utilised.

High capital costs and limitations due to product size and material composition will hinder the degree of implementation in the UK market.

Research and development work concerning the microwave firing of ceramics, which includes vitrified grinding wheels, is currently proceeding [141].

Conclusions

The following conclusions can be drawn from this analysis of the UK clay brick manufacturing industry;

1. The proportion by weight of bricks manufactured by the stiff plastic and semi dry processes has decreased significantly over the last decade, while production employing extruded and soft mud techniques have increased.

2. The brick industry has decreased in size and is directly related to the slump in the UK building industry during the 1990s. The production of common bricks has fallen significantly over the last decade, with competition from light weight concrete bricks being an influencing factor.

3. Total energy requirements for drying and firing varied between 0.79 and 8.85 GJ/tonne in 1994. The use of intermittent kilns significantly increases the firing and drying specific energy consumption.

4. In 1994 an estimated 16.6 million GJ of energy was consumed for the manufacture of 2858.4 million bricks (6614.1 x 10^3 tonnes). Figures show that average SEC for drying and firing have increased by 6.5% per weight of bricks produced since the 1980s.

5. Tunnel dryers were found to be more efficient than chamber kilns. Extruded processed bricks consumed less energy than soft mud bricks (0.74 GJ/tonne and 1.89 GJ/tonne respectively).

6. Little information was found concerning the quantity of equipment utilised or the degree of waste heat usage in the UK. The lack of waste heat information hindered an exact estimation of drying energy consumption.

7. Calculated figures for drying SECs were found to be slightly less in comparison to other studies.

8. An estimated 8.02 million GJ of energy was consumed for drying processes, representing 48% of the total sector energy consumption in 1994, if no waste heat was utilised.

9. Information from the industry showed that heat recovery from the kiln cooling zone for dryer heat input was widely practised, although the extent of utilisation was indeterminable. Figures showed that waste heat recovery was well practised in the fletton brick industry.

10. If all dryers in the UK derived 85% of their energy from waste heat a SEC value of 0.18 GJ/tonne would apply.

11. Average figures showed an overall drying energy consumption of 4.6 million GJ in 1994, representing 28% of the total conventional fuel consumed.

12. Energy recovery from kiln exhaust would provide significant savings in drying energy consumption, however the corrosive nature of the gasses hindered application.

13. The benefit of using heat recovery systems on dryer exhausts, dehumidifier drying systems, and improving dryer control and process integration was shown to provide energy savings, while in specific cases addition rewards of quality and productivity could be achieved.

14. Airless drying systems may provide significant energy savings, although the technique is only in a laboratory scale at present.

The following conclusions can be drawn from the analysis of energy utilisation within the refractory industry;

1. Production of refractory products fell by 69% between 1978 and 1985, and only decreased slightly between 1985 and 1990.

2. Refractory products are dried in tunnel or chamber systems, with initial material moisture content varying from about 5-15%, and <1% after drying. Drying temperatures vary from 50-90°C.

3. A survey of the refractory industry has not been conducted since 1978.

4. In 1990 0.475 million tonnes of refractory products were manufactured, consuming an estimated 5.275 million GJ, thus suggesting an total SEC of 12.94 GJ/tonne.

5. Comparison of the 1978 and 1990 total SEC showed that SEC values have increased slightly by approximately 8%. The movement to the manufacture of high performance products and the low utilisation of equipment has contributed to this trend.

6. This study has calculated a drying SEC value of 4 GJ/tonne, with a typical drying efficiency of 24%. Comparison of the findings with previous studies has shown that drying SEC has doubled since 1978. Moreover, figures vary by up to 3 times for surveys conducted the same year. The accuracy of past figures is thus questionable.

7. In 1990, an estimated 1.6 million GJ was consumed for drying processes, representing 31.5% of the total energy consumed.

8. Total SEC values have only increased slightly, unlike drying SEC which has doubled in comparison to a survey conducted in 1978 [33], [36]. This suggests that savings have been implemented for the kilning stages of refractory manufacture, although drying now consumes a larger proportion of the total energy than in 1978.

9. Complete analysis of the energy utilisation within the refractory industry has been hindered by the lack of co-operation from manufacturers [57]. Major firms regarded information on fuel and power consumption as

commercially sensitive. Limited data was collected regarding typical drying SEC figures. Information relating to the degree of implementation of heat recovery systems, ranges of SEC values, quantity and type of equipment in use, fuel type and exact product specification would enable a more accurate assessment of the industry to be made.

The following conclusions can be drawn from the analysis of drying processes within the plasterboard industry;

1. The production of plasterboard is forecast to increase during the 1990s, after decreasing slightly during the 1980s. An estimated 170 million m^2 was produced in 1991.

2. The production of plasterboard is a very energy intensive process requiring an estimated 22.7 MJ/m^2 [32].

3. Overall energy consumption figures relating to plasterboard manufacture are not published for the UK. Consequently, analysis of the energy consumption for drying processes within the industry is not conducted on a regular basis.

4. Conventional gas fired tunnel dryers consume an estimated 2953 kJ/kg water removed, yielding a thermal efficiency of 71%.

5. For a 9.5 mm board containing 3.5 kg/m^2 of water, 11.46 MJ/m^2 of energy is consumed for drying, including 1.13 MJ for drying raw materials.

6. In 1994 an estimated 2.33 million GJ was consumed for drying processes, representing 50.5% of the total energy consumed.

7. Comparison of the finding of this study with previous surveys showed that the energy efficiency of drying equipment has improved over the last decade. Improvements in energy utilisation were attributed to; improved burner design, improved dryer control through use of cooling air jets to reduce calcination, the implementation of IR board temperature monitoring, and condition monitoring of equipment.

8. Heat recovery is practised within the industry. Air/air heat exchangers are commonly used to supply heat from the initial zones of the kiln to subsequent sections. The high thermal efficiency of equipment demonstrates the benefits of implementing heat recovery systems.

9. The lack of information regarding the production of cove material has hindered the analysis of energy utilisation. Cove dryers analysed during the study consumed more energy than plasterboard equipment per unit of production. The energy consumed in cove manufacture may be significant.

10. Various electrical drying techniques have been investigated for plasterboard drying. RF heating is used to a limited extent for the drying of high value decorative cove. The application of RF, microwave and direct resistance electric heating cannot be economically justified for large scale implementation in the UK.

The following conclusions can be drawn from the analysis of drying processes within the abrasives industry;

1. Chamber and tunnel systems are used within the abrasives industry for the drying of bonded/vitrified and coated abrasives respectively. Many of the systems investigated were over 30 years old.

2. The drying of raw materials varied significantly depending upon the product mix. Little evidence of the energy monitoring of raw material drying was uncovered during this survey of the industry.

3. The efficiency of drying processes varied from 14% for drying coated abrasives to 79% for a microwave system drying vitrified wheels. Energy consumed for drying only represented about 6.8 - 7.3% of the total SEC. This was attributed to the low initial moisture content of the material entering the drying phase.

4. An estimated 9.35 TJ of energy was consumed for drying processes in 1995, representing 7.3% of the total energy consumed within the sector.

5. Comparison to previous studies showed that the energy used for drying had not changed significantly over the last decade.

6. Microwave drying systems were used to a limited extent for drying bonded/vitrified ware. Savings in the order of 6420 GJ/year could be realised if microwave technology was implemented by the industry. Although the unit cost of electricity is high in comparison to fossil fuels, microwave systems are still more economical due to the high thermal efficiency (typically 70-79%). Implementation is hindered by high capital costs.

CHAPTER 6

ENERGY UTILISATION IN THE TIMBER DRYING INDUSTRY

Introduction

The drying of timber can be divided into two parts;

- Pre-kiln drying. Including air drying and low temperature drying, &
- Kiln drying.

This survey of the industry has only examined sawn timber and does not include the drying of wood chips or fibre board manufactured from chips. Kilning facilities can be batch processes using chamber kilns, or continuous using progressive tunnel kilns. Chamber kilns can be directly fired using a variety of fuels (Electricity, gas, and oil being most common), or indirectly heated using a hot water, steam or thermal fluid system. One form of drying kiln is the dehumidifier. Using electricity as a fuel the dehumidifier system is fundamentally a heatpump, recovering latent heat energy from the vaporised moisture within the kiln. Progressive kilns are not common in the UK, and can also be directly or indirectly heated. Descriptions of kiln types, common operating procedures and utilisation within the UK are well documented [170], [290] and a full description is not warranted here. Figure 6.1 shows the drying stages in a typical timber process sector.

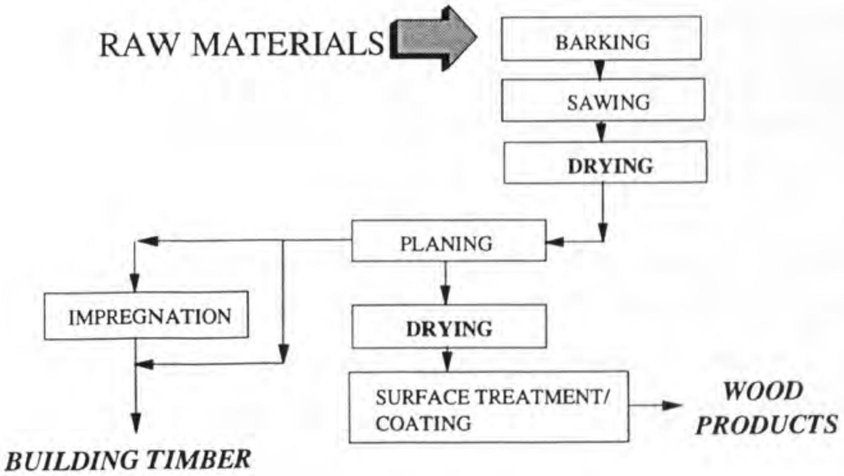


Figure 6.1 - Simplified production flow for the wood products industry [161]

Timber is normally dried after initial sawing, but prior to final planing to size. A margin is thus allowed for defects such as warping, shrinkage and surface flaws. However, one kiln user contacted during the survey [62] cut their timber to the final size and kilned to a very conservative schedule. The benefits were highlighted as economic savings due to less labour requirements, and reduced wastage. This practice is not common and would not be feasible for a large timber operator due to the long drying schedules and economics of work in progress. In the UK very little drying occurs after planing of the timber. Only batches which are substandard i.e. have not achieved the correct moisture content are rekilned. If the timber is left out in normal atmospheric conditions after planing redrying may be necessary before further processing, although this practice is not common in the UK.

Wood morphology includes solid cells with bound water, lumens partially filled with free water and the remaining space of lumen is occupied by air, vapour and liquid water. The moisture content of the timber is lowered and equalised by drying to enable the material to be used and processed. Stresses, cracks, mould etc. present special problems in drying [161]. The initial moisture content, defined as the ratio of the weight of water to that of an oven dried sample [9], of a kiln load of timber can vary substantially. Initial moisture contents of freshly felled timber of British woods are high, for example Sitka Spruce 164%. [13], [169]. However these are average figures and it has been found that there is considerable variation which can be attributed to [13];

- Difference in tree location,
- Differences between trees on a single site,
- Differences within a tree,
- Differences associated with log sizes,
- Change in moisture content with season,
- Change in moisture content associated with delay in extraction and conversion.

Research has shown that there is a marked gradient in moisture content across a stem and at all heights in a tree. Variation within a single kiln load of wood can vary by ±7% in the summer and ±9% in the winter [13].

Estimates of energy consumption for kilning processes are complicated further by kiln operators mixing species and timber thickness within a single batch. There is an economic reasoning behind this procedure including complete utilisation of the kiln, reducing operating costs and maximising production capacity. However it is very uncommon to kiln dry hard and softwoods as a single batch.

The final moisture required from drying depends on the use of the timber. Newly felled timber is normally dried to a moisture content of between 15 and 20%. It is estimated [161] that 50% of the timber is not dried further but is used directly in the construction industry. Timber for making furniture, fitments, etc. is dried to a moisture content of between 6 and 12% to render it suitable for joinery. This further drying is carried out either in the sawmill or in the processing plant itself [161], [195].

British Standards BS 5268 (1991) and BS 4978 (1988) cover timber drying and use of structural timber. BS 5268 (Part 2) states that European softwood is normally dried to about 23% moisture content before shipping, whereas softwood from North America need not be dried provided the timber undergoes a fungal treatment. Moreover, wood is less prone to decay if dried to a moisture content of 25% or less. Other specification exist for timber which will be laminated or glued. BS 4978 (1988) specifies the moisture content of softwood for structural usage. Unless the timber is to be used in a high moisture environment or is over 100mm thick the moisture content must be 20% or less, with no reading over 24%. The moisture content requirement for some timber products are not stated, e.g. BS 1722 for fencing. However, preservation of timber for fencing and similar hazards requires the moisture content to be 28% or less (BS 5589). Moisture contents can be determined by electrical probe (conductivity) or by oven test samples. The methods, techniques and available equipment are well documented [38] [195].

Industry

The forestry products industry is very diverse in nature ranging from management of woodland to the processing of wood and pulp products. Britain's growing domestic markets and expanding supply of high quality timber from British forests has attracted over £100 million of new investment in the processing sector over the last 8 years [349]. Furthermore while Britain still remains a relatively small producer compared with the larger softwood producing nations, British processors are able to compete aggressively within large import markets where quality, technological innovation and distance to markets give them the balance of advantage [349].

Nearly 90% of Britain's annual consumption of forest products is currently imported. Some 75-80% of this is softwood based, and two thirds is in processes or semi-processed form. The UK demand is forecast to double by volume (in wood raw material equivalent) over the next 60 years [349]. Figure 6.2 shows the forecast variation of wood products over the next 50 years.

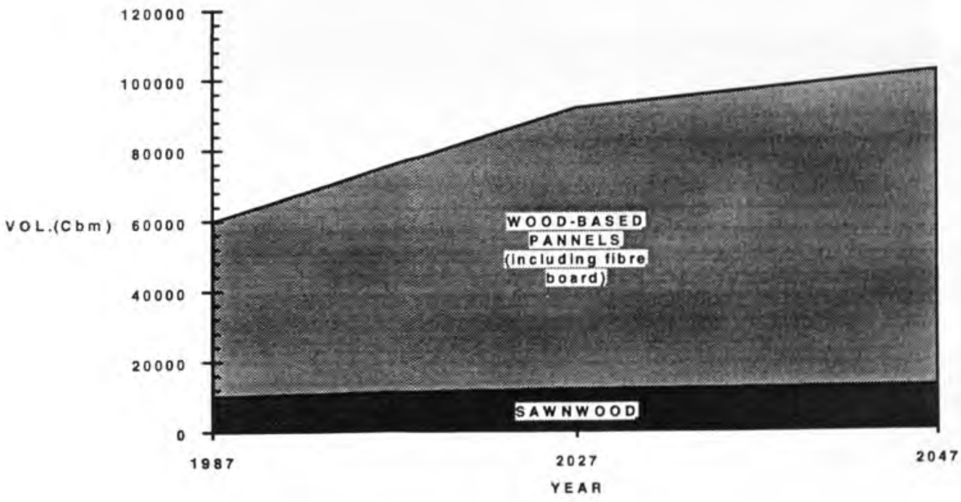


Figure 6.2 - Predicted demand for major wood product groups

In 1992 7,052,000m^3 of timber was produced [349]. Figure 6.3 shows the forecast production for the UK forest sector.

Survey of Kiln Installations

The energy utilisation for drying processes within the timber industry has in the past been the focus of many projects. Contact with TRADA, The British Softwood Sawmillers Association, The Forestry Commission, The British Timber Merchants Association (BTMA) and the Building Research Establishment [77], [78], [86], [92], [94] has revealed that analysis of the current kilning facilities within the UK has not been conducted within the last fourteen years. Furthermore, an up-to-date list of companies operating kilning facilities was not available. The last survey of the timber kiln drying installations in the UK was published in 1981 by R.A. Hooks of the Timber Drying Section of TRADA [181]. The 1981 study up-dated the earlier work performed by G.H. Pratt and N.P. Skinner of the Building Research Establishment in 1971 [289].

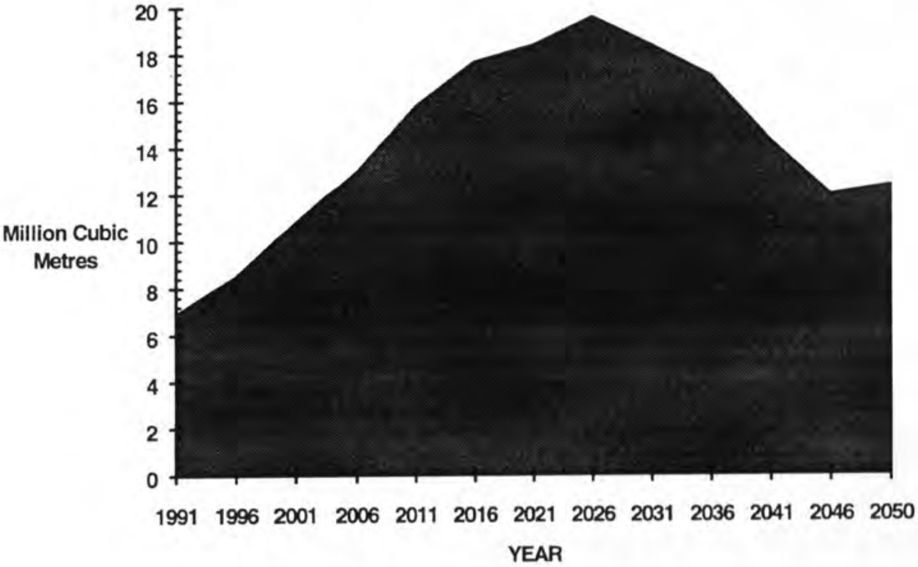


Figure 6.3 - Total UK forecast of annual production to 2050 [349]

Many studies have investigated the nature of kilns and the principles have been thoroughly researched and documented e.g. [18], [38]. Further work has also been carried out involving energy studies of specific kiln equipment e.g. [2], [5]. These studies are mostly specific in nature and no reference was found relating to energy utilisation and efficiency of the whole timber drying industry in the UK.

Timber Production and Trends in Timber Drying

From over 400 contacts within the timber industry 116 companies were found to be operating timber kilning facilities in the UK (Excluding Northern Ireland). Only two companies who were known to operate kilning units were unwilling to provide basic information.

Table 6.1 shows the production of sawn timber in the UK.

(000'm^3 sawn)	**1973-74**	**1994-95**
Hardwood	675	139
Softwood	4250	1897
Total	*4925*	*2036*

Table 6.1 - Comparison of the sawn timber in the UK

Table 6.2 shows the estimated amount of timber dried in 1994-95.

	VOLUME DRIED IN 1973-74 [181] (/000'm^3)	**VOLUME DRIED IN 1977-78 [181] (/000'm^3)**	**VOLUME DRIED IN 1994-1995 (/000'm^3)**
Hardwood	472.5	392.5	164.2
Softwood	212.5	167.6	116.9
Hard & Softwood	-	-	104.5
Total	*685*	*568.5*	*385.6*

Note. 12 companies were unable to provide volumetric data relating to their production.

Table 6.2 - Volume of timber dried in 1995

Table 6.2 shows that there has been a reduction in the consumption of dried wood over the last 20 years. However, Table 6.1 shows that there has been an increase in the total consumption of timber in the UK over the last 20 years. Home production has nearly doubled and imports have increase slightly since the late seventies.

Published sources in the early eighties [131], [181] suggest that approximately 70% of hardwood and 5% of softwood timber used in the UK has to be kiln dried. Results obtained from this study suggest that these figures do not describe the situation in the 1990's. Comparison of statistics of sawn timber [349] and data collected from kiln operators suggests that more hardwood is dried in the UK that sawn, although figures are disrupted by the fact that many facilities dried both types of timber and were unable to indicate the production percentage of each. However, it can be noted that a larger percentage of UK sawn softwood is being dried in the UK in comparison to the production in the early 1970's.

Table 6.3 shows a comparison of the timber utilised in the UK over the last 20 years.

VOL. (million m^3 raw)	**1978**	**1980**	**1992**
Imports	12.4	11.5	15.7
Exports	n.a	n.a	0.3
Home	3.8	3.9	7.0
Total	*16.2*	*15.4*	*23.0*

Table 6.3 - Comparison of timber utilised within the UK 1978 - 1992

Many sources have suggested that imported timber is usually dried in the country of origin [131], [181]. Figures in Table 6.3 agree that this is the situation in the 1990's with the amount of timber dried in the UK decreasing in comparison to that processed in the 1970's (Table 6.2) whereas overall consumption has increased.

The introduction of BS 4978, which defines the moisture content limits for dried structural softwood, will most certainly affect the kilning of softwood in the UK. Several companies contacted were presently installing new capacity or adapting old equipment for the kilning of softwoods. However, communication with these groups [62] has revealed that timber users are reluctant to conform to the new standard and the increase in softwood drying has not matched the predicted increase in demand for structural softwood. Stricter regulation of the users of softwood will most probably result in an increase in softwood kilning.

Classification of Company Operation and Material Processed

Figure 6.4 shows the types of companies operating timber kilning facilities.

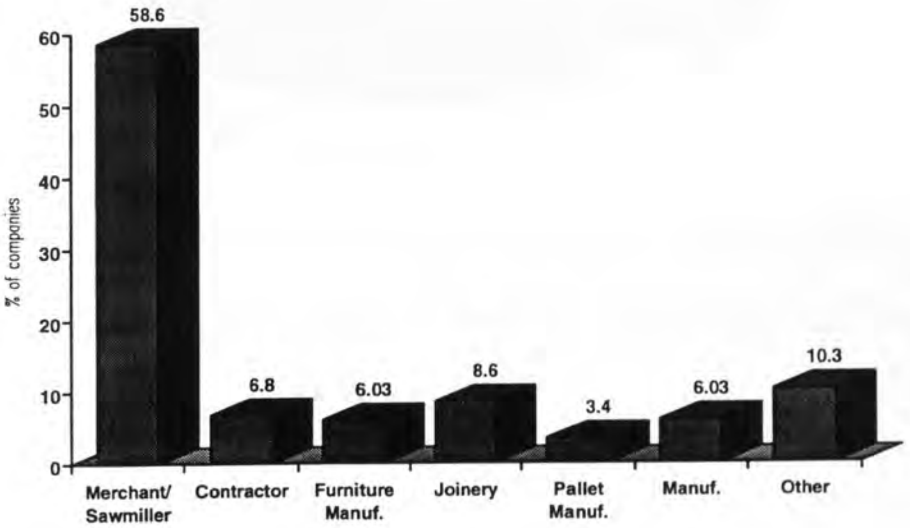


Figure 6.4 - Type of companies kiln drying timber in the UK

The survey was not restricted to sawmillers and timber merchants, although Figure 6.4 shows that the largest percentage of companies fell in this category.

In 1978 over 290 timber drying plant installations were identified in a survey of the UK industry [181]. The comprehensive survey conducted in 1995 identified 116 operators, a reduction of 60%. The greatest reduction in kilning installations appears to have occurred with end-users (Manufacturers drying timber for on-site fabrication into products of added value) and specialist timber kilning contractors. A study in 1974 by the Electricity Association [353] revealed that 13% of companies were contractors and 11% were joinery firms. The reduction in kilning facilities in this area during the last 20 years was probably caused by;

- Competitively priced timber from foreign sources,
- An excess of UK kilned timber due to the declining market, and hence closure of uncompetitive companies,
- The closure of out-of-date kilning facilities, with the above points highlighting that limited capital was probably available for the purchase of new or refurbished equipment,
- The decline and closure of smaller companies in the timber processing and manufacturing industry due to competitive pressures from larger companies.

Figure 6.5 shows the proportional split of the 116 sites reviewed concerning the type of materials processed. Figure 6.6 shows data from 1978.

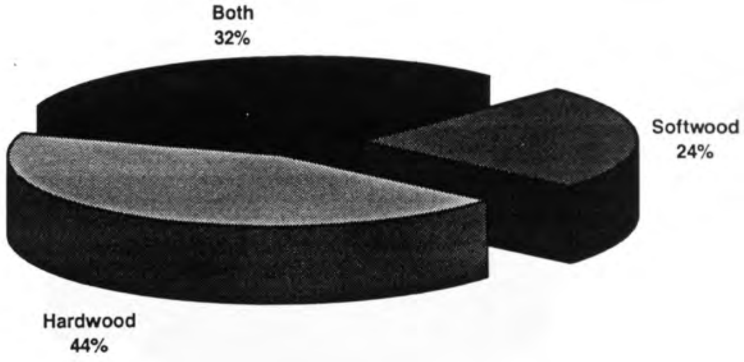


Figure 6.5 - Type of material dried by companies in survey (percentage of companies - not volumes) - 1995

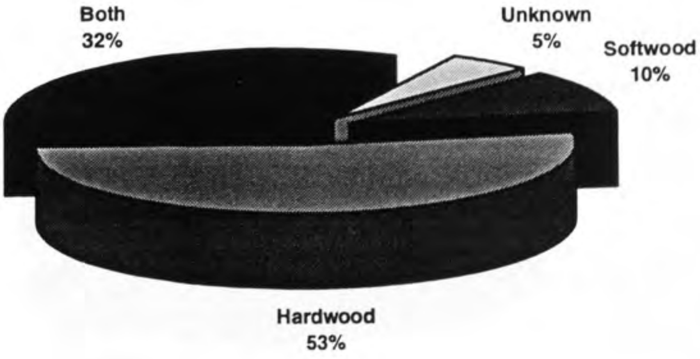


Figure 6.6 - Type of material dried by companies in survey (percentage of companies - not volumes) - 1978

Figure 6.5 shows that in 1995 the largest proportion of kiln operators dry hardwoods. However, the proportion of companies drying softwoods has increased since the 1970's thus reducing the proportion of exclusive hardwood kiln operators. Many companies have the capabilities of drying both hard and softwood (32%). Increase in competition due to the shrinking market and customer demands are the most probable reasons for this increased flexibility.

Types of Drying Equipment

From the 116 drying plant operators identified 467 drying units i.e. individual kilns were surveyed. Figure 6.7 shows the distribution of these units.

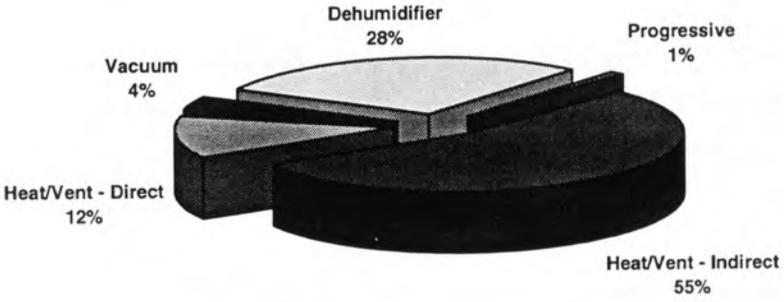


Figure 6.7 - Equipment type of kilning facilities in the UK (Proportion of total number)- 1995

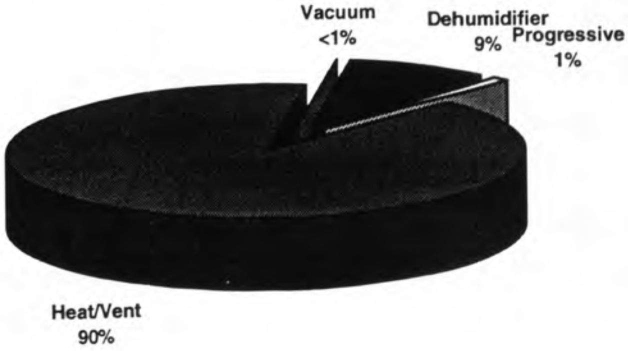


Figure 6.8 - Equipment type of kilning facilities in the UK (Proportion of total number)- 1976

Previous studies have estimated 1210 drying units operating in 1978 [181] although only 672 kilns were covered by a survey in 1976 [353]. Figure 6.8 shows the number of kiln facilities surveyed during a study in 1976 [353]. The reduction in kilning units reflects the declining UK market for timber drying in the UK.

From comparison of the above figures it can be seen that the use of dehumidifiers for drying has increased over the last 20 years. Results published by TRADA in 1981 [181] revealed that about 17% of kilning units were dehumidification based. Discussion with kiln operators [62] revealed that dehumidifiers were popular due to their close control of drying characteristics, low capital cost, no centralised steam raising boiler required, and their compact size which suits timber companies with a small throughput.

The application of vacuum kilns in the timber drying industry has also increased over the last 20 years. It was reported that only one was in operation commercially in 1976 [353], while the 1995 survey revealed 18 and a further two vacuum press kilns which were not fully investigated during this study. Users have reported commercial advantages with this equipment including; Added product value due to improved product quality, faster drying times, and improved energy efficiency [62].

The number of progressive kilns in operation in the UK has been relatively constant since the early 1970's. It was suggested that progressive kilns produce dried timber of relatively lower quality than conventional methods [13]. This has been contradicted by the users of this type of equipment in the UK, however comments were received portraying the limited flexibility of this equipment.

Materials Processed in UK Timber Kilns - 1995

Table 6.4 shows the number of kilns processing soft, hard and both types of timber.

WOOD	**HEAT/VENT**		**VACUUM**	**DEHUMIDIFIER**	**PROGRESSIVE**
	INDIRECT	DIRECT			
HARD	82	18	11	95	0
SOFT	45	3	0	9	3
BOTH	128	35	7	29	2
Total	*255*	*56*	*18*	*133*	*5*

Table 6.4 - Number of each kiln type processing timber types

Table 6.4 shows that heat/vent kiln type are the most common with indirect heating as the heat source, either steam/hot water or air/air heat-exchanger system. The largest proportion of softwoods are processed using indirect heat/vent chambers or progressive units.

The difficulty in maximising yield by minimise loss due to damage during drying in a compromise with minimising drying time is reflected in Table 6.4 for processing hardwoods. The number of vacuum and dehumidifier units used for drying hardwood is larger than those used for softwood. The drying characteristics of these types of equipment have been recognised in recent years and fully utilised by kiln operators. However, it must be noted that many other factors influence the selection of kiln facilities including; acceptable quality, final use of the timber dried, existing kilning and boiler facilities, and throughput required.

Fuel Usage in Timber Kilns

Table 6.5 shows data concerning the number of kilns, number of companies and estimated process capacity with respect to the fuel type.

KILN TYPE	No. OF KILNS	No. OF CONTACTS	ESTIMATED TOTAL CAPACITY (m^3)
HEAT/VENT- DIRECT			
Oil	47	6	1680
Gas	9	3	404
HEAT/VENT-INDIRECT			
Oil	75	17	3778
Gas	37	5	2247
Wood	139	17	6482
Electricity	4	1	n.a.
VACUUM			
Oil	14	8	60
Wood	1	1	6
Gas	3	2	20
DEHUMIDIFIER			
Electricity	133	53	4105
PROGRESSIVE			
Oil	3	2	320
Wood	2	1	800

Table 6.5 - Summary of kiln fuel type and number of kilns, operators and an estimation of capacity

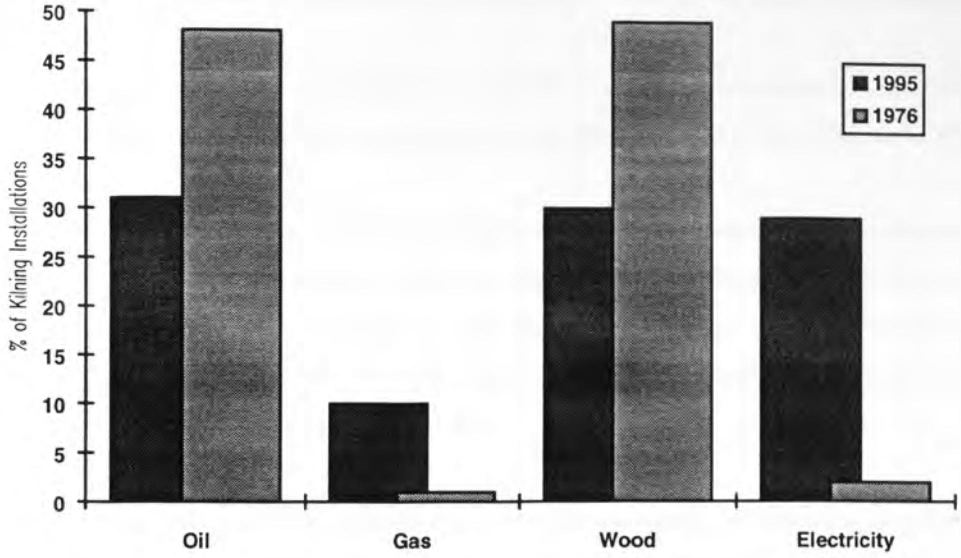


Figure 6.9 - Proportions of kiln facilities using gas, oil, wood, and electricity

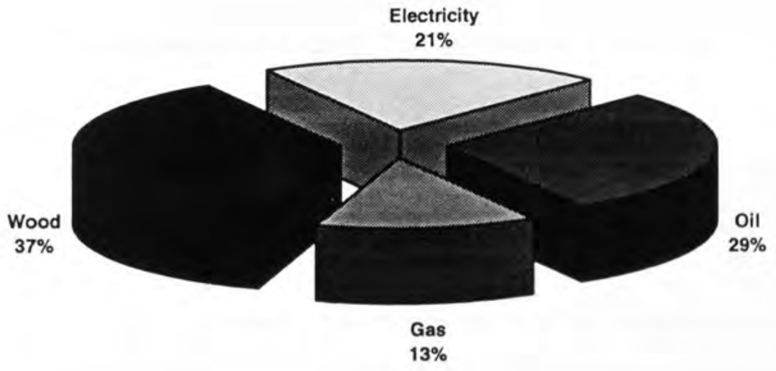


Figure 6.10 - Capacity proportion of kiln presently in operation (1995) using wood, oil, gas and electricity

Figure 6.9 shows that there are roughly equal numbers of kilns using oil, wood and electricity (30%) presently operating in the UK. Gas is less popular, supplying only 10% of the total number of kilns. A survey conducted by the Electricity Association [353] suggested that in 1974 45% of the total number of kilns units were using wood waste as a fuel source. The decline in the use of wood waste as a fuel over the last 20 years may be due to the following;

- The maintenance requirements of a wood waste fired boiler are quite substantial in comparison to other fuel systems.
- The increase in the cost of drying due to the need to dry chips before combustion. Published literature has estimated that the cost of drying has increased by 50% when the main fuel was wood chips at 140% moisture content compared with the use of similar chips at 80% moisture [13], [324].

- Increased manpower requirements (essential for operating the wood waste boiler) in comparison to other heating techniques.
- Environmental regulations regarding atmospheric emissions. Wood has a low calorific value and wet chips give dirty stack emissions, with the risk of prosecution under the provisions of the clean air acts of 1956 and 1968 [13].
- The larger capital cost of installing a centralised steam/hot water boiler fired by wood in comparison to one fired by gas or oil e.g. In 1990 comparative costs were £165,000 and £45,000 respectively [13].
- Alternative markets for wood waste encouraging resale. Clean white chips have a market around £20/tonne.
- Availability of wood waste becoming restricted due to closure of sawmilling facilities and improved drying/sawmilling techniques resulting in less wastage.

Figure 6.10 shows a graphical representation of the kiln fuel type and capacity of kilns using that fuel for current installations in the UK. Although the proportion of the total number of kilns using wood waste as a fuel source has decreased over the last 20 year, it still accounts for a large proportion of the presently installed kiln capacity in the UK.

The variation in the price of gas and oil has probably influenced the utilisation of these fuels. Figure 6.9 reflects this hypnosis. Many operators, especially those employing a centralised steam/hot water boiler commonly used a dual fuel system depending upon fuel price and supply. The investigation of these systems was beyond the scope of this survey.

Kiln Capacity, Construction and Orgin

The 116 kiln units survey in 1995 represented a total capacity of 19,902m^3, a reduction of approximately 31% since 1976. Figure 6.11 shows comparison of the capacity of kilns with the type of kiln utilised.

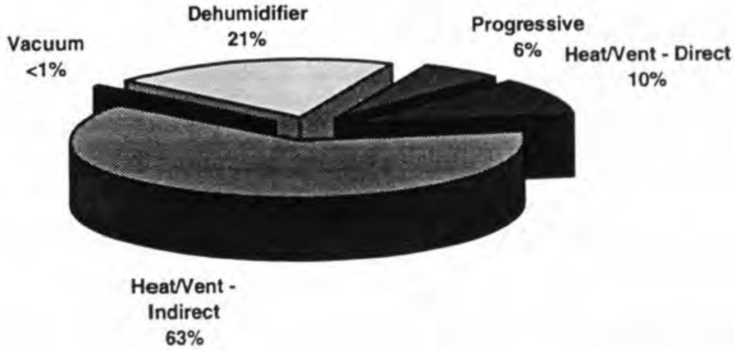


Figure 6.11 - Proportion of the total capacity for specific kilns types

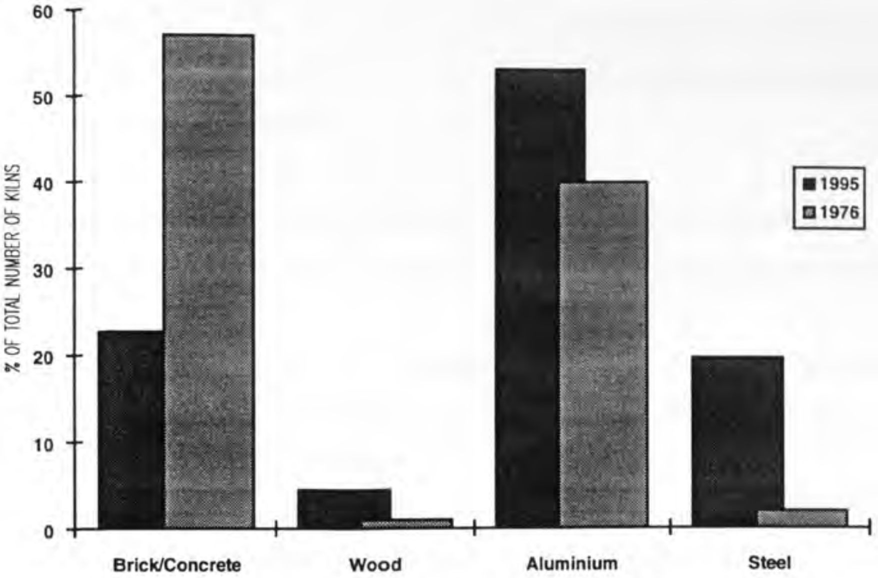


Figure 6.12 - Material construction of present and past kilning facilities in the UK

Results obtained by a survey conducted by TRADA in 1978 [181] suggested that although their were 210 dehumidifiers operating in the industry at the time, they represented less than 5% of the total UK drying capacity. Results of the 1995 study presented in Figure 6.11 show that dehumidifiers have taken a distinct proportion of the timber drying market share with a capacity of 21% of the total.

By convention, the nominal capacity of a kiln refers to the volume of timber accommodated when it is loaded with 25mm thick boards and with 25mm stick thickness, i.e. separation between each layer of boards [181]. The kiln will be of greater volume, sufficient to accommodate the necessary fans, heat exchangers and other equipment. Table 6.6 shows the average, maximum and minimum capacities for specific kiln types.

KILN TYPE	AVERAGE VOL. (m^3)	MAXIMUM VOL. (m^3)	MINIMUM VOL. (m^3)
Heat/Vent - Direct	37.2	56	17
Vacuum	4.7	10	0.5
Heat/Vent - Indirect	49.8	170	6
Dehumidifier	30.8	400	3
Progressive	224	400	40

Table 6.6 - Capacities of presently installed kiln equipment

The total capacity of kiln installations in the UK has decreased by approx. 31% since 1976, however the number of single units has fallen from 1210 in 1976 to 467 in 1995, a reduction of 61%. This implies, with reference to Table 6.6 that the average individual kiln capacity has increased. An estimated average unit capacity based upon Table 6.6 and the number of each type of kiln yields a timber volume of $43m^3$. (It was suggested that in 1976 that the average volume was $28m^3$, although a large proportion of installations were smaller). Various factors have been identified concerning the selection of particular unit capacities and include [181];

- The normal size of batches,
- Usual lengths of timber,
- Production mixes of species and thickness,
- Handling and storage before and after kilning,
- The turnover of timber required,
- The ultimate use of the kilned timber, &
- The final standards of drying quality.

The above factors and others relating to capital expenditure vary from company to company. The number of kilns per operator varied widely from a single unit to 28 kilns. The following points were identified during the survey;

- Kiln users appeared very conservative in their approach to equipment selection. It was quite common for equipment of the same type to be installed based upon past experience of operation rather than considering the benefits other equipment types may have to offer.
- Kilns utilising steam/hot water heating would commonly be added to a group of kilns currently using this heating medium, thus in most cases eliminating the need for any additional boiler unit.
- Dehumidifiers are commonly operated in smaller groups and single low capacity kilns are presently quite popular, especially amongst the small timber merchants/joiners.

Figure 6.12 shows the material construction type of currently installed capacity for both 1976 and 1995 [181]. There has been a decrease in the number of kilns of brick and concrete construction over the last 20 years. The shrinkage of the timber drying industry in the UK and the closure of older facilities may have been a possible cause. However, the proportion of dehumidifier systems in comparison to the total number of kiln units has increased over the last 20 years. Many dehumidifier units are of aluminium construction. The increase in use of dehumidifier units may have also attributed to the increase in steel constructed kilns, with the widespread use of ex-cargo and shipping containers. These are especially popular amongst the smaller timber drying companies.

Figure 6.13 shows the proportion of kilning equipment with overhead and side fans.

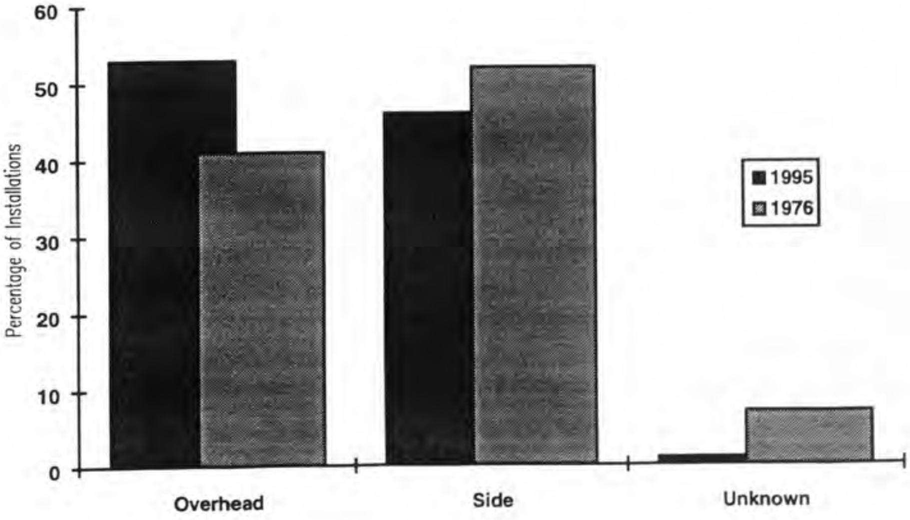


Figure 6.13 - Fan position for kilning facilities in the UK

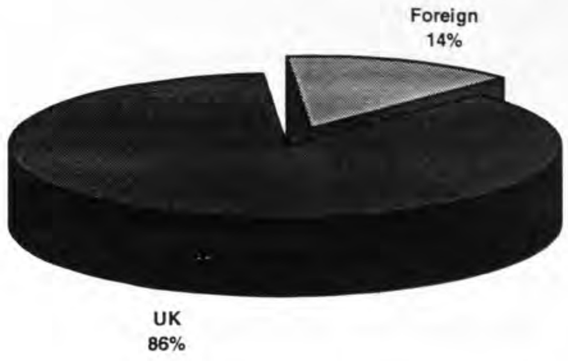


Figure 6.14 - Origin of kilning facilities in the UK

It can be seen from Figure 6.13 that there is a greater number of current kilns using overhead fans than side fan arrangements. A comparison with results from a survey conducted in the 1970's showed an opposite trend during that time [181]. TRADAs survey in the 1970's suggested that side fans were commonly being installed with prefabricated aluminium kilns. Although the number of aluminium kilns has increased over the last 20 years the installation of side fans has not followed this trend. The development and installation of dehumidifiers (currently a larger proportion of the total number of kilns than in the 1970's) using aluminium constructed kilns with overhead fans is the most probable cause.

Figure 6.14 shows the origin of kilns presently installed in the UK. Results show that the majority of current kilns are of UK manufacture. However competition from foreign competitors has increased significantly over the last 20 years especially in the field of vacuum (Germany and Italy) and dehumidifier (Germany) equipment. In 1976 it was estimated that only 1% of kilns utilised in the UK were of foreign manufacture [181].

Age of Timber Drying Equipment

The utilisation of direct heated heat/vent chamber kilns appear to have declined over the last 20 years, although the proportion of direct kilns in comparison to the total number is larger than that in the 1970's (12% in 1978 compared with 48% in 1995). Data collected describing the age of kilning facilities showed that most direct systems are relatively old (21years+). Problems with environmental emissions and interaction of the products of combustion with the timber has probably led to the reduction in commissioning of new installations.

Table 6.7 shows an age profile of the equipment studied in the survey.

AGE (years)	HEAT/VENT - INDIRECT %	HEAT/VENT - DIRECT %	VACUUM %	DEHUMIDIFIER %	PROGRESSIVE %
0-5	18.8	3.5	22.2	48.8	0
6-10	7.8	12.5	66.6	36.8	40
11-20	27.4	35.7	16.6	11.2	60
21+	45.8	48.2	0	3.0	0
Number of kilns	*255*	*56*	*18*	*133*	5

Table 6.7 - Age profile of present timber kilning equipment

Data shown in Table 6.7 demonstrates clearly the technological changes in equipment utilisation over the last 20 years. Investment appears to have declined with respect to the installation of directly heated heat/vent chamber and progressive kilns. There has been moderately constant investment in indirect heated units, however a large number of dehumidifier and to a lesser extent vacuum dryers have been installed. Table 6.8 shows the age profile and construction material of kilns presently installed in the UK.

AGE (Years)	0-5	6-10	11-20	21+	TOTAL NUMBER OF KILNS[1]
Concrete/Brick	8	4	10	86	*108*
Wood	11	6	4	0	*21*
Aluminium	68	52	86	40	*246*
Steel	31	28	10	22	*91*

Notes: 1 - One operator with a single kiln was unable to provide data

Table 6.8 - The age and construction of present kilns in the UK

Table 6.8 shows that aluminium kilns are most abundant in the UK timber drying industry. The installation of kilns using a steel construction has also increased significantly over the last 20 years. The utilisation of single unit dehumidifiers at many small timber handling sites has most probably been the cause for this trend. The majority of brick kilns are more than 21 years old. Many factors have influenced the selection of kiln construction materials over the last 20 years including; kiln type and capacity, capital cost, foundations required and ease and speed of kiln erection.

Control of Drying Processes

The understanding of drying theory, heat and moisture transfer characteristics within timber, instrumentation and the advent of cheap microprocessor systems has rapidly increased the knowledge and implementation of control theory over the last 20 years. However many kiln operators are reluctant to install modern kiln control equipment [62].

Figure 6.15 shows the various types of control for timber drying and the number of kilns utilising them. Figures do not sum to the total number of kilns in the UK since several techniques are commonly used when operating a single kiln. e.g. A hand held test moisture probe checks the condition of the material while an oven test sample is prepared.

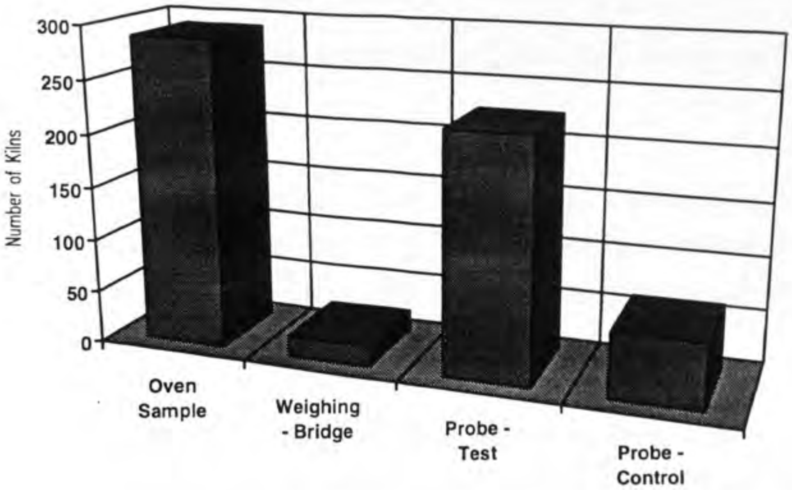


Figure 6.15 - Control of kilning facilities in the UK

All kilns surveyed were operating automatically, usually using basic venting and heating control loops with feedback from wetbulb and drybulb temperatures. This shows the advances and development in control since the mid 1970's, for comparison, in 1976 18% of companies were using complete manual control [181]. However a large proportion, covering some 48% of the total number of kilns, still analysed the progression of the kilned timber using oven sample tests.

Data collected demonstrated that electronic moisture probes were commonly used in the industry. However, automatic control of the kiln by installing moisture probes within the timber stack was not as common. The introduction of low cost microcomputer control systems and improved education and demonstration may evoke a switch to this type of control procedure. Several companies contacted revealed that a competitive edge may be gained by use of on-line moisture measuring equipment [62]. Moreover, it was found that automatic computer control systems were being utilised to a greater extent on newly installed drying systems, in particular vacuum drying equipment.

Future Planned Changes in the Timber Drying Industry

Information relating to future plans was obtained from 31 out of the 116 companies surveyed. The following comments were observed;

- 14 operators had plans to increase the capacity of their timber drying facilities, although exact details of equipment types, capacity or construction material could not be identified.

- 5 companies had plans to refurbish their drying equipment within the next five years.
- 2 operators had plans to implement modern control on their drying equipment, including on-line moisture measurement facilities.
- 1 operator was planning to install a vacuum dryer, while 3 companies were commissioning dehumidifier units.
- 1 operator was aiming to reduce the energy requirements and hence costs for timber drying by examining pre-kiln drying methods.
- 1 operator was planning to install a wood waste boiler replacing an oil based system which was obsolete and uneconomical to run.

The need to become competitive in the timber drying market, which has reduced some-what over the last 20 years, was highlighted by many of the companies contacted during the study. Kiln operators were becoming more aware of the need to become energy efficient although few companies had focused targets, or a defined methodology to achieve these goals.

Many operators utilising centralised boilers were capable of using different fuel sources; commonly oil, wood or gas. One company interviewed stated that the choice of fuel depended solely upon the cost, whereas other companies were restricted by the types of fuel available at their sites. Only a handful of operators regularly monitored the performance of their kilns.

With regards to equipment types, many companies surveyed were not up-to-date with the modern equipment now available for timber drying. Several contacts for instance were not well informed of dehumidifier or vacuum techniques, and some had never heard of dehumidifiers. Many of the companies, although not all, appeared very traditional in their selection of equipment and operational characteristics/control of their kilns. These views will have to change if significant advances in timber drying in the UK are to proceed.

Energy Utilisation for Timber Drying

Introduction

Many researchers have suggested that kiln drying is the most energy intensive process in the manufacture of timber products. It is estimated that 60-70 percent of all energy used in the timber sector is consumed for this purpose [9], [180], [325], [334], [360], [361]. The cost of fuel is one of the most significant factors in determining the economic success of a kiln drying enterprise [119].

The amount of energy used for drying depends on a number of factors; the amount of water evaporated being by far the most dominant, with dryer design, ambient air conditions, maintenance of equipment and drying procedures all having an important bearing [95]. Figure 6.16 shows a typical distribution of energy for a chamber kiln (Kiln temperature 76°C, Timber - Douglas Fir) [98].

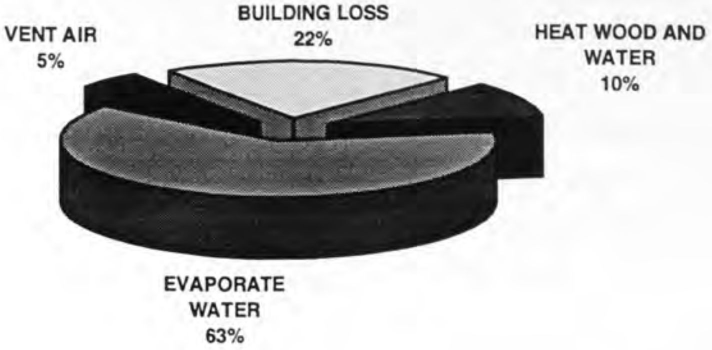


Figure 6.16 - Energy consumption for a typical kiln load

The proportion of the components shown in Figure 6.16 are depend upon many factors such as kiln design, drying schedule, timber species, initial and final moisture contents and outside air conditions. TRADA estimated energy requirement of a kiln of about 4.5 MJ per kg of water removed plus losses. Eckleman and Baker [119] noted the following as being factors effecting the time for drying;

- Initial and final moisture content,
- Proportion of heartwood and sapwood,
- Temperature of the kiln air,
- Size of charge,
- Relative humidity,
- Velocity of kiln air,
- Distance of air travel around the kiln.

Losses are commonly due to poor kiln sealing and insulation. During a survey of 32 kilns it was found that insufficient air interchange due to poor sealing nearly doubled energy consumption [3]. Losses can be minimised by improving insulation including sealing brickwork and repairing faults door and cent seals. Losses for a single kiln load increases with time. Drying times are linked to schedules relating to moisture content variation, species, thickness, atmospheric conditions and damage acceptable [161], [227], [240]. Ideally the kiln would use no more air than was necessary to remove the water from the wood. However, it has been suggested that an efficient kiln probably use 5-25% excess, with a badly sealed unit consuming more than 200% [170].

Energy Utilisation for Timber Drying

METHODOLOGY

Above approximately 30% moisture content the energy required to remove the water is fundamentally the heat of vaporisation. However, around 30% moisture content a critical point is reached; the fibre saturation point (FSP).

Below this point energy is required to remove the bound moisture in the material (Energy of wetting and heat of vaporisation). The phenomena is shown by the increased drying time required at low moisture contents. The energy requirement increases with decreasing moisture content. At 10-12% the energy required per kg of water removed is 20% greater than that at the fibre saturation point [170]. The fibre saturation point is not a constant value within a species, but covers a range. The extent of the range varies between species, within species and within individual boards. FSP also varies with temperature. Figures for the energy of wetting for common species of timber subjected to a variety of conditions are not available. Moreover, assessment of the increase in energy requirement due to the moisture content reducing below the fibre saturation point would entail monitoring the moisture content on-line and accounting for the energy consumed during this time.

This survey of the timber industry demonstrated that energy monitoring of timber drying installations was not common practice. Only a small proportion of the kiln users contacted during this survey held sufficient data to analyse general energy characteristics. Stockwell [334] analysed nearly 400 kiln runs of a direct oil fired chamber for four species of timber. The data collected for similar runs varied substantially and a relationship between FSP and moisture content could not be derived. Without detailed fuel consumption and moisture content data the analysis of the increase in energy consumption due to the FSP are thus beyond the scope of this general study. Information regarding the energy utilisation of kiln equipment was collected from manufacturers and kiln operators. Past studies rarely noted the heating types of the kiln and data was specifically collected concerning indirect and direct fired units, timber species and kiln type.

Brazier [13] noted that the calorific value of wood chips burnt in boilers to generate steam/hot water for kiln heating varied considerable due to moisture content. It was reported that the cost of drying rose by 50% when the main fuel was wood chips at 140% moisture content compared with the use of similar chips at 80% moisture content. A further complication arose due to the lack of monitoring of wood chip consumption, most probably due to their being an adequate waste supply from the sawmill. The analysis of timber kilns using a centralised wood fired boiler for heating (steam or hot water) was excluded from the study due to the lack of data.

RESULTS OF ENERGY STUDY

Table 6.9 summarises the findings.

DRYER	FUEL	DIRECT/ INDIRECT	SPECIES	MJ/kg		GJ/m^3 (Theory)		EFFICIENCY (%)		No. OF CASES
				LOW	HIGH	LOW	HIGH	HIGH	LOW	
Chamber	Oil	Direct	Hard	4.96	10.10	1.46 (0.76)	1.08 (0.28)	52.2	25.66	30
			Soft	7.07	20.33	1.03 (0.38)	1.14 (0.15)	36.6	12.7	18
		Indirect	Hard	-	-	-	-	-	-	-
			Soft	4.29	8.01	1.01 (0.61)	1.88 (0.61)	60.4	62.3	3
	Gas	Direct	Hard	9.38	15.48	1.27 (0.35)	3.33 (0.56)	27.6	16.7	2
			Soft	-	-	-	-	-	-	-
		Indirect	Hard	7.77	21.78	1.78 (0.60)	3.82 (0.45)	33.3	11.9	2
			Soft	4.99	6.30	0.68 (0.36)	3.86 (0.36)	51.9	41.1	2
	Electric	-	Soft	4.72	-	0.13 (0.07)	-	54.8	-	1
Vacuum	Gas	-	Hard	4.17	4.59	0.74 (0.46)	0.81 (0.46)	62.1	56.5	2
			Soft	4.83	8.23	0.50 (0.27)	0.84 (0.27)	53.6	31.5	2
	Oil	-	Hard	10.6	-	1.33 (0.32)	-	24.4	-	1
			Soft	-	-	-	-	-	-	-
Dehumidifier	Electric	-	Hard	2.33	7.53	0.15 (0.16)	0.58 (0.20)	111.3	34.4	6
			Soft	1.51	-	0.35 (0.61)	-	171.86	-	1

Table 6.9 - Summary of the energy survey conducted

Table 6.10 shows the average values of energy consumption for the kilns analysed.

DRYER	FUEL	DIRECT/ INDIRECT	SPECIES	MJ/kg	Efficiency	COST p/kg
Chamber	Oil	Direct	Hard	7.53	34	2.2
			Soft	13.7	19	4.1
		Indirect	Hard	-	-	-
			Soft	6.1	42	1.8
	Gas	Direct	Hard	12.4	21	5.2
			Soft	-	-	-
		Indirect	Hard	14.7	17	6.2
			Soft	5.6	46	2.4
	Electric	-	Soft	4.7	55	11.3
Vacuum	Gas	-	Hard	4.3	59	1.8
			Soft	6.5	40	2.7
	Oil	-	Hard	10.6	24	3.1
			Soft	-	-	-
Dehumidifier	Electric	-	Hard	4.9	52	11.7
			Soft	1.5	172*	3.6

Note : Cost based upon fuel costs of; Electricity 8.6p/kWh, Gas 1.52p/kWh, Oil 1.07p/kWh.

* Thermal efficiencies of over 100% are possible with dehumidifier systems due to the addition of heat input from sources other than electricity, i.e. heat sink source

Table 6.10 - Average energy consumption values for the kilns studies

Table 6.10 shows a large variation of energy requirements for specific kiln types. The energy required to remove the water from the timber varied from 1.51 MJ/kg for a dehumidifier drying softwood to 21.78 MJ/kg for an indirect gas fired chamber kiln drying hardwood. The variation is most probably related to individual operating aspects (schedules), and other points mentioned before in this report (e.g. condition of insulation etc.). The average values displayed in Table 6.10 show clearly that dehumidifier kilns are the most energy efficient type of timber dryer, requiring on average only 4.9 MJ/kg of water removed and 1.5 MJ/kg for drying hardwood and softwood respectively. Dehumidifiers drying hardwood commonly run continuously, whereas softwood units cycle on and off. This factor contributes to the increased energy requirements for dehumidifier drying of hardwood in comparison to softwood.

Vacuum kilns do not appear to provide any energy savings in comparison to conventional techniques. Electric heating is efficient however is offset by the unit cost of the fuel. Although electrical heating techniques are expensive, electricity offers added benefits such as eliminating emissions, improving product quality, and lower maintenance and capital costs of kilns. Dehumidifier kilns have become increasingly popular over the last 20 years and now represent 21% of the total UK capacity [195].

With slight discrepancies with data for direct oil fired and vacuum kilns Table 6.10 shows that less energy is used to kiln dry softwood than hardwood. More case study information would be required to analyse this aspect further. Due to lack of data realistic comments cannot be made concerning the comparison of the energy efficiency of kilns using different fuel types or direct/indirect heating systems.

Comparison With Previous Studies

Previous Studies

A literature search showed that many researchers have examined the energy aspects of timber drying. Many of the models produced have examined the component energy requirements such as heat for vaporisation, heat losses in the kiln with time, requirements to heat primary air flow, and heating of the kiln structure and wood load [95], [170], [181]. Further studies have involved the thermodynamic phenomena of timber drying with respect to moisture migration (capillary flow of free liquid, vapour diffusion and transfer of bound water) and energy transfer [189], [286], [329], [330], [331]. Researchers have developed equations for the interpretation of the drying phenomena. However these theories are complex and the nature of the timber can render these solutions inaccurate in commercial conditions, because:

- Drying schedules are dependent upon the user, user experience and degrade acceptable,
- No consideration for species type or thickness,
- Variations of moisture content within the timber,
- Mixing of species type and thickness in batch kiln loads,
- Use of very specific parameters which are not commonly or easily monitored e.g. mass transfer coefficients of moisture in timber.

Sources of information on the energy aspects of timber drying include equipment manufacturers, research establishments, case studies or examples within reports on energy/process modelling. Much of the past information reviewed was of a very general nature and included studies conducted world-wide. As discussed, the energy requirement for drying timber is dependant upon many factors, especially moisture change and timber species. Many reports state examples of energy consumption but details of kiln, species, and fuel type are mostly excluded. Previous work has been summarised in Tables 6.11 to 6.14.

To enable comparison of figures, energy values have been expressed in the form of the heat required to vaporise a unit mass of water from the product. No consideration has been given to any changes due to bound moisture or moisture content changes below the fibre saturation point.

SPECIES	THICKNESS	MOISTURE		ENERGY	EFFICIENCY (%)	REF./YEAR/
	/mm	IN	OUT	MJ/kg$_{water}$		NOTE
-	-	-	-	8 - 14	-	[94]/1988
-	-	-	-	-	15 - 50	[170]/1988/1
General	-	-	11	5.48 - 4.77	-	[346]/1982/5
Hardwood	-	-	-	upto 10	-	[300]/1982
Oak	25-63	80	7	6.5-15.5	-	[318]/1980/2
Oak	50 (65m^3)	80	6	7+	47-49	[95]/1975
Oak	-	80	6	2.7	33	[8], [321]/1977
Utile	63	80	15	4.6	-	[273]/1979/3
Softwood	-	-	-	3.6-7.2	-	[300]/1982
Pine	(3m^3)			4.5-5.25	-	[346]/1982/4
Douglas fir	-	45	45	4.65-7	-	[95]/1975
Pine	50 (65m^3)	100	12	3.7-5.1	65	[95]/1975

1: Excluding mechanical requirements, steam generation or distribution losses.

2: Including fan power requirements, up to about 0.9 MJ/kg

3: Assuming 0.5 MJ/kg fan power

4: Electrical energy varied from 0.25 - 0.75 MJ.kg according to drying time; 80 hours at 73°C and 30 hours at 120°C.

5:Kiln temperatures 90°C and 115°C respectively.

Table 6.11 - General Studies

SPECIES	THICKNESS	MOISTURE		ENERGY	EFFICIENCY	REF./YEAR/NOTE
	/mm (VOL.)	IN	OUT	MJ/kg	(%)	
-	-	85	18	4.3	-	[119]/1982/4
-	-	85	18	5.4	-	[119]/1982/5
-	-	47	18	3.96-4.48	-	[161]/1982
-	-	20	8	5.04	-	[161]/1982/2
Oak	32	27	14	10.4	-	[319]/1978
Beech	32	27	14	13.6	-	[174], [173]/1981
Oak	-	80	6	8.5-21.1	12-30	[8]/1988/6
Maple	(59m^3)	70	10	6.72	38	[317]/ 1974/3
Softwood	47	80	20	4.8	53	[13]/1991/7
Softwood	47	60	20	5.7	44	[13]/1991/7
Pine	(59m^3)	120	7	3.27	79	[317]/ 1974/3
Pine	(59m^3)	80	7	3.62	71	[317]/ 1974/3
Yellow Popular	-	30	8	8.1-8.3	31	[8]/1988/6
Redwood	50 (500m^3)	80	18	3.6-4.2	-	[239]/1978/1

1. Energy corresponding to 20 and 0°C outside air temperature.
2. High temperature dryer
3. 2°C outside air temperature. Kiln temperature = 71°C.
4. 5°C outside air temperature. Average electrical energy 0.3 MJ/kg water removed. Ventilation losses found to represent 82% of the energy supplied.
5. With heat recovery
6. Variation due to fuel type; wood, coal, gas, & oil. Oil firing being the most efficient, wood the least.
7. Based upon manufacturers figures.

Table 6.12 - Chamber kilns

SPECIES	THICKNESS /mm	MOISTURE		ENERGY MJ/kg	EFFICIENCY (%)	REF./YEAR/ NOTE
		IN	OUT			
-	-	47	18	3.2-5.0	-	[161]/1982
-	-	47	18	2.9-3.9	-	Ditto/1
Softwood	-	Green	18	3.2-3.9	77- 63	[127]/1982/2

1. With heat recovery
2. Outside air temperature 5°C.

Table 6.13 - Progressive kilns

SPECIES	THICKNESS /mm	MOISTURE		ENERGY MJ/kg	EFFICIENCY (%)	REF./YEAR/ NOTE
		IN	OUT			
-	-	-	-	1.4-2.9	-	[278]/1982
-	-	-	-	2.1-3.9	-	[161]/1981
-	-	-	-	3.2	-	[300]/1981
Afrormaia	25 (12.9m^3)	49	12	2.92	-	[174], [173]/ 1981
Mahogany	32 (13.2m^3)	65	9	2.3	-	[174], [173]/ 1981
Mahogany	50 (14.6m^3)	40	12	3.29	-	[174], [173]/ 1981
Mahogany	75 (19.5m^3)	38	12	3.22	-	[174], [173]/ 1981
Meranti	-	35	10	1.88	-	[191]/1988/2
Beech	25 (10.9m^3)	48	9	2.65	-	[174], [173]/ 1981
Beech	-	50	10	1.15	-	[191]/1988/2
Oak	-	50	10	1.9	-	[191]/1988/2
Pine	(120m^3)	-	-	3.1	-	[300]/1981
Pine	-	50	10	1.62	-	[191]/1988/2
Pine	25 (12.7m^3)	55	9	3.73	-	[174], [173]/ 1981
Douglas Fir	50 (16.7m^3)	27	14	4.4	-	[174], [173]/ 1981

1. High temperature heat pump
2. Low temperature heat pump

Table 6.14 - Dehumidifier Kilns

A survey of vacuum kilns suggested that 3.3-8.7 MJ was consumed per kg of water removed [300]. Experimemtal work using high frequency heating showed that 9-10 MJ/kg water removed was required for drying timber [161].

The above tables show that the energy consumption for removal of the water from timber varies considerably. Many sources of literature [170], [290] have suggested that water is more easily removed from softwoods in comparison to hardwoods due to difference in structure of the two species. However, dehumidifiers were found to consume more energy to dry softwoods than hard, although for both species total energy requirements were less than other types of kiln. The energy benefits of using vacuum kilns for timber drying have been questioned by many researchers [13], [170]. Results of previous studies suggest that generally vacuum kilns are no more efficient than chamber kilns. The lack of detailed information relating to timber species, type of kiln heating, load volume, atmospheric conditions, and drying schedule have hindered an exact comparison of previous studies.

Comparison of Results to Previous Studies

Table 6.15 shows a comparison of the present and previous studies.

DRYER	SPECIES	NEW DATA MJ/kg	PREVIOUS DATA MJ/kg
General	General	-	8.0-14.0
	Hard	-	2.7-15.5
	Soft	-	3.6-7.2
Chamber	General	-	3.9-5.0
	Hard	4.9-21.7	6.7-21.1
	Soft	4.3-(8.0)-20.3*	3.3-4.2
Dehumidifier	General	-	1.4-3.9
	Hard	2.3-7.5	1.1-2.9
	Soft	1.5	1.6-4.4
Vacuum	General	-	3.3-8.7
	Hard	4.2-4.6	-
	Soft	4.8-8.2	-
Progressive	General	-	2.9-5.0
	Hard	-	-
	Soft	-	3.2-3.9
High Frequency	General	-	9.0-10.0

Note * : Figure related to a kiln operated without concern for product degrade.

Table 6.15 - Comparison of present and previous studies

The lack of energy monitoring in the UK has hindered the study of several types of timber dryer. Progressive kilns only represent 1% of the present number of drying installations in the UK [195] and no data was available concerning energy utilisation. There are no commercial high frequency dryers presently installed in the UK. Recent work has been carried out involving drying timber using microwaves, however to date an industrial unit has not become economically viable.

VACUUM KILNS

The energy utilisation of vacuum kilns in comparison to past studies appears to be similar, requiring about 4 MJ of energy to remove 1 kg of water. The installation of vacuum kilns in the timber drying industry has increased over the last 20 years, and 89% of the present units are less than 10 years old [195]. However vacuum kilns only represent a very small proportion (4%) of the present number of kilns and less than 1% of the timber drying capacity. The lack of wide spread application of this kiln type has probably slowed development and adjustment of kiln schedules which may reduce drying times, maximising productivity, reducing drying costs and hence energy consumption. A large proportion of the vacuum kilns analysed were monitored on a regular basis, and most incorporated computer control. The degree of instrumentation is reflected in the modern nature of the equipment although many operators expressed that the data obtained was not used to its full potential in terms of energy saving.

DEHUMIDIFIER

Figures in Table 6.15 show that the present energy utilisation of dehumidifiers drying hardwood is greater than that revealed in past studies. However, data for softwood drying showed a marked reduction in energy requirements, although limited information was available. Some of the case study data was obtained through load profile consumption analysis performed by Midlands Electricity plc and was considered to be very reliable.

Pratt [319] found that the energy consumption in dehumidifier drying ranged from 15 to over 50% less than in conventional kiln drying depending on species. Chech and Pfaff [319] also found energy reductions of over 50%. Results of the present study also agree with these findings, with energy consumption reductions of 89% in comparison to an inefficient chamber kiln processing hardwood.

The application of dehumidifiers for drying timber has increased rapidly over the last 20 years, with nearly 50% of the presently installed units being under 5 years old [195]. The type of dehumidifier installation varies significantly from site to site. Unlike modern chamber kilns which are commonly double aluminium skin insulated units, many dehumidifiers are custom built devices. Converted lorry/cargo bodies or old brick kilns are commonly utilised with limited instrumentation for assessment of the energy consumption.

A large proportion of the dehumidifiers presently in use in the UK are of a custom nature. Many of these kilns probably have insufficient insulation and air sealing, thus resulting in the large energy consumption obtained in comparison to previous studies. In these cases energy consumption was sacrificed for the capital cost of the unit. Energy utilisation for timber drying using dehumidifiers may be improved by implementing good housekeeping measures.

CHAMBER

Chamber kilns represent the largest proportion (67%) of current timber drying installations in the UK, and 73% of the capacity. Table 6.15 shows that energy utilisation for drying hardwoods is similar and softwoods high in comparison to previous studies.

The softwood figures are rather misleading since the highest energy value of 20.3 MJ/kg of water removed related to a kiln operated to a very severe schedule where degrade was not important for the application of the dried timber. This study showed that 45% of the chamber kilns were over 21 years old. Unless retrofitted, instrumentation on many of these units is inadequate for assessment of the energy consumption. The energy consumption figures obtained for chamber kilns may be prejudice towards new installations from which figures were obtained. This is noted in Table 6.15 by the slightly lower figures obtained for hardwood kilns in comparison to previous studies.

Total Energy Consumption for Timber Drying in the United Kingdom

The energy consumption of timber drying processes in the UK has not been examined for over 15 years [195]. Figures of limited nature were uncovered during a comprehensive literature survey regarding total drying energy consumption in the UK. An overall breakdown of energy consumption into kiln type and timber species has, to the knowledge of the author, never been investigated before.

This study has demonstrated that the energy consumption of timber drying equipment varies widely. To enable energy calculations to be performed average figures have been generated based upon commonly dried species, equipment and process conditions [62]. There will be exceptions to the general guidelines but it was considered that the figures used represented a large proportion of the timber industry. Table 6.16 shows the variation of moisture content (initial and final) for common species of hardwood and softwood processed in the UK [195].

SPECIES	INITIAL MOISTURE CONTENT (%)	FINAL MOISTURE CONTENT (%)
Softwood	150 - 50 (80)	18 - 30 (20 - 28)
Hardwood	30 - 50 (40)	10 - 13 (12)

Note : Figure in brackets represent average figures.
Large variation in softwood initial moisture content due to differences in timber species.

Table 6.16 - Common moisture content changes in softwood and hardwood

To enable the weight of moisture lost from a volume of timber to be calculated two typical species commonly kilned in the UK were selected; Spruce - Density at 15% moisture content - 450 kg/m^3 [355], & Oak - Density at 15% moisture content - 720 kg/m^3.

High, low and average values of the energy consumed per weight of water removed were utilised. Production figures were combined with moisture calculations and energy consumption values were estimated for specific machine type, form of heating and timber species.

Trends in Total Drying Energy Consumption

Figure 6.17 shows the variation of the total energy consumption for timber drying as a proportion of the volume of wood processed.

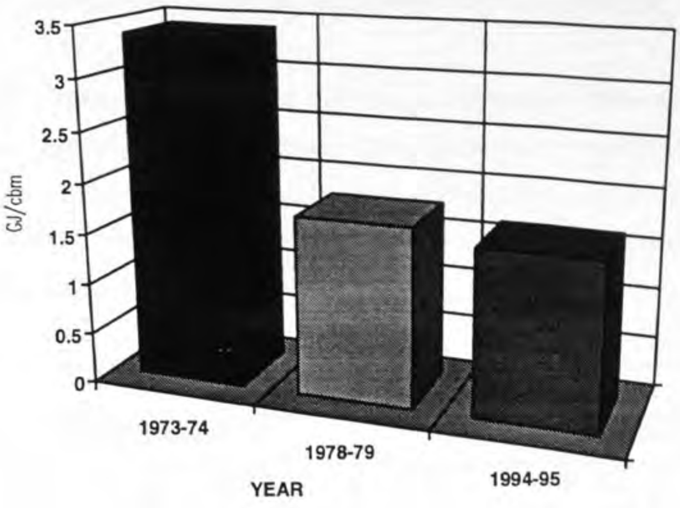


Figure 6.17 - Energy consumption for timber drying as a proportion of the total timber processes

Figure 6.17 shows that the energy utilised for timber drying decreased during the last 20 years in comparison to the quantity of timber processed. Perhaps explained by the declining use of conventional heat/vent kilns and introduction of energy efficient dehumidifier units. There is further scope for greater energy savings by implementing dehumidifier units for timber drying.

Comparison to Previous Studies

A literature survey revealed four previous studies regarding the energy utilised for drying within the UK timber industry. Table 6.17 shows a comparison with the results of this study.

YEAR	ENERGY FOR DRYING (10^9 MJ)	SOURCE/NOTE
1973-74	1.31	This study
1976	0.38	[177]/1
1978	4.00	[161]
1978	0.56	[382]/2
1978-79	1.01	This Study
1981	3.00	[131]
1994-95	0.63	This study

Notes:

1. Based upon 170 x 10^3 tonnes of water removed.
2. Based upon 250 x 10^3 tonnes of water removed.

Table 6.17 - Energy for timber drying in the UK

Table 6.17 shows some variation between results of this and previous studies, with results varying by a factor of 7 for work conducted in the same year. The accuracy and validity of previous studies is thus questionable.

Effect of the Introduction of New British Standards Relating to the Drying of Softwood

The introduction of British Standards concerning the moisture specification of softwoods will have had a direct effect on the energy requirements of drying these species. These standards were analysed during the energy study and average estimated figure for the 1970's were calculated from softwoods dried to 28% moisture content, and for the 1995 estimation to 20% moisture content. Table 6.18 shows a comparison of the energy figures for 1994-95 before and after the introduction BS 4978 (1988).

ENERGY 10^6 GJ					
BEFORE INTRODUCTION			AFTER INTRODUCTION		
LOW	HIGH	AVERAGE	LOW	HIGH	AVERAGE
0.35	0.91	0.62	0.38	0.93	0.63

Table 6.18 - Energy consumption before and after introduction of BS 4968 for 1995.

Table 6.18 shows that there is only a very slight increase in the overall energy consumption with the introduction of BS 4978 (1988), with the average estimation only increasing by 1.6%.

Effect of Air Drying Hardwoods

Figure 6.18 shows the variation of the total drying energy consumption with initial moisture content.

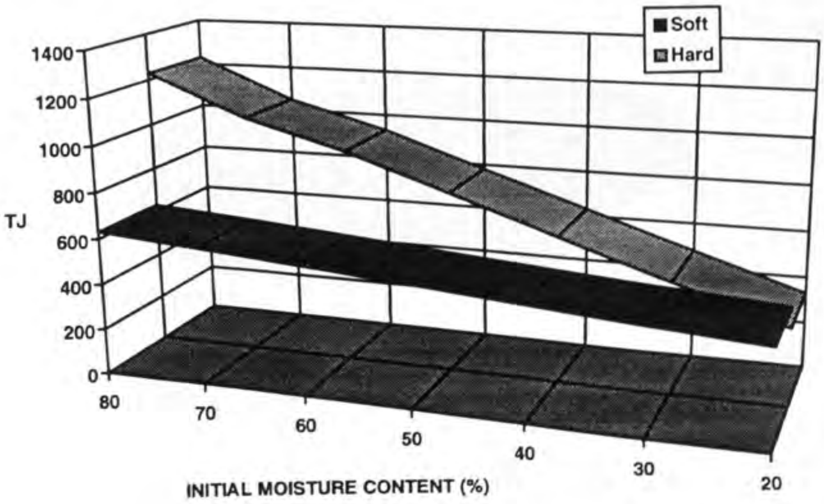


Figure 6.18 - Variation of total energy consumption with initial moisture content

Figure 6.18 shows that there is a considerable decrease in the total drying energy consumption by reducing the initial moisture content of hardwood. However, only a slight variation in the total energy consumption is obtained when the initial moisture content of softwood is reduced. The result reflects the greater energy requirements required to dry hardwood in comparison to softwood.

Information from kiln operators [62] showed that hardwoods are commonly air dried prior to drying to reduce kilning times and improve product quality. However, not all sites contacted [195] airdried hardwoods to 30% moisture content. The energy savings achievable by implementing air drying methods are substantial. An energy saving of over 23% of the total consumption can be made by reducing the initial moisture content of hardwood by 10% from 40 to 30%, and savings of nearly 50% by air-drying from 80 to 30% prior to kilning. Wengert [319] estimated a 40% reduction in total drying costs of oak by combining air-drying and kilning compared to purely kiln drying. His results agree well with the findings of this study.

The methodology of air drying timber is described in detail in the Timber Drying Manual [290]. The economics of air drying are addressed by Brazier [13] and Pratt [290]. It was noted that the time for drying and the capital cost of holding work in progress and storage were key factors affecting the viability of air drying. Additional items such as the value of land, changing value of timber with time, and overheads including depreciation, maintenance and insurance also require consideration. The savings in energy costs, although substantial, may not encourage a kiln operator to air-dry its timber before kilning.

Energy Consumption for Specific Kiln Types

Figure 6.19 shows the proportion of energy utilised in 1995 and Figure 6.20 shows the capacity of various kilning facilities in the UK.

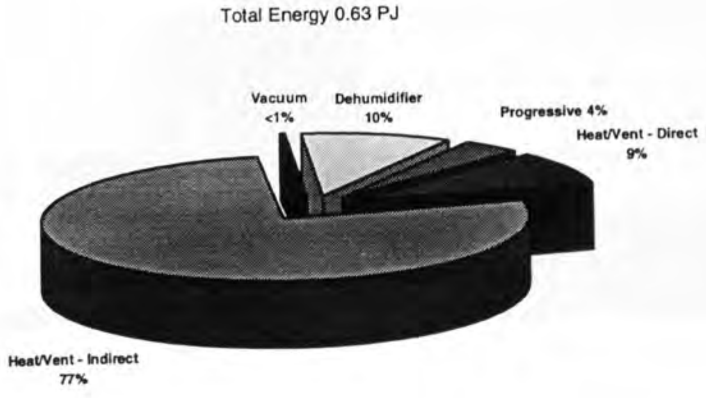


Figure 6.19 - Energy utilised by kiln type for 1995

Figure 6.19 shows that the largest proportion of energy used for timber drying is consumed by indirect heat/vent kilns. Vacuum kilns consume the smallest proportion of the total due to the limited number and timber capacity of this equipment.

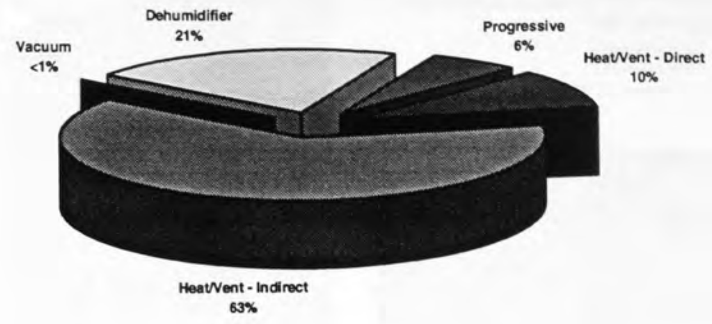


Figure 6.20 - Proportion of the total capacity for specific kiln types - 1995

Energy Consumption for Specific Timber Species

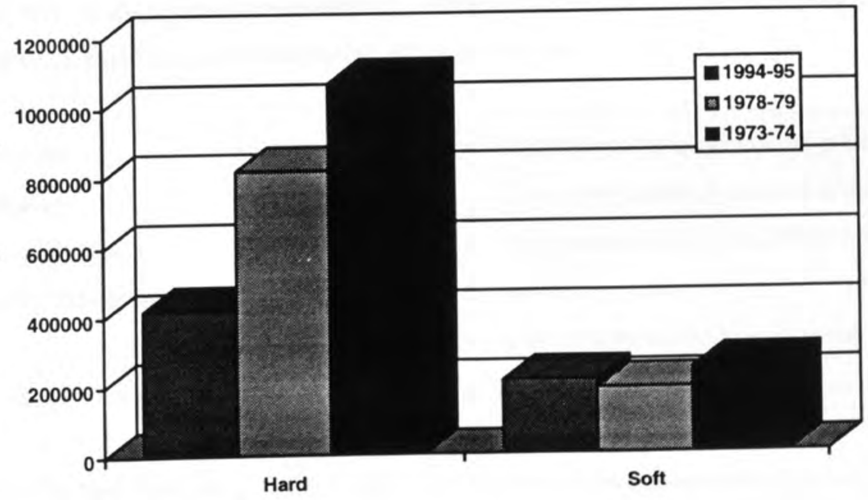


Figure 6.21 - Energy utilised for softwood and hardwood drying

Figure 6.21 shows that the energy consumed for drying hardwoods has fallen, while that for softwoods has remained fairly constant since the early 1970's. Moreover, in 1995 a greater amount of the energy is used for drying hardwoods than softwoods. Figure 6.22 shows that the SEC for drying hardwood has fallen during the last 20 years. However, the SEC for softwood drying has increased slightly since 1978.

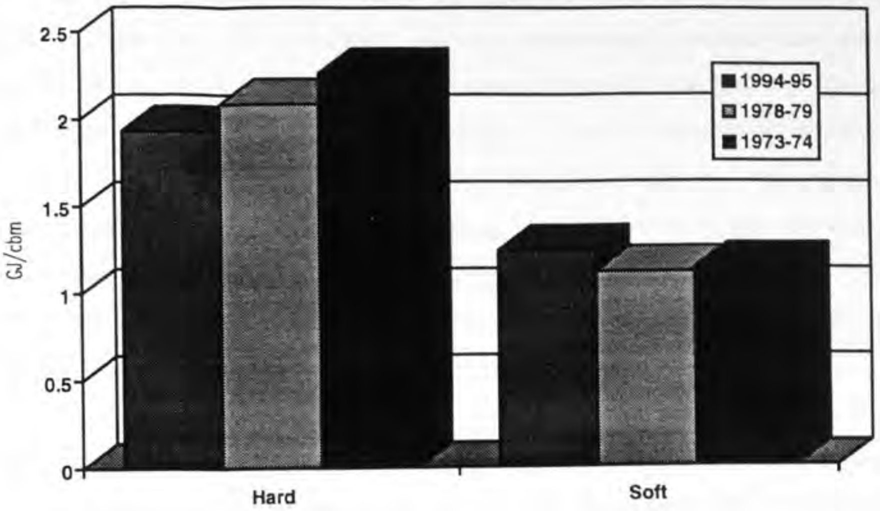


Figure 6.22 - Specific energy consumption (SEC) for the drying

Energy Efficient Concepts

Many authors have discussed aspects of energy saving within the timber industry [161], [170], [278], [290]. Espring [127] describes details of good house-keeping methods, and their affect on the energy consumption of timber drying equipment. Practices to improve energy efficiency include;

- Prevent gas leakage,
- Improving insulation,
- Correctly loading the kiln,
- Reducing over-dry timber by improving process control,
- Using heat exchangers for heat recovery,
- Monitoring equipment on a regular basis,
- Using heat pumps to recover heat,
- Using exhaust from one kiln to heat another,
- Air drying timber,
- Correct design of kiln equipment,
- Drying at the lowest possible air speed.

The study demonstrated that monitoring of the energy consumption of drying equipment is not conducted on a regular basis. There is thus little impetus to improve the energy efficiency of equipment.

Little information was found during the study relating to the use of heat exchangers for heat recovery, or any utilisation of the waste heat from timber kilns. Work conducted in Sweden [127] has shown that heat exchangers fitted to a progressive kiln have reduced the energy requirements from 319 kWh/m^3 to 260 kWh/m^3. The capital cost of installing heat recovery systems will be a deciding factor relating to whether an operator utilises this form of energy saving measure. A pay back time of less than two years would be required if the technique was to be successful. Malmquist [239] showed that if 80% of the exhaust heat is recovered then a saving of about 0.7-0.9 MJ/kg water removed may be made. No literature regarding the cost verses energy saving benefits of installing heat recovery systems on batch timber kilns could be found. Payback times of 3-10 years were calculated for progressive kilns [127].

The electric power consumption theoretically increases by the third power of the air speed. Measurements have indicated that timber with less than 40% moisture content dries approximately as evenly and quickly irrespective of the airspeed [127]. Brunner [35] looked at the effect of regulating the speed of the fan motor on energy consumption. With single fans at conventional air speeds the fan power represented about 3.4 MJ/kg water removed in the case of hardwoods such as oak, and 0.34 MJ/kg for a softwood. With speed regulation it is claimed that fan power can be reduced by 70% for hardwood and 50% for softwood. The energy requirements being linked to the size of kiln, moisture change, operating characteristics and drying time. Calculations performed with data obtained from this study have found fan power consumption's of 5 MJ/kg water removed for spruce, and 0.76 MJ/kg water removed for beech dried in an indirect gas heated chamber kiln.

Other design factors such as burner design and the quality of the fuel type will also affect the energy utilisation of a kiln. One kiln operator [62] has reported that savings had been made by installing a burner cut-off thermostat. The device monitored air temperature in the air/air heat exchanger inside the kiln and reduced the oil supply to the burners when the required temperature was meet. In the old case the burner would run until the temperature sensor on the far side of the kiln registered the level. Simple and cheap devices like these could reduce the overall energy requirement in the timber drying industry.

Developments in the field of kiln design and the application of new drying techniques for timber drying are proceeding although to a limited extent in the UK. Techniques such as high temperature drying are among many processes that have been introduced over the last 20 years. Brazier [13] provides a full discussion of the advantage and disadvantages of high temperature drying, although energy costs are not addressed. Taylor [346] examined the energy consumption of high temperature drying schedules. Harsher, high temperature schedules were shown to use up to 15% less energy than that consumed with similar loads at lower temperatures, although the effects on product degrade are not discussed.

Conclusions

The timber drying industry in the UK has changed remarkably over the last 20 years. The following points conclude the main findings of the 1995 study and summarise significant changes :-

1. The demand for wood products has increased since the late seventies and it has been predicted that demand will increase further over the next decade.

2. The production of home-grown timber has doubled in the UK since 1976 representing over 7 million cubic meters of timber. It is predicted that the amount of home-grown timber will increase further and could reach 20 million cubic meters in 2026. However, less sawn timber is presently produced in the UK. A reduction of 58% since 1978. The decline in the production of sawn timber is reflected in the 44% reduction in the volume of timber dried in the UK since 1978. An estimated 385600 m^3 was dried in 1994-95. Results suggest that more timber is used without drying, although the production of fibre products, which was not examined during this study, may reflect these statistics.

3. companies were identified as operating kilning facilities in the UK, representing 467 individual kilns with an estimated total capacity of $19{,}902m^3$.

4. The number of kiln operators has decreased by 60% since 1978.

5. It is envisaged that the introduction of new British Standards, especially BS4978 which reduces the moisture limit of softwood for constructional purposes, will lead to an increase in the amount of timber dried in the UK.

6. A substantial number of kilns (58%) are operated by timber merchants and sawmillers.

7. of companies dry hardwood, 24% softwood and the remainder process both. More companies are drying softwoods than in the 1970's.

8. of companies dry timber for their own use or resale. 7% deal with only contract work, while 23% operate in both streams.

9. of kilns identified were indirect heat/vent chamber type, 12% were direct heat/vent, 28% dehumidifiers, 4% vacuum, while under 1% were progressive.

10. There has been an increase in the number of vacuum kilns operated in the UK. The proportion of kilns of the heat/vent type has decreased during the last 20 years, whereas the proportion of dehumidifiers has increased. The number of single, low volume dehumidifiers installed during this period has been quite significant. There has been no major investment in progressive kilns in the UK.

11. Dehumidifier, indirect heat/vent, and vacuum kilns are most commonly used for processing hardwood. It was found that progressive kilns were not utilised for drying hardwood in the UK.

12. There has been a reduction in the number of kilns using oil and wood fuel since the 1970's, with a greater number of kilns using electricity and gas. The increase in use of dehumidifiers in respect to heat/vent type kilns has been an influencing factor.

13. Currently about 90% of kilns in the UK are using wood, oil and electricity as fuel. Gas, although having increased in use since the 1970's only supplies 10% of kiln installations.

14. In capacity terms, 37% of the total capacity uses wood as a fuel, 29% oil, 21% electricity, and 13% gas.

15. The largest proportion of the total capacity, 63% are indirect heat/vent type kilns. 10% direct heat/vent kilns, 21% dehumidifiers and 6% progressive. Vacuum kilns having only small capacities in relation to other kiln types and represent less than 1%. The proportion of the total capacity provided by dehumidifiers has increased by 300% since 1978.

16. The average capacity of individual kilning installations (timber volume basis) has increased by 53% since the 1970's.

17. The number of kilns per operator varies widely from a single unit to 28. Indirect heat/vent kilns are commonly operated in groups of three or more, using a centralised boiler system. Dehumidifiers are often smaller and single units are quite widespread. Vacuum kilns are commonly found in pairs.

18. The number of kilns of brick/concrete construction has reduced from 56% in 1978 to 22% in 1995. The utilisation of aluminium, steel and wood kilns has increased. Steel constructed kilns using ex-cargo transportation containers are common amongst small single dehumidifier units.

19. There has been an increase in the number of kilns using overhead fans since the 1970's. Presently 53% of the total. The increase in the number of dehumidifier units has probably influenced this trend.

20. of dehumidifier kilns are 0-5 years old, and 66% of vacuum kilns were installed 5-10 years ago. This reflects the development, demonstration and utilisation of these equipment types over the last 20 years. Results have shown that 48% of direct and 45% of indirect heat/vent kilns are 21+ years old.

21. Kilns constructed from aluminium and steel have become abundant in the last 10 years. Wood construction is also currently popular probably owing to its low capital cost and ease of erection. Brick/Concrete kilns are not commonly constructed nowadays, with 80% of brick/concrete kilns being 21+ years old.

22. of kilns in use in 1995 were of UK origin. Foreign competition penetrating the UK kiln market has increased substantially over the last 15 years. Foreign equipment only representing 1% of the total number of kilns in 1978.

23. of kilns surveyed were automatically controlled, a large proportion of which were using measurements taken from wet and dry bulb temperature within the kiln. 289 kilns out of a total 467 (62%) used oven sampling methods of monitoring the timber during drying. Hand held moisture probes were used on 48% of kilns, while only 12% of kilns had on-line moisture probes installed during operation. Several operators utilised two or more control methods.

24. The results of this study will be correlated with energy assessments of equipment presently utilised in the UK. This will enable a complete review to be made of the trends in energy utilisation and equipment operational characteristics with reference to energy efficiency and good operating practices.

25. Many researchers have examined the energy requirements of moisture removal from timber. Many of these studies are very general in nature and details of machine type, timber species, and moisture content changes were not disclosed.

26. Examination of past studies has shown that evaluation of the energy utilisation of a kiln with respect to the form of heating and fuel type has not been conducted.

27. Past studies revealed that the energy consumption for the removal of water from timber varied considerably from 1.1 MJ/kg to 21.1 MJ/kg.

28. Dehumidifiers were found to consume less energy per kg of water removed in comparison to conventional methods. Energy savings upto 89% were shown in comparison to an inefficient chamber kiln.

29. The study has shown that that no savings in energy were achieved by using vacuum kilns in comparison to conventional methods. Vacuum kilns only represent a small proportion of the capacity in the UK and thus are insignificant in comparison to other kilning methods.

30. Various British Standards have been enforced during the last 20 years relating to the final moisture content of timber. Softwoods for structural purposes are presently required to have a final moisture content of 20%.

31. There is a lack of energy monitoring of kiln equipment in the UK. Newer kilns were found to have sufficient instrumentation for the analysis of energy utilisation, however figures were rarely examined.

32. Insufficient data was obtained to allow an analysis of the effects on the energy required for moisture removal from timber at a moisture content below the fibre saturation point.

33. Electric drying systems, especially dehumidifiers, were found to be very energy efficient. However, the unit cost of electricity offset the energy advantage of using these techniques in comparison to conventional fossil fuel kilns. Electric kilns offer additional benefits such as no emissions, improved product quality due to controllable heating, less maintenance and lower capital costs.

34. This study demonstrates that the energy requirement to remove moisture varied from 1.51 MJ/kg for a dehumidifier drying softwood to 21.78 MJ/kg for an indirect gas fired chamber kiln drying hardwood.

35. Dehumidifiers use more energy for removing moisture from hardwood than softwood in comparison to studies conducted in the 1970's.

36. In comparison to previous studies chamber kilns consumed a similar quantity of energy for drying hardwood, although softwoods required on average more.

37. The energy consumption of a timber kiln varied considerably and was dependant upon many factors such as; species, kiln type, form of heating, moisture content change, and outside climate conditions.

38. The total energy consumption for drying processes in the UK has not been examined since 1982.

39. Comparison of past energy studies showed no correlation with some work for similar years varying by a factor of 7. The accuracy and validity of previous studies is questionable.

40. It is estimated that 0.63 PJ of energy was consumed for timber drying in 1994-95.

41. The total energy consumption for the drying of timber in the UK has fallen since the 1970's.

42. The total SEC of timber dried has decreased by an estimated 14% during the last 20 years. The closure of old inefficient and dated equipment and the utilisation of energy efficient dehumidifier kilns is the most probable cause for this trend.

43. Introduction of new British Standards relating to the drying of softwoods will have little affect on the total energy consumption for drying in the timber industry. An increase of less than 2% of the total was estimated from average energy figures.

44. It was estimated that significant saving can be achieved by air drying hardwood before kilning. Reducing the moisture content by 10% from 40-30% before kilning could achieve saving of 23% of the total energy consumed. Saving of 50% can be achieved by air-drying hardwood from green to 30% moisture content. Other economic factors such as storage, work in progress and additional labour costs need to be addressed in order to implement air drying techniques.

45. Only a slight decrease in the total drying energy consumption is achieved by reducing the moisture content of softwood before kilning.

46. In 1973 95% of the total energy was used by heat/vent kilns. In 1995 the study showed that 77% of the total energy was consumed by indirect heat/vent kilns, 10% by dehumidifiers, 9% direct heat/vent kilns with progressive and vacuum kilns utilising the remainder.

47. Less energy per unit volume of wood was used for drying hardwood in 1994-95 in comparison to 1973 figures. However, there have been no realistic saving in the energy required to dry softwood.

48. It is suggested that implementation of good house keeping measures could produce significant saving in the timber industry. Demonstration schemes and technical information describing energy saving techniques could be beneficial.

49. The energy monitoring of equipment provides essential information and produces targets that can be the focus for the implementation of energy efficient measures. Information from kiln operators has demonstrated that very little monitoring occurs within the UK timber industry. Better monitor of equipment can lead to improved control providing additional benefits of improved quality, reducing drying times aswell as reducing energy costs.

50. Research and development of heat exchangers for heat recovery systems, work on the variation of kiln air flow and fan utilisation, together with burner design could produce significant energy saving.

CHAPTER 7

ENERGY UTILISATION IN THE PAPER MANUFACTURING INDUSTRY

Introduction

Paper is a web of fibres usually of vegetable origin. Common fibres used in the UK are of wood, rag and grass origin [374]. Grant [164] provides a good background and introduction to the structure of paper and paper drying technologies. The first patent for drying paper by holding the web against a steam heated cylinder was taken out by Crompton in 1821. Before that, the paper was hung by hand to dry [277].

Qualities of Paper

The manufacture of paper for printing purposes, whether for newspapers, magazines, or packaging, is subjected to a very high level of quality [374]. Factors affecting quality include;

- Basic weight,
- Calliper (Thickness),
- Contour,
- Moisture,
- Porosity,
- Opaqueness,
- Printability, &
- Strength.

Thickness/Weight

The thickness of the paper web is a very relevant property in relation to drying, with thinner papers drying more rapidly than thicker ones. Paper is normally characterised by its grammage (g/m^2).

Papers range in grammage from very thin electrical capacitors tissue at 6 g/m^2, via single ply tissue of 25 g/m^2 up to 500 g/m^2 for folding carton board. Paper board varies up to 5000 g/m^2, but such grammage represents only a small proportion of the total UK production.

Printability/Strength

The strength of a paper web is determined by the reduction in bond forces between fibres during manufacture. Quality factors such as smoothness and picking or linting properties are important, especially for printing papers. Excessive drying regimes and rates of moisture removal can severally affect the strength and printablilty properties of paper.

Moisture Profile

Final moisture content of paper varies according to grade, weight and end-use. The paper may be coated, where a dry web will require further drying after the coating process. Final moisture contents commonly fall within the range 4-9% wet basis [68]. A coating typically applies 3-20 g/m^2 of pigment per side depending upon coating. An important aspect of the paper properties is the uniformity of the moisture content of the paper, both across the web (CD) and along the run (MD). Paper is sold by weight, thus reducing the spread of moisture content permits the average moisture of the paper to be increased without breaching the upper limit in the grade specification. Energy can be reduced by preventing over drying of the paper if efficient moisture levelling can be maintained. Many techniques have been developed to monitor and level moisture within a paper web including, infra-red heaters, radio frequency and induction applicators.

Paper Making Process

Figure 7.1 shows a schematic of a typical paper making process. The first stage in paper making is the preparation of logs by removing the bark. Bark is commonly used as a fuel source for steam generation. The paper making process is briefly described below;

PULPING

There are two process by which pulp can be manufactured from wood;

- **Mechanical Processing** - Wood is ground by mechanical means producing high yield (Typically above 90%) pulps that are highly lignified, weak and bulky. Newsprint is commonly manufactured from this form of pulp.

- **Chemical Processing** - Wood chips are processed under pressure in a sodium or ammonia based liquor. This process dissolves the lignin in the wood leaving the fibres free. Lower yield pulps are produced (Typically about 45%) but are brighter, stronger and drain more readily on the paper machine wire than mechanically produced pulps. They are commonly used for the manufacture of quality printing paper.

STOCK /WIRE

The fibres are mixed with water to form a thin mixture called 'stock' containing about 1 part fibre to 200 parts water. The stock is cleaned and pumped into the chest or headbox section at a constant head. It issues from the base through a fine parallel slot onto the moving wire. Water is removed from the wire by gravity and capillary forces [160].

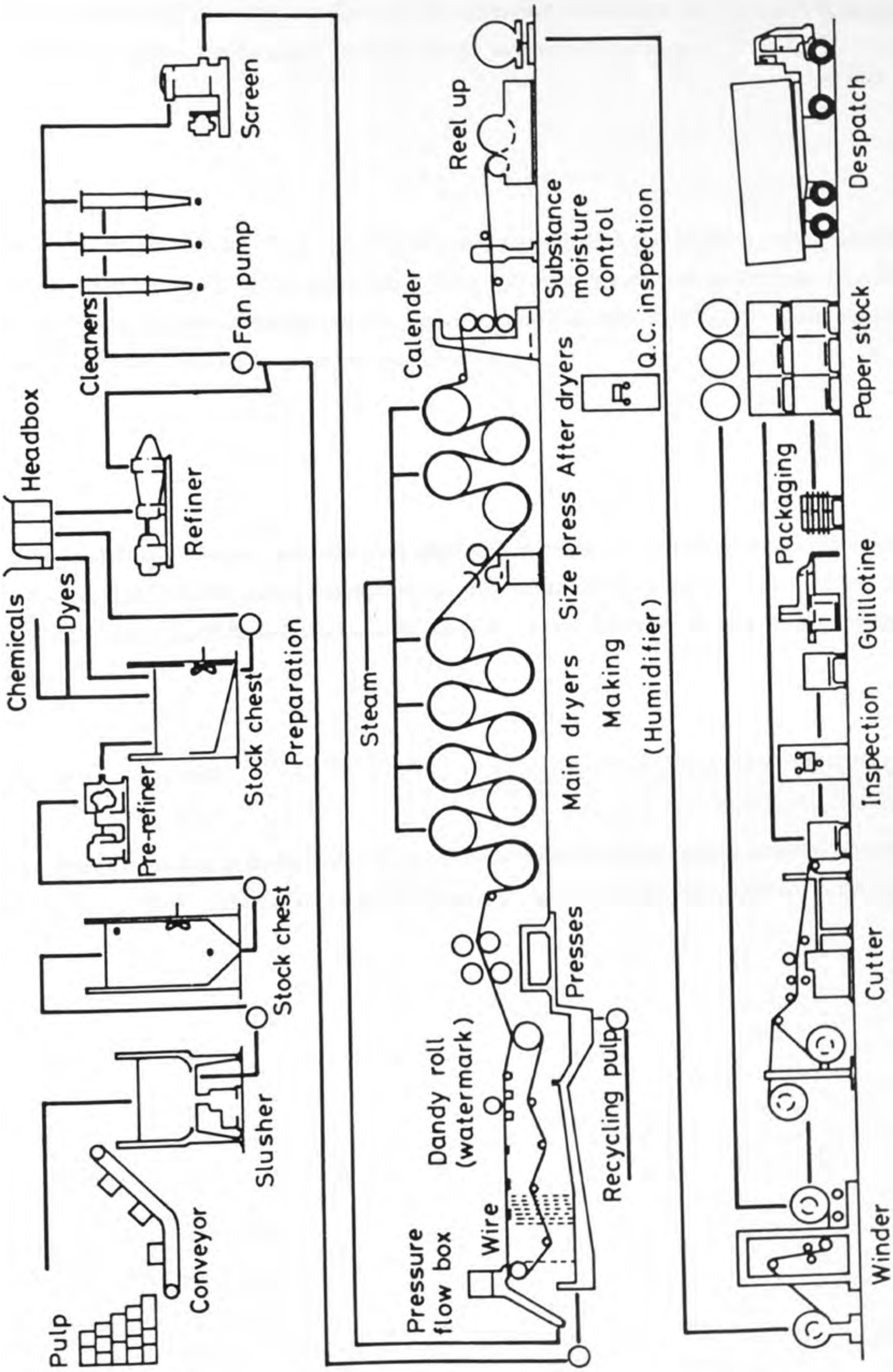


Figure 7.1- Schematic of paper manufacture

VACUUM

Vacuum units are also used to remove water from the web. Vacuum cannot be applied to the web too early during the processing as this would cause compaction of the fibres thereby loosing their resilience.

FELT/PRESS

After the vacuum section the web is picked off the wire and supported on a felt where it passes through mechanical presses. There are usually two or three press sections, thus removing as much as the water from the web as possible. Following the press section the web can contain some 62% of water (wet basis). The felt ensures that there is continuous contact between the sheet and cylinder surfaces.

DRYER

The majority of paper and board products are dried while advancing around the perimeter of a series of rotating, steam heated cylinders [284]. The wet web is pressed onto the dryer surface by the tension of a permeable dryer fabric. Steam heated cylinders are most commonly used for the drying section, reducing the web moisture content to around 4-9% [376].

COATING AND AFTER DRYING

Coatings may be applied to the web in the form of latex, starch with a filter or glazing agent to improve the paper printing quality. A further dryer section is then applied to the web reducing its moisture content to the final specification.

Types of Paper

Many types of paper materials are manufactured in the UK. Different grades are normally classified into five product groups;

Newsprint -	Suitable for printing at high speed. It is normally made from mechanically produced pulp on large high web speed machines.
Printing and Writing -	These are white papers made from a mixture of chemical pulp with mineral fillers to increase properties. Chemical pulps increase quality but at a cost.
Wrapping and Packaging -	Papers for bags, sacks and case material. Case includes corrugated board.
Tissue -	These comprise mainly of toilet paper, facial tissues handkerchiefs. They are made from chemical and mechanical pulp, and additional waste paper which does not require much cleaning.
Industrial and Special -	Manufactured from mainly chemical pulps and include water proof, fire and oil resistant types. The production of these paper products only represents a small proportion of the UK output.

Industry

In 1993 it was estimated that 5.3 million tonnes of paper was produced by 88 mills operating a total of 198 paper machines [193]. Table 7.1 shows the industry structure in 1993 [193].

CAPACITY (Tonnes)	No. OF MILLS	% OF TOTAL MILLS	% OF TOTAL UK CAPACITY
<5000	6	6.8	0.3
5001-10000	9	10.2	1.2
10001-25000	19	21.6	5.5
25001-50000	21	32.9	14.0
50001-100000	16	18.2	20.9
100001 & over	17	19.3	58.1
Total	*88*	*100.0*	*100.0*

Table 7.1 - Industry structure 1993

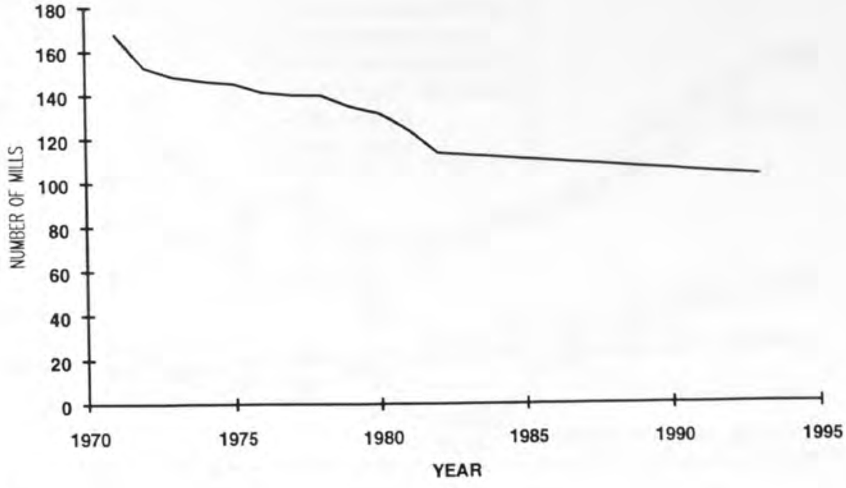


Figure 7.2 - Variation of the number of paper mills in the UK.

Figure 7.2 shows that the number of mills has decreased since the early 1970's, although the rate of closure of mills has slowed during the last 10 years [7], [8]. Table 7.1 shows that most mills produce 25001-50000 tonnes/year, although over 50% of the output is produced by the larger operators. The industry has focused on mills with large capacities. The closure of small, older, inefficient mills in a very competitive industry is the most probable cause of the trend shown in Figure 7.2. Figure 7.3 shows the variation of the total production of paper over the last decade.

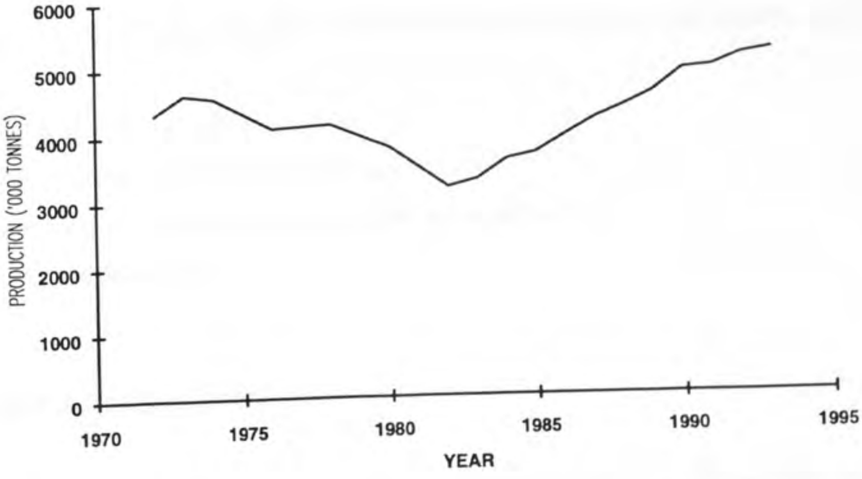


Figure 7.3 - Production of paper products (1973-1993)

Although production decreased during the early eighties Figure 7.3 shows that production has increased significantly over the last 8 years and now stands at over 5.2 Mt/annum. Figure 7.4 shows the production variation for specific product lines from 1973 to 1993.

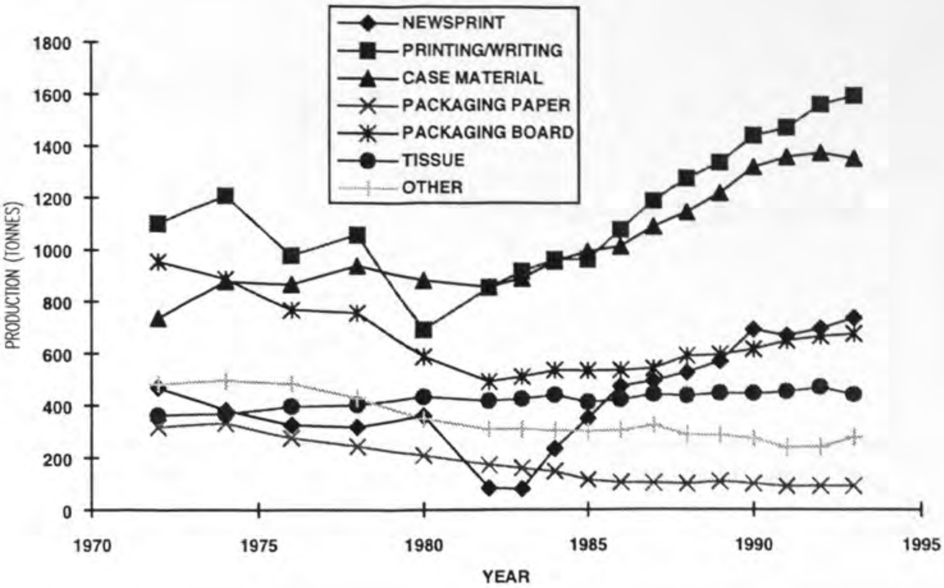


Figure 7.4 - UK production for product types (1973-1993)

Figure 7.4 shows that the production of all types of paper and board have increased over the last 20 years, with the exception of packaging paper and board. Significant increases have been noted in the production of printing and writing paper, case material and newsprint during the last 5 years.

Energy Utilisation

Energy in the form of process steam is required throughout paper manufacture and consists mainly of;

- Steam supplied to the drying cylinders,
- Heating for the air being supplied to the machine,
- Conditioning of air in the machine to maintain ambient conditions, &
- Direct heating of the paper web.

Total Energy Usage in the Paper Industry

It has been estimated that the paper industry in the UK consumed 105.72 x 10^9 MJ in 1992, representing 5 % of the total UK industrial consumption [122], [299]. Figure 7.5 shows the variation of the total and paper sector energy consumption over the last decade.

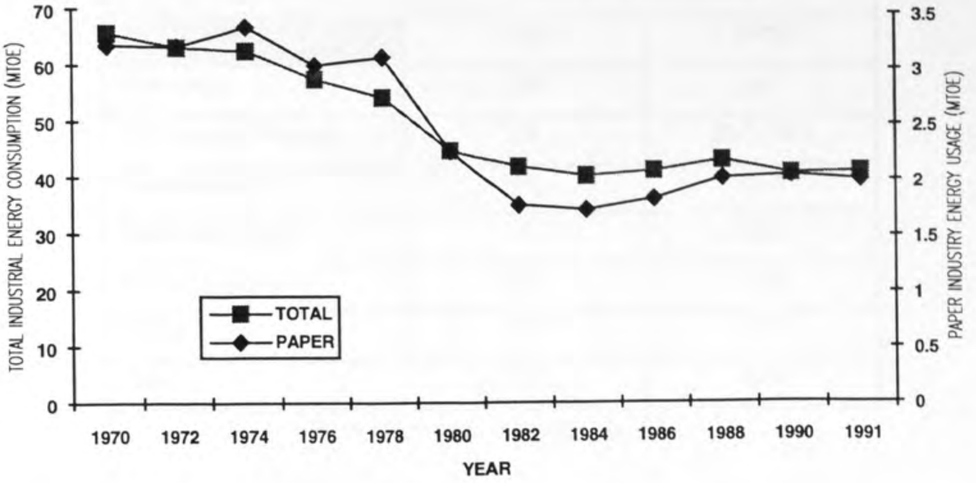


Figure 7.5 - Variation of total and paper sector energy consumption over the last decade

Figure 7.6 shows the variation of the proportion of the total energy used in the paper industry.

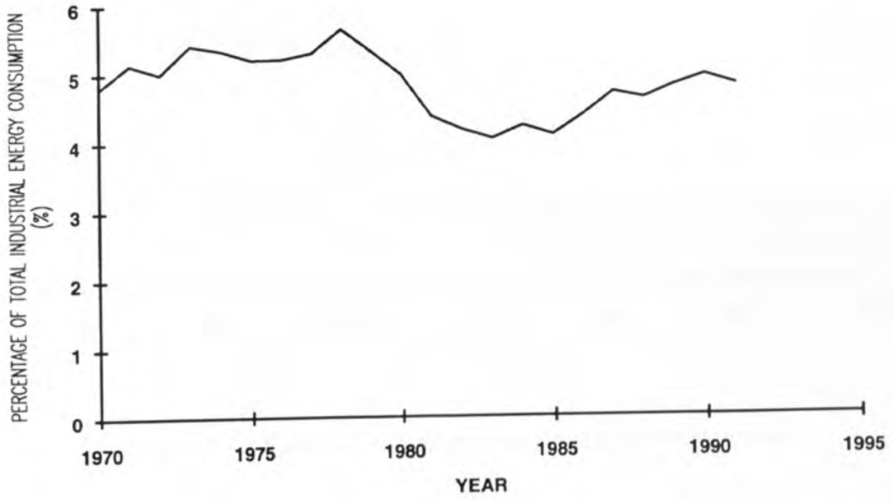


Figure 7.6 - Proportion of the total industrial energy used within the paper industry

Figures 7.5 and 7.6 show that the total industrial energy demand has fallen over the last decade. The proportion of the total energy used within the paper industry decreased during the early eighties, however, has slowly increased over the last five years. Table 7.2 shows a comparison of the energy requirements to product a tonne of finished product [124], [299].

PRODUCT	ENERGY GJ/Tonne	
	1993	1978
Newsprint	28	n.a.
Printing and Writing	23	29.7-38.3
Case Material	14	16.5
Packaging Paper	27	36.8
Packaging Board	23	32.9
Tissue	31	19.7
Other	49	27.0

Note : Energy is in primary terms.

Table 7.2 - Specific energy consumption by product type

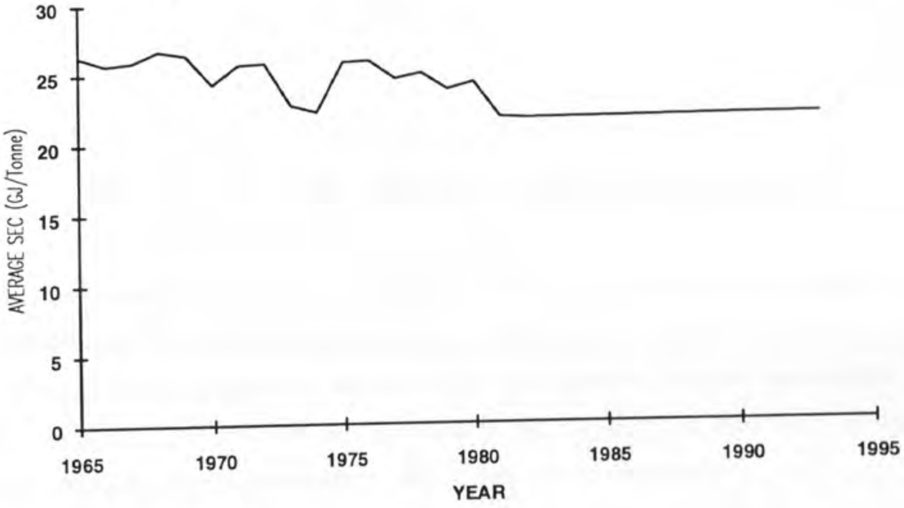


Figure 7.7 - Variation in average specific energy consumption

Various sources [124], [299] have commented upon an average specific energy consumption (SEC). Table 7.2 shows that the specific energy consumption for the majority of products has decreased during the last 20 years. Improved monitoring of equipment, closure of old inefficient plant, implementation of modern equipment and operating techniques has attributed to this trend. The accuracy of tissue SEC figures is questionable.

Figure 7.7 shows that the average SEC has not changed significantly since the early 1980s. A target figure of 18 GJ/tonne of paper produced was suggested in 1984 [124]. Although many energy saving measures have been implemented this target has not been met to date. The factors affecting the SEC of the paper making processes have been documented in detail [124].

Comparison of Figures 7.3 and 7.5 shows that the paper industry has become more energy efficient since the early 1970s. Total energy consumption has decreased whereas total production has increased. The introduction of monitoring and targeting schemes and closure of older inefficient plant may have attributed to this trend.

Drying and Dewatering Techniques Employed in the Paper Industry

Many types of dryer section are currently in use in the UK for paper production. However, a comprehensive literature search revaled little information relating to the exact number of the machine types in operation in the UK. McConnell [244] examined the distribution of dryer types in the US. Figure 7.8 shows the finding.

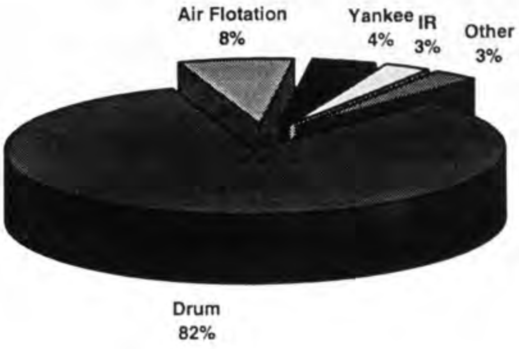


Figure 7.8 - Distribution of dryer types for paper production in the US

Figure 7.8 shows that drum dryers dominate in industry, with Yankee and air flotation systems representing less than 10% of installations. Infra-red systems were found to be less than 3% of the total, being used mainly for coatings and moisture control. Information from industrial manufacturers contacted during this study suggested that the trend in equipment use was very similar to that in the US [68]. The main types of drying section are described below, including information relating to energy utilisation and operation.

Steam Heated Cylinders

Steam heated cylinders are used throughout the paper drying industry. Cylinder vary from about 1.2 m to 1.8 m in diameter and a dryer can consist of 40-110 cylinders depending upon the nature of the product. Steam pressure varies from 0 to 1035 kPa.

The overall energy efficiency of a conventional dryer section depends on factors such as the types of paper dried and the condition of the machine. An efficiency of 70% has been suggested for a modern system [21], [288]. Steam is supplied to the cylinders where the condensate rims the shell as it rotates. Condensate is removed by using a siphon arrangement. Many researchers have investigated the effects on heat transfer characteristics due to cylinder diameter and speed [362]. The dryer section is commonly surrounded by a hood, which assists both with the evacuation of the moisture laden air and heat recovery. Warm air is often circulated through these sections to enhance drying [164].

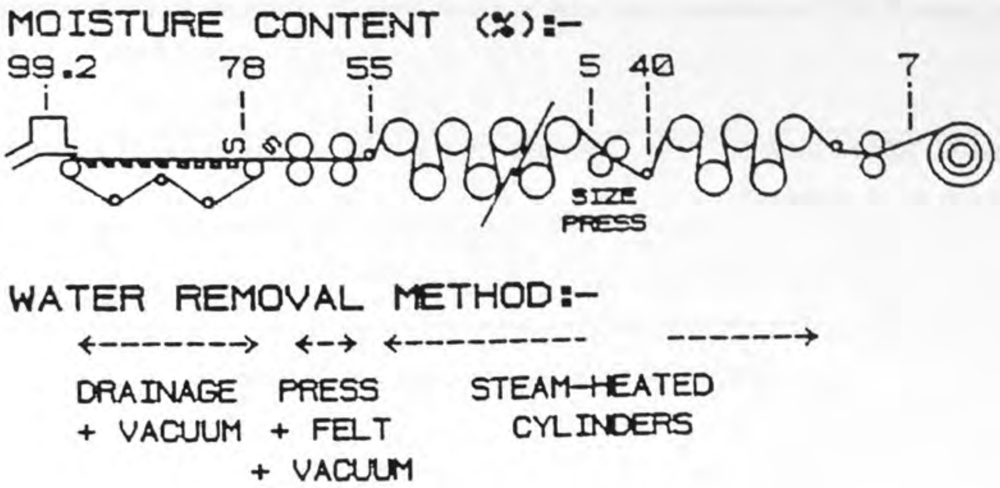


Figure 7.9 - Drying cylinders and a typical variation of moisture through the machine

Rodencal and Atkins [304] describe details of the theoretical energy required to evaporate water from a paper web. A value of 1.3 kg steam/kg water removed was considered excellent, although in practice values in the region of 1.5-1.7 are common. Table 7.3 shows steam requirements to remove a kg of water.

REQUIREMENT	MINIMUM AMOUNT OF STEAM kg
Heat and Evaporate Water	1.09
Desorption heat	0.01
Heating Air	0.06
Vacuum Condenser Waste Steam	0.03
Lost in Paper Web	0.03
Heat Losses	0.03
Total	*1.25*

Table 7.3 - Steam requirement to evaporate a kg of water

Typical dryer heat consumptions have been evaluated by Hill [175]. Table 7.4 summarises the findings.

CONSUMER	ENERGY kJ/kg water removed
Sheet Heating	198
Evaporation	2303
Air Heating	407
Non-Condensable Bleed	46
Venting	0
Total	*2954*

Table 7.4 - Typical heat consumption for a paper dryer

Webell commented briefly on the aspects of energy consumption for paper manufacture [374]. Results for steam usage are shown in Table 7.5.

THROUGHPUT Tonnes/Hour	**PAPER WEIGHT GSM**	**STEAM USAGE Tonnes steam/tonnes water removed**
5.9	49-85	2.06
7.1	35-130	1.43

Table 7.5 - Steam consumption for paper drying [374]

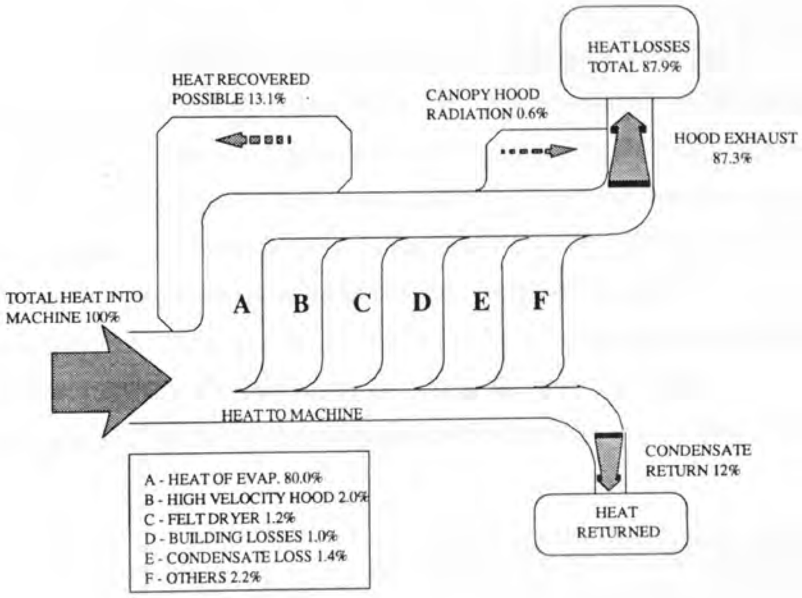


Figure 7.10 - Paper machine heat balance

Figure 7.10 shows an energy balance for a typical paper machine [374]. Parti [279] describes details of methods of increasing the efficiency of a paper machine. According to an energy balance, 68% of the heat obtained from the steam is used for the evaporation of the moisture, 2% to heat the product, and 15% to heat the air. An energy consumption of 2800-3000 kJ/kg moisture removed was quoted, estimated to be equivalent to 1.3 kg steam per kg of vapour removed.

Sayegh, Pikulik and Simonsen studied 92 dryer sections from 30 Canadian newsprint mills in 1985 [312], [313]. They revealed that machines speeds varied from 400 m/min to over 1000 m/min, with web widths of 3-6m. 74% of the machines were installed with drying cylinders of 1.5 m diameter, within the range of 1.2-1.8 m. On average 1.2-3.0 kg of steam was required to dry 1 kg of newsprint. This represented approximately 1.0-2.2 kg steam/kg water removed. A survey of US and Canadian newsprint installations conducted in 1976 revealed that 2.15 kg steam/kg product and 1.6 kg steam/kg water removed [381]. It was noted by Sayegh, Pukulik and Simonsen that their values were on average 5% less than the survey conducted in 1976 [312], [313].

Stenstrom [332] suggested that the specific energy consumption in a dryer assuming an initial moisture content of 40% was 4020 kJ/kg water evaporated or 1.8 times the theoretical heat of vaporisation. It was noted that this value varies from old to new installations and for different paper grades. A survey by Nygaard [268] showed that in a modern paper dryer the specific energy consumption is 2920 kJ/kg evaporated water. This could decrease to as low as 2740 kJ/kg evaporated water with improved heat recovery.

An energy consumption of 2948 kJ/kg water removed was reported during a survey of a light weight paper machine (37 GSM) by Eskelinen [126]. The heat recovery system was attributed to the excellent efficiency of the installation. Bell et al. [21] suggested a consumption figure of 4500-14500 kJ per kg of paper produced for typical systems, representing nearly one third of the total energy consumption of an integrated mill [50].

Many researchers have reviewed general concepts of optimising an existing dryer section [101], [175], [279], [311]. Details commonly discussed include steam control and dryer drainage, dryer fabrics, pocket ventilation, dryer hoods and exhaust details. Ubras [362] suggested that the energy required to dry paper decreased linearly with a decrease in initial moisture content. It is portrayed that 80% of machines use up to 30% more energy than required due to poorly operated condensate systems. Richardson and Jenson [301] assessed the energy efficiency of paper dryers and found they ranged as low as 10% for some configurations, although values were typically 40-45%. Samilo [311] calculated efficiencies of 41.3% and 70.5% for a machine running at 500-800 m/min, using 40-48 cylinders to dry the web from 57-5% moisture content. A figure of 14 GJ/tonne of paper is suggested by the Energy Technology Support Unit (ETSU) as an average consumption for a steam heated cylinder dryer [124].

Pocket Ventilation

Uniformity of temperature and relative humidity in the region between the drying cylinders is often assisted by 'pocket ventilation'. Figure 7.11 shows an arrange for the system.

A hot air system evacuates the moisture laden air from these pockets while at the same time assisting uniformity of evaporation and CD moisture profiles. It has been reported that modern pocket ventilation equipment greatly increases the drying efficiency although exact figures are not published [100].

Steam Showers

Steam showers, where the paper web passes through a steam filled compartment, dates from the 1940s where they were located above the wire vacuum boxes. Modern machines commonly apply them before the press section. Steam showers increase the web temperature and increase web dryness thus improving the mechanisms of heat and mass transfer. Vacuum assisted steam boxes displace air with steam, thus increasing web compressibility, and allow the initial drying cylinders to be operated at a higher temperature.

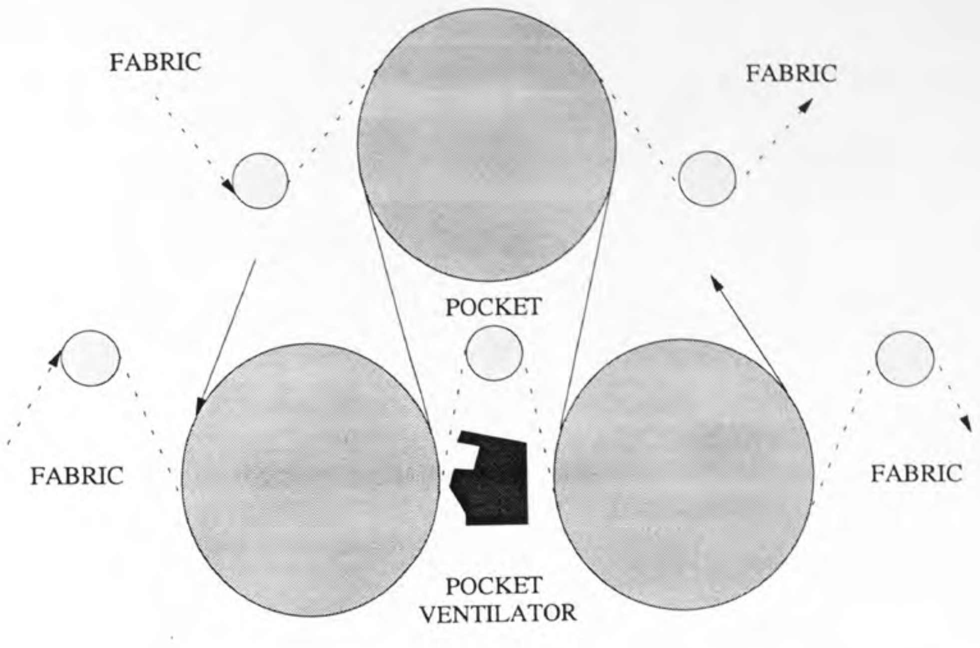


Figure 7.11 - Positioning of pocket ventilation units

High Velocity Dryer Hoods

For thin papers, such as tissue, the drying load is such that a single large diameter (3-6 m) steam heated cylinder can be used for drying [219]. It is called a Yankee or MG cylinder. The surface is heated to about 85°C and the press rolls operate at about 2 MPa [272]. Figure 7.12 shows a typical system layout.

The cylinder incorporates a hood which comprises of a series of hot air jets and slots with which heated air is directed onto the web. Jets of hot air impinge onto the surface of the sheet at temperatures around 490 °C and velocities of 122 m/s [46].

Chiogioji [50] suggests that Yankee type dryer sections are more economical than conventional dryer sections. Energy consumption of 6400-8100 kJ per kg product are claimed in comparison to 6500-12500 kJ/kg product for conventional methods [21].

A demonstration project regarding the use of a new style of 'Yankee' hood incorporating humidity sensor control of air-flow, exhaust heat recovery and series counter-curent air flow is presently being implemented [143]. It has been estimated that energy savings of 48070 GJ/year could be realised. Figure 7.13 shows a schematic of the drying system.

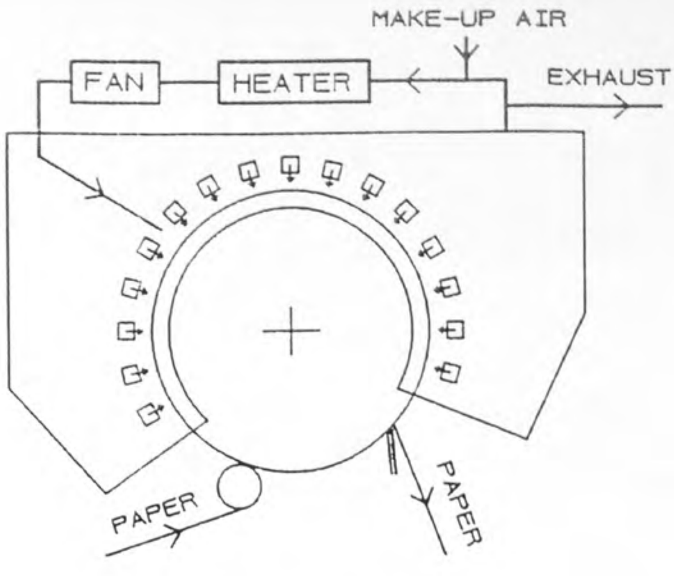


Figure 7.12 - Yankee cylinder layout

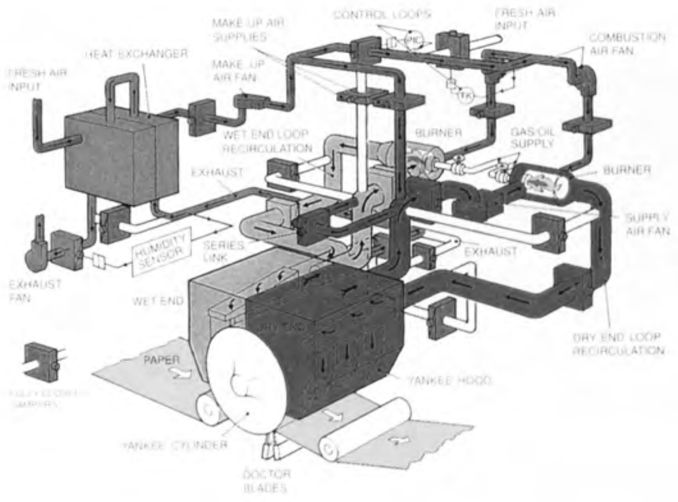


Figure 7.13 - Schematic of a 'Yankee' hood system incorporating heat recovery and humidity sensor control.

Air Flotation Dryers

These dryers are effectively low velocity hoods and are usually in the flatbed configuration [68], [164]. The paper web passes through the dryer where it is supported by jets of heated air, or combustion gasses from gas firing. Figure 7.14 shows a flatbed system.

Air flotation dryers have been applied to the drying of resin-coated and sized paper [140]. Although improvements in productivity and quality were achieved energy savings due to implementation were insignificant.

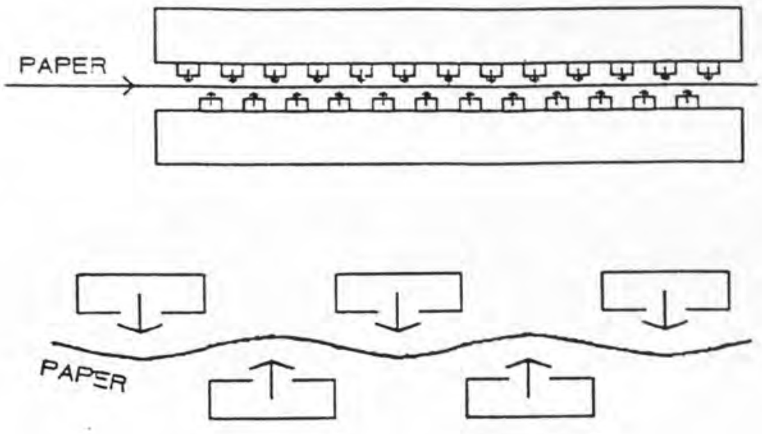


Figure 7.14 - Air flotation dryer

Press Drying

From a thermodynamic point of view, the amount of water evaporated is the most important factor influencing the steam requirement. A 1% improvement in press exit consistency will reduce the evaporation load by 4% [175]. It has been reported that drying with steam is almost seven times as costly as removing water by pressing [124]. Modern effective extended long nip presses can achieve over 45% dry content [332] and a survey of a Swedish mill revealed after pressure moisture of 38 to 45% [27]. Energy consumption decreased from 4160 to 3320 MJ/ tonne of paper produced. Garcia [159] has reported after press dryness of under 50% for Spanish mills.

During the last decade, hot pressing has become widely used throughout the industry [284]. The wet web is often heated just before the second press nip. The bulk of the water has been removed at this point. The application of inexpensive, low pressure steam makes hot pressing very energy efficient, particularly as the steam used to preheat the sheet removes more water than the steam used in the drying cylinders [284]. Improvements in wet pressing in order to reduce drying costs or improve production have been the subject research for many years [103], [165].

The demonstration of hot press drying of board grade paper products is described in an Energy Efficiency Office Best Practice Programme [136]. The system was the first of its kind to be installed in the UK, in 1989. The original machine was set up with a five nip press section, followed by 101 steam heated cylinders of 1.2m diameter. A Tem-sec hot press, developed by DG International was installed with a 2 m diameter cylinder. The two nip presses operated at conventional nip loading of 90 and 140 kN/m. Although problems were encountered during initial commissioning due to 'picking' these were successfully overcome. Production rates were increased by 16.4% on average, increasing the solids content by 4.3%, thus reducing the steam requirement of the cylinders by 13.9%. Energy savings of 66000 GJ/year were realised.

Infra-red Heating

The application of IR for paper drying has become widespread throughout the industry. IR heating has been applied at many stages during the paper making process. Figure 7.15 shows a schematic diagram of possible positions for IR drying techniques.

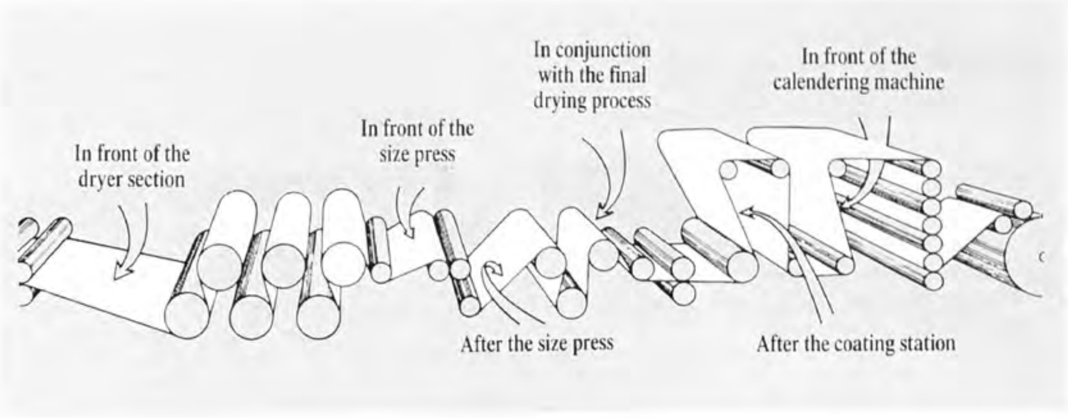


Figure 7.15 - Application of IR drying units.

Many researchers have investigated the application of IR systems for paper drying and it is well documented in the literature [161], [164].

A single row of electric IR drying units have successfully been installed to carry out moisture profile control on a paper machine manufacturing paper in the weight range 40-240 GSM [148]. Fish [148] reported that significant savings in energy have been reported by implementing IR units for the drying of coated paper. Research and development into gas and electric IR systems has been conducted [250]. Gas emitters were found to be 40-50% efficient in drying paper where as electric 25-35% efficient. The tests were conducted at a laboratory scale.

Dielectric Heating

The rapid oscillation of water dipoles resulting from an alternating field applied to the web heats the moisture in the paper. The characteristics and application of radio frequency heating to paper webs were developed during the 1970, and although the technique offers considerable benefits with respect to moisture profiling, capital costs have restricted widespread application.

A 200 kW unit installed in 1980 on a Fourdrinier paper machine has enabled a constant quality to be maintained. The unit replaced two of the original drying cylinders in the final stages of product drying. Figure 7.16 shows the variation in moisture content of the web before and after implementation. It was reported that considerable energy savings have been achieved although specific figures have not been quoted [262].

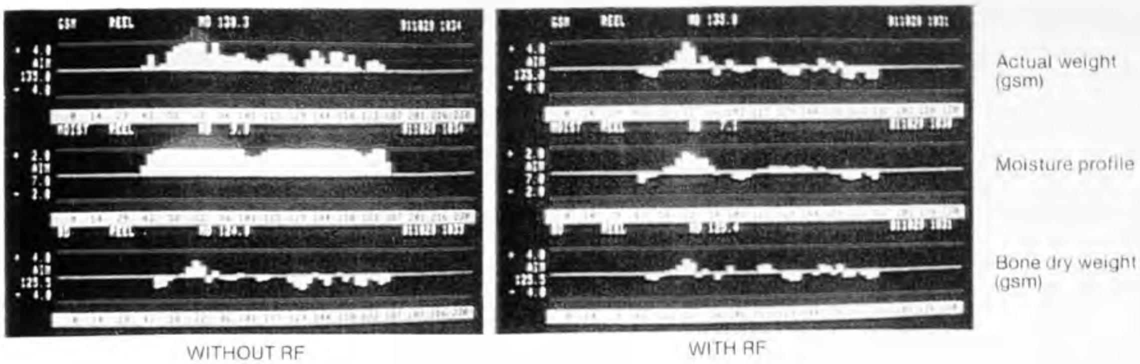


Figure 7.16 - Moisture profile before and after the installation of RF heating [262]

The combination of RF and air heating techniques have been developed at EA Technology (Formally the Electricity Council Research Centre). The configuration is effectively an air flotation dryer with a RF field applied to the web. Although energy effective the capital costs have discouraged application. There are thought to be only two RF installations on paper machines in the UK, both used for improving CD moisture profile.

Survey of Paper Dryer Sections

From 1983 onwards the UK paper industry (through the British Paper and Board Industry Federation [68]) was one of the first industrial sectors to adopt monitoring and targeting (M&T). Despite the very real benefits of continued implementation of the methodology, participation in M&T has declined [133].

The lack of steam consumption data, combined with measurement errors make the assessment and implementation of energy conservation measures very difficult. For the evaluation of the overall energy efficiency of a paper dryer the total steam consumption must be known. It is often not clear where steam is used, whether for cylinder heating, hood ventilation or preheating.

This work examines the energy consumption characteristics of drying equipment presently installed within the paper manufacturing industry. Comments are made concerning the range of operating conditions and typical energy utilisation. Data is based upon dryer section audits from industry, equipment manufacturers and research organisations.

Methodology

Energy consumption figures were collected by direct contact with paper manufacturers. Over 50 companies were contacted. Data was also analysed from equipment manufacturers and research and development establishments [68]. Information relating to 192 dryer section surveys was collected, covering the five main product areas in the paper industry. The following details were collected for typical dryer sections;

- Paper type,
- Details of the machine type and layout,
- Paper weight (Final),
- Speed of web,
- Web width,
- Details of heat recovery,
- Moisture content change through dryer section,
- Steam consumption,
- Electricity consumption, &
- Energy for producing steam.

Table 7.6 shows the number of dryer sections and paper product group. Table 7.6 reflects the production of product lines, with a large number of machine producing newsprint, writing and case material. Problems were encountered obtaining data for the manufacture of tissue due to the commercially sensitivity of information.

PRODUCT TYPE	No. OF CASE STUDIES
Newsprint	38
Tissue	6
Writing	65
Packing	11
- Liner	22
- Fluting	51
- Board	3

Table 7.6 - Number of dryer sections analysed

Energy Consumption for Steam Production

The theoretical energy required to produce 1 kg of steam can be calculated from steam tables. As the pressure of the system increases the amount of latent heat decreases due to the increase in the boiling point of the water. Latent heat input at 7 bar is 2050 kJ/kg in comparison to 2257 kJ/kg at atmospheric pressure. From the point of view of steam economy, the lower the steam pressure, the lower the steam consumption for a given heat. However, problems arise due to surface area of the boiler and likely-hood of water-carry over. A design compromise is usually met. Paper mills typically operate their steam supply systems with pressures of 4-25 bar and temperatures of 160-240°C. Flow rates vary from 2-35 kg/s [69]. This corresponds to a theoretical energy requirement of 2749-2769 kJ/kg steam produced.

This survey showed that paper manufacturers monitored steam consumption on a regular bases, although the energy utilised in creating steam was not a commonly recorded commodity. There are two fundamental types of boiler; the water tube type and the shell type. Table 7.7 shows typical efficiencies [350].

BOILER TYPE	EFFICIENCY %
WATER TUBE BOILERS	
Steam Generator	75-78
Water Tube with Economiser	75-78
SHELL BOILERS	
Condensing Gas	88-92
High Efficiency Modular	80-82
Shell Boiler Steam	75-77
Reverse Flame	72-75
Case Iron Sectional	68-71

Table 7.7 - Typical efficiencies of steam boilers

54 mills, representing 52% of the total self-generate electricity using combined heat and power units [299]. Figure 7.17 shows the percentage of installations and type of generation [299].

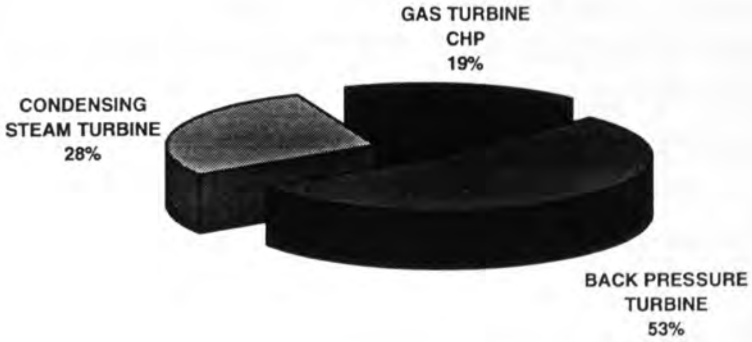


Figure 7.17 - Sources of self-generated electricity

Combined heat and power installations are typically about 50-60% efficient, depending upon steam/electricity characteristics required and system layout [69]. A weighted average steam boiler energy efficiency of 68% was assumed for the purpose of generalised mass balance calculations.

Measures for improving energy efficiencies of steam boiler systems are well documented in the literature [135], [155], [156], [157], [158], [234], [350] and include heat recovery from flue gases and boiler blowdown. Steam condenses after giving up heat to the drying cylinders. It has been suggested that the condensate carries about

20% of the original heat content of the fuel. Heat recovery systems on condensate return could result in substantial energy savings.

Results of Survey

Information was characterised by product type for steam heated cylinder dryers with additional information relating to air flotation drying of writing paper. Table 7.8 shows the variation of parameters for the dryer sections investigated. The moisture content of the web at points during the forming and drying process were found to vary according to methods of web formation and effectiveness of the press section. Moisture of the web at the felt section varied between 75-88% (wet basis) and typically 40-63% onto the drying cylinders.

The final moisture content of the paper web varied widely according to product type. Writing and tissue papers are commonly dried to a lower moisture content than packaging paper and newsprint.

PAPER TYPE	**MOISTURE CONTENT %**			**GSM g/m^2**	**SPEED m/min**	**WEB WIDTH m**
	FELT	**CYLINDER**	**FINAL**			
Newsprint	84-86	45-56	8-9	36-69.6	535-1420	2.9-9
Writing	88	45-60	3.3-5	32-183	123-1300	1.8-8.5
Tissue	87-88	40-60	4-5	12-40	300-1800	4-7
Packing	75-80	50-54	7	93-400	90-710	2.7-4.7
- Liner	-	51.5-63	7	105-150	176-515	1.9-6.4
- Fluting	-	40-65	7	105-180	175-572	1.9-6.2
- Board	-	52-56	7	385-540	53-110	2.8-4.3

Table 7.8 - Variation of machine parameters for present dryer survey

The speed of the paper web through the dryer section was found to be dependant upon product type, moisture content and layout of machine. Newer equipment typically ran at a higher speed, with a larger web width. Speeds varied between 53 m/min for a heavy gauge board to 1800 m/min for tissue production. In many cases the moisture extraction capability of the dryer section was a significant speed limiting factor [68].

Although advances in technology have enabled web widths to be increased to 12m [68], very few machines of this capacity are currently being utilised in the UK. Machines producing board and packaging/case material typically processed smaller webs. The larger webs are commonly found on high speed newsprint and writing paper machines. Table 7.9 summarises the energy utilisation characteristics of presently installed drying equipment.

Paper Type	kg steam/kg paper			kg steam/kg water			Efficiency %		
	High	**Low**	**Average**	**High**	**Low**	**Average**	**High**	**Low**	**Average**
News	1.95	0.95	1.24	2.44	0.96	1.16	75.74	30.83	56.73
Writing	4.27	0.81	2.31	3.72	0.58	1.58	81.94	8.39	54.70
Tissue	3.24	0.57	1.16	2.32	0.73	1.11	56.79	23.56	48.48
Pack	4.98	1.0	1.95	5.79	1.02	2.46	80.21	12.98	47.22
- Liner	3.19	1.35	1.97	2.46	1.19	1.69	63.19	30.54	49.27
- Fluting	3.85	1.42	2.21	3.53	0.73	1.66	64.76	27.27	38.55
- Board	2.00	1.38	1.65	2.09	1.24	1.58	60.64	35.99	49.97

Note : Air flotation dryer 52.7% efficient for drying writing paper.
Average values are weighted.

Table 7.9 - Summary of energy consumption data 1993

Figures shown in Table 7.9 demonstrates that the energy consumption for the manufacture of paper products varies widely and depends upon the nature of the dryer section. Figures are for the dryer section only and do not include steam consumption for the press section or any pre-press heating.

It was noted that the lowest weighted average value for the steam required to remove water from the product did not coincide with the lowest average consumption for drying a mass of product. Steam consumption varied from 1.16-2.31 kg steam/kg product, and 1.11-2.46 kg steam/kg water removed.

Yankee dryers were found to consume the least steam per kg of water removed, whereas packaging material the greatest at 2.46 kg steam/kg water. Tissue machines also consumed the least steam per kg of product produced, demonstrating the ease of removing moisture from a thin web. Dryer sections processing writing paper were found to consume the largest amount of steam per kg of product produced, with a weighted average of 2.31 kg steam/kg product. The high steam consumption in comparison to other paper types can be attributed to the redrying after coating processes. Over drying to ensure average moisture conditions are met, and low final moisture specification also attribute to the steam consumed.

Table 7.9 shows that the efficiency of dryer sections vary from 8.4% to 82%. On a weighted average basis, newsprint machines were the most efficient at 56.7%, whereas the production of fluting for case material was the lowest at 38%. Table 7.10 shows generalised values of steam consumption and efficiency for the survey.

DRYER TYPE	ENERGY kg steam/kg water		ENERGY kg steam/kg product		EFFICIENCY %	
	Minimum	**Maximum**	**Minimum**	**Maximum**	**Minimum**	**Maximum**
General Cylinder Dryer	1.16	2.46	1.24	2.31	38.55	56.73
Yankee Dryer	0.73	2.32	0.57	3.24	23.56	56.79

Table 7.10 - Generalised variation of energy consumption parameters

Table 7.10 shows that there is a large variation in the energy utilisation of both steam heated and Yankee type machines. Yankee dryers use less steam per kg of water removed, although on average more steam per kg product than conventional drying cylinder arrangements. This contradicts work performed by Chiogioji [50] who suggested that Yankee cylinders were more economical than conventional dryer sections. An in-depth study comparing the characteristics of Yankee and conventional cylinders was limited due to the lack of data relating to tissue production.

Comparison of Steam and Energy Consumption Data with Previous Dryer Section Studies

Table 7.11 shows a comparison of steam consumption figures and data from other sources relating to dryer type.

DRYER TYPE	**ENERGY kg steam/kg water removed**		**ENERGY kg steam/kg product**	
	Present	**Previous**	**Present**	**Previous**
General - Steam Heated Cylinders	1.16-2.46	1.3-2.1	1.24-2.31	1.5-1.7
Yankee Cylinder	0.73-2.32	-	0.57-3.24	-
Newsprint - Cylinder Dryer	0.96-2.44	1.0-2.2	0.95-1.95	1.2-3.0

Table 7.11 - Comparison of steam consumption for dryer types

Average figures of steam consumption of general steam cylinders for the present study were higher than those of previous surveys. Comparison of the steam consumption of present newsprint dryer sections to surveys conducted by Sayegh, Pikulik and Simonsen in 1988 [313] and Wiseman in 1978 [381] showed that there has been little change in steam consumption requirements per mass of water removed. However, present equipment consumed less energy per mass of product produced. Improvements such as additional heating using pocket ventilation systems, more accurate control of equipment and refined operating conditions would have attributed to this trend. Improved press techniques would have also attributed to these findings.

Table 7.12 shows a comparison of primary energy consumption for dryer types.

DRYER TYPE	**ENERGY kJ/kg water removed**		**ENERGY kJ/kg product**	
	Present	**Previous**	**Present**	**Previous**
General - Steam Heated Cylinders	4000-7484	2800-4020	4276-7966	3320-14500
Yankee Cylinder	2517-8001	-	4966-11173	6400-8100
Air Flotation	4917	-	3576	-

Table 7.12 - Comparison of energy consumption for dryer sections

The energy required to remove water from the paper web varies considerably as shown in Table 7.12. Comparison of the present and past studies showed that dryer sections currently installed in the UK use considerably more energy to remove water than previously estimated.

Steam boiler plants incorporating heat recovery systems have become more widespread within the industry. The primary energy requirements to produce steam have thus been reduced in recent years. Advances in drying technology and awareness of energy saving measures should have produced figures showing a reduction in steam energy requirements. The findings of the present survey cast a shadow of doubt on the accuracy and validity of previous surveys.

The variation of the energy required per kg of product for a current dryer section showed less variation in comparison to previous studies. The closure of smaller inefficient plant may have attributed to these findings.

Air flotation dryers were found to be the most energy efficient system with respect to the energy required per kg of product produced. However, limited data relating to their operation was available.

Total Energy Consumption for Paper Manufacture in the UK

Previous Studies

A literature survey showed that very few studies have been conducted regarding the energy consumption for paper drying processes within the UK. Table 7.13 summarises the results of pervious studies.

The survey conducted by ETSU [131] was based upon a large scale industrial audit, while that of Baker and Reay [16] was derived from averaging specific energy values for a variety of products. Hodgett [177] and Witt [382] used a similar methodology of estimating the water removed from specific products. The largest errors were noted for studies using similar methods. Discrepancies were also revealed between published values of the total energy consumption.

YEAR	TOTAL ENERGY 10^6 GJ	DRYING ENERGY 10^6 GJ	REFERENCE/NOTE
1982	67.8	38.57	[131]
1978	137	45.00	[16]
1976	181 (1972)	20.76	[177]/1
1976	108.7	15.30	[382]/2

Notes :

1 - Total energy figure for 1972. Drying energy figure based upon 9.2×10^6 tonnes of water removed at 50% efficiency.

2 - Drying energy figure based upon 6.8×10^6 tonnes of water removed at 50% efficiency.

Table 7.13 - Previous UK paper sector energy studies

Due to the large variation in SEC figures obtained during the present survey of paper dryer sections, weighted average values were used for the estimation of the total drying energy consumption.

Table 7.14 shows a comparison of the present survey and a study conducted at the National Engineering Laboratory in 1980 [131]. Figures show that savings have been made with regards to energy consumed per mass of product, with the largest reduction of 70% for the manufacture of tissue. Large savings have also been achieved in the production of writing and packaging products.

PAPER TYPE	**1993 Survey**		**1980 Survey [124], [131]**	**ENERGY SAVING 1980-1993**
	kg steam/kg paper	**kJ/kg paper**	**kJ/kg paper**	**%**
Newsprint	1.24	4276.45	5000	14.4
Writing	2.31	7966.6	18200	56.2
Tissue	1.16	4000.5	13400	70.1
Packaging Paper	1.96	6759.55	9950	32.1
Packaging Case Material	2.21	7621.73	8560	10.9
Packaging Board	1.65	5690.44	8560	33.5
Others *	1.8	6207.75	11900	47.8

Note * : Average value taken

Table 7.14 - Weighted average values of energy consumption for product type

Table 7.15 shows total energy consumption values for 1993.

PAPER TYPE	**PRODUCTION '000 Tonnes**	**ENERGY 10^9 MJ**
Newsprint	741.3	3.17
Writing	1604.6	12.78
Tissue	445.0	1.78
Packaging Paper	91.7	0.62
Packaging Case Material	1360.8	0.70
Packaging Board	679.6	3.87
Others	280.5	1.74
Total	***5203.5***	***24.66***

Note : Including coating processes

Table 7.15 - Energy consumption for drying of specific product types - 1993

Figures 7.18 and 7.19 shows the proportion of the total drying energy for product type in 1982 and 1993.

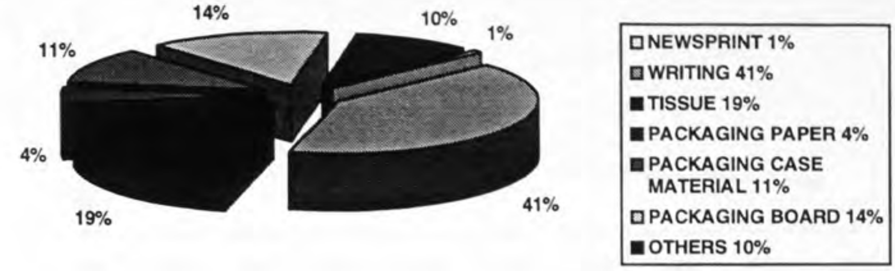


Figure 7.18 - Proportion of drying energy consumed by each product type - 1982

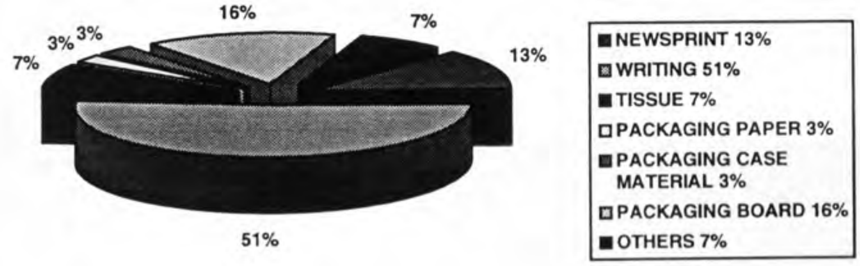


Figure 7.19 - Proportion of drying energy consumed by each product type - 1993

The proportion of energy used for drying specific lines is directly related to the magnitude of production. The proportion of drying energy has increased for the manufacture of newsprint and writing paper which corresponds with increases in production. The production of tissue has remained fairly constant while that of case material has increased slightly since the early 1980s. However, the proportion of energy used to dry these products has decreased significantly over the last decade. The implementation of energy efficient measures, improved control and advances in equipment technology could have attributed to this trend.

Figures shown in Table 7.15 showed that an estimated 24.66 x 10^9 MJ was consumed for drying processes within the paper industry, representing 23.3% of the total energy consumed in 1993.

Figure 7.20 shows a comparison of the present estimation of total energy consumption with previous studies.

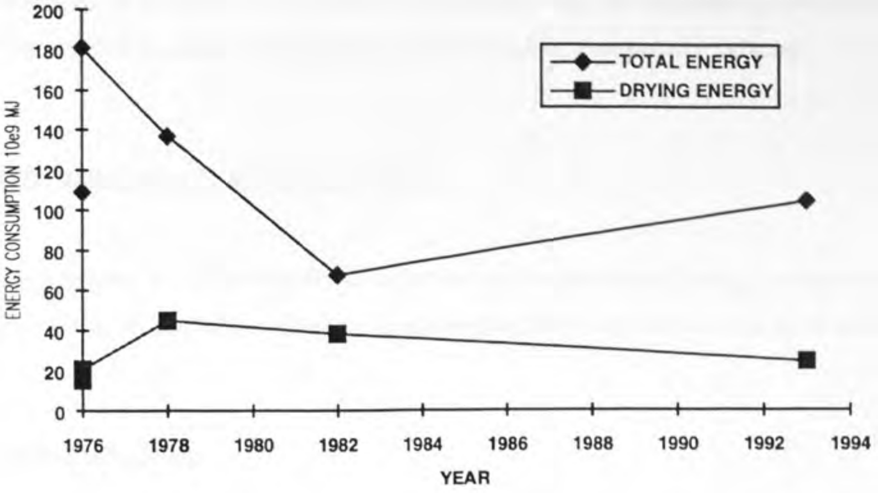


Figure 7.20 - Variation of the total and drying energy consumption in the UK paper industry

Figure 7.20 shows that energy used for drying processes within the paper industry has fallen since the early 1980s. Figure 7.21 shows the variation in the percentage of the total energy used for drying.

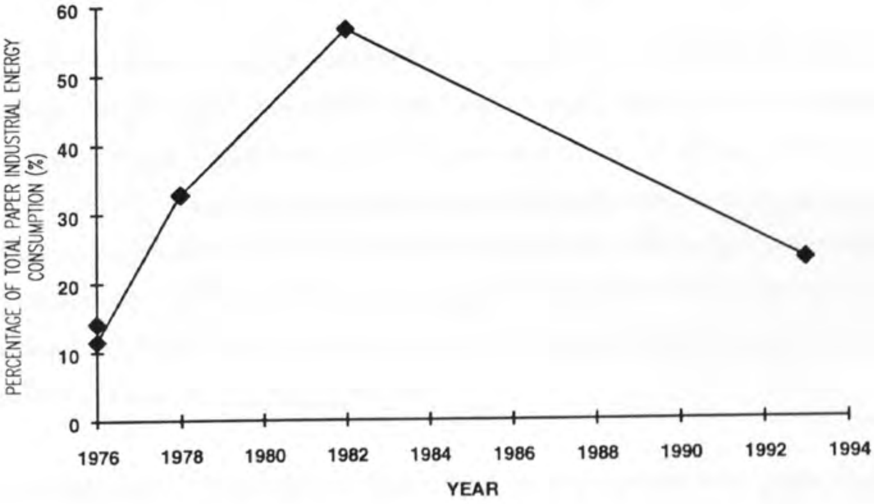


Figure 7.21 - Variation of the percentage of the total energy used for drying in the UK paper industry

Figure 7.21 shows a large variation in the proportion of the total energy consumed in the paper industry for drying processes. It is not realistic to comment upon a trend in energy usage and the accuracy and validity of previous surveys is questionable.

The decrease in the proportion of the total energy used for drying, increase in production and decreasing trend in the consumption of energy within the industry over the last decade suggests that energy saving measures may have been implemented.

There has only been a small reduction in the closure of mills since the early 1980s. Thus the effect of the elimination of inefficient drying equipment and the resultant effect on reducing SECs, and hence decreasing drying energy utilisation, is minimal. This supports the hypothesis that manufactures are more energy aware and are taking effective measure to reduce drying energy costs in this very competitive industry.

Developing Technologies in the Paper Drying Industry

Many researchers have been involved with the development and application of energy saving measures on paper making equipment. The most significant advances in paper manufacture are commented upon below.

Heat Recovery From Paper Dryers

Sayegh, Pukulik and Simonsen [312], [313] commented on the implementation of energy saving measures. They suggested that about 16% of the heat used for drying could be recovered. It was revealed that although many paper installations in 1985 had the potential for energy recovery it was largely under-utilised. Further comments discussed the effects on blow through steam, which represents on average 5-15% of the total steam consumption, although heat recovery measures using air heat systems in the hood extract system were now common practice.

Villalobos [370] describes details of the application of pocket ventilation and auxiliary equipment and comments on the energy savings. The performance of a dryer hood heat recovery system has been the subject of an Energy Efficiency Office Best Practice Programme [144]. The system enclosed the drying cylinders both above and below the machine floor level. A heat recovery system was used to preheat the dryer pocket ventilator air supply and provide heating to the machine house. The system proved reliable and energy savings of 75500 GJ/year (28% of the total energy) were realised, representing savings of £248000/year for a production of 110000 tonnes. The capital investment of £419000 gave a payback period of 1.7 years. Energy savings from the hood recovery system alone represented 8% of the total energy utilised.

Friedel [152] has investigated the application of heat pumps for heat recovery from paper dryers. A two stage absorption heat pump was identified as the best solution. A payback time of less than three years was suggested using an average economic energy analysis.

The coupling of exhaust heat recovery and direct flame-heating of drying air to a paper machine has been the subject of a Caddet Demonstration Scheme [250]. Savings of 25000 GJ/year were estimated, although no figures relating to capital costs and pay back time were quoted. Direct contact heat exchangers have been applied for recovering waste process heat at a board mill [250]. Energy savings of 112600 GJ/year have been reported with a payback time of only 6 months. Aluminium air/air heat exchangers with a water washing system have also been installed on a paper making machine [250], producing energy savings of 31800 GJ/year with a payback time of 9 months.

Press Drying

Several areas are developing along the lines of press techniques. Heat may be applied to the paper web via the press rollers, or by combining sheet preheating and direct press heating. Development and analysis of the effects and implementation of pressing at elevated temperatures are currently under review [345]. Cronin, Lange and Nelson [102] describe the benefits of press drying and comment upon the lack of industrial applications. Energy savings of up to 30% are reported.

Gas Heated Direct Cylinders

Recent developments have implemented gas burners in drying cylinders removing the requirement for process steam. Figure 7.22 shows a direct gas fired drying cylinder [164].

Reports have stated that the system can be 75-80% efficient in transferring energy to the paper web. Further savings can be made by utilising the exhaust gas in the pocket ventilation supply system.

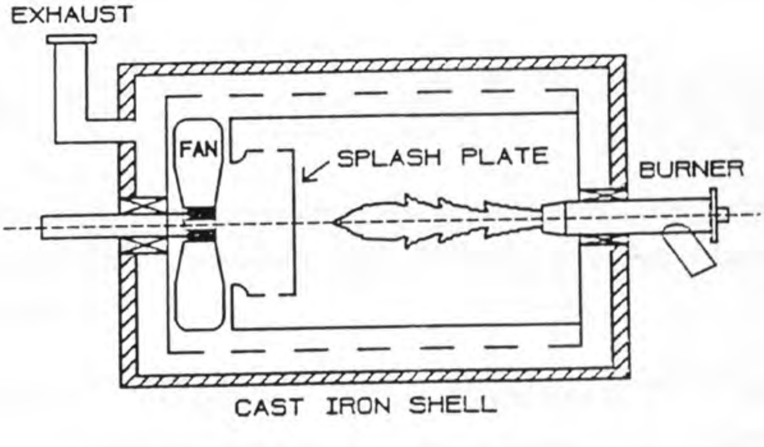


Figure 7.22 - Direct fired gas heated drying cylinder

Impulse Drying

Impulse drying is where the paper web is brought into contact under high pressures with a very hot cylinder surface. The drying process is very rapid and at the same time as liquid water is pressed, displaced out of the sheet.

The potential for achieving high solids contents with impulse drying has been well documented in the literature [7], [225], [228], [338].

Traditional steam heated cylinders commonly achieve drying rates in the order of 10-30 kg/m^2/h. Drying using impulse techniques has achieved 2000-8000 kg/m^2/h [332]. Table 7.16 shows a comparison of impulse and traditional systems.

Although impulse drying offers the potential for energy savings, quality problems, principally delamination of the paper web have been encountered. Lavery [225] describes details of the impulse drying of newsprint. It is noted that paper properties were equivalent to conventional methods when comparing surface appearance and roughness. It was noted that energy use was reduced in comparison to cylinder drying, as up to 50% of the water is removed as a liquid.

PARAMETER	TRADITIONAL STEAM CYLINDER TECHNIQUES	IMPULSE TECHNIQUE
Cylinder Temperature, °C	100-150	200-450
Mechanical Pressure on Web, kPa	2-5	1000-5000
Residence Time, s	0.2-0.5	0.005-0.05
Drying Rate, kg water/m^2/h	10-30	2000-8000
Specific Energy Consumption, kJ/kg water	2800-3500	500-2200

Table 7.16 - Comparison between traditional drying cylinders and an impulse dryer

High Temperature Dryer

Research into high temperature heating of cylinders has been conducted [333]. Cylinder material was investigated with the aim of improving heat transfer. Table 7.17 shows a comparison of various alternatives for high temperature cylinder heating.

HEATING MEDIUM	CYLINDER TEMPERATURE, °C	MAXIMUM HEAT FLUX, kW/m^2	ENERGY EFFICIENCY, %
Steam	< 200	< 25 Fe < 75 Cu	> 95
Gas	< 375	50-70	70-90
Induction	> 450	< 1000	> 90

Table 7.17 - Comparison of heating mediums for high temperature cylinder heating

The economic aspects of providing the heating medium must be assessed, i.e. cost of upgrading steam distribution systems, and the cost of fuel.

Dry Forming

Alternative paper making techniques avoiding the use of a wet web have been investigated [124]. Two processes have been examined;

- Carding techniques, &
- Air laid technique.

The carding technique involves binding dry fibres in a web using chemical reactants or heat fusion. The air laid method has a greater potential for a much higher rate of throughput. Fibres are suspended in an air stream and a moving web is formed from this suspension. Additional binders may be used.

Research has been conducted into dry forming techniques, however there are no significant commercial installations in the UK [374]. A literature search showed that there is no current research or development of dry forming techniques in the UK.

Moisture Profiling By Induction

Pulkowski and Wedel [293] describe details of the application of induction heating for the moisture levelling of a paper web. The application uses inductors to selective heat circumferential bands on a Yankee shell. Six of these units are reported to be in operation in Europe. Moisture variations of ± 0.3 % have been reported together with increases in machine speed of 5-10 %, and significant improvements in both machine and converting efficiencies. The energy required to overdry the web can be eliminated, thus the overall energy consumption (kJ/Tonne of dry product) have decreased by 5-10 %. A French induction heating application for the moisture profiling of paper has been documented. [191]. Figure 7.23 shows the positioning of the electromagnets on the drying cylinder.

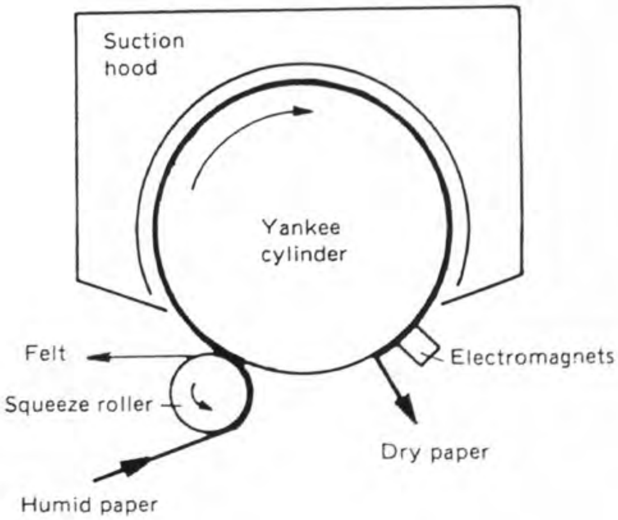


Figure 7.23 - Induction heating of a Yankee drying cylinder

Efficiencies of 95.5% were reported together with other benefits such as reduced maintenance, safe operation, and minimum installation space.

Super Heated Steam Drying

Superheated steam drying refers to the drying of paper by direct contact with impinging jets of superheated water vapour [284]. A benefit of using this drying medium is the potential for heat recovery thus improving energy efficiency. The exhaust of a superheated steam dryer could be used in steam showers, for water or building heating, or for the heating of dryer cylinders [28]. Heat recovery from low pressure steam is easier than heat recovery from low temperature humid exhaust from a multi-cylinder dryer hood. Pilot scale superheated steam dryers are currently under development [29], [116], [243], [287].

Conclusions

The following conclusions can be drawn from the analysis of the paper industry;

1. Paper is a widely used commodity and users are demanding increases in product quality while maintaining costs.

2. In 1993 an estimated 5.3 million tonnes of paper was produced by 105 mills operating 198 paper machines.

3. The number of paper mills has decreased significantly over the last 20 years.

4. The variation of the total energy used within the paper industry has corresponded to changes in total industrial consumption, decreasing over the last 20 years.

5. The UK industry consumes 105.72×10^9 MJ of energy a year, representing 5% of the total UK industrial consumption.

6. Comparison of SEC for the manufacture of paper types has shown that savings have been made. However, average SEC values have not changed significantly since the 1980s.

7. The production of paper has increased over the last 10 years, recovering from a depression during the 1970s. Significant increases in production have been noted in the manufacture of printing paper, newsprint and case material.

8. Drum type dryer sections dominate the industry. Yankee, IR and air flotation equipment represents less than an estimated 15% of the total.

9. Many researchers have estimated the energy/steam consumption characteristics of dryer sections. A literature survey revealed a large variation in figures.

10. The benefits of removing water by the press section and effect in reducing energy consumption has been demonstrated, although technology and paper quality factors are the present limiting criteria.

11. Various projects have demonstrated the effectiveness and potential energy savings by recovering heat from the dryer section.

12. Developing technologies have been discussed including press drying, direct gas heated cylinders, impulse and high temperature drying. Dry forming, the use of induction heating for moisture profiling and drying using superheated steam have been examined. Comments were made concerning the potential of energy savings by the implementation of these technologies.

13. A survey has been conducted which has estimated the operating characteristics and energy utilisation of 192 dryer sections.

14. The energy required to produce steam has been addressed, and typical efficiencies of 68-92% have been revealed for conventional boilers and 50-60% for CHP units. Over 52% of mills currently use CHP for power/heat production.

15. Initial moisture contents vary from 75-88% off the felt and between 45-63% after the press. Final end moisture corresponds to the end use of the product and are in the range of 4-9%.

16. Paper machine speed and web width varied considerably. Age of equipment, layout of plant, product type and specification were influencing factors. Packaging material and board were commonly processed in smaller webs in comparison to writing paper, tissue and newsprint.

17. The energy consumption of presently utilised dryer sections was found to vary considerably. Steam consumption varied from 1.16-2.31 kg steam/kg product produced and 1.11-2.46 kg steam/kg water removed (Weighted average figures).

18. Yankee dryers consumed the least steam per kg of water removed, and product produced. Dryers processing packaging material consumed the largest amount of energy at 2.46 kg steam/kg water, although writing paper consumed the largest amount of energy at 2.31 kg steam/kg product produced.

19. Newsprint machines were found to be the most energy efficient at 56.7%. The manufacture of case material was the least efficient at 38%.

20. Using a weighted average, Yankee machine were found to consume more energy than conventional cylinder dryers per kg of product produced, although limited data concerning Yankee machines was available.

21. Comparison of energy utilisation figures for the present survey with past studies showed that average steam consumption for conventional dryers were higher for present equipment.

22. Comparison of newsprint machines showed that there has been little change in steam consumption requirements per mass of water removed. However, present equipment consumed less energy per mass of product produced. Improved press techniques was attributed to these findings.

23. Present dryer sections were found to consume considerably more energy to remove water from the web than previous estimations. Advance in boiler design and heat recovery systems contradict the comparison and questions the validity of previous studies.

24. The variation of the energy required per kg of product of current dryer sections showed less variation in comparison to previous studies. The closure of smaller, inefficient plants may have contributed to these findings.

25. Air flotation dryers were found to consume the least energy per kg of water removed, although limited information was available.

26. Few studies have been conducted regarding estimation of the energy consumption for drying within the paper industry. Discrepancies were found when comparing previous estimates.

27. Energy savings up to 70% were revealed when the present findings were compared to previous studies.

28. It was estimated that 25×10^9 MJ was consumed for drying processes within the paper industry, representing 23% of the total energy consumed in 1993.

29. Comparison of the proportion of energy used for the drying of specific products showed that newsprint and writing paper has increased since the 1980s. Increases in production were attributed to this trend. The extent of energy saving measures were demonstrated by the reduction in the proportion of drying energy used to manufacture tissue and case material, whereas production had remained constant and increased respectively.

30. Comparison of the proportion of the total energy consumed in the paper industry for drying processes showed a large variation and a trend could not be established. The accuracy and validity of previous surveys is questionable.

31. The advances in dryer technology and the implementation of efficient systems will lead to future saving in energy consumption for drying in the paper industry.

CHAPTER 8

NEURAL NETWORKS FOR MODELLING AND CONTROL

Introduction

This chapter describes the modelling of drying processes and the theoretical principles and applications of neural networks. It forms an important part of this work since the understanding and control of drying systems are an essential aid for future innovation through product and machine development and process optimisation. Improvements will inevitably lead to savings in energy with possible benefits of improved productivity, quality, safety and environmental aspects. The following points are addressed;

- History of the modelling of drying processes,
- Purpose of modelling and traditional techniques utilised,
- Problems associated with traditional mathematical techniques,
- Theoretical principles of neural networks, &
- Industrial applications of neural networks, including the modelling of drying processes.

Modelling and Control of Drying Processes

Industrial drying is an energy intensive operation, consuming an estimated £300 million annually in the UK [82]. In recent years advances in drying have been achieved [303]. However drying is still not well understood (meaning that good phenomenological models may not be readily available), due mainly to the complexity involved in the simultaneous transfers of heat, mass and momentum during the process. Modelling has increased our knowledge, but many models are complex and in many cases require data that is either unavailable or outdated. Escalating energy costs and more intense competition provide the impetus for continued efforts in improving drying efficiency.

In practice most systems encountered in industry are non-linear to some extent, and in many applications non-linear models are required to provide acceptable representations [258]. One of the major obstacles to the widespread use of advanced modelling and control techniques is the availability and cost of accurate process models [43].

The history of the modelling of drying dates back to a paper by Lewis in 1921 [231] and a paper titled 'The Drying of Solids' by Sherwood in 1929 [316]. Development of mathematical models to describe drying has been a topic of research in many fields for several decades [373]. Models are needed to enable scientific process design and the minimisation of energy and capital costs within acceptable quality constraints. Several review articles have recently been presented on the topic of drying. Keey [207], and Waananen et al. [373] describe the historical development of drying theory. Van Brakel [366] provides a critical review of the topic of mass transfer during convective drying. Chirife [51], [52], Bruin and Luyben [34], Fortes and Okos [151], Holdsworth [178], Rossen and Hayakawa [307], and Vab Arsdel [365] review drying theory applied to food. King [216], Rosen [307], and Simpson [320] have described the drying of food and timber. The classification of drying models has been assessed by Waannanen, Litchfield and Okos [373] and the selection of drying technology process parameters has been reviewed by Urosevic and Stefanovic [363].

The first step in understanding a drying process is a detailed investigation of the drying and equilibrium properties of the material and the dynamics of the machine [10]. Until general models are developed which successfully predict drying rates and internal moisture and temperature profiles, the design of drying processes will remain largely an art. A sound understanding of existing drying theory together with new experimental data will enable further advances in the description of the drying phenomenon.

Drying processes consist of three simultaneous processes; conduction of heat and moisture in the bulk of the solid, heat and mass transfer through the solid-gas interface, and convection and conduction in the gas phase [371]. The drying rate and fundamental characteristics are limited by the slowest of these parameters. Problems generally arise in the description of the differential equations because of the presence of a solid phase and evaporation transfer coefficients are not known [207]. The work of Luikov is considered the most successful and the only theoretical treatment of drying that has won acclaim the world over [363]. However, the partial differential equations with variable coefficients do not lend themselves to exact solutions. Simplifying assumptions are therefore introduced.

The rate of drying in many practical situations is controlled by internal mass transfer [34]. In porous solids, internal mass transfer may occur within the solid phase, or within the void spaces [203]. Several mechanisms of internal mass transfer have been proposed including liquid and vapour diffusion, surface diffusion, hydrodynamic or bulk flow and capillary flow. Modelling is complicated because more than one mechanism may contribute to the total flow, and the contribution of different mechanisms may change as drying proceeds [34]. The development of a generally applicable drying model requires the identification and inclusion of all contributiuting mechanisms [373].

Simple analytical expressions are not satisfactory for the determination of drying operational units and processes [305]. In most cases evaluation of microscopic terms limits the application of such theories without experimental investigation of the material. For the calculation of the transfer coefficients there are many dimensionless equations which are based on the results of numerous experiments [315]. Many empirical and numerical procedures have been proposed for the solution of internal material characteristics [207], [305]. Constant external conditions are usually supposed throughout the calculation. In a real dryer this postulation is not valid.

Combination of flux equations with mass and energy balance equations gives rise, in general, to a system of non-linear partial differential equations which are difficult to solve. Finite element analysis has been applied to drying methods to solve these differential equations [167], [351]. Irreversible thermodynamics theory has also been used to develop drying models that account for cross-effects between different mechanisms [373]. Phenomenological laws such as Fourier's law, Flicks's law, and Ohm's law are based on proportionalities between a flux and a driving force or mechanism. Application of the principles of irreversible thermodynamics enables consideration of coupled transport processes. Instead of separate differential equations for heat and mass transfer a system of interconnected equations is obtained [254], [375].

Theories have been devised by conducting a large number of time consuming experiments yielding empirical values. The drawback is that empirical determined process parameters are applicable only under the conditions in which they have been determined [363]. Simplifying assumptions are often made in many instances to enable a tractable solution to the modelling problem. A first principles model will therefore often be very costly to construct and will be subject to inaccuracies due to the assumptions made during the development [379]. In some cases theoretical drying models are developed, but no attempt is made to apply the models or assess their validity.

Until the advent of process computers, manual and automatic feedback systems were the most commonly used methods for process control [250]. Many of these techniques are still in operation in older plants. The availability of process computers and advances in sensor technology, such as humidity, temperature and moisture measurement, has increased the use of control systems combining feedforward and feedback loops. Control of drying processes is an important factor which is directly related to an understanding of the drying system. A poorly controlled process is likely to be wasteful, both in terms of energy and inferior quality product. An understanding of the process will enable both the control and design of a dryer to be optimised, enhancing product quality, maximising throughput rates and minimising energy costs.

Feedforward control techniques have superseded feedback systems where there is a significant time lag between a control change being made to an input and its effect being felt on the outputs. Feedforward control depends upon having an accurate mathematical model of the system. Drying systems, like most industrial processes are very complex and sufficiently accurate models do not exist [250]. Due to the non-linear dynamic nature of drying processes linear based modelling and control methods are unsuitable. The characteristics of drying may vary because of changing raw materials properties, gradual changes in process equipment and changes in environmental variables.

Artificial Neural Networks

Introduction

An approach that has evolved as a powerful computational technique in the past few years is artificial neural networks [19], [26], [172], [200]. Neural networks offer a powerful set of tools for solving problems on pattern recognition, data processing, and non-linear control, which can be regarded as complementary to those of more conventional approaches.

The conventional approach to computing is based upon an explicit set of programmed instructions. Neural networks offer an alternative computational paradigm in which the solution to a problem is learned from a set of examples [26]. The inspiration for neural networks comes originally from studies of the mechanisms for information processing in the biological nervous system, particularly the human brain [202], [310].

As well as offering high processing speed due to its parallel structure, neural networks have important capabilities of learning a general solution to a problem from a set of specific examples. For many examples this circumvents the need to develop a first-principles model of the underlying physical process, which is difficult or impossible to find [26]. In addition, neural networks offer the significant benefit of reduced development costs; the 'learn-by-experience' technique allows accurate models to be developed in a fraction of the time of traditional approaches [43]. A further benefit is their potential to provide adaptive solutions. Most real world processes change with time and neural networks configured for on-line learning have the ability to adapt automatically to these changes.

Neural Architecture

A variety of neural network configurations and training algorithms have been developed over the past 20 years [26]. Morris et al. [258] suggested that well over 50 different types of neural architecture and a number of different neuron processing functions have been developed. Many articles provide a basic review of neural architectures and applications [26], [172], [200].

Two common neural models are multilayer perceptron and the radial basis function network. These form part of a general class of networks known as feedforward networks, which have been the subject of considerable research in recent years [26]. Cybenko [379] claimed that any continuous function can be approximated arbitrarily well on a compact and fixed continuous nonlinearity i.e. a feed forward network can be used to model a wide range of non-linear relationships. A feedforward neural network can be regarded as a non-linear mathematical function which transforms a set of input variables into a set of output variables. The precise form of the transformation is governed by a set of parameters called weights whose values can be determined on the basis of a set of examples of the required mapping. The process of determining the weight parameters is often called learning or training [26].

A simple mathematical model of a single neuron was introduced in 1943 by McCulloch and Pitts [245]. Figure 8.1 shows a representation of their model.

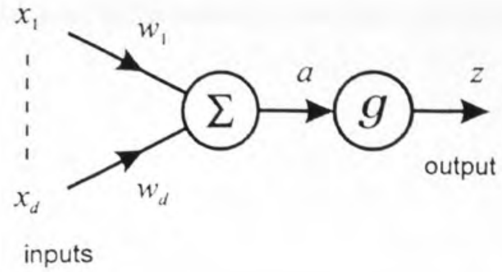


Figure 8.1 - McCulloch-Pitts model of a single neuron

In the McCulloch-Pitts model, the signal x_i at input i, (out of d inputs) is first multiplied by a parameter w_i known as a weight. This is then added to all the other weighted input signals to give a total input to the unit of the form;

$$a = \sum_{i=1}^{d} w_i x_i + w_0 \qquad (8.1)$$

where the offset parameter w_0 is called the bias. This bias shifts the space of the non-linearity. The output z of the unit is given by operating on a with a non-linear activation function g(). Examples of activation functions take the form of linear, sigmoidal or threshold terms. This model of a neuron forms the basic mathematical element in many neural network models. By linking together many elements it is possible to construct a very general class of non-linear mappings, which can be applied to a wide range of practical problems. Figure 8.2 shows a network with two successive layers of units, and thus two layers of weights. Units in the middle layer are known as hidden units since their activation values are not directly accessible from outside the network.

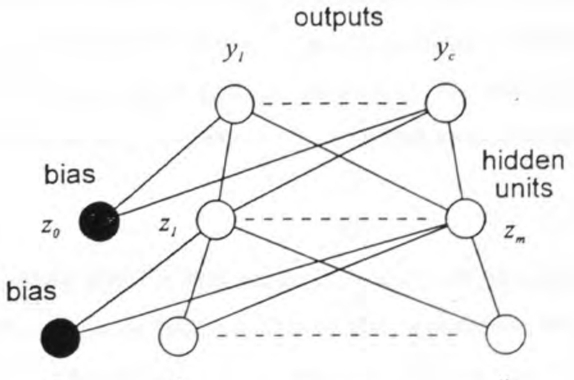


Figure 8.2 - Representation of a multilayer perceptron neural network.

One of the limitations of the multilayer perceptron is that the training process can be computationally very intensive [26]. The radial basis function network is based on the simple intuitive idea that an arbitrary function can be approximated as a linear superposition of a set of basis functions. The structure is very similar to multilayer perceptron. There are many possible basis functions, of which the Gaussian is commonly utilised. Unlike in the perceptron structure the bias of each unit is replaced by a parameter which describes the width of the Gaussian basis function. Radial basis neural networks have been used effectively for interpolation and for smoothing data [258].

Neural Network Development

Data for network development is split into thirds; two thirds for training and a third for testing. Data may be scaled before or/and after the neural model to enable a well conditional architecture to be constructed. The problems of determining the network parameters can be considered essentially a non-linear optimisation task. If the network approximation is adequate then the squared error between the training data and outputs and network predicted outputs should be relatively small and, more importantly, should be uncorrelated with all combinations of past inputs and outputs. The error function can be regarded geometrically as an error surface sitting over weight space [26]. The problem of network training corresponds to the search for the minima of the error surface, termed the global minimum. There may however exist other higher minima, called local minima. Some algorithms will find the nearest minimum, while others are capable to escape local minima and offer the possibility of finding a global minimum. In general, the error surface will be extremely complex and for many practical applications a good local minimum may be sufficient to achieve satisfactory results. Since the error functions for neural network training are highly non-linear, there is no simple prescription for deciding when to halt the training process. In practice, various stopping criteria are used, such as training for a fixed number of iterations, until the error falls below a threshold. Many articles review the methodologies of error functions and training techniques and are beyond the scope of this introduction to neural networks [25], [26], [310].

The simplest optimisation techniques makes use of the objective function to determine the search direction. A learning rate term which influences the rate of weight adjustment is used as the basis for a commonly used back-error propagation algorithm [258]. In order to train the network input data is presented to the network. For each data set the input set is propagated through the network to give a prediction of the output. The error in prediction is then used to update the weights based upon gradient information. The error in prediction is thus in a sense back-propagated through the network. Such an approach is termed supervised learning since at any time both the input and output is available.

There are many problems associated with the back propagation approach, and difficulty arises when the search approaches the minima. If the surface is relatively flat in this region then the search becomes inefficient. Therefore, in most neural network applications, a momentum term is added. The current change in weight is thus forced to be dependant upon the previous weight change. Although this modification does yield improved performances, gradient techniques can require significant convergence times in large dimensioned problems [258]. Furthermore, in adopting a down-hill search technique, the question arises to whether the minimum is local or global.

An alternative technique is that of Conjugate Gradients [229]. Although quasi-Newton methods are usually more rapidly convergent than conjugate gradient methods, they require significantly more storage for development. The basis philosophy is to generate a conjugate direction as a linear combination of the current steepest descent direction and the previous search direction.

By using a very large network and a small training data set, it is generally easy to arrange for the network to learn the training data reasonably accurately. However, it must be emphasised that the goals of network training are to capture the underlying trends in the training data set in such a way as to produce reliable outputs when the network is presented with data which do not form part of the training set. If there is noise with the data, as will be the case for most practical applications, then a network which achieves too good a fit to the training data will have learned the details of the noise on that particular data set. Such a network will perform poorly when presented with new data which do not form part of the training set. These issues can be generalised with an analogy with polynomial curve fitting. Figure 8.3 shows the function fitted to a set of noise corrupted data points. Figure 8.4 shows the result of over fitting the data, where the resulting curve gives only a poor representation of the trends in the data. A similar situation occurs with neural networks where the weights in the network are analogous to the coefficients in a polynomial.

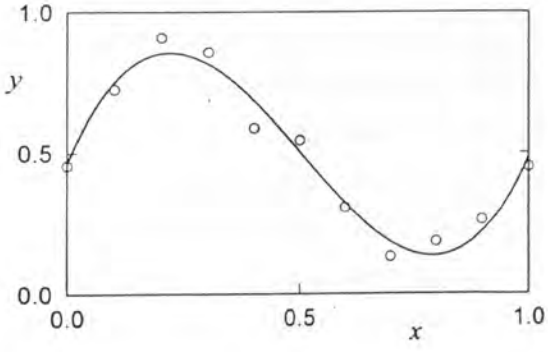


Figure 8.3 - Function with noise-corrupted data

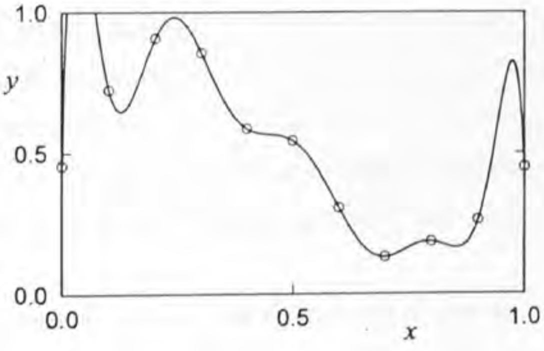


Figure 8.4 - Over fitting of data

Figure 8.5 shows a plot of error against number of hidden units with respect to being subjected to training and test data. Figure 8.5 shows a decrease in error with increasing number of units at first as the network aquires flexibility, but then starts to increase as the problem of over fitting sets in. Regular checking of the networks capabilities to model both training and test data require careful monitoring during development to prevent over fitting.

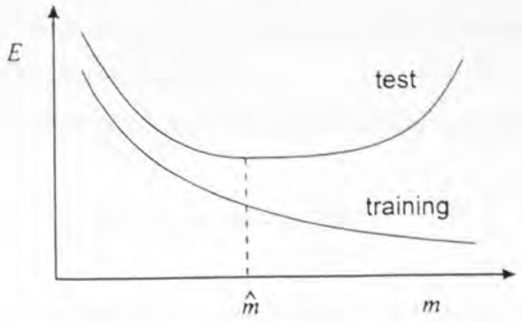


Figure 8.5 - Schematic plot of error with number of hidden units for training and test data

Application of Neural Networks

Introduction

Neural networks have been applied in many fields. Applications include [105];

Aerospace - High performance aircraft autopilot, flight path simulation, aircraft control systems, autopilot enhancements, aircraft component simulation, aircraft component fault detection.

Automotive - Automobile automatic guidance system, warranty activity analysis.

Banking - Cheque and other document reading, credit application evaluation.

Defence - Weapon steering, target tracking, object discrimination, facial recognition, new kinds of sensors, sonar, radar and image signal processing including data compression, feature extraction and noise suppression, signal/image identification.

Electronics - Code sequence prediction, integrated circuit chip layout, process control, chip failure analysis, machine vision, voice synthesis, non-linear modelling.

Entertainment - Animation, special effects, market forecasting.

Financial - Real estate appraisal, loan advisor, mortgage screening, corporate bond rating, credit line use analysis, portfolio trading program, corporate financial analysis, currency price prediction.

Insurance - Policy application evaluation, product optimisation.

Manufacturing - Manufacturing process control, product design and analysis, process and machine diagnosis, real-time particle identification, visual quality inspection systems, beer testing, welding quality analysis, paper quality prediction, computer chip quality analysis, analysis of grinding operations, chemical product design, machine maintenance, project bidding, planning and management, dynamic modelling of chemical process systems.

Medical - Breast cancer cell analysis, prosthesis design, optimisation of transplant times, hospital expense reduction, hospital improvement, emergency test advisement.

Oil and Gas - Exploration.

Robotics - Trajectory control, forklift robot, manipulator controllers, vision systems.

Speech - Speech recognition, speech compression, vowel classification, text to speech synthesis.

Securities - Market analysis, automatic bond rating, stock trading advisory systems.

Telecommunications - Image and data compression, automated information services, real-time translation of spoken language, customer payment processing systems.

Transportation - Truck brake diagnosis systems, vehicle scheduling, routing systems.

The application of neural networks can be divided into three groups;

Optimisation - The aim of process optimisation is to determine control setpoints by consideration of the current process economics and the effect of varying operating conditions. This can be very complex and must be repeated as raw materials and energy costs vary and as demand for the product changes. A neural network, trained over the full range of operating conditions, can learn the complex relationships between these variables. Such a predictive neural network model can be integrated within an optimising scheme to determine process controller setpoints which maximise the process efficiency [43].

Process control - Neural networks can be used for control either by replicating the required process behaviour or by modelling the process itself. Improved control will enable the process to be operated closer to process constraints and can lead to more efficient use of raw materials, improved product quality, reduced energy costs and the minimisation of wastage.

Measurement - There are many industrial situations where on-line measurement of the primary control variable is impractical or impossible with existing sensor technology. Often measurements are only available off-line from infrequent, time-delayed laboratory analysis rendering them inadequate for effective control purposes. The control problem would be alleviated if the process operators were provided with more frequent and timely information derived from secondary measurable process measurements. Neural networks have been utilised to derive relationships between secondary parameters and primary variables.

In chemical engineering neural networks have been applied to solve a wide variety of problems including; fault diagnosis [182], [229], [369], sensor data interpretation [26], non-linear predictive control of polymerisation reactors [232], blow moulding [114], design and analysis of liquid-liquid extraction columns [322], and reducing industrial fuel bills [4].

Over the past 12 years, model predictive control has become the standard procedure for control using a process model. In this architecture, an on-line model of the process is used to predict the outcome of future control actions. Pao [275], Bhat and McAvoy [23], Psichogios [292], and Ydstie [383], Hunt [187], are among many researchers who have investigated the use of neural networks in process control. Several types of neurocontrol architectures have been employed by researchers in the past and many of these require on-line training. Such training is feasible if it is fast and inexpensive, but in many cases on-line training will disrupt the normal operating environment and may even raise some safety concerns.

One important characteristic of neural networks that make them a good candidate for process control applications is adaptive learning. In many processes changes in parameters are gradual and hard to detect, such as equipment ageing, sensor degrade, slight variations in raw materials. The gradual changes can be incorporated into a neural network model through continuously updating the weights.

Drying Process Modelling and Control

A literature search showed that there has been limited investigation into the application of neural networks to drying processes and no information was located relating to the application of neural networks to the control of drying systems or interpretation of instrumentation.

Huang and Mujumdar [183] have applied a multilayer perceptron network with a back-propagation learning algorithm to predict the drying rate of paper in a Yankee dryer. A three layer network with 4 inputs and 2 outputs was constructed with tanh(x) transfer functions. The performance of the network was analysed for varying stages of training, and between 5 - 20 hidden neurons.

Inputs included; machine speed, inlet paper moisture, hood air temperature, and hood jet velocity. 800 cases of input and outputs were generated randomly using a model derived by Karlsson and Heikkila [204]. Reel moisture and paper exit temperature were analysed as output.

Results showed that the network was capable of predicting the output parameters to a high degree of accuracy. Error deviation between model and predicted values were in the order of 3-4%, although larger errors were encountered at the higher end of the temperature scale. Figure 8.6 shows typical results for network testing.

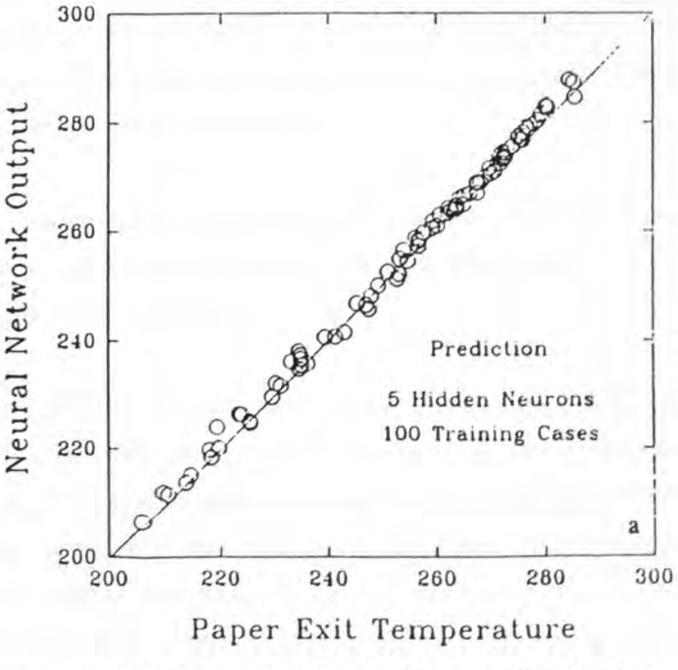


Figure 8.6 - Correlation of network output using test data

The method of randomly selecting training data is not considered efficient practice since an area of the multi-dimentional space may be wrongly interpreted due to limited data [89]. However, comparison of training and test cases showed that errors induced due to limited space interpretation were small.

The analysis of quality properties of paper during drying using neural networks has been examined by Elo et al. [120]. Figure 8.7 shows the model constructed.

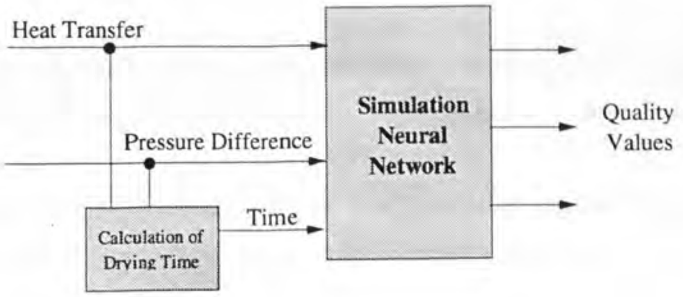


Figure 8.7 - Parameters studied

Parameters included; heat transfer, pressure difference, drying time, paper moisture, paper temperature, calibre, smoothness, porosity, and optical and tensile properties. Experiments were conducted using an experimental rig with paper inlet and exit moisture content being fixed. The time for drying was calculated using values of heat transfer and pressure difference.

A perceptron neural network with one hidden layer was constructed. A back-propagation algorithm with a momentum term was used for training. Although the network produced absolute values for quality, trends in quality terms were analysed using a graphical format. Comments were not made concerning the capability and accuracy of the neural network to model quality terms.

The modelling of drying kinetics and the kinetics of deterioration processes taking place during drying is currently being examined at the Technical University of Lodz [84], [201], [339], [384]. However, limited information regarding their work was available.

The classification of objects in n-dimensional space is currently under examination at the University Politehnica of Bucharest, Romania [80]. This methodology may be applied to the modelling of drying processes in a time domain. Jinescu and Laveric [196] applied back propagation neural networks to the drying of grain. The network was capable of predicting drying rate with respect to dimensionless drying time. Detailed algorithms were examined and comments were made concerning the training performance of the network. Limited information was published concerning parameters, data collection or capability of the network produced.

Conclusions

The following conclusions can be drawn from the survey of drying modelling and the application of neural networks;

1. Drying is not well understood due to the complexity of the simultaneous transfers of heat, mass and momentum during the process. Escalating energy costs and more intense competition provides the impetus for continued efforts in improving dryer efficiency, a methodology that relies on an accurate process model.

2. Many researchers have investigated the modelling of drying. Techniques such as empirical calculation based upon experimental data, irreversible thermodynamics and finite element analysis have been applied.

3. Traditional techniques are hindered by the need for time consuming, expensive experiments, or theories are limited by simplifying assumptions often made in order to enable a tractable solution.

4. There has been a large increase in research into neural networks and many industrial applications have been demonstrated successfully.

5. Neural networks offer a convenient platform for capturing the dynamics inherent in a non-linear system. Drying processes are commonly non-linear and are thus potential systems for the application of neural modelling techniques.

6. Neural models could be applied as the model component in a predictive control system, for optimisation of a process, or evaluating data from secondary control parameters.

7. The architecture and development of neural networks have been described, including details of neural structures, training and testing methodologies.

8. There has been little research regarding the application of neural networks for the modelling of drying processes. Studies describing the modelling of paper drying, quality and grain drying were reviewed. Comments regarding parameters, development and testing of the models produced have been described.

9. There is potentially a large range of applications of neural network within the field of drying processes which have remained undeveloped.

CHAPTER 9

THE APPLICATION OF NEURAL NETWORKS TO THE MODELLING OF DRYING PROCESSES

Introduction

Several possibilities existed for the application of neural networks to the modelling of a drying system. Kinetic properties, such as heat transfer coefficients, could be modelling with respect to other parameters within the system and the results combined with existing traditional models involving heat and mass balance. Alternatively, a model could be developed to predict overall parameters such as mass loss, temperature, which could be analysed directly.

The restrictions due to assumptions imposed by traditional modelling techniques, and the complexity of solutions rendered the concept of modelling kinetics impracticable. Industrialists contacted during this study concluded that in many situations expertise were not available to interpret complex modelling data, and although many traditional models of systems have been developed, their application within industry is limited. The decision was thus made to use parameters with direct meaning to general industrial engineers.

Optimising the energy efficiency of a machine and maximising product throughput may adversely affect product quality. The importance of product quality has been addressed by many researchers [24], [207], [210]. However, as described in Chapter 8, the inclusion of quality terms within models of drying characteristics is not common practice. The development of a neural tool capable of predicting quality factors was thus an important aim of the models conceptual design.

Neural models developed so far for drying processes either lacked verification and investigation of the model accuracy, were based upon traditional modelled data which may not have described completely the underlying fundamentals of the process, or did not included a material quality term. The aim of this investigation were thus;

- Model the drying characteristics of a material laden with water,
- Use parameters which were of 'real' meaning to an industrial process engineer,
- Include parameters to assess the quality of the material during drying,
- Verify the model with experimental data and comment upon the accuracy of the system developed,
- To investigate the possible utilisation of the model to optimise the drying process, application to control theory, and measurement of parameters where traditional primary instrumentation is not available e.g. moisture and temperature profiles during the drying cycle.

Selection of a System

Data Acquisition

Examination of other practical applications of neural networks to industrial processes, as described in Chapter 8, showed that several hundred data sets may be required for network training. Until initial network development commenced the quantity and quality of data required was unpredictable [89]. The means of data acquisition thus had to provide sufficient information. Furthermore, verification of the accuracy and repeatability of data was necessary to produce an accurate model.

Data from industry was limited mainly due to the lack of monitoring of drying equipment and detailed historical information. Using an industrial dryer section posed problems of disrupting the normal process flow and possibly endangering the product, machine and operator while varying parameters. Equipment commonly lacked accurate instrumentation, and the time required to collect sufficient experimental data was unknown. On the basis of these factors the decision was made to use laboratory based equipment.

Material Properties

The following material properties were sought;

- Adequate supply and consistent quality,
- Ability to be laden with a known quantity of water,
- Have no adverse affects/reactions with water or the heating medium,
- Demonstrate general drying characteristics, including acceptable rate of moisture loss,
- Suffer from detectable product defects if subjected to excessive drying regimes.

Trials were conducted to examine the above criteria using conventional ovens, Infra-red systems (IR), including short, medium and long wave, a dehumidifier chamber and a microwave unit operating at 2450 MHz. Products included paper, reconstituted potato, plaster board and paper coated gypsum cove.

IR techniques proved effective on sheet material but the penetration of energy on bulkier objects proved insufficient. Paper qualities were hard to assess without specialist techniques. Drying using the heat pump dehumidifier was slow and limited data could be obtained.

A variety of drying characteristics, including several quality factors, were achieved when gypsum cove was dried using both microwave energy and a hot air chamber. The susceptibility of the gypsum to degrade in excessive drying regimes was noted and a paper coated Gyproc cove was selected for a drying specimen. The industrial processing of cove has been examined and is described in Chapter 5.

Heating Properties of Gypsum Cove

The drying characteristics of a material are governed by heat and mass transfer as discussed in Chapter 8. These phenomena vary with heating and material properties including chemical and physical-phase changes.

To gain an understanding of the drying characteristics of the paper coated gypsum cove, including parameters and phenomena which may affect drying processes or quality issues, the following properties were examined;

- Chemical composition of the cove and reaction with water,
- Physical-phase characteristics with respect to temperature (STA analysis),
- Dielectric properties with respect to moisture, material chemical phase and temperature.

Chemical Analysis of Material

Gypsum ($CaSO_4.2H_2O$), the dihydrate, and anhydrite ($CaSO_4$) are naturally occurring forms of calcium sulphate, and the by product of flue gas desulphurisation. When pure, gypsum is colourless white and shows very little variation in chemical composition. In terms of oxide it contains 32.5 % calcium oxide, 46.6 % sulphur trioxide and 20.9 % water [166]. Commercial deposits of gypsum rarely approach this purity, but usually contain varying amounts of clay and shale, anhydrite, limestone, dolomite, iron compounds and silica. Gypsum usually has a massive structure type, consisting of an aggregate of intergrown crystals and may be grey, brown, red or pink. High grade material (>98 % dihydrate) is used in the production of plaster of Paris, medical plaster and other quality products. Lower grade material (typically around 90% dihydrate) is used for the production of plaster board and decorative cove. Calcium sulphate has many phases as shown in Table 9.1 [184].

COMPOSITION	CRYSTAL STRUCTURE	AGGREGATION STATE	POROSITY
$CaSO_4 - 2H_2O$	Monoclinic	Natural rock	Low
		Rehydrated β-hemihydrate	Low
$CaSO_4 - ½H_2O$	Hexagonal	α-hemihydrate	Low
		β-hemihydrate	High
		Aged β-hemihydrate	Low
$CaSO_4$ III	Hexagonal	Dehydrated α or β-hemihydrate	High
$CaSO_4$	Orthorhombic	Natural	Low
		Deadburnt	High

NOTE - Porosity measured by nitrogen absorption.

Table 9.1 - Phases and properties of calcium sulphate

Alpha and beta plasters can be blended together and properties can also be influenced by using additives to control initial fluidity, setting time, expansion and strength. Fluidity can be increased by the use of polysulphates, and/or by ageing the plaster for a minimum of one month. Potassium sulphate and borax (or keratin) can be used to increase/reduce the setting time respectively [184].

Unlike beta-hemihydrate, alpha-hemihydrate with its lower porosity exhibits lower initial water uptake and lower rate of drying. Calcium sulphate dihydrate also shows different drying behaviour for natural gypsum and gypsum obtained by hydration of hemihydrate. Hughes [184] suggests that in an industrial environment where a product is often a mixture of several calcium sulphate phases, the design of the drying procedure is difficult.

Dry set plaster (dihydrate) will absorb moisture, although it has a low porosity (Table 9.1). Initial trails conducted showed that the maximum quantity of water retained by the gypsum is about 34% of the weight of the dry basis. Szentgyorgyi [344] suggested that gypsum can be classified as a typical porous material and Lutsik suggested that gypsum is a typical colloidal capillary porous body capable of retaining moisture in various types of bonds with solid substance [235]. Turk et al. [357] concluded that the amount of free moisture uptake in gypsum depends on the physical structure of the sample as indicated by the adsorption and thermodynamic equilibrium. The drying process becomes a shift in equilibrium when the temperature and relative humidity are intentionally changed to promote drying. Turk went on to state that when a drying temperature is selected, the relative humidity should not be too low so as to initiate calcination, or too high as to promote surface adsorption and capillary condensation. In addition the drying conditions of temperature and relative humidity must not affect the chemical equilibrium. However, since each calcium sulphate compound has its own stability region the drying condition must be where all of the phases present in the sample remain stable.

Groves [166] suggested that gypsum is soluble in water (1 part in 495 parts water). Moreover it was stated by British Gypsum [309] that impurities such as salts present in the gyproc would increase solubility. A series of experiments were conducted involving accurately weight samples, soaking in water and drying in a convection oven at 40°C for 24 hours. Results suggested that the weight lost due to the product dissolving in water was negligible.

Lutsik et al. [235] performed tests to establish the moisture retention of the gypsum. Table 9.2 summarises their findings. Their study suggested that gypsum is a typical colloidal capillary-porous body capable of retaining moisture in various types of bonds with the solid substance.

MOISTURE (% by weight)	POSITION
1.2	Monolayer
8.7	Adsorbed
13.7	Hydroscopic state in micropores (including adsorbed water)
10.7	Capillary forces in macropores

Table 9.2 - Moisture within the gypsum material

Turk et al. [357] proposed that care was needed during the drying of gypsum to ensure that water of hydration was not removed, hence affecting the dry weight and physical properties of the material. They went on to highlight international standards for the drying conditions necessary for the removal of free water. Typical conditions for a 100g sample being 40-50°C for 24 hours using a conventional hot air convection dryer. Pijevsky [283] stated that the temperature during which the water of hydration is removed varies between 97-125°C.

Table 9.3 shows a typical chemical composition of the gypsum core material [56]. The cove is coated with a heavy paper known as a liner of weight 220 g/m^2.

COMPONENT	PROPORTION (% by Weight)
Gypsum	89.400
Sodium oxide	0.018
Starch	0.030
Marl	0.542
Magnesium oxide	0.685
Aluminium oxide	1.699
Silicon oxide	5.349
Potassium oxide	0.654
Calcium oxide and Calcium carbonate	0.781
Titanium oxide	0.105
Iron oxide	0.137
Foaming agent	0.600

Table 9.3 - Chemical composition of gypsum cove core

Thermal Analysis

A thermal analysis was performed to examine the phase change characteristics of the paper coated gypsum cove, including phenomena which may affect drying processes or quality issues.

The thermal-physical characteristics of gypsum have been analysed by many researchers [235], [283], [344], [357], [364]. However, the chemical composition of the Gyproc used during the experiment varied significantly from that of pure gypsum due to the addition of fillers and setting agents during manufacture. A thermal study was performed using a PL Thermal Sciences STA analyser. Two tests were performed using factory dry and moisture laden samples.

Figures 9.1 and 9.2 shows a graphical representation of the results. Curve A shows the percent variation of sample weight. Curve B represents the difference in thermocouple reading in comparison to a standard material.

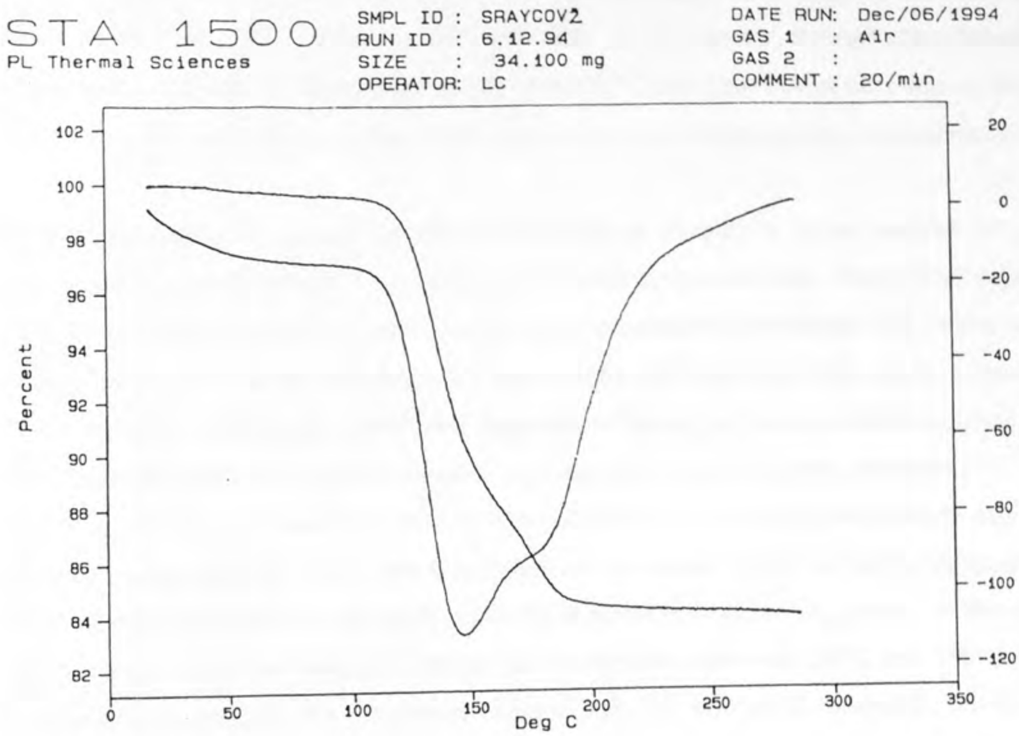


Figure 9.1 - STA plot for 34.10 mg factory dried sample subjected to a heating rate of 20°C/min.

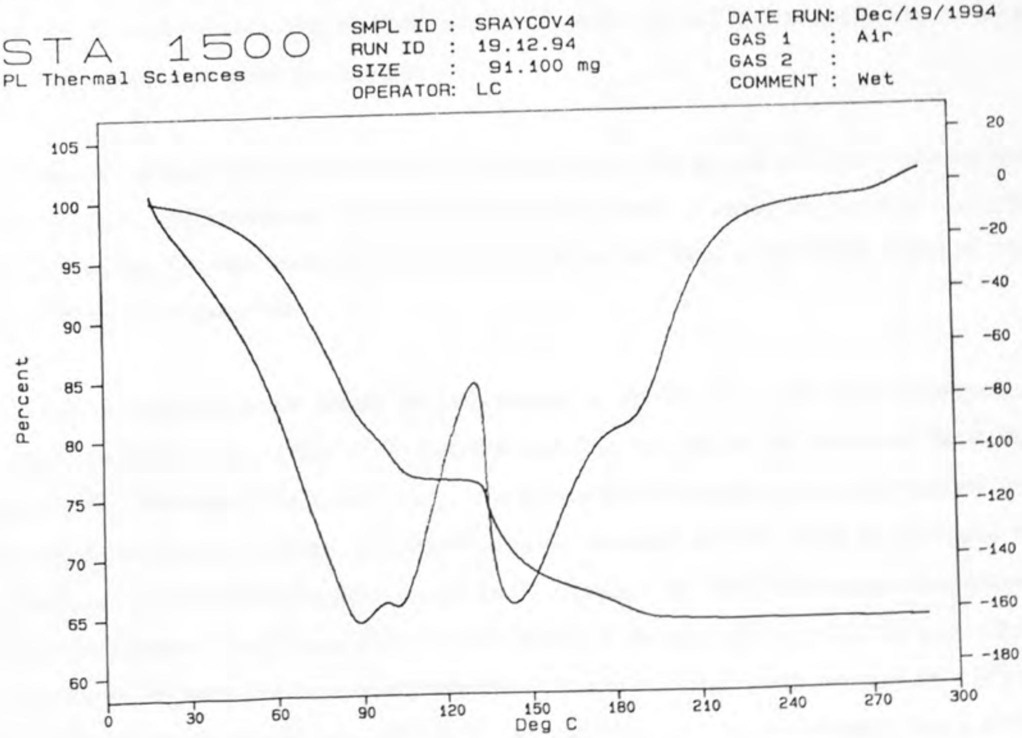


Figure 9.2 - STA plot for 91.10 mg water laden sample subjected to a heating rate of 10°C/min.

Figure 9.1 shows the STA plot for a factory dried sample. During the initial stages of heating the sample rose in temperature from room temperature to the boiling point of water. The rise was less than that of the standard sample as shown by the lagging microvolt reading. There was little weight loss during this stage of heating. Literature [166] suggests that formation of hemihydrate will occur in gypsum at temperatures above 60°C. The results suggest that this formation is only very slight and can be virtually ignored at temperatures below 98°C for the short drying times considered. The constant weight below 98 °C also suggests that there was no free water in the material. Oven tests conducted showed that free water can be removed from gypsum at temperatures of 50°C.

At 98°C the temperature of the sample was relatively constant in comparison to the standard. At 103°C the sample lost weight at a great rate and continued to do so as the temperature rose. The lack of weight loss at temperatures below 100°C indicated that very little free water was present in the sample. The sudden weight loss at temperatures above 98°C can be attributed to the loss of water which has been absorbed by sodium sulphate and calcium chloride salts. These salts, which were impurities in the original mineral, absorb moisture especially in the cases where the product is slightly over dried, and can lead to various quality problems [56]. Literature [166] suggests that the rate of calcination increases with temperature. Formation of hemihydrate may have also attributed to the weight loss. At 138°C, the temperature of the sample started to rise in comparison to the standard. This was accompanied by a decrease in the rate of moisture lost from the sample. At this stage three quarters of the bound water had been removed leaving hemihydrate. Between 158°C and 180°C the rate of moisture loss was again constant. The temperature of the sample was sufficient to remove the remaining bound water. Between 160°C and 175°C the rate of temperature rise of the sample reduced indicating a phase change. Soluble anhydrite was formed. This soluble anhydrite would change rapidly into hemihydrate on contact with air and will set to a solid form when mixed with water [166]. After 175°C the sample temperature rose drastically until it was virtually equivalent to the standard. The weight loss after 175°C was negligible. At temperatures above 200°C non-soluble anhydrite was formed.

Figure 9.2 shows the drying phase characteristics of a sample which was ground and mixed with water to form a paste before analysis. Any hemihrdrate formed during factory process or laboratory grinding would have been converted back to the dihydrate state before the sample was heated. Thus at the initial stages of drying only dihydrate and free water was present.

Free water was removed from the sample at temperatures as low as 35°C. This was accompanied by the temperature of the sample lagging that of the standard as energy was utilised in vaporising the water and not heating the material. The rate of free water removal was increased as the sample temperature reached about 70°C. The small sample temperature change in comparison to the standard at 90°C could be attributed to uneven particle grinding or a nonuniform moisture profile in the material. At 100°C the sample temperature rose in comparison to the standard. Weight was constant at about 75% of the original weight. At this stage all of the free water in the material had been removed leaving only dihydrate and any hemihydrate that may have formed during drying. The constant weight profile from 100-130°C indicates that very little calcination occurs below 130°C during the time period studied (about 11 mins). Heating the sample at temperatures of around 130°C for times greater than 11 mins. cannot be commented upon and more extensive hemihydrate formation may occur if the drying time are extended. At 130°C the rate of temperature rise of the sample again lagged that of the standard. Weight was again lost indicating that some of the bound water was removed. After 130°C the drying characteristics were very similar to those of the factory state sample; with the phase changes into hemihydrate between 130-140°C, soluble anhydrite formation around 180°C and non-soluble anhydrite formation around 200°C.

The major difference between the factory and re-wet samples was the constant weight region for the rewet sample between 100 and 130°C. Both samples would have the same initial chemical composition and the only differing factor was the physical characteristics of the specimen; one a compacted powder, the other a thick slurry. Groves [166] suggests that the drying characteristics and the temperature of phase changes is affected by the physical composition of the gypsum. Groves further revealed that the temperature at which hemihydrate is formed has varied experimentally from 100°C-190°C, with another researcher suggesting that a proportion of hemihydrate could still exist at 500°C. Results from the factory and rewet sample tests suggest that that the physical structure of the sample may have affected the drying characteristics below 130°C.

The state of impurities within the mineral due to rewetting, and the effect on the moisture retention properties relating to the water transport mechanisms, may have been a contributing factor to the varying drying characteristics below 130°C. Little is known due to commercial sensitivity as to the exact composition of the gypsum; proportion of binders and fillers used and the chemical/physical characteristics of each. A slight reaction or moisture retention property with moisture content may have affected the drying phases of the gypsum at low temperature. There was no sudden change in the rate of weight loss in the factory sample around 130°C. This would suggest that calcination of the gypsum initially starts at a temperature as low as 100°C.

Dielectric Property Measurement

The dielectric loss factor of a material is one measure of its ability to absorb microwave energy. The dielectric properties of a material are dependant upon density, frequency of the applied electromagnetic field, temperature and moisture. The values of permittivity, loss factor and loss tangent describe the heating characteristics of the material in an electromagnetic field. Metaxas [253] suggests that a product with a loss factor within the range 10^{-2} to 5 is suitable for dielectric heating. Dielectric properties were examined in order to gain an understanding of the heating properties of the paper coated cove in a microwave field and establish any links between microwave heating characteristics and the thermal-phase properties.

Many researchers have documented dielectric properties of materials including Von Hippel [372] and Nelson [261]. However, a literature search found little material concerning the properties of gypsum [56], [64], [252]. The measurement of dielectric properties requires specialised techniques and developments in the area have been progressing since the 1950s [45], [211], [221], [252], [261], [302], [314], [341], [377].

Dielectric property measurements on gypsum cove were conducted at Staffordshire University [147]. A cavity perturbation technique was used [188], [326], with a TM_{10} cavity resonating at 2450 MHz. Additional apparatus included a Hewlett Package network analyser (HP8753C) and a conventional electrically heated tube furnace. Samples were held in tubes made from fused vitreous silica.

The cavity perturbation theory uses measurements of the change in resonant frequency and Q-factor of the cavity with the proviso that the change in resonant frequency caused by the introduction of the sample is small compared to the resonant frequency. The theoretical principles of the technique are well documented [253].

Dielectric tests were performed on the core material of the paper coated cove. Due to the nature of the material and measuring technique a sample coated with paper could not be examined. The gypsum sample was prepared by drilling out a proportion of the central core, crushing into a fine powder and soaking in a humid atmosphere for three days. Groves [166] suggests that merely grinding gypsum will result in the formation of a proportion of the anhydrite, an undesired reaction. The soaking period in the humid air allowed the reformation of the dihydrare, leaving a sample of dihydrate and a small amount of free water. Moist samples were prepared by mixing dry powder with a known quantity of water. The moisture content was verified by oven drying methods. Two series of tests were performed;

- **Temperature analysis** - Dielectric properties of a prepared sample were analysed over the temperature range 26-200°C.
- **Moisture Analysis** - Dielectric properties of samples with varying free moisture contents were analysed at ambient conditions.

Figures 9.3 and 9.4 show the variation of the permittivity and loss factor with temperature respectively. The sample mass was 0.125g with a density of 0.847 mg/cm^3.

Comparison of Figure 9.4 with the results of the (STA) phase/temperature analysis show that the dielectric properties vary directly with the temperature phase changes of the gypsum material. As the temperature rises from ambient the value of the loss factor gradually increases. A critical point is reached at about 75°C, and the loss factor decreases with increasing temperature. The complete removal of the free water within the material may have been a contributing factor. A minimum value for the loss factor is reached about 130°C. This temperature corresponds exactly with the formation of the hemihydrate. The loss factor then rises to a maximum at a temperature between 160-180°C. This peak in the loss factor corresponds to the formation of the soluble anhydrite. The loss factor then decreases as the temperature approaches 200°C and the sample forms the non-soluble anhydrite.

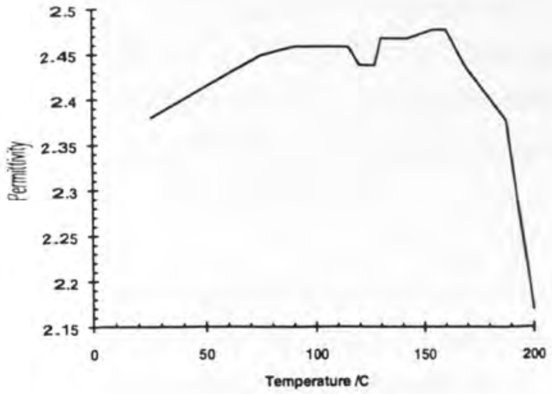


Figure 9.3 - Permittivity variation with temperature

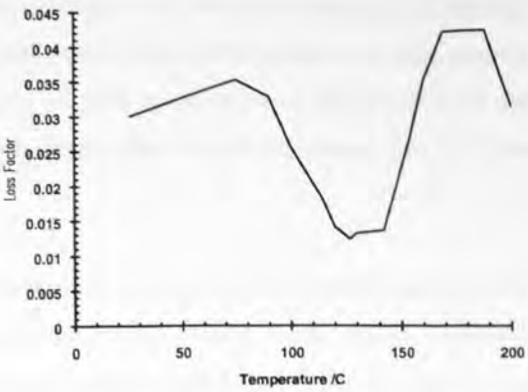


Figure 9.4 - Loss factor variation with temperature

Although the loss factor decreases, the reduction does not occur until a large proportion of the sample has formed the hemihydrate. The decreasing loss factor suggests that the hemihydrate is less susceptible to energy at microwave frequency. However, a material with a loss factor of 0.0125, and hence the hemihydrate sample, will still absorb a substantial amount of energy [253].

Results published by the Centre for Materials Fabrication [5] on the dielectric properties of gypsum wall board at RF frequencies suggest that a near zero loss factor is obtained for a material with a zero free moisture content, hence preventing any possibility of overdrying and resulting calcination. Values of the sample temperature or material density were not disclosed, and no indication was given of the value of the loss factor at zero free moisture content. Results, as shown in Figures 9.5 and 9.6 demonstrate that a zero loss factor was not obtained at microwave frequencies. The equipment utilised was unable to calculate properties at RF frequencies, and the validity of the results at RF frequency could not be verified.

Figures 9.5 and 9.6 show the variation of permittivity and loss factor with free moisture content.

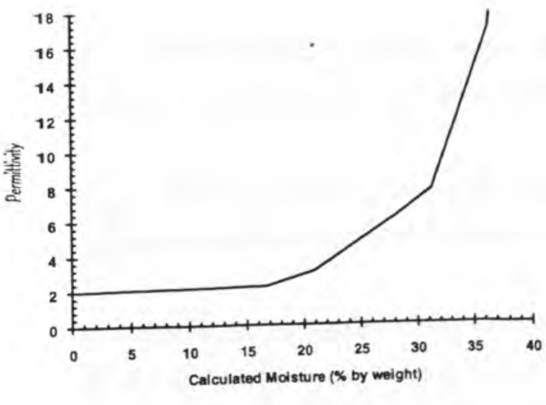


Figure 9.5 - Permittivity variation with moisture

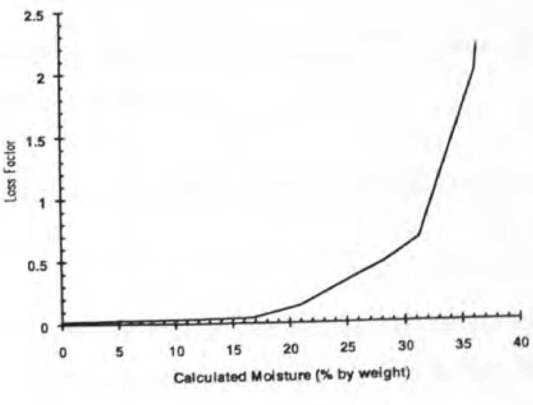


Figure 9.6 - Loss factor variation with moisture

The equipment utilised was not capable of maintaining a set relative humidity within the specimen holder. Thus, at an elevated temperature moisture would be rapidly lost from the sample, causing error in the measurement of the dielectric properties. The small amount of moisture, specimen size and the time required for the silica tube/sample to reach the equilibrium temperature prevented a multi-varible temperature-moisture analysis from being performed. However, the experimentation conducted allowed examination of the variation of dielectric properties with free moisture content and a comparison with those of the absolute dry sample (no free water) and the values for pure water.

The values of permittivity and loss factor rose dramatically with increasing sample moisture content as shown in Figures 9.5 and 9.6. The variation of permittivity and loss factor are in accordance with typical characteristics as shown in Figure 9.7 [253]. As the material dries the loss factor decreases with falling product moisture content.

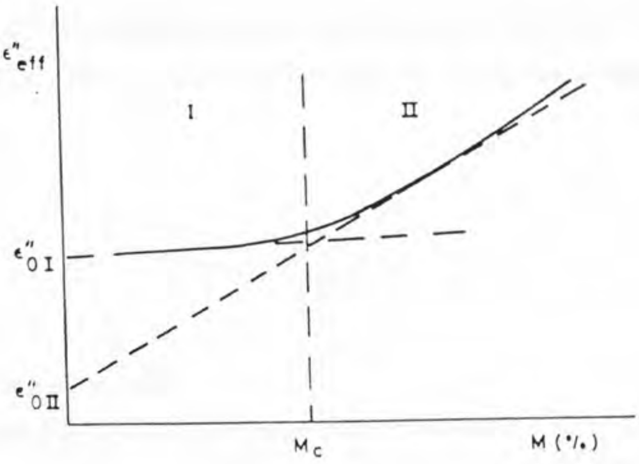


Figure 9.7 - Typical variation of loss factor with moisture

Metaxas states that the dielectric properties of absorbed water show marked differences to that of liquid water [253]. Furthermore, the variation of loss factor with moisture can be divided into two distinct regions;

Region I - Water molecules 'bound' in the first uni-molecular layer at the surface of the material are less rotationally free than that of the water resident in the capillaries and cavities.

Region II - The loss factor is much greater than in region I due to the ability of the water molecules in cavities and capillaries within the material to rotate freely.

The two regions can be represented by two straight lines. The intersection representing the critical moisture content of the material. It can be seen from Figure 9.6 that the properties exhibit a gradual change in slope making an accurate identification of the two regions difficult. Results suggest that the critical moisture content of the sample lies between 25-30% (wet basis). Figures have demonstrated that the moisture content of gypsum has a greater influence on the loss factor than product temperature. This phenomena is due to waters ability to absorb energy in a microwave regime and hence large loss factor.

The general slope of the loss factor-moisture curve and the value of the critical moisture content determine the extent and effectiveness of the moisture levelling in a microwave field. Results expressed in Figure 9.6 show that moisture levelling will occur for moisture contents above the critical value ≈25% (wet basis) since the high dε"/dm ensures that the wetter parts of the material absorb more power and tends to level off the initial uneven moisture content. However, little levelling will occur at moistures below 20% (wet basis). The effect of moisture levelling was not examined in detail using experimental methods.

Initial trails showed that a sample soaked for 24 hours will result in a moisture content of roughly 30% (wet basis). Thus, as the sample is dried very little moisture levelling will occur below moisture values of ≈20%. This could result in localised overheating in the product which may cause the loss of bound water calcinating the gypsum.

The penetration depth is defined as the distance from the surface of the material at which the power drops to e^{-1} from its value at the surface. The penetration depth for gypsum, a low loss material (where $\varepsilon''/\varepsilon'<1$) can be expressed as;

$$D_p = \frac{\lambda_0 (\varepsilon')^{0.5}}{2\pi\varepsilon''} \qquad (9.1)$$

Where, Dp = Penetration depth

λ_0 = Free space wavelength = (speed of light/frequency)

ε'= Permittivity

ε'' = Loss factor

An in depth discussion of the theory can be found in Metaxas [253]. Figure 9.8 shows the variation of penetration depth with moisture. Figure 9.9 show the variation of penetration depth with cove temperature.

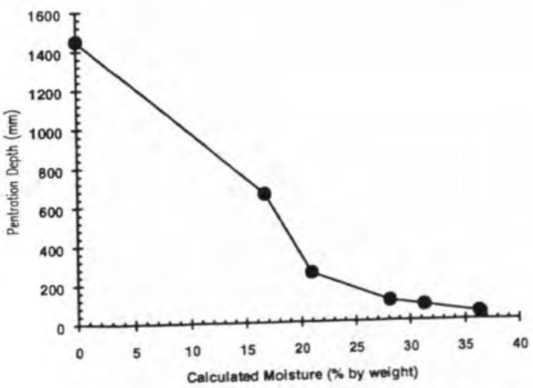


Figure 9.8 - Variation of penetration depth with moisture

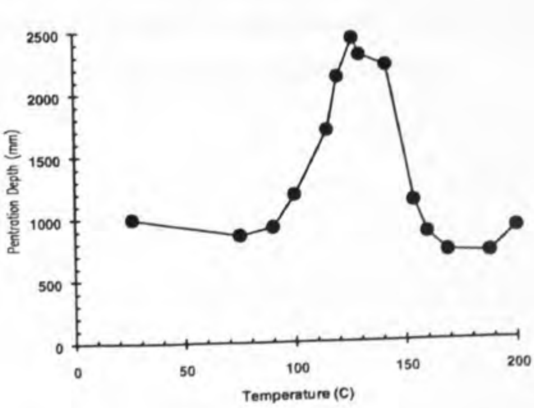


Figure 9.9 - Variation of penetration depth with temperature

The way in which the microwave energy is dissipated within the cove is directly related to the dielectric properties of the material. For many materials, especially ones with a high moisture content the penetration depth may be smaller than the material, thus causing problems of temperature uniformity during microwave heating. Due to the low loss dielectric properties gypsum does not exhibit these phenomena.

An estimation of the penetration depth and dielectric properties showed that gypsum material exhibited a loss factor which was suitable for the application of microwave heating at a frequency of 2450 MHz.

Metaxas and Driscoll [252] examined the dielectric properties of 230 g/m^2 board, which is similar to the gypsum liner. Loss factor and permittivity were found to decrease with decreasing moisture content at 2450 MHz. Figure 9.10 shows the variation of loss factor with moisture. A critical moisture content of 14% (dry basis) was estimated at 22°C.

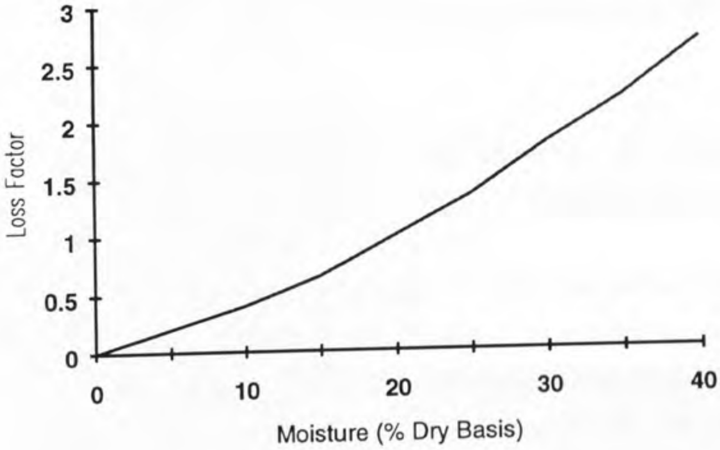


Figure 9.10 - Variation of loss factor with moisture for 230 g/m^2 board

Figure 9.10 shows that the dielectric properties of the liner were similar to the gypsum core. However, at low moisture contents the liner was more susceptible to electromagnetic radiation than the core. This may be the cause of paper burning quality defects at high microwave powers and low material moisture contents.

Modelling of the Microwave Drying of Gypsum Cove

Introduction

The theoretical principles and application of heating in electromagnetic fields are well documented in the literature and a description of principles is not warranted here. Metaxas [253] provided an excellent introduction to the subject, while Perkin [281] describes the continuum equations for moisture, momentum, and heat transport in a dielectrically heated porous medium.

Microwave heat generated at 2450 MHz is due primarily to dipole rotation of free polar or polarizable molecules [104], [253]. The power developed in a material is proportional to frequency, electric field strength and the dielectric loss factor. The application of microwave technologies varies widely from the drying of pasta [198] to ceramic bodies [142]. A good summary of the process advantages of microwave systems is given by Sciffmann [260], [359].

Mudgett [259] states that the design of microwave processes has been largely empirical, often with un-predicted and disappointing results due to a lack of basis models for the heating characteristics of materials.

In recent years several papers have been published on predicting field patterns and heating rates in materials exposed to microwaves and others are devoted specifically to microwave enhanced drying [2], [22], [106], [107], [197], [228], [230], [271], [274], [309]. Many models derive the moisture transport equation and the temperature diffusion equation and apply Maxwell's equations. They define, respectively, the distribution of moisture, temperature and electric field inside the wet material [309], such as the work of Perkin [281], Chen and Pei [48], Chen and Schmidit [49] and Turner and Jolly [359] where the rated heat dissipation of the electric field has been incorporated into heat and mass transfer equations. However, many of these equations and techniques introduce so many physical parameters that the resolution of the problem is tedious. Furthermore, many of the parameters involved, such as the dielectric constant, the specific heat, the thermal diffusivity, and the heat transfer coefficients are, themselves, functions of the temperature and of the local moisture content. Roussy [309] suggests that the models proposed so far are so complicated that calculations cannot be done in real time.

The difficulty in determining the local distributions of temperature and electric field strength inside a microwave cavity and material have hampered development of reliable models. Developments in this area have included analysis of the field, temperature and power distributions in multimode cavities [108], [109], [110], [111], [112], [153], [154].

The dielectric properties of a material being dried vary with moisture and temperature as shown in the previous section. The lack of a comprehensive set of dielectric properties can often invoke the choice of crude approximations to be included in numerical models of microwave drying [358]. This often produces misleading results and wrong conclusions.

The process of microwave induced desorption in moist porous hydroscopic materials may be divided into two distinct processes. The first is the freeing of bound polar molecules to allow them to rotate and effect heat generation. The second is the use of the generated heat to thermally activate mass desorption [1]. Adu et al. [1] suggests that literature on microwave heating and moisture loss involving porous hygroscopic solids does not account for the effect of changing hygroscopicity.

Previous Studies Relating to Microwave Heating of Gypsum

Microwave drying in the ceramics industry is only used to a very limited extent. Oda, Woods and Foster [269] describe work involving the drying of ceramic 'green bodies' although gypsum is not involved in the drying process. Chabinsky and Eves [44] comment further on the drying of ceramics forms including the processing of ceramic ware in gypsum moulds during slip casting. Microwave/vacuum drying of slipcast ware and moulds at Goodson Lighting Ltd [142] and Nuthall Lighting (2450 MHz, 10.5kW Power output) are two such examples of production process microwave systems.

Turk [61] describes details of studies involving the microwave drying of various forms of gypsum. A 600W 2450MHz microwave unit was utilized which incorporated an accurate balance system.

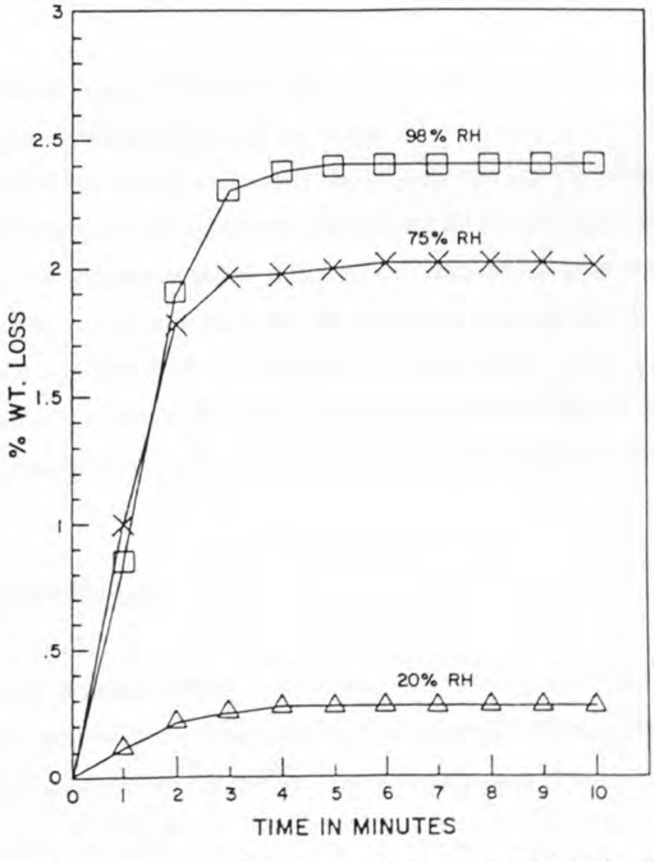


Figure 9.11 - Microwave drying curves for calcium sulphate hemihydrates

Figure 9.11 shows typical drying curves for commercial β-hemihydrate that was preconditioned in three different environments. i.e. different amounts of free moisture was added to the sample. Turk suggests that the curves exhibit a definite plateau region after only a few minutes of exposure to microwaves and this was attributed to the fact that only the free moisture was removed.

Table 9.4 shows the variation in moisture loss for different lengths of time and initial moisture condition.

	WEIGHT LOSS (%)					
$CaSO_4\frac{1}{2}H_2O$	**0h**	**3h**	**6h**	**12h**	**24h**	**48h**
	98%RH					
β-hemihydrate	0.25	0.91	1.47	1.98	2.40	2.84
β-hemihydrate - Aged	0.24	0.79	1.22	1.66	2.27	2.57
α-hemihydrate	0.04	0.35	0.52	0.66	0.97	1.17
	75%RH					
β-hemihydrate	0.25	0.82	...	1.42	2.01	...
β-hemihydrate - Aged	0.24	0.64	...	1.34	1.71	...
α-hemihydrate	0.04	0.17	...	0.59	0.82	...
$CaSO_4II$	0.05	0.10	...	0.10	0.18	...

Table 9.4 - Microwave drying curves for calcium sulphate hemihydrate [357]

Turk and Bounni [357] found that the percent combined water determined for all the cases in Table 9.4 was essentially constant for each sample regardless of the weight loss by microwave treatment. They suggested that complete drying was achieved and that the chemically bound water was not affected by microwaves at any level of free water. Experimentation was only conducted at 600W and no monitoring of the sample temperature was performed. However, the low microwave power may not have been sufficient to raise the sample temperature sufficiently for the water of hydration to be removed. Trials conducted on gypsum samples during this study with an initial moisture content of about 35% by weight, using 6kW of microwave power have resulted in the calcination of a proportion of the sample. The edges and sharp protruding features of the material appear to be very susceptible to calcination probably due to the concentration of microwave energy at these areas.

Microwave Drying Experimentation

Although not commercially processed using microwaves, initial drying trials and analysis of the dielectric properties of gypsum cove demonstrated good susceptibility to microwave energy. Furthermore, the cove showed a diverse range of drying characteristics and quality defects relating to moisture content, magnetron power and the rate of drying.

In an industrial situation there may be many parameters that effect the characteristics of the system, however a three input model was selected for initial investigation. Figure 9.12 shows the parameters studied.

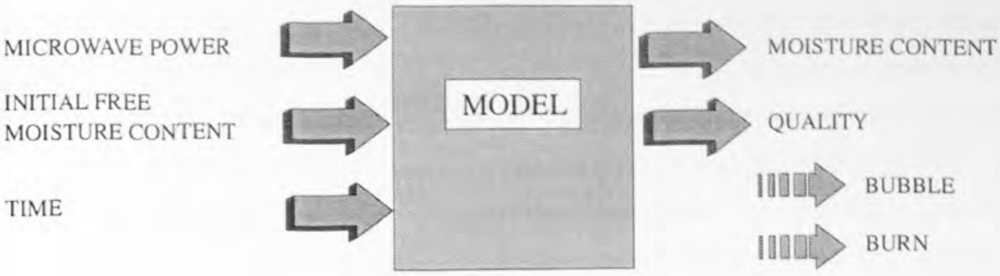


Figure 9.12 - Model parameters

Trials were conducted to measure the temperature of the gypsum core using both shielded and unshielded thermocouples. Both types of instrumentation were susceptible to interference caused by the electric field within the cavity, and acted as antennas, propagating the electromagnetic field out of the unit. Optical fibre systems have been developed [81], [83] but were not available. On-line temperature analysis of the product during heating could thus not be performed. An infra-red technique monitoring the surface temperature provided limited information and could not be related to the chemical-phase changes within the gypsum core.

Experimental Set-up and Data Collection

Drying trials were conducted using an industrial 6kW microwave unit with a 1 m^3 multimode cavity. Tests were carried out using 100mm lengths of 'Gyproc' cove. The drying cavity was modified and an electronic data-logging balance installed allowing the product weight to be recorded throughout the drying process. Tests were conducted during a period of settled weather, and the variance in ambient atmospheric conditions of temperature and humidity were negligible.

Figure 9.13 - General view of microwave equipment

Drying characteristics were analysed for samples with moisture contents between 0g and 60g of added water, subjected to input magnetron powers of between 0 and 100% (6kW). Added water and magnetron powers were varied in steps of 10g and 10% respectively. In an industrial situation parameters may only vary by 5-10% of target values. Extreme changes were utilised to demonstrate the networks capability to model a sizeable n-dimensional space. Product quality defects were noted using a video camera with digital timing facility. Figures 9.13 and 9.14 shows a layout of the experimental rig. 77 basic drying tests were performed, with data recorded automatically every three seconds for approximately 1500 seconds. The repeatability of data was verified by duplicating tests and comparing results. Error of less than 5% were encountered.

Results were transferred directly to a PC version of MATLAB, where a third of the data was retained for model verification. The MATLAB Neural Network Tool Box was used to develop the neural networks.

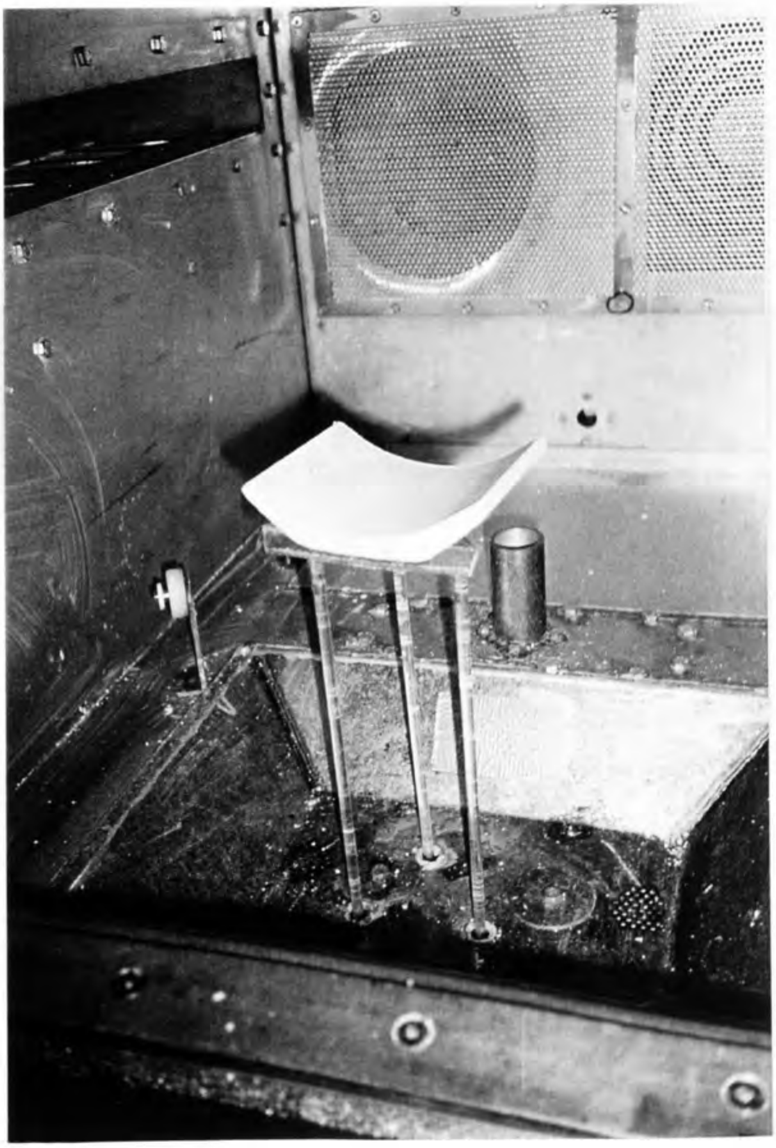


Figure 9.14 - Product on balance tray in microwave cavity

General Characteristics of Data Collected

Comparison of the drying curves (moisture loss with time) for samples subjected to microwave energy showed a general characteristic form [253]. Figures 9.15 and 9.16 show a typical example of a sample subjected to low and high microwave power respectively.

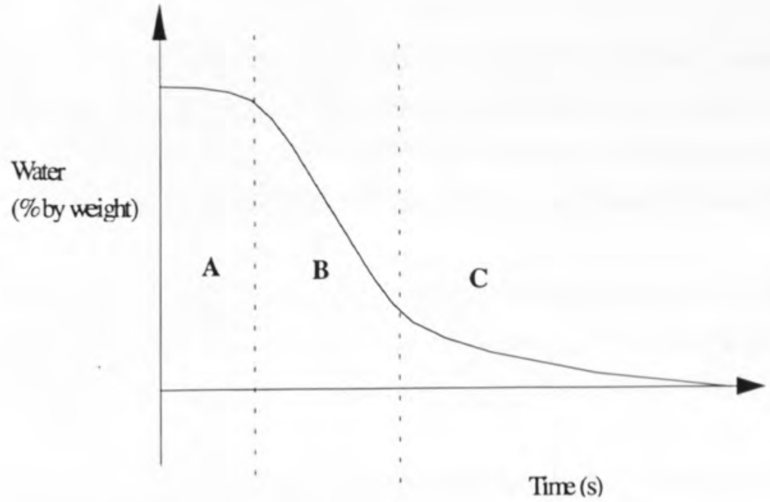


Figure 9.15 - Typical low power drying curve

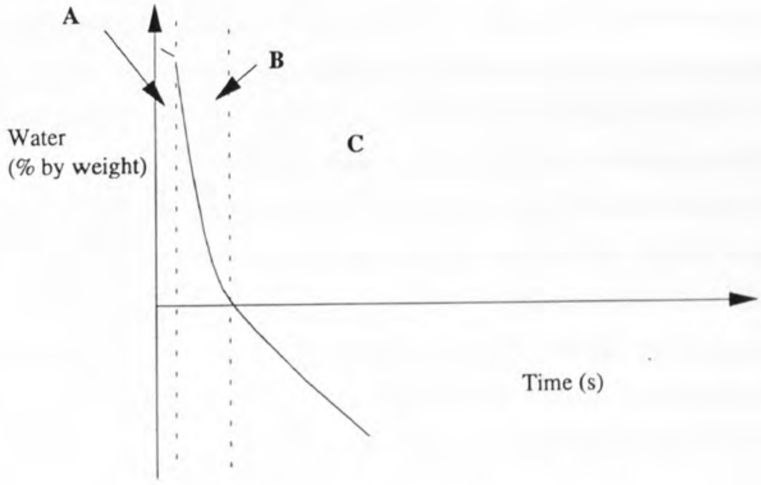


Figure 9.16 - Typical high power drying curve

The drying characteristics can be divided into three distinct fields.

A - Heating phase. The material absorbs energy from the microwave field and the temperature of the body (including the free water) rises. i.e. The addition of sensible heat to the body. There is little loss in mass during this period.

B - The constant drying phase. Once the body has absorbed sufficient sensible heat the moisture is driven from the material. The rate of moisture removal is nearly constant.

C - The falling rate period. As the moisture content of the sample falls past a critical point the effectiveness of moisture removal decreases. In conventional drying [253] this period is designated by the moisture front receding into the material and capillaries within the material drying up thus reducing the ability of moisture to migrate to the surface of the body. The mass transfer characteristics during microwave heating are different due to the influence in energy absorbed due to changing dielectric properties and the internal heating characteristics in a electric field.

It was noted during initial heating, especially with a sample of high free moisture content, that moisture was removed from the material in the liquid phase. This phase of drying precedes the constant drying rate period and is commonly known as the liquid movement phase [237], [253]. The mass transfer during this period is governed by the total pressure gradients due to the rapid establishment of the vapour phase in the wet solid.

Results indicated that the critical moisture content, i.e. the start of the falling drying rate period, was dependant on the microwave power level; 0 to 3% water at low power (<50%) to 0 to 5% at high power (>50%). The dielectric properties of gypsum directly affect the microwave heating characteristics of the gypsum sample [147].

As the sample moisture content reduces during the constant drying rate, the loss factor of the material also falls and the material is less susceptible to absorbing microwave energy. The effectiveness of moisture removal decreases thus the falling rate period commences. It can be seen from the drying curves that the critical point at the start of the falling rate period cannot be pinpointed exactly as the drying characteristics gradually change between the two defined phases. The loss factor decreases by a factor of three between product temperatures of 100-120°C. This loss of material susceptibility to microwave energy together with the decreasing loss factor with moisture content suggests that the drying of gypsum is a self limiting factor when zero moistures are reached. Results suggest that at low microwave power this is the case, however an increasing quantity of the bound water in the gypsum core is removed with increasing microwave power levels. Results indicate that a power level of only 10% is sufficient to cause calcination of a gypsum sample, a phenomena which is independent of the initial product moisture content provided the exposure time is sufficient. Power levels below 10% did not sufficiently effect the bound water within the gypsum due to the lack of absorbed energy in comparison to losses from the sample and cavity. The calcination of the cove at relatively low microwave powers highlights the thermal sensitivity of the material during drying and effect on overall product quality and mechanical strength.

The loss of bound water from the product and formation of the hemihydrate indicates that a temperature above 120°C was obtained in the sample during heating at high power. The power factor increases at a temperature above 150°C. Analysis of the drying curves suggest that at a high microwave power the sample absorbs energy indicating that this temperature region has been attained. All microwave tests which reached these conditions were stopped due to excessive paper burning. However results suggest that gypsum could be calcinated using microwave energy, although probably not economically efficient.

BUBBLING

Paper bubbling occurred at microwave powers above 5% for samples with moisture contents above 40g of added water, and power levels of 30% and above for a free water content of 40g. No deformation occurred during heating of samples with free water contents of 30g and less.

Paper deformation occurs due to the porosity of the paper coating being much less than that of the gypsum core. As the water is removed from the core, especially during the liquid movement phase that proceeds the constant drying period, the porosity of the paper is insufficient to allow the volume of moisture to migrate through the coating. The paper is thus forced away from the gypsum core.

BURNING

The liner coating the gypsum core was susceptible to burning when subjected to microwave energy. The time taken for the paper on the concave side of the sample to burn was noted during experimentation. Figure 9.17 shows a scatter diagram of the absolute water content verses the time for the initial burning on the concave side for various microwave power levels (%).

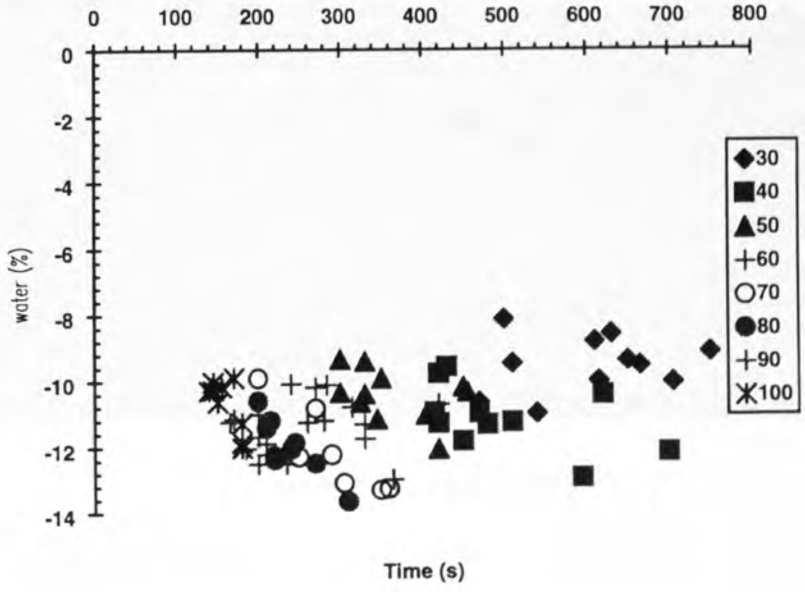


Figure 9.17 - Time and moisture plot for concave burning

Results shown in Figure 9.17 suggest that the time taken for gypsum cove to deform due to paper burning was dependant on microwave power level and product moisture content. The higher the incident microwave field the shorter the heating time before burning occurs. The time to burn and dependence on the power level can be attributed to the rate of removal of moisture from the body. At a high power setting a sample rapidly loses moisture and the core of the gypsum rises in temperature due to the energy dissipated within it. The paper coating loses moisture until an absolute zero content is reached, and the effect of the hot core body and absorption of the incident energy is sufficient to cause the paper to discolour (charring) and finally burn.

Figure 9.18 shows burning defects during heating. Paper bubbling defects can be seen on the right hand specimen.

Results shown in Figure 9.17 suggest that the gypsum sample reaches a given temperature sufficient to initiate paper burning at a moisture content of between -8 to -14%. i.e. a proportion of the bound water within the material has been removed. The figure shows only a slight variation with power level with the moisture content rising slightly as the power level decreases. This phenomena is probably due to the prolonged heating times at low power and energy absorption of the paper coating during this period.

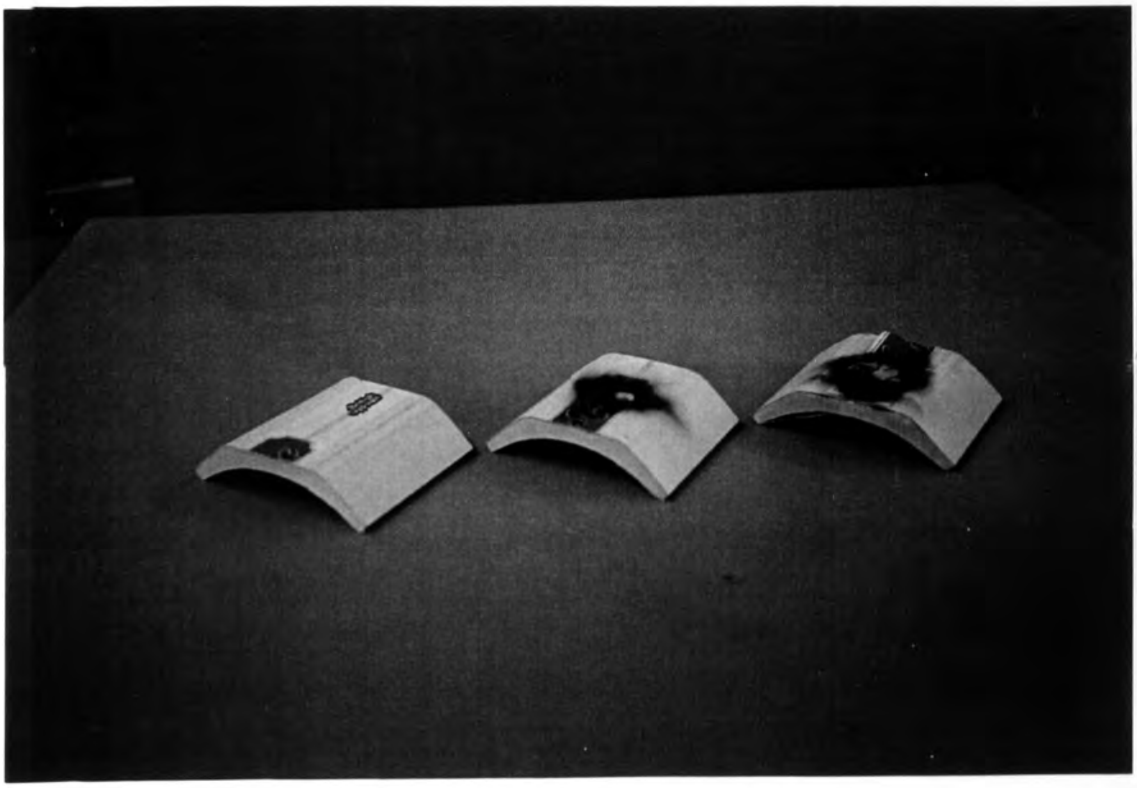


Figure 9.18 - Heating defects

Development of Neural Network Model

The experimental data was divided into thirds. Two thirds was used for network training, the remainder for test and network validation. A backpropagation architecture network using a Levenberg-Marquardt algorithm, an approximation of Newton's method, was constructed for each case [105].

Two and three layer network structure were implemented during the analysis. An outline of a three layer networks is shown in Figures 9.19, where w are weights, b bias, and F represents a transfer function of a layer of neurons.

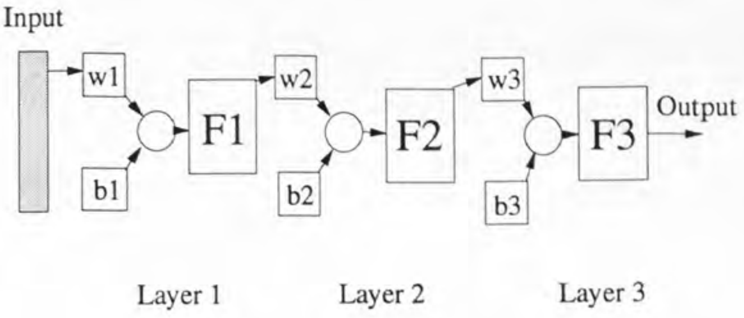


Figure 9.19 - Systematic of a three layer network

The number of neurons in the hidden layers and the mathematical form of the transfer functions were varied during development. A linear output transfer function was utilised with all networks. The size of the training set, i.e. specific input and output cases, varied from around 19000 to 6300 depending upon the nature of the test. The goal of network training is not to minimise the sum square error, but to compromise between error and the capability of the network to model non-training data. Table 9.5 shows a summary of the most significant tests performed.

TEST	LAYERS	NEURONS	TRAINING EPOCHS	SUM SQUARED ERROR OBTAINED
Full Dataset				
NET4	TAN-LOG	4-4	150	20000
NET6	TAN	8	150	22000
Half Dataset				
NET8	TAN-LOG	6-6	150	13000
NET9	TAN-LOG	6-7	150	10500
NET20A	TAN-LOG	6-7	100	5840
NET22	TAN-LOG	7-6	100	4691
NET23	TAN-LOG	7-6	36	47207
NET23A	TAN-LOG	7-6	48	38773
NET23B	TAN-LOG	7-6	150	4310
Third Dataset				
NET24	TAN-LOG	8-9	6	469624
NET24A	TAN-LOG	8-9	24	28609
NET24B	TAN-LOG	8-9	126	1278

Table 9.5 - Summary of the most significant network training performed

Many problems were encountered with computer memory during training. The size of the training data set was reduced allowing a network with more layers and a greater number of neurons to be constructed. The number of training epochs required to reach a satisfactory sum squared error was reduced dramatically i.e. time for training. The results of NET24 show that the combination of less training data and a larger number of hidden neurons enabled a reasonable error to be reached without extensive training.

Figures 9.20 and 9.21 show a comparison to modelled data and experimental training data for two typical drying curves; Low (10%) and High (60%) magnetron power respectively.

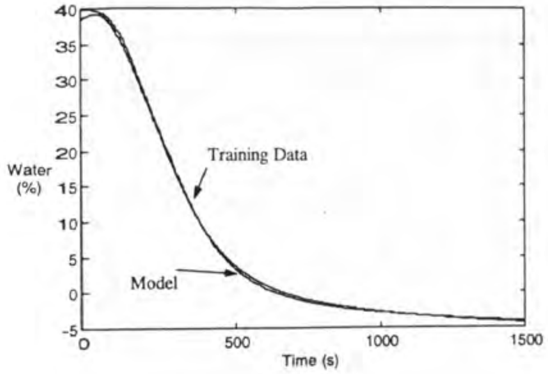


Figure 9.20 - Comparison between model and training data for a low power drying characteristic

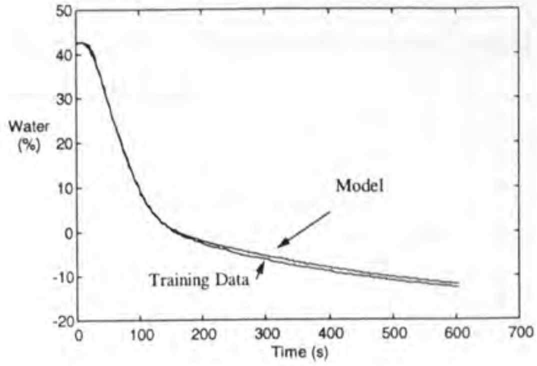


Figure 9.21 - Comparison between model and training data for a high power drying characteristic

Figures 9.20 and 9.21 show that the neural network can successfully model the drying characteristics when presented with input data which formed part of the training set. Slight errors were induced during the initial stages of heating for a low power characteristic, and small discrepancy at very low moisture contents for high power. The model produced was perfectly adequate in assessing the time at which all of the free moisture within the material has been removed - A very important commodity since product quality is adversely affected if the gypsum is dried beyond this point.

Although comparison of the model output to the training data gives an indication of the progress of the network implementation, a comparison of non-training data to a known target set is essential in assessing the validity of the model. Figures 9.22 to 9.29 show a variety of comparisons of non-training target data and the model output for average and extreme cases.

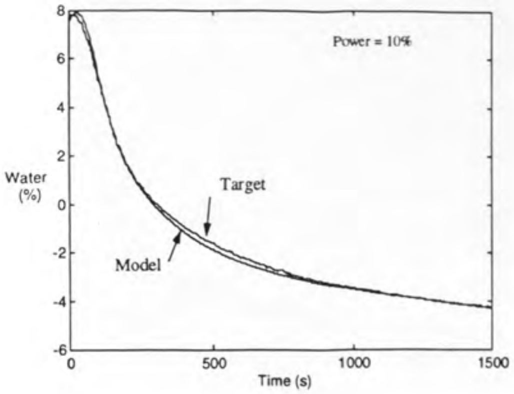


Figure 9.22 - Comparison between model and experimental data

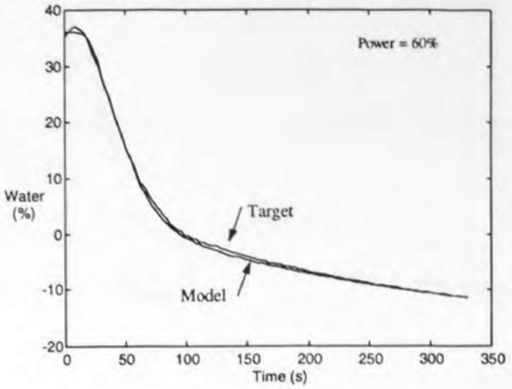


Figure 9.23 - Comparison between model and experimental data

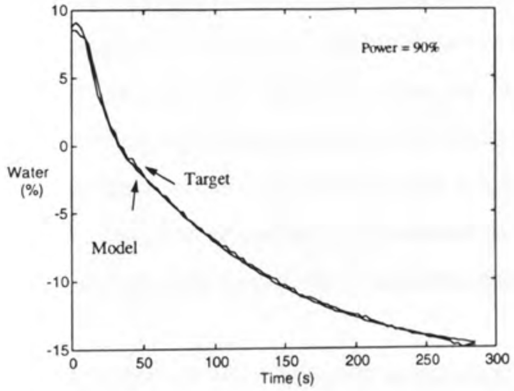


Figure 9.24 - Comparison between model and experimental data

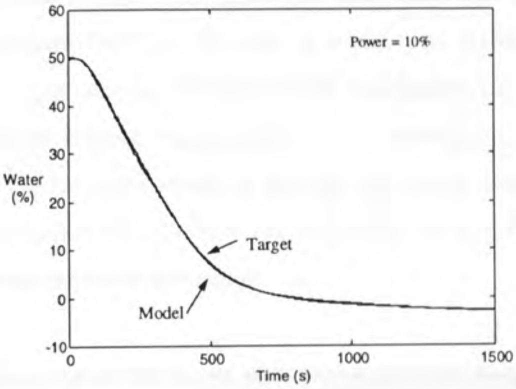


Figure 9.25 - Comparison between model and experimental data

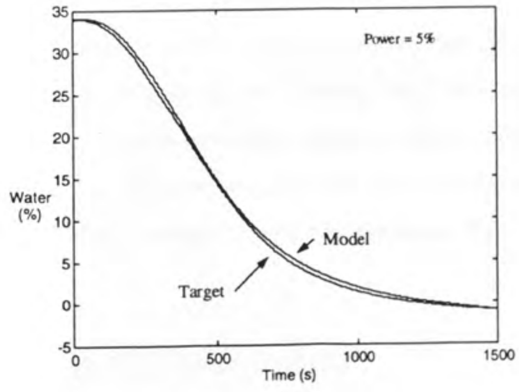


Figure 9.26 - Comparison between model and experimental data

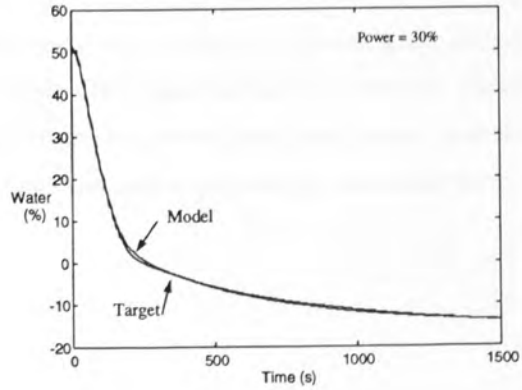


Figure 9.27 - Comparison between model and experimental data

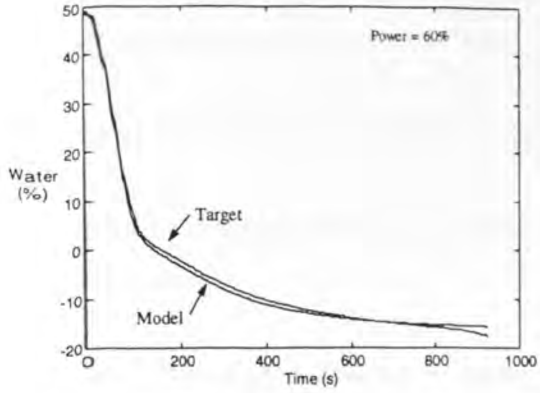


Figure 9.28 - Comparison between model and experimental data

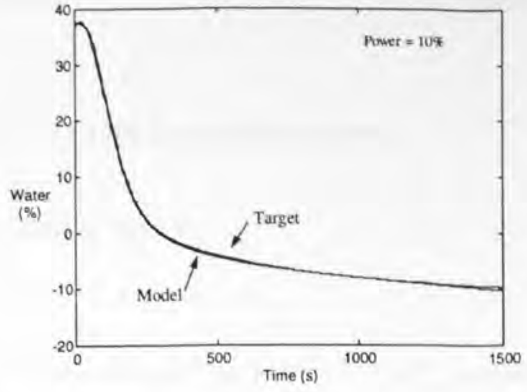


Figure 9.29 - Comparison between model and experimental data

The figures displayed above represent a variety of comparisons of model output to target data which was not part of the training set. Generally the model agrees well with experimental data, however in a few cases errors up to 6% were encountered. Errors modelling the low moisture characteristics during product calcination, i.e. below zero free moisture content, were comparable to those when the network was presented with a training data set. A second form of error was found to occur occasionally during the initial stages of heating. The model acted in a similar manner to an overfitted polynomial as shown in Figure 9.24. Although the occurrence of this form of error was small, the magnitude of the deviation from the target data was substantial.

The occurrence of error during the modelling of the drying process could not be attributed to an exact magnetron power or product moisture level, with the exception of those at low product moisture content. Although the output sometimes deviated from the target data set during initial heating, results showed that the model was capable of accurately predict an output for moistures down to a zero free content. Results suggested that error increased as lower moistures were attained.

The accuracy of the experimental data used to test the network must be taken into account when analysing the error in comparing non-training data and the model output. The experimentation conducted showed that microwave tests were repeatable to a degree, and the error between comparable tests was generally less than 5%. However, slight error in the data used to train the network and that used to perform the tests would have lead to errors in the model fitting the non-training data.

Modelling of Material Bubbling

Paper bubbling occurred during microwave heating trials and was attributed to the paper coating being much less porous than the gypsum core. The water was removed from the core due to internal pressure and temperature gradients being established during heating. As this water was removed, especially during the liquid movement phase that proceeds the constant drying period, the porosity of the paper was insufficient to allow the volume of moisture to migrate through the coating. Paper deformation due to the coating being forced away from the gypsum core thus occurred. Furthermore, due to the bubbling occurring during the initial stages of heating, the time for deformation to occur was not analysed. Paper shrinkage may have also contributed to the movement of the paper away from the central gypsum body.

The degree of deformation was noted during experimentation. Two broad categories were used;

- Movement of the paper coating away from the core but no paper rupture,
- Paper ruptured.

Since any form of paper deformation cannot be tolerated on a standard production line [56] a model was produced to predict if any bubbling will occur.

A model was produced which could predict the likely occurrence of paper deformation on the basis of magnetron power and product free moisture content. Time was not a variable due to occurrence of the deformation during the initial stages of heating. Figure 9.30 shows a plot of the experimental data obtained.

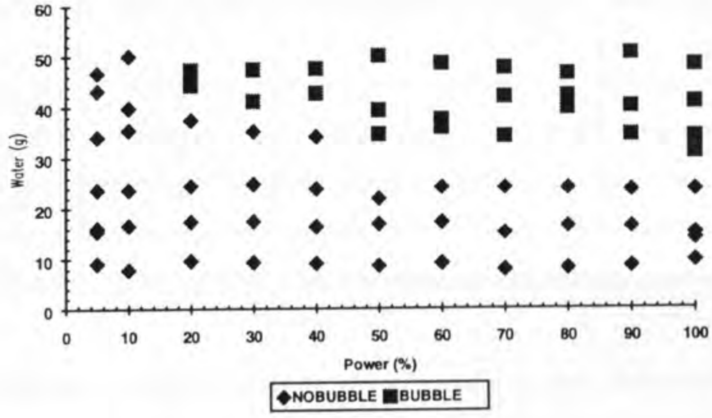


Figure 9.30 - Paper-bubble deformation as a function of magnetron power and added water

Figure 9.30 clearly shows that bubbling is most likely to occur at a high microwave power and high product moisture content. Furthermore, a distinct region can be defined in which the probability of paper bubbling occurring is very high.

A backpropagation architecture network using a Levenberg-Marquardt approximation [105] was used. A two layer network structure was implemented. The number of neurons in the hidden layer was kept constant at 8, and a logsigmoid transfer function was used for an output. The output of the network was between 1 and 0, indicating bubbling and no bubbling respectively.

The network was trained using a two parameter input; power (magnetron), and added water, and a single target output; bubbling (1 or 0). Approximately 70 data sets were used for training the network and a further 70 used for verifying the model produced. Figure 9.31 shows the data used for network training and testing.

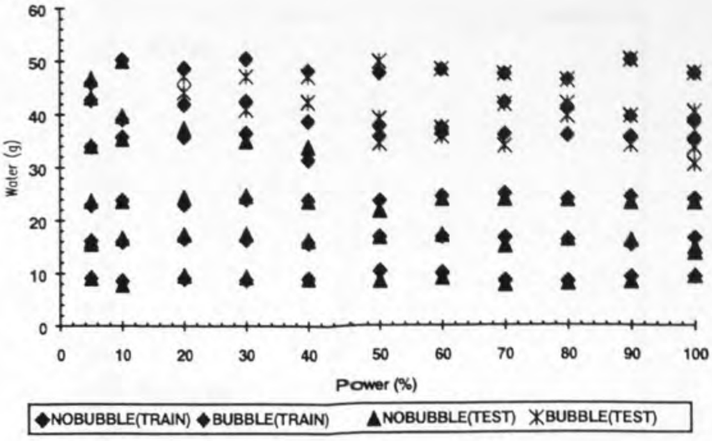


Figure 9.31 - Data used for network construction and testing

Several networks were developed and tested. Table 9.6 shows a summary of the most significant tests performed.

TEST	LAYERS	NEURONS	TRAINING EPOCHS	SUM SQUARED ERROR OBTAINED
NETA	TAN-LOG	8	25	0.715
NETB	TAN-LOG	8	30	0.083
NETC	TAN-LOG	8	55	0.00037

Table 9.6 - Summary of the most significant network training performed

Table 9.7 shows a comparison of network output and experimental data when presented with data of part of the training set. The model demonstrated an excellent predictive capability when presented with training data as input. Table 9.8 shows that the model is capable of predicting the bubble characteristics for non-training data. Errors between model output and non-training target of less than 7.5% were attained.

The transition between the two regions of bubble and non bubble was examined by analysing the network output when presented with a varying product moisture content at a fixed magnetron power. Figure 9.32 shows the resultant output as the moisture was increased in steps of 1g at a power of 60%.

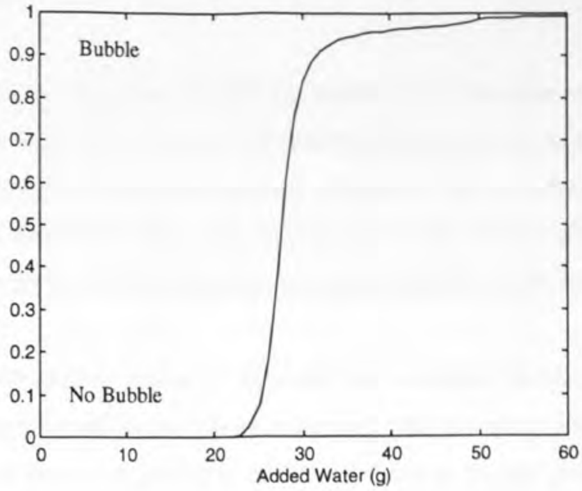


Figure 9.32 - Transition between bubble and non-bubble region

Training Data	Network Output
0	0.0000
0	0.0003
1.0000	1.0000
1.0000	1.0000
0	0.0000
0	0.0000
1.0000	0.9807
1.0000	0.9999
1.0000	0.9996
1.0000	1.0000
0	0.0000
0	0.0013
0	0.0000
1.0000	0.9991
1.0000	1.0000

Table 9.7 - Comparison of the network output for modelling the training data

Test Data Target	Output From Network
0	0.0000
0	0.0001
0	0.0001
0	0.0000
0	0.0000
0	0.0004
0	0.0000
0	0.0002
1.0000	0.9249
1.0000	1.0000
1.0000	0.9997
1.0000	1.0000
1.0000	1.0000
0	0.0000
0	0.0003

Table 9.8 - Comparison of the network output for modelling of new non-training data

Figure 9.32 shows a steep transition between the bubbling and non-bubbling region within the model. A simple probability algorithm can be utilised to determine the exact regional location of the dataset, and hence bubble characteristics.

Modelling of Material Burning

A second quality factor, paper burning, was noted during heating trials. The time to burn and dependence on the power level can be attributed to the rate of removal of moisture from the body. At a high power setting a sample rapidly loses moisture and the core of the gypsum rises in temperature due to the energy dissipated within it. The paper coating loses moisture until an absolute zero content is reached, and the effect of the hot core body and absorption of the incident energy is sufficient to cause the paper to discolour (charring) and finally burn.

Since any form of paper deformation cannot be tolerated on a standard production line [56] a model was produced to predict if any burning will occur. Material burning does not occur with free moisture remaining in the sample. It must be noted that in an industrial process the aim is to only remove the free moisture. The likelihood of gypsum samples burning in a well controlled dryer is minimal, thus the exercise of modelling the burning phenomena is purely academic.

A backpropagation architecture network using a Levenberg-Marquardt approximation was used. Two and three layer networks were developed and verified. The number of neurons in the hidden layers and the mathematical form of the transfer function were varied during experimentation. A logsigmoid output transfer function was utilised with all networks. The network was trained using a three parameter input; power (magnetron), time (for heating), and added water weight, and a single target output; time for burning. The size of the training set varied from around 19000 to 6300 depending upon the nature of the test.

Although several architecture were successful in reproducing training data to a high degree, many of these networks were very inaccurate when presented with test data. A network consisting of a three layer architecture (Tan-Log-Log), and 8-10 neurons in respective layers was the most successful. The network underwent 225 training epochs, producing a sum-squared error of about 75.

Figures 9.33 to 9.36 show a comparison between network output and target for a data set which is part of the training set.

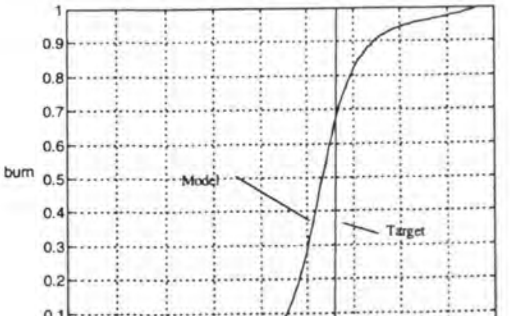


Figure 9.33 - Comparison between model and experimental data

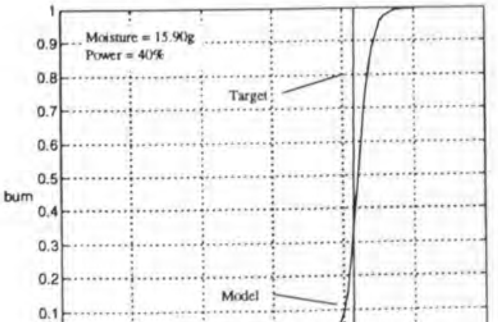


Figure 9.34 - Comparison between model and experimental data

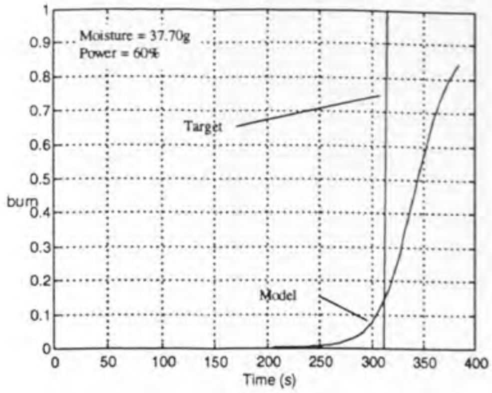


Figure 9.35 - Comparison between model and experimental data

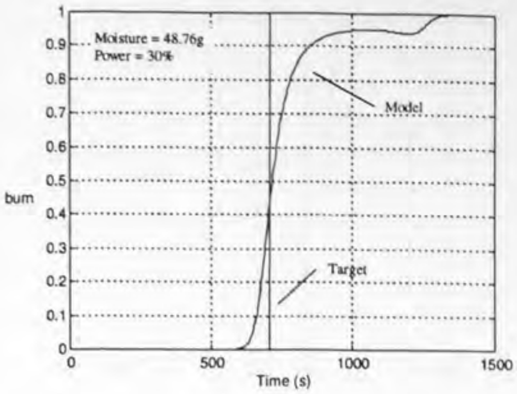


Figure 9.36 - Comparison between model and experimental data

Figures 9.37 to 9.42 show the resultant network output and experimental value for an input of non-training information.

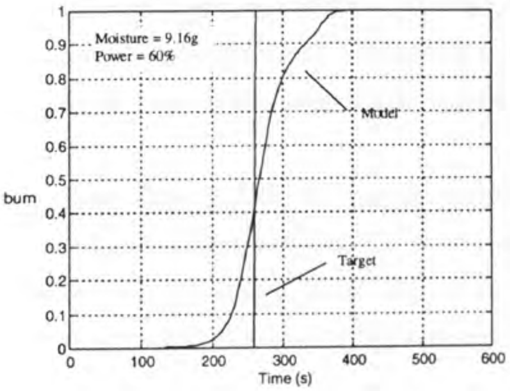


Figure 9.37 - Comparison between model and experimental data

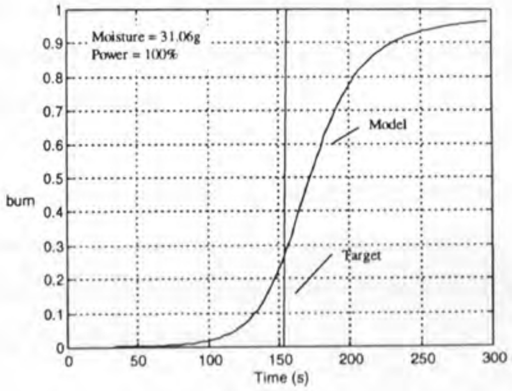


Figure 9.38 - Comparison between model and experimental data

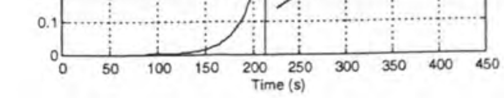


Figure 9.39 - Comparison between model and experimental data

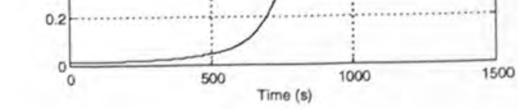


Figure 9.40 - Comparison between model and experimental data

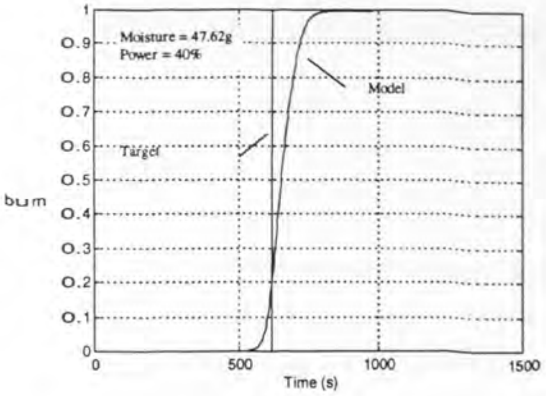


Figure 9.41 - Comparison between model and experimental data

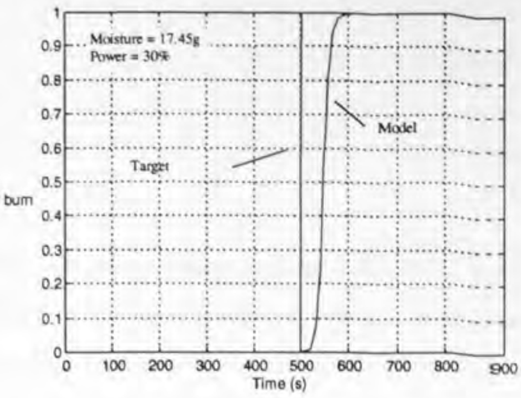


Figure 9.42 - Comparison between model and experimental data

Errors in the order of 20% were attained when comparing testing and target data. Furthermore, it was noticed that the output of the network when subjected to test data was not a distinct step function. In a few cases a rapid response was achieved. However, in many tests the exact time for burning was not well defined; the output taking a logsigmoidal shaped characteristic. The time for burning was estimated by evaluating the function at 0.5 with 1.0 representing burning and 0 representing no burn. The probability of the function and average value may be estimated more accurately using simple integration/probability techniques.

The figures show that the burning characteristics of gypsum cove subjected to microwave heating can be modelled using neural networks. The result is not as accurate as the other drying parameters modelled; weight loss or bubbling. However, the accuracy of the experimental data used to train the network must be taken into account when analysing the error in comparing non-training data and the model output.

The experimentation conducted showed that the time for burning tests were repeatable to a degree. However, due to the rather crude method employed for data collection, error in the region of 10-30 seconds was considered approximate. The exact definition of the start of burning; paper discolourisation, smouldering, was difficult to evaluate accurately even using the video camera with timing facilities. Accounting for this error the neural net model of the burning appears to be appropriate to the amount of noise in the training data. A more accurate model could be produced on the collection of more repeatable experimental information.

Further training was considered ineffective and data preparation/further experimental verification may yield a more accurate representation. A new experimental set-up for data collection would be required perhaps involving instrumentation which can identify colour changes and yield a more accurate prediction of the time for the onset of burning than a simple manual video camera.

Modelling of the Convection Drying of Gypsum

Introduction

Gypsum cove is processed industrially using gas fired tunnel dryers operating at about 140-170°C. Material is dried from an initial moisture content of approximately 30% to a final specification of 1-2%. A brief description of the systems utilised are discussed in Chapter 5. Fundamental problems of controlling the process to prevent calcination during drying is one of the largest factors resulting in quality rejects [56].

Previous Studies Relating to Conventional Drying of Gypsum

The dehydration of gypsum is one of the technically important reactions that leads to the formation of dehydration products which form the backbone of the gypsum based industry [364]. Amongst the researchers who have examined the solid state decomposition reactions in terms of mathematical models, the contributions of Ridge [256], McAdie [242], Ball and Narwood [18], and Khalil [215] are noteworthy. These theories are mostly based upon assessment of experimental results derived from non-isothermal methods and multi dimensional diffusion theories. The focus of their work is mainly the calcination process and is beyond the scope of this investigation of free water removal.

Lutsik [235] experimentally analysed the drying of water soaked gypsum blocks. A hot air convection oven was used and drying took place at 183°C in an air flow velocity of 1.5m/s. Moisture content, differential pressure within the material and temperature of the sample were recorded. During the initial drying period the gypsum was heated throughout its entire volume and the moisture content of all layers dropped at the same rate suggesting that flow of weakly-bonded moisture from macropores to the sample surface and vaporisation occurred at the surface. At the end of the constant drying period moisture and temperature gradients were established within the material. The moisture content of the outer layer was lower than the inner. Moisture was vaporised within the material generating an excessive vapour pressure within the material. The temperature at which this occurred was 60°C. As the temperature rose a gradient was established until 93°C where upon it vanished and a pressure difference between layers was noted. The pressure was found to be greatest near the surface of the material. As the moisture content fell below 15% the relaxation of the pressure indicates that the moisture is lost from the macropores and transition from the moist to hydrogen state, whereby the moisture is held only in the micropores. Pressure pulses continue and moisture is lost from the micropores being forced from the middle plane to the surface of the sample.

As the length of the constant drying rate period increases, the moisture content drops to 4% meaning loss of hydroscopic moisture and also some of the polymolecular absorbed moisture. The core temperature rises to 145° C. The last stage of drying involves slow loss of adsorbed moisture and heating of the dry gypsum. The excess pressure in the surface layers decrease gradually, and the pressure in the middle of the sample rises slightly due to the increase in the temperature of the air in the pores.

The study was conducted at a single air temperature of 183°C and initial product moisture content of approximately 34% (by weight). Results indicated that the temperature at which the constant drying rate proceeds is between 60-93°C. This is above the recommended international drying specification to prevent calcination, which limits the temperature to about 50°C [357]. This could have resulted in the removal of a proportion of the water of hydration although it was suggested that only free water was removed. Pijevsky [283] also suggested that gypsum can start to lose its water of hydration at a temperature as low as 70°C. No comments were made concerning product quality (deformation etc.) or the extent of the removal of the water of hydration. With reference to the STA conducted at Aston a gypsum temperature of 145°C would have resulted in product calcination.

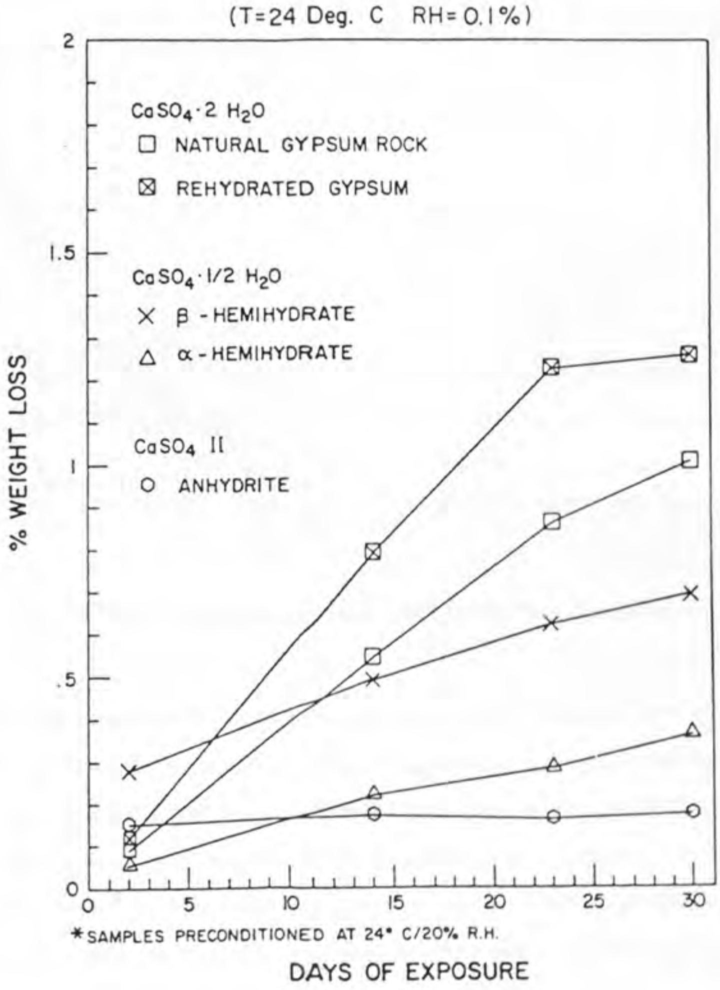


Figure 9.43 - Drying curves for samples dried over magnesium perchlorate

Turk et al. [357] performed controlled drying tests on various forms of gypsum. Drying curves were obtained by oven drying at temperatures ranging from 35-55°C. It was noted that reducing the relative humidity had the same effect on the removal of moisture as increasing the temperature. Figure 9.43 shows the drying curves obtained for drying with a desiccant (magnesium perchlorate). It can be seen that a constant weight plateau was not obtained and thus it was suggested that the desiccant was capable of removing the bound water of the sample. For the oven drying technique a constant weight was gained after 22h.

All of the drying tests were performed at low temperature. Although their paper gave a good insight into the chemical changes during drying and equilibrium between moisture and the phases of gypsum, no analysis of the rates of moisture extraction and product quality effects relating to crack formation from excessive moisture removal rates were investigated.

Kryuchkov and Komskii [222] devised an empirical method for calculating the convection drying time for gypsum moulds. Their relationships were based upon experimental data devised for the drying kinetics of water absorption and the original moisture content of the specimen. Figure 9.44 shows the results used, where U is the moisture content, N is the drying rate in the first period and τ is the drying time.

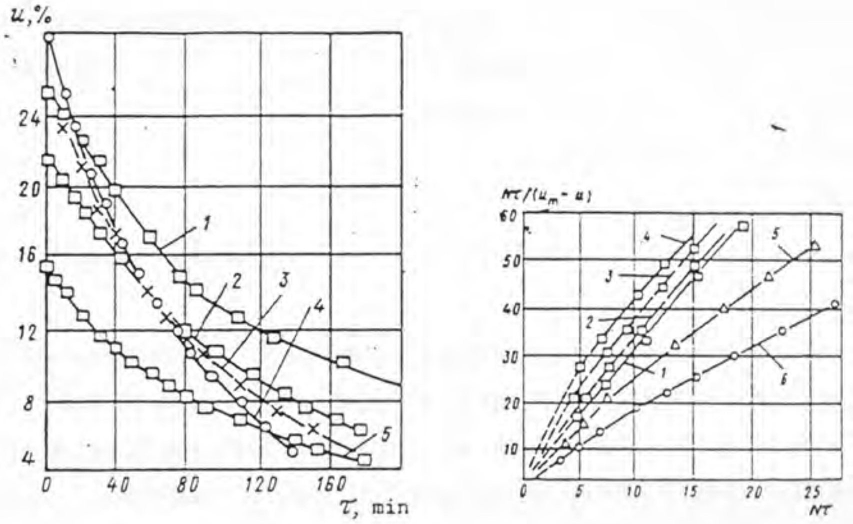


Figure 9.44 - Experimental results used for the empirical analysis

A temperature of 80°C was used with an air velocity of 2.4 m/s. The water content of the dry air entering the dryer was 16g/kg of dry air. Details of the exact experimental set-up, or the chemical composition of the sample were not disclosed. An empirical equation was devised from the drying data. The Reynolds, Nusselt and Hookman numbers were incorporated into the equation yielding an expression for the drying time. It was suggested that the error between calculated and experimental results of 14% was sufficiently low for estimating the practical drying time for the gypsum moulds. The methodology used is a typical case of an expression derived from purely experimental investigation using traditional mathematical techniques.

The error of 14% obtained could lead to serious overdrying in the worst case, which may affect product chemical/physical characteristics and other quality factors. The model also does not take into account any concept of product quality.

Szentgyorgyi and Orvos [344] presented details of an approximate method for the determination of the distribution of temperature and of moisture content in the falling rate period of drying of gypsum blocks, a typical example of a capillary-porous body. The method was based upon determination of the approximate temperature distribution as a function of location and time by varying the parameters of; weight of material, time, temperature, humidity and velocity of the drying gas.

During the first falling rate period moisture is removed and a critical moisture content is reached. From here onwards the material dries rapidly at the surface. It was revealed that the temperature distribution is very unstable and only the time averaged temperature distribution is consistent and can be reproduced. The formula for heating up the material and evaporation of the moisture is as expressed in equation (9.2).

$$\alpha\,(T_g - T_s) = \frac{M_d}{A} c_w \frac{d\overline{T}}{dt} + \Delta h_v \overline{M}(t) \quad (9.2)$$

Where, α = Heat transfer coefficient, g = Gas,
T = Temperature, s = Surface,
M = mass, d = Dry,
A = Area,
t = Time,
h = Specific heat of evaporation.

From equation (9.2) an expression of the temperature distribution within the material was developed based upon the mechanisms of heat and mass transfer. During the second falling rate period Szentgyorgyi noted that the evaporation front will recede into the deeper layers of the material. In the capillaries whose cross section are changing irregularly, and between these capillaries, the connection of the columns of liquid are interrupted at more and more sites in the material with decreasing moisture content. Thus at this stage the moisture does not diffuse in liquid form any more but only as vapour. Equations to describe the movement of the moisture front in the material and temperature profile were developed based upon an approximate method to determine the function of drying rate with time.

The method described was approximate and no comments were made concerning accuracy. The model was only concerned with the movement of the moisture and temperature profiles within the material and there was no consideration for product quality. The structure of the gypsum material used was not described and no relation was made between different chemical compositions. Turk [357] suggested that the drying characteristics of gypsum varies considerably with the nature of its chemical composition. The approximation model presented would thus be of a limited nature in a industrial process situation.

The work of Pijevsky [283] describes the kinetics of drying gypsum and ceramic building material. The study was aimed at establishing the effect of the heat carrier temperature, velocity and moisture content on the drying kinetics and material quality of gypsum. Tests were performed on plaster board of varying thickness. Figure 9.45 shows a kinetics drying curve for 8mm thick paper coated plaster board. The drying conditions were; temperature = 177°C, velocity = 3.8m/s, and the drying air had a moisture content of 14g/kg dry air. The following notation is used;

1 & 1' – Temperature of gypsum and paper board surface,

2 & 2' – Layer temperature at 2.8mm from surface, &

3 & 3' – Temperature at the centre of the material.

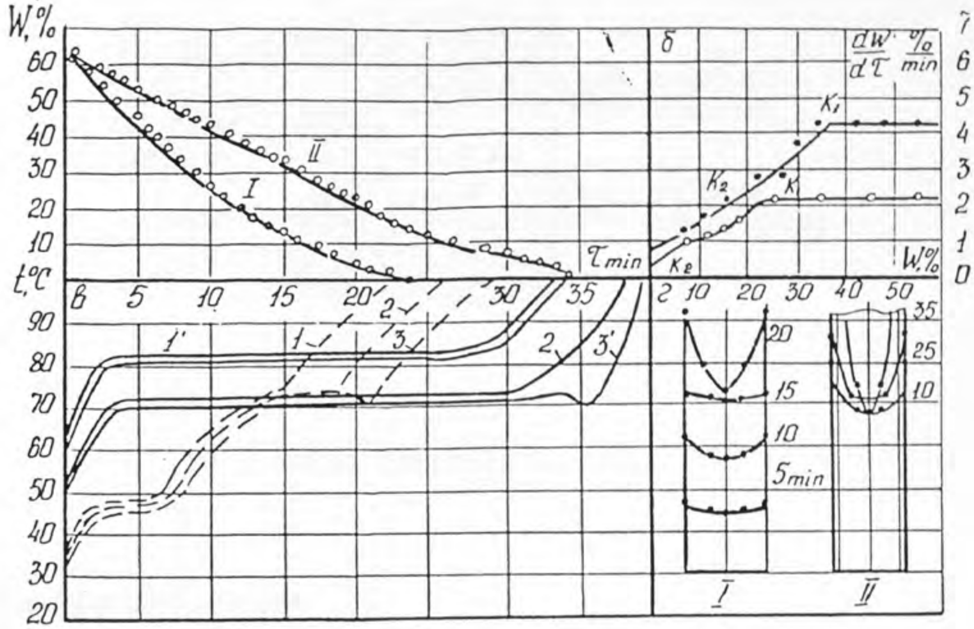


Figure 9.45 - Drying kinetics of 8mm gypsum plaster board

Pijevsky [283] reports that the paperboard creates a certain additional resistance to moisture removal from the material. The temperature of the gypsum core reinforced by the paperboard is much higher in the first drying period than the wet bulb temperature. For the paper resistance to be overcome the temperature of the gypsum surface grows up to the value corresponding to the vapour pressure which provides the vapour motion through the paperboard. It was noted that the vapour depression effect improves the kinetics of the material drying since the temperature increases within the gypsum core. As the material diffusion coefficient grows the conditions are created for intensification of the external heat exchange and the total drying process. No comments were made about product quality during drying; either chemical or physical characteristics.

Conventional Drying Experimentation

In an industrial situation there may be many parameters that effect the characteristics of the drying system. However, proceeding initial drying trials, a four input model was selected for investigation. Figure 9.46 shows the parameters studied.

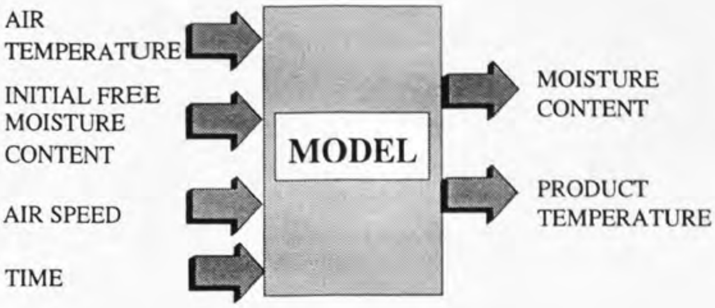


Figure 9.46 - Model parameters

Experimental Set-up and Data Collection

Drying trials were conducted using a custom made 9 kW electrical hot air dryer. Tests were carried out using 100mm lengths of 'Gyproc' cove. The oven temperature was controlled using an Eurotherm PID unit (range 0-200°C), fan speed set using a variable frequency speed controlled (0-150 Hz range), and an electronic data-logging balance allowed the product weight to be recorded throughput the drying process. Various amplifiers and noise filters were used to condition the weight signal, which was prone to electrical noise from the variable speed controller.

Drying characteristics were analysed for samples with moisture contents of 20, 25 and 30g of added water, subjected to air temperatures of between 100, 120, 140 and 160°C. Fan speeds of 35, 50 and 75 Hz were used. A double glazed vacuum insulated door allowed visual inspection of the product during heating. Unlike during microwave experiments, paper burning and bubbling were not noted during conventional drying tests due to there being no direct internal energy dissipation. The gypsum core temperature was monitored using a K-type thermocouple and comparison to the STA results and weight loss curves enabled an assessment of the degree of calcination to be established.

Figures 9.47 and 9.48 show a general view of the experimental rig and a sample on the balance tray, with air control and product monitoring thermocouples visible.

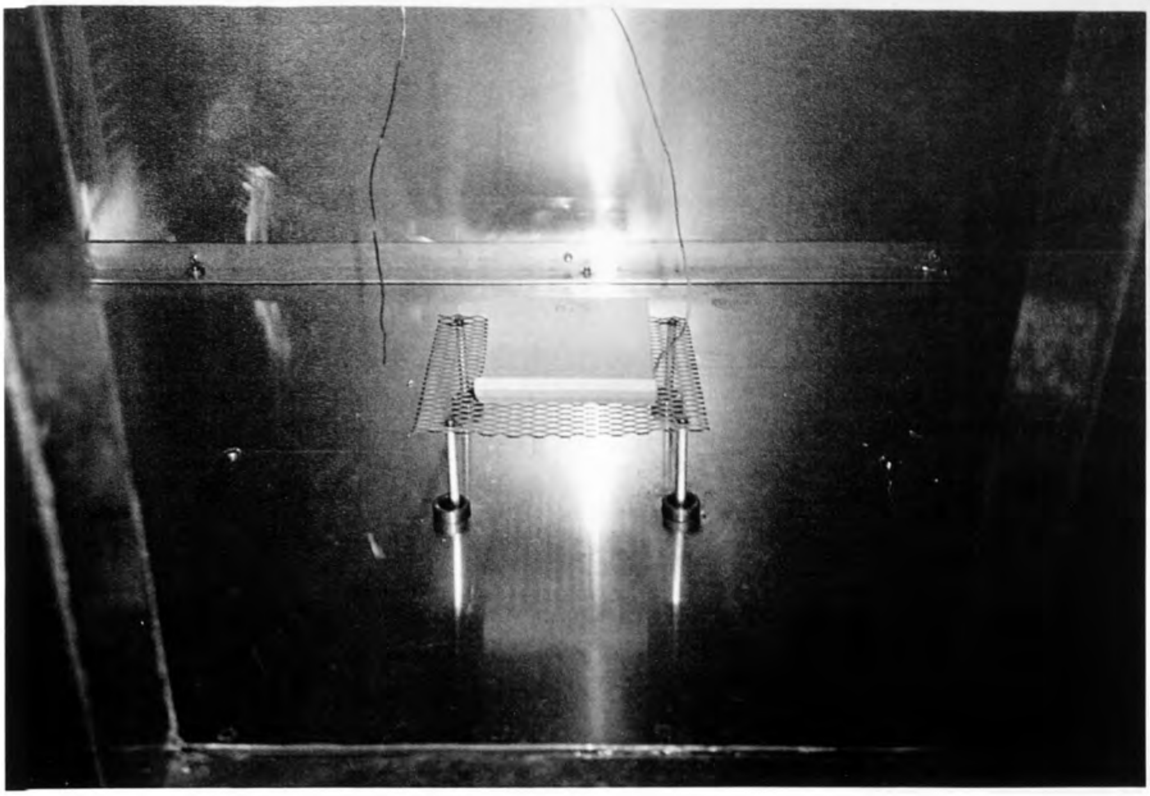


Figure 9.47 - View of product on balance table.

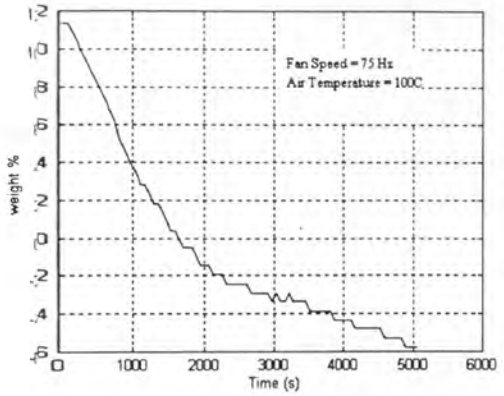
Figure 9.48 - General view of rig

36 basic drying tests were performed, with data recorded automatically every 30 seconds for approximately 6000 seconds. The repeatability of data was verified by duplicating basis tests and comparing results. Errors less than

5% were obtained proving accurate reliable information was attainable. Results were transferred directly to a PC version of MATLAB, where a third of the data was retained for model verification.

General Characteristics of Data Collected

The drying curves obtained showed a general characteristic form. Figures 9.49 to 9.52 show gypsum core temperature and moisture loss curves for typical results.



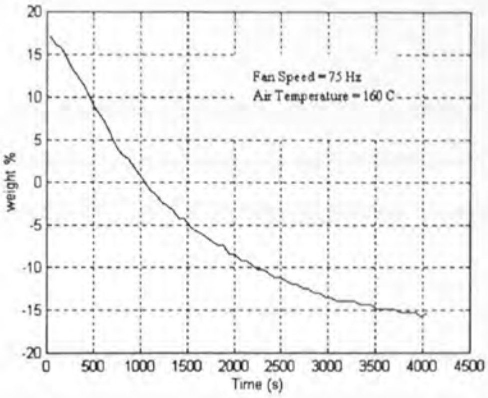
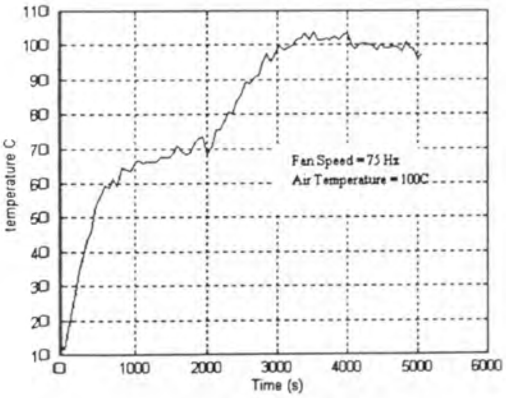


Figure 9.49 - Moisture curve for an air temperature of 100°C

Figure 9.50 - Moisture curve for an air temperature of 160°C



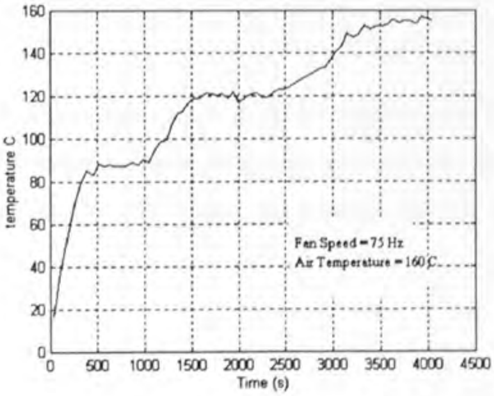


Figure 9.51 - Gypsum core temperature variation for an air temperature of 100°C

Figure 9.52 - Gypsum core temperature variation for an air temperature of 160°C

Results indicated that the rate of drying increased with increased temperature and fan speed. The moisture loss curves show distinct regions of the heating phase, constant drying phase and falling rate period, as described in the microwave modelling section. Analysis of the curves show that the heating phase is commonly very short and can only just be detected in Figure 9.49.

Comparison of Figure 9.50 and 9.52 showed that the temperature of the gypsum core rose steadily until 80°C. The heating phase is not readily detectable from the graph due to the relatively small size of the sample in comparison to the bulk air temperature within the chamber. The exact shape of the temperature profile was dependant upon moisture content, air speed and air temperature. The temperature levelled out as more moisture was lost from the product, indicating the start of the falling rate period. At zero free moisture content the temperature rose sharply again up to a plateau at 120°C. This sudden rise in temperature could be attributed to the loss of evaporative cooling, resulting in the formation of hemihydrite. The rise in temperature at 0% free moisture is substantial, and highlights the severe problem of controlling the drying process to prevent hemihydrite formation. Further weight loss continued as bound moisture was removed from the product and the temperatures rose again as anhydrite was formed.

Figures 9.49 and 9.51 show that calcination still occurred when the sample was subjected to temperatures of only 100°C. Figure 9.51 demonstrated that for this combination of initial product conditions and heating environment all free moisture had been lost before the core temperature reached 75°C, and a substantial amount of calcination occurred.

The results agree well when compared with the findings of the STA analysis carried out using a moist gypsum sample. However, due to the rate of gypsum temperature rise during convection tests, heating periods are not well defined in experimental results in comparison to the STA. The heating regions before the loss of bound water as indicated by a constant mass in the STA is not easily identifiable in experimental results due the simultaneous acquisition of energy to remove bound water, and the end of the falling rate period and loss of the remaining free water. Trials have suggested that bound water could be removed at temperatures as low as 60°C at the end of the falling rate period.

Comparing experimental results with previous studies showed that there was a large discrepancy between the exact region of chemical-physical phase changes within the gypsum during heating. This showed that, although similar materials were examined, the exact drying characteristics of the system are product dependant, thus highlighting the inaccuracies of using generalised models.

Development of Neural Network Model

The experimental data was divided into thirds. Two thirds was used for network training, the remainder for testing and network validation.

Modelling of Moisture Content

Based upon experience gained during the development of the microwave drying model three layer networks were implemented. A backpropagation architecture using a Levenberg-Marquardt algorithm for training was used. The number of neurons in the hidden layers and the mathematical form of the transfer functions were varied during development. A linear output transfer function was utilised with all networks. The goal of the network was not to minimise the sum square error, but to compromise between error and the capability of the network to model non-training data.

The most successful network produced consisted of a three layer structure with 8 hidden neurons within two layers of tan and log transfer functions. The network underwent 100 training epochs. Figures 9.53 to 9.58 show a comparison of modelled data and experimental data for cases where the model was subjected to input data which was part of the training set.

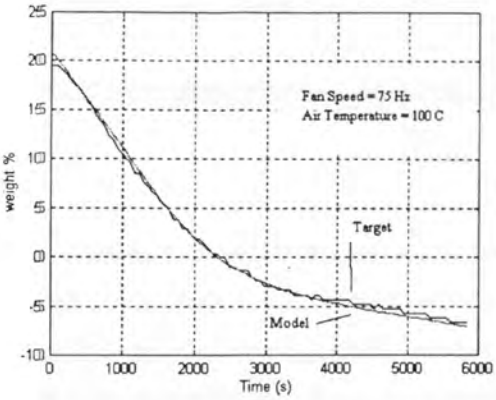


Figure 9.53 - Comparison between model and training data

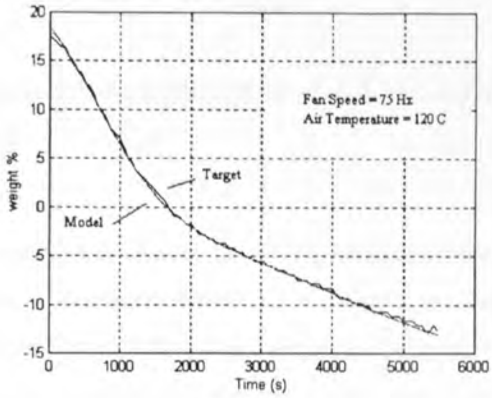


Figure 9.54 - Comparison between model and training data

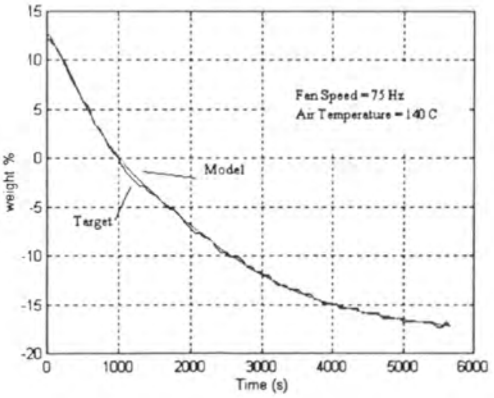


Figure 9.55 - Comparison between model and training data

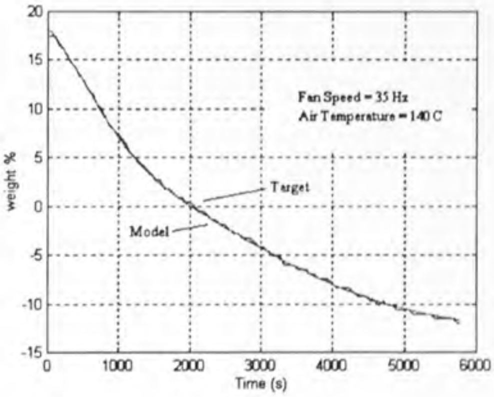


Figure 9.56 - Comparison between model and training data

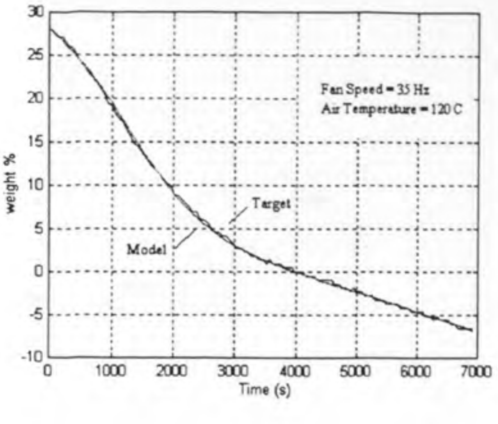


Figure 9.57 - Comparison between model and training data

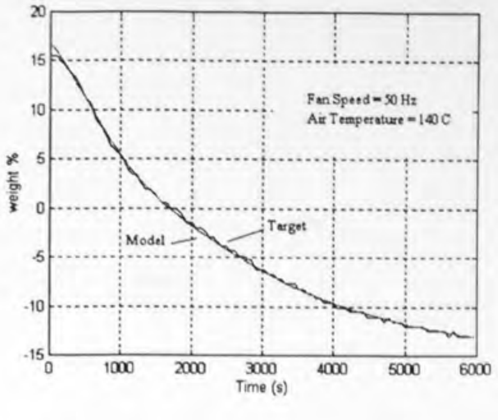


Figure 9.58 - Comparison between model and training data

Figures 9.53 to 9.58 shows that the neural network can successfully model the drying characteristics when presented with input data which formed part of the training set. A maximum error of 1.5% weight was calculated, although the target proportion of errors were below 0.5% weight. Figure 9.59 shows a histogram of training error. As with modelling microwave drying characteristics, slight errors were noted during the initial stages of heating, and small discrepancy at very low moisture contents. However, the model was perfectly adequate in assess the time of zero free moisture content.

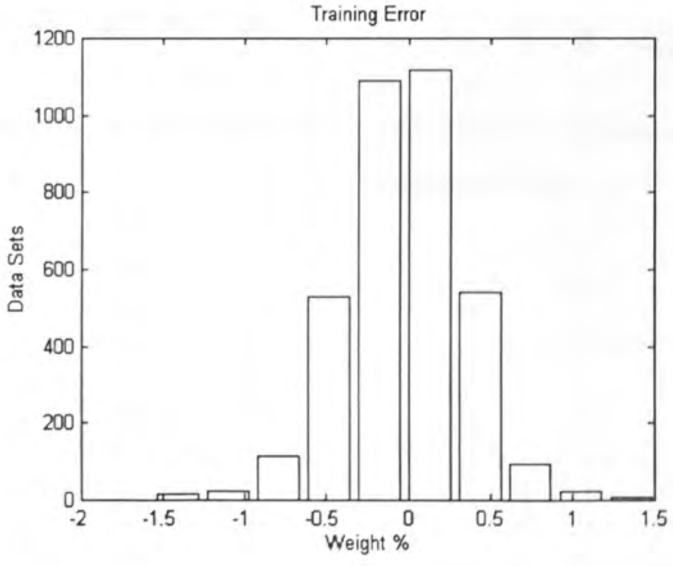


Figure 9.59 - Histogram of error between model output and training data

Figures 9.60 to 9.69 show a variety of comparisons of non-training target data and the model output.

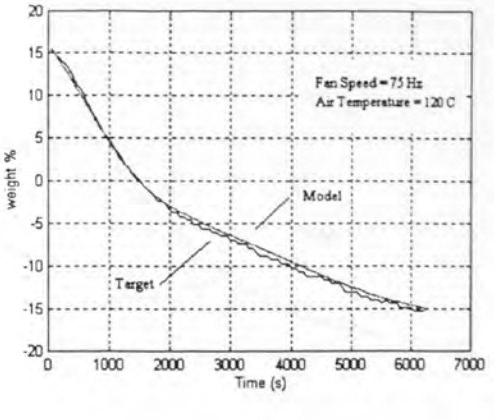


Figure 9.60 - Comparison between model and experimental data

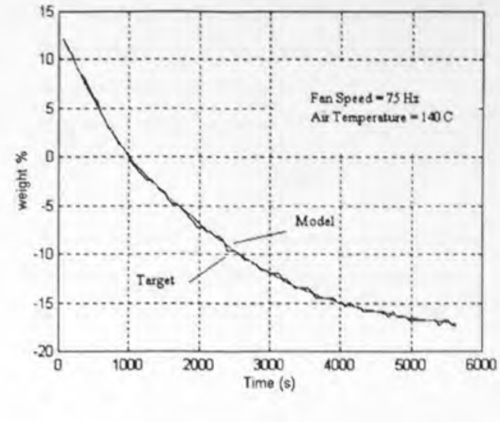


Figure 9.61 - Comparison between model and experimental data

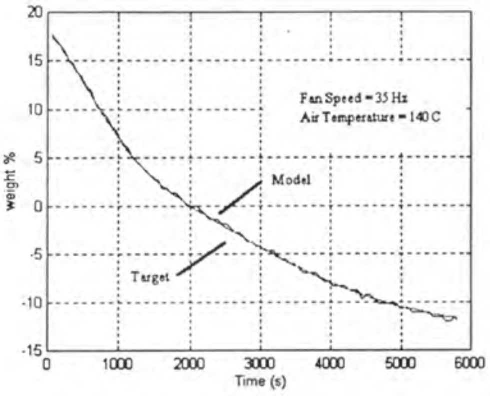


Figure 9.62 - Comparison between model and experimental data

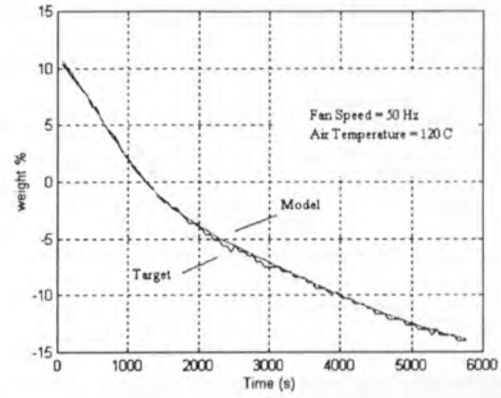


Figure 9.63 - Comparison between model and experimental data

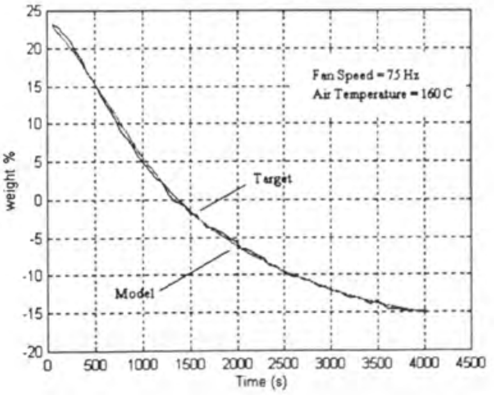


Figure 9.64 - Comparison between model and experimental data

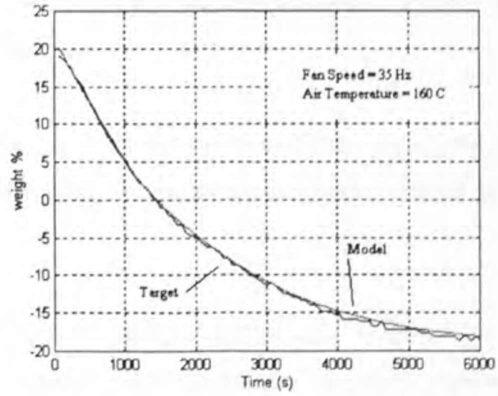


Figure 9.65 - Comparison between model and experimental data

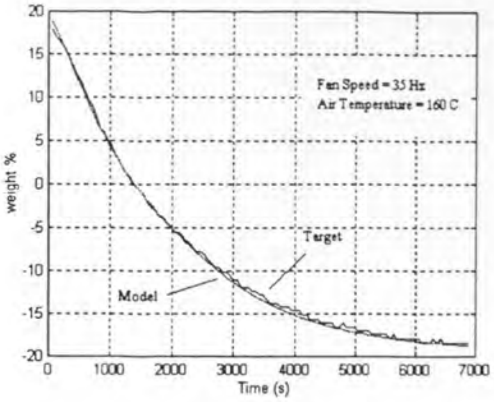


Figure 9.66 - Comparison between model and experimental data

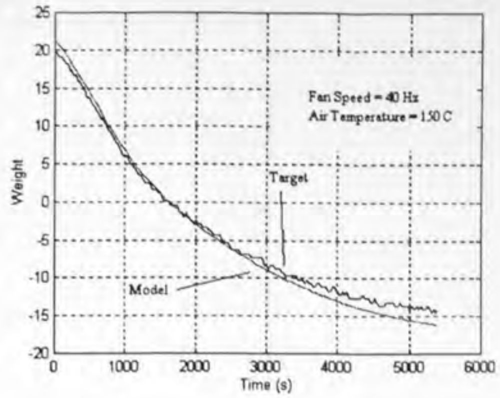


Figure 9.67 - Comparison between model and experimental data

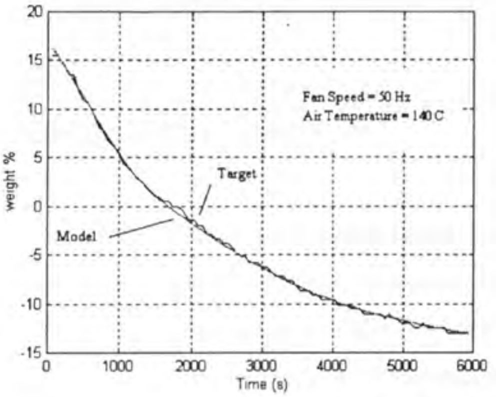


Figure 9.68 - Comparison between model and experimental data

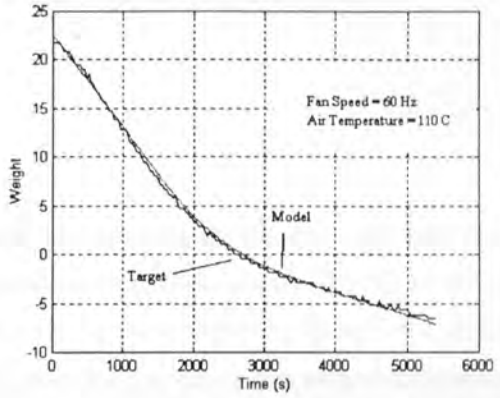


Figure 9.69 - Comparison between model and experimental data

The figures displayed above represent a variety of comparisons of model output to target data which was not part of the training set. Figure 9.70 shows a histogram of error. A maximum error encountered was 2.33 % by weight, although the largest proportion of errors were below 0.5 % weight.

Discrepancies in the comparison of model and target data were of a similar nature as those encountered during the simulation of training data i.e. during the initial stages of heating and during the removal of bound moisture from the product.

Although a 6th order Butterworth filter was used to reduce high frequency electrical noise from the fan speed controller, a small degree of noise was present in the recorded weight signal. The networks capability to effectively smooth noisy data was demonstrated and the underlying fundamental characteristics were successfully simulated e.g. Figure 9.62.

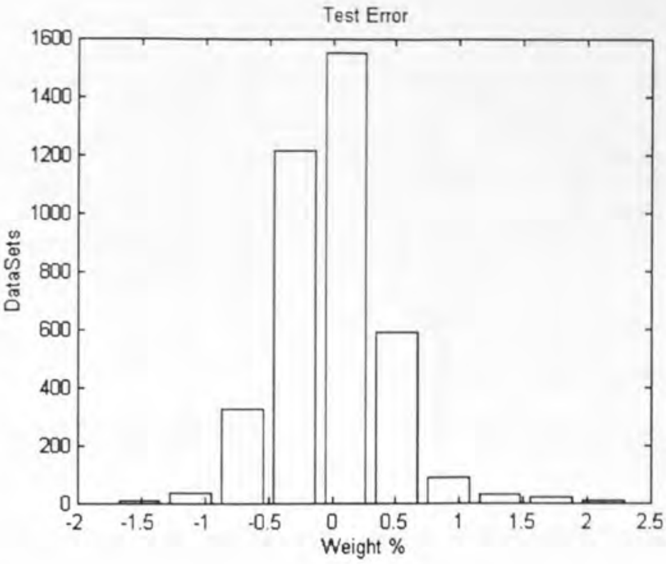


Figure 9.70 - Histogram of error between model output and non-training data

Modelling of Material Temperature

Two network architectures were implemented during the analysis; back-propagation and radial basis structures. Computer memory problems were encountered using the radial basis technique and the 486 DX-66 PC with 20 Mb of RAM was insufficient to allow the training algorithm to operate effectively. Experts within the field suggested that a system with about 65 Mb was required to simulate the proposed system using radial methods due to the methodology of the training iterations [89].

A variety of two layer networks were implemented as shown in Table 9.9. A scaling factor of 170 was used to reduce the size of the temperature data before training enabling the application of a Tan or Log transfer function. The same scaling factor was used with the network output to produce temperature values.

TEST	LAYERS	NEURONS	TRAINING EPOCHS	SUM SQUARE ERROR
NET1	TAN-LOG-TAN	10-10	100	1.89
NET2	TAN-LOG-TAN	12-12	70	1.48
NET3	TAN-LOG-LOG	12-12	70	3.60
NET4	TAN-LOG-LOG	8-8	90	5.42
NET5	TAN-LOG-LOG	10-10	120	0.93

Table 9.9 - Summary of most significant network training

Although many of the networks produced were capable of modelling training data to a high degree of accuracy, poor results were noted in several cases when the network was subjected to non-training data. Figures 9.71 to 9.78 show a variety of comparisons of training target data and the model output for NET5.

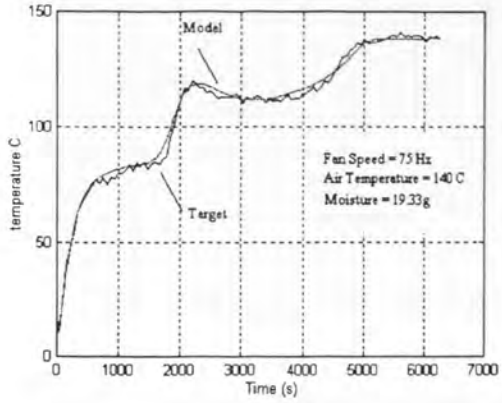


Figure 9.71 - Comparison between model and training data

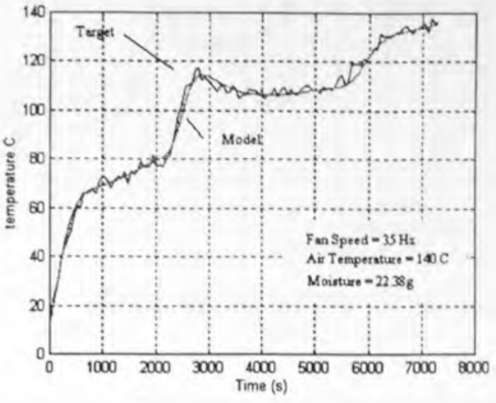


Figure 9.72 - Comparison between model and training data

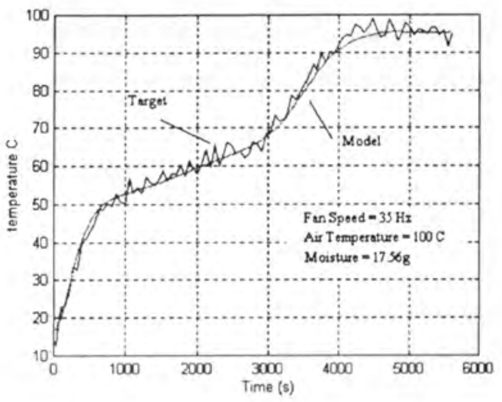


Figure 9.73 - Comparison between model and training data

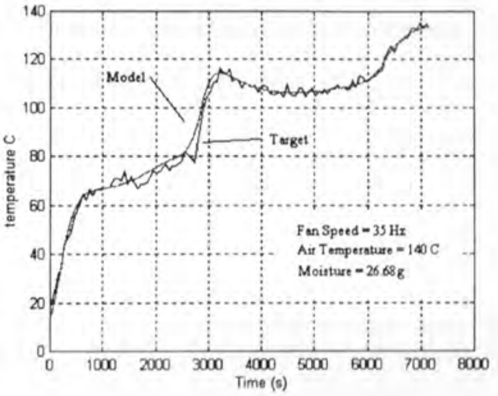


Figure 9.74 - Comparison between model and training data

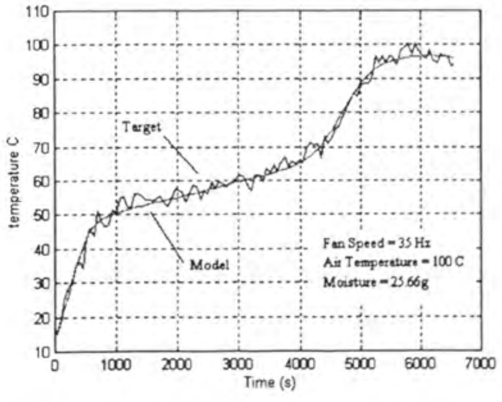


Figure 9.75 - Comparison between model and training data

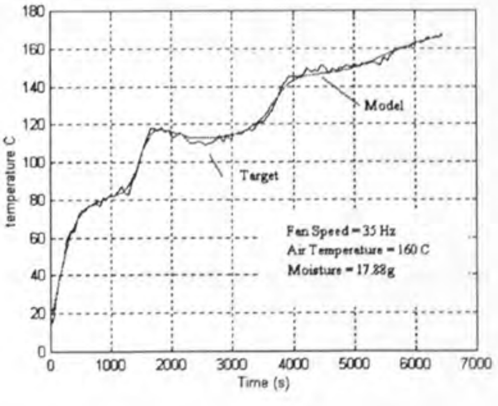


Figure 9.76 - Comparison between model and training data

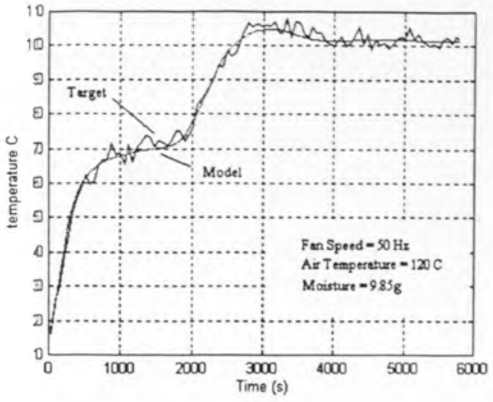


Figure 9.77 - Comparison between model and training data

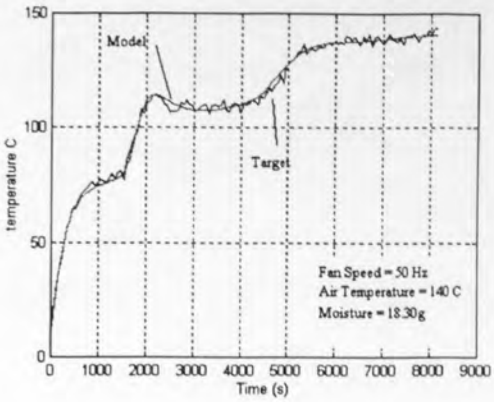


Figure 9.78 - Comparison between model and training data

Figures 9.71 to 9.78 shows that the network was capable of modelling data which was part of the training set. The maximum error encountered was 16.7°C, although in many cases results with errors of lower magnitude, typically less than 4°C, were obtained. Figure 9.79 shows a histogram of the error for 3530 training sets.

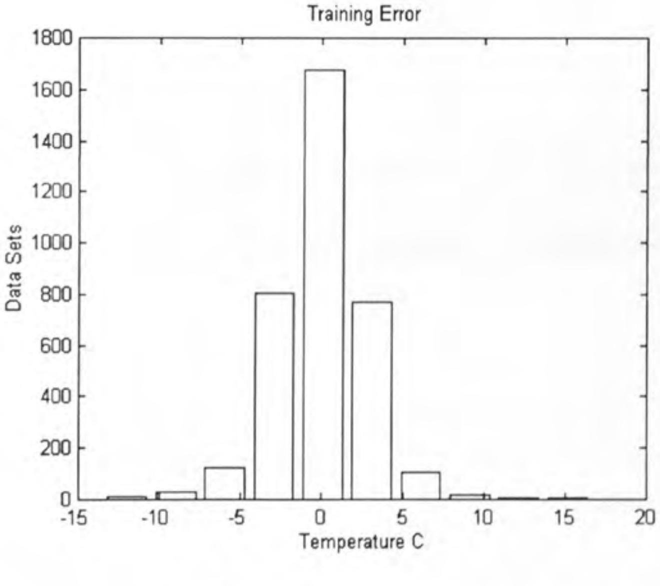


Figure 9.79 - Histogram of training error

Figures 9.80 to 9.85 show a variety of comparisons of model output and target data which was not part of the training set.

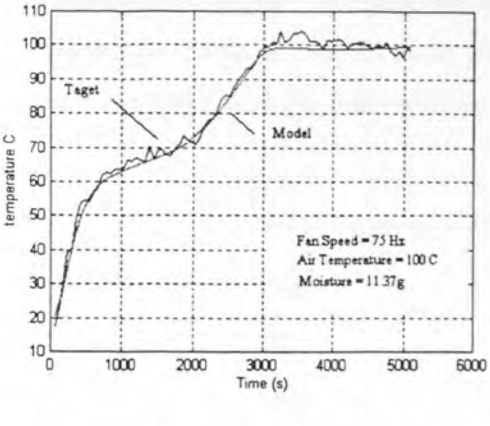


Figure 9.80 - Comparison of model and non-training data

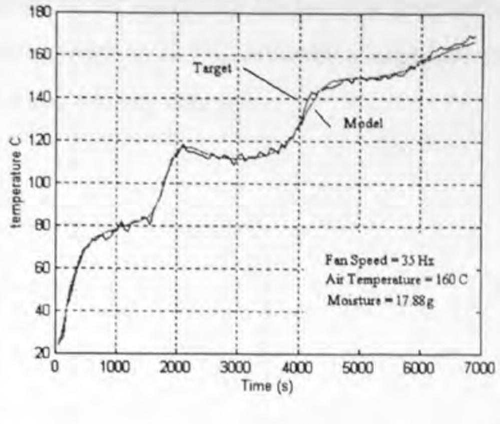


Figure 9.81 - Comparison of model and non-training data

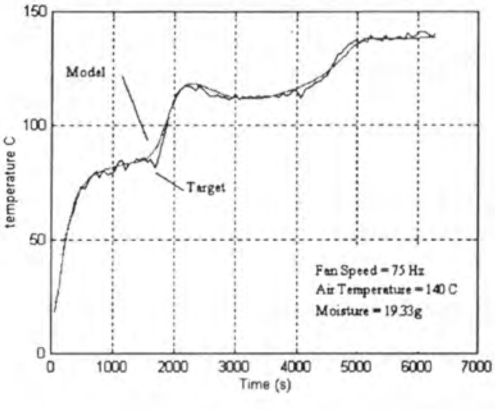


Figure 9.82 - Comparison of model and non-training data

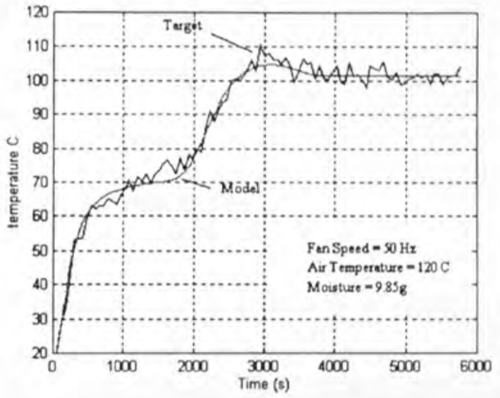


Figure 9.83 - Comparison of model and non-training data

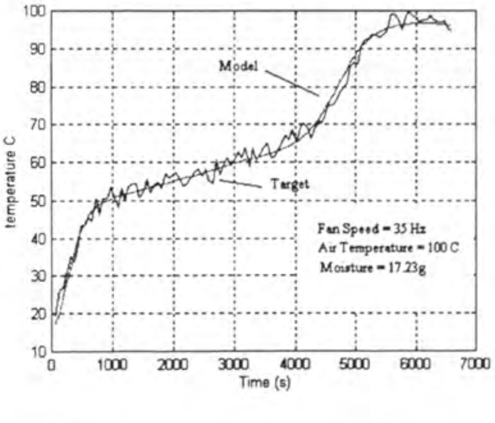


Figure 9.84 - Comparison of model and non-training data

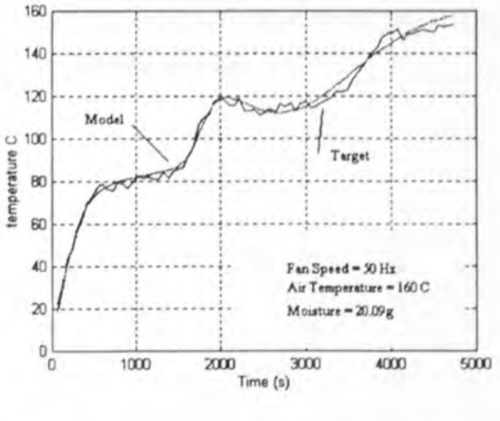


Figure 9.85 - Comparison of model and non-training data

The above figures show that the network was capable of modelling the underlying fundamental properties of the non-training data. Errors between output and target value were as high as 15.8°C, although a large proportion of cases were less than 5°C. Figure 9.86 shows a plot of error for non-training data sets.

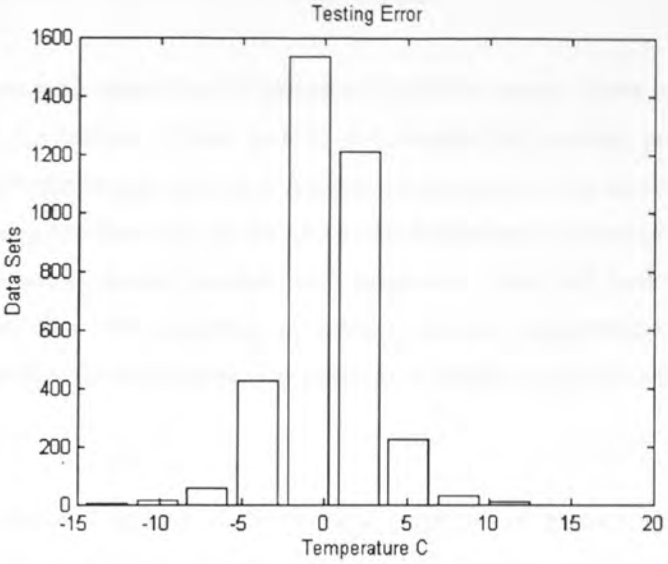


Figure 9.86 - Histogram of error with non-training data

The experimental data contained a significant portion of noise caused by electrical interference, mainly from the fan speed controller. Shielded thermocouples and signal suppression circuits were tested and proved ineffective. However, the above graphs show that the neural network was capable of effectively modelling the underlying fundamental properties of the signal. Further training was considered inappropriate since the network would start to model the noise component, thus resulting in a larger error when simulating non-training data.

Initial trials using radial basis networks showed that the network was capable of smoothing data, although a more accurate model could not be produced due to computer memory limitations. Further development using this technique may produce a more accurate model that using back-propagation methods.

Conclusions

The following conclusions can be drawn from the neural network modelling of the drying characteristics of paper coated gypsum cove subjected to microwave and hot air regimes;

1. Comments have been made concerning the selection of a drying system. Points assessed included the nature of the model and application, product quality, data acquisition, material properties required and the characteristics of different heating processes. A paper coated gypsum cove material subjected to microwave and convection heating mediums was selected due to the diverse range of product and drying characteristics. The decision was made to develop a model with parameters which will have direct meaning to general industrial engineers. Thus the modelling of kinetics was not implemented and parameters such as temperatures and air flow rates were used. The inclusion of quality terms within the model was an important factor.

2. Literature and experimental analysis of the chemical properties of gypsum have been examined. It was concluded from previous work that gypsum was very heat sensitive and its physical properties changed markedly with chemical phase. Temperature STA and dielectric properties were experimentally analysed to gain an understanding of the drying characteristics.

3. The results of temperature phase STA tests and investigation of the dielectric properties of gypsum with respect to moisture and temperature have been described. Brief comments have been made on the findings of these tests and the influence on the heating characteristics of gypsum, including mass loss and product quality defects during drying. Results have shown that the gypsum cove is extremely heat sensitive and accurate control of the drying process is required to prevent the loss of bound moisture. Furthermore, results suggested that the physical form of the gypsum had a direct affect on the chemical-phase and drying characteristics thus highlighting the inefficiency of a generalised model. The STA analysis showed distinct phase changes;

Removal of free water	35-130°C	Formation of hemihydrate	130-140 °C
Formation of soluble anhydrite	160-180°C	Formation of non-soluble anhydrite	200°C

4. Dielectric properties showed typical characteristics increasing with rising product moisture content. Loss factor was found to be directly proportional to the gypsum's chemical phase, decreasing upon formation of the hemihydrate while remaining significantly higher in the anhydrate and dihydrate states. Analysis of the magnitude of the loss factor and pentration depth has been described highlighting that gypsum is susceptible to electromagnetic microwave energy during all phase states. Furthermore, results showed that gypsum was calcinated using microwave energy thus contradicting previous literature which suggested that the heating was self limiting upon the removal of all free moisture.

5. The theoretical principle of microwave and convective heating and traditional modelling techniques have been briefly discussed highlighting the complexity, application and problems of traditional methods.

6. The microwave experimental set-up has been described including equipment utilised, parameters studied, and procedures conducted. General experimental drying characteristics have been examined and related to theoretical principles of the process and the influence of material properties. Comments were made concerning product quality in the form of paper burning, bubbling and calcination during microwave heating.

7. The development of neural networks to model weight loss, and product quality (burn and bubbling) have been described including details of network architecture, training and verification using experimental data. A three input model using parameters of magnetron power (0-6kW), product free moisture content (0-60g) and time (0-1500s) was implemented. Two and three layer back-propagation networks using Tan and Log transfer functions with between 8 - 10 neurons in the hidden layer were constructed. A Levenberg-Marquardt training algorithm, an approximation of Newton's method, was utilised in each case.

8. Results showed that the networks were capable of simulating the microwave drying characteristics to a high degree of accuracy. Errors up to 6% and 7.5% were encountered when modelling moisture loss and paper bubbling respectively. However, errors of up to 20% were encountered when modelling paper burning. It was noted that the accuracy of the experimental data severely influenced the accuracy of the model produced. Methods to improve accuracy have been addressed including further training, analysis of data and refinements to experimental methods.

9. The modelling of the convection drying of gypsum has been described. Previous studies relating to hot air drying were reviewed highlighting techniques, findings and the accuracy of results. Experimental analysis has been conducted and comments made concerning equipment utilised, methods and parameters involved.

10. A four dimensional input model was successfully implemented using neural networks to model moisture loss and product temperature characteristics during convective drying. Input parameters included product moisture (20-30g), air temperature (100-160°C), circulating air speed (35-75 Hz variable frequency) and time (0-6000s). Two and three layer back-propagation networks with Tan and Log transfer functions with between 8 - 10 neurons in the hidden layer were implemented. Radial basis structures were tested but problems were encountered due to limited computer memory. A Levenberg-Marquardt training algorithm was used in each case and network inputs for the temperature network were scaled using a factor of 170.

11. The neural models produced were capable of predicting product weight to an accuracy of 0.5%, while temperature generally within 5°C. The models clearly showed that the network was capable of predicting the underlying characteristics of the data although a high degree noise was present in the raw information.

12. The work conducted has shown that artificial neural networks offer a convenient platform for capturing the non-linearity and dynamics inherent in drying systems. Results have shown that the neural models could achieve a high degree of accuracy within the parameter ranges analysed. Furthermore development was straightforward and required only a basic knowledge of the system under investigation.

CHAPTER 10

CONCLUSIONS

Introduction

Industrial drying processes have been the focus of this research. There is a great variety of drying technologies available, a variety which continuous to expand through development of new techniques, products, processes and technology. The high energy consumption associated with drying and the development of drying technologies warrant an energy inventory and analysis of various types and features of drying processes.

This thesis presents work investigating the energy utilisation and efficiency of industrial drying processes, and the modelling of drying characteristics using artificial neural networks, with reference to control and system analysis. Not only is this thesis a representation of the work undertaken by the present author, it also provides a comprehensive literature review of previous, current and planned work in the area.

Background

Chapter 1 provided an introduction to drying processes. The generalised objectives of the work have been described and a brief outline of the thesis chapters are detailed showing the progressive flow of work from the analysis of literature, conceptual ideas, development and description of results and the conclusions reached.

An introduction to the theoretical principles and fundamentals of drying and the investigation of equipment types, design, construction and general operating principles was the focus of Chapter 2. Drying has been defined and comments made concerning the reasons for drying and methods employed in such processes. The basic fundamentals have been described including reference to the heating, constant drying and falling rate periods. Although mathematical forms of heat and mass transfer were not addressed reference was made to a variety of literature. Details of psychrometric properties governing evaporation and their effects on the dynamics of drying were described. Moisture content has been defined and a comparison made between wet and dry weight basis. The importance of defining the exact nature of the moisture content was demonstrated.

Types, structure, and specific operating principle of drying equipment have been addressed. Previous methods of classifying equipment and materials was assessed and it was discovered that there is a lack of common approach in previous studies. Results of a postal survey of UK equipment manufacturers were described. Little published literature was located relating to the nature of equipment manufacturers in the UK. Comments were made concerning the types of dryers manufactured and product sectors where sales were focused. Results showed that the chemical, food, textile and mineral sectors were common sales areas for equipment manufacturers, demonstrating that a wide variety of drying systems are employed within these industries. A smaller number of companies supplied equipment to the paper and timber industry.

Criteria concerning the selection of a drying system have been addressed including drying characteristics of both materials and equipment. Problems associated with selection were described together with the application of expert system technology to dryer selection. Communication with experts within the field expressed that expert systems were unlikely to fully replace small scale testing and decisions made on past experience. However, it was envisaged that these systems could reduce development time and costs by focusing in on specific equipment areas at the onset of a project.

Energy Utilisation and Efficiency of Drying Processes

Chapter 3 described energy related topics with reference to drying systems. Since the two oil crises in the 1970s previous literature and modern thinking emphasised that energy is an important commodity which is used widely throughout industry. Overall industrial energy trends have been examined and since the 1970s the quantity of energy used in industry has reduced dramatically. However, overall industrial production has increased indicating that more efficient processes are being implemented.

It has been proposed that an understanding of where energy is used and technologies available is essential before plans can be made concerning the implementation of energy efficient concepts. To enable comparison of processes and equipment the energy efficiency and specific energy consumption of drying equipment has been defined.

Published figures indicated that energy costs can represent approximately 80% of the total costs incurred over the equipment lifetime, Thus implementation of energy efficient measures could result in significant cost and environmental savings.

It has been estimated that between 6000 to 8200 million tonnes/year of carbon dioxide, a contributing 'green house' gas, is released by industry on a global scale. Approximately 2% of these emissions are from the UK. In 1994 a 'Climate Change Programme' was unveiled by Government stating that the 1990 level of CO_2 release will be regained by the year 2000. 158 Mt of CO_2 was emitted in 1990, although during the last five years emissions have decreased reaching 151 Mt in 1993. The Department of the Environment has estimated that UK industry is on target for achieving this goal, and further savings of 6 - 13 million tonnes of CO_2 below the 1990 level may be realised by the year 2000.

Previous estimates of the thermal efficiency of drying equipment varied widely, although in general many studies failed to describe exact processes, equipment or product type, thus providing limited scope for further application in an energy estimate. General energy saving measures have been briefly described highlighting many aspects from control to heat recovery systems and benefits of the performance monitoring of plant.

Previous studies concerning the energy consumption for drying processes in the UK have been examined in detail. Methods, results and inaccuracies have been described. Data was compared demonstrating that a trend in dryer energy consumption could not be established. Results showed that the analysis of the energy utilised for drying is not a topic for regular assessment. Furthermore, a complete review of the industry has not been performed since 1982. Based upon this information an energy update using a method proposed by Baker and Reay was performed. Points addressed included the aims of the update, selection of a methodology and details of the calculations performed. Comments were made concerning the total and drying energy consumption within six sectors highlighting large consumers of energy for drying and general trends over the past decade. Results showed that the overall energy consumption within industry fell dramatically during the early 1980s, reaching a plateau in about 1985. Drying energy consumption also reduced between 1980 and 1982 reaching a minimum around 1982. However, during the latter part of the 1980s drying energy consumption increased steadily, and represented approximately 18% of the total energy consumed in 1990 i.e. equivalent to 28 million tonnes of CO_2 emitted. The chemicals, food building materials and paper industry were shown to be large energy consumers. Moreover, a large proportion of the total energy is used for drying within the paper, food and chemicals industry. Less energy was consumed for drying within the buildings materials and textile industry, although still a significant proportion of the total.

Although the updated figures were based on a previous methodology, which assumed that the energy efficiency of equipment had not changed radically over the last decade, data was considered to yield sufficient information regarding a general overview of the variation and magnitude of energy utilisation for drying processes. Using results of the update study, examination of conclusions drawn from previous studies and information from industry, an introduction to the analysis of drying processes within industry has been presented. Details examined included aims and objectives, and the selection of areas to focus efforts. Comments have been made concerning the methods employed in data collection and proposed benefits of the study. The decision was made to use industrial data and aim the results at process engineers in industry, research consultants and equipment manufactures who have a responsibility within their organisation for drying processes. The intention is to simulate ideas, introduce concepts of energy efficiency, and energy targets in the industrial drying field by analysing industrial applications.

The energy utilisation and efficiency of drying processes have been examined in detail in three industrial sectors;

- Ceramics, (including building materials such as bricks, plaster board, abrasives and refractories),
- Timber, &
- Paper.

In each sector the industry has been described including details of production trends, equipment utilisation and product ranges. Comprehensive results of the analysis of the specific energy consumption of equipment and trends over the last decade have been examined. Comparisons have been made to previous studies involving energy utilisation or efficiency and comments made concerning energy targets, effectiveness of previous energy efficient measurers and predicted energy demands. Recent developments in drying technologies and energy saving measurers applicable to processes within the sector have been addressed. Where appropriate evaluation has been made regarding energy savings and additional benefits such as productivity, quality and environmental aspects.

Ceramics Industry

A detailed examination of the energy utilisation and efficiency of drying processes within the ceramics industry has been performed and is described in Chapter 4. The industry has been divided into four subsectors; sanitaryware, tiles, tableware and electrical/technical ceramics.

SANITARYWARE

The sanitaryware industry has been analysed and published figures have shown that the production of sanitaryware products has fallen during the last five years due to a slump in the house building market. A survey conducted by direct communication with industry showed that direct fired chamber dryers, heat pump systems, tunnel dryers and vacuum dryers were commonly being utilised. Average thermal efficiencies of chamber dryers were found to be approximately 10%. Space heating techniques for drying processes were found to be widely practised, however, limited data was found concerning energy utilisation for space heating techniques due to that lack of monitoring. A detailed audit of an industrial manufacturer showed that the thermal efficiency of a space-heating system was about 13%. Many previous studies discounted energy used for space heating during analysis of the sector.

Using industrial data collected an estimated total SEC of 15.6 GJ/t of finished product was calculated for sanitaryware, of which 9.7% was electricity. An average drying SEC of 2.25 GJ/t was estimated, representing an overall drying efficiency of 12.5%. Heat pump systems were found to consume 0.91 GJ/t.

It was estimated that drying utilises about 14% of the energy consumed within the sanitaryware industry. An estimated 3.7 million GJ was consumed in 1992, implying that 0.52 million GJ was used for drying processes.

Comparison to previous estimates showed that total and drying SEC figures have decreased over the last decade. Figures indicated that greater savings have been achieved for drying equipment in comparison to other processes within the sanitaryware industry. Total SEC was estimated to have reduced by 67% since 1978, while drying SEC was estimated to have reduced by 85%. The closure of older plant due to the declining market, improved monitoring, control and energy saving measurers may have contributed to this trend.

TILES

The tile industry has been examined and published figures have shown that the production of tiles has decreased since the mid 1980s. An estimated 13.65 million square meters were produced in 1991. A survey of UK manufacturers showed that traditional techniques of forming/drying still dominate, representing an estimated 82% of the total production. The majority of industry used tunnel drying systems, with the exception of a few low volume hand crafted producers.

Energy calculations were performed based upon detailed figures from industry. An estimated 1.8 million GJ of energy was consumed for tile manufacture in 1990, yielding a total SEC of 0.132 GJ/m^2, or approximately 13.04 GJ/t. Calculations showed traditional drying methods consumed 3.13 GJ/t while roller methods consumed 2.94 GJ/t. Thermal efficiencies were estimated at 25% and 26% for traditional and roller methods respectively. Results demonstrated that the roller methods offer little energy benefits in comparison to traditional techniques due to the low efficiency of spray drying systems.

Industrial data showed that up to 68% of the energy supplied for spray drying can be derived from waste heat, which would reduce the drying SEC by 63%. In 1991 an estimated 0.43 million GJ was consumed for drying, represent 23% of the total energy used. If waste heat systems on spray drying equipment were fully implemented in the industry an estimated yearly consumption of 0.17 million GJ would be realised, representing 9.4% of the total energy, a reduction of 59%. Figures have shown that there is a large potential for achieving energy savings by implementing heat recovery systems, especially on spray drying plant. Data has demonstrated that savings in the order of 1.8 GJ/t could be realised, representing 0.26 million GJ/year and 23 kt CO_2 emitted based upon 1991 figures.

Comparison with previous studies showed that the total and drying SECs have fallen slightly since 1980, with the total and drying SEC reducing by 22% and 15% respectively. The implementation of roller techniques and closure of inefficient plant will have attributed to this trend.

TABLEWARE

The tableware industry has been examined including bone china, porcelain, earthenware and stoneware products. An estimated total output of 100,839.5 tonnes of tableware was manufactured in 1993. Analysis of sales figures, the price index variation and discussion with industry suggested that the production of chinaware has not varied significantly over the last decade. The validity and accuracy of the 1980 chinaware figures are questionable, and production may have been underestimated. Direct communication with industrial companies estimated that 18% of the total flatware production is manufactured by isostatic pressing techniques.

A survey of industry showed that a wide variety of drying equipment was utilised within the industry and included continuous tunnel units, mangle style dryers, hot air chambers and custom built systems. Operating conditions varied considerably depending upon the nature of the product, and drying temperatures ranged from 40-160°C. A survey of manufacturers showed that the thermal efficiency of drying equipment varied from 2.2 % to 45% for a direct chamber and IR system respectively. Spray dryers producing granular materials for pressing were found to be 20-22% efficient.

Analysis of specific process techniques showed that the total energy consumed for producing earthenware by isostatic pressing is only slightly less than using traditional techniques due to the inefficient spray drying methods. However, significant energy savings of up to 96% were demonstrated for chinaware in comparison to traditional plastic forming methods. Drying SEC for isostatic pressing techniques were estimated at 2.73 and 2.48 GJ/t for earthenware and bone china respectively. Traditional techniques using a greenware process, plastic forming or slip casting, consumed an estimated 3.75 GJ/t for drying earthenware and a some what higher figure of 70.9 GJ/t for bone china. The large consumption for the traditional drying of chinaware, and hence significant saving by pressing methods, is due to very low thermal efficiency of traditional equipment. Moreover, drying techniques for chinaware consume more energy than that for earthenware due to the more conservative drying regimes, the schedule being directly related to material composition and high value of china products.

Calculations showed that the proportion of the total energy used for drying varied from 5% for a IR system drying hotelware to 48% for the production of bone china. An assessment of energy consumed for mould drying could not be made due to the lack of data although thermal efficiencies of 48% were recorded.

An estimated 3.1 million GJ was consumed for drying processes, representing 43% of the total energy consumed in 1993. Comparison to previous studies showed that energy savings have been achieved within the tableware sector. Total SEC have reduced from 249 GJ/t in 1978 to 146 GJ/t in 1993 for chinaware, while those of earthenware have reduced by 80%. Drying SEC for chinaware production have only decreased slightly over the last decade, although approximately 64% less energy is consumed for drying earthenware.

Figures have demonstrated that significant savings could be achieved by implementing isostatic pressing techniques for bone china manufacture. If all bone china and earthenware was manufactured by isostatic pressing methods a drying energy saving of 3.3 million GJ/year could be realised, a reduction of 92% of the energy consumed in 1995. This corresponds to a reduction in CO_2 emissions of 0.3 million tonnes based upon 1995 figures. Additional benefits could be achieved due to the elimination of mould preparation and subsequent drying stages. The survey showed that the largest proportion of savings have been achieved by improved kiln operation and substantial savings could be achieved through implementation of energy efficient measures on drying equipment.

ELECTRICAL/TECHNICAL CERAMICS

The electrical ceramics market was found to be very diverse in nature. Examination of published figures and information from trade organisations showed that the production of electrical and technical ceramics has decreased by approximately 65% since the 1970s, and production was estimated at 12154.2 tonnes in 1995.

Turning, pressing and extrusion of either plastic clay or spray dried granules were found to be common manufacture processes. Industrial data showed that chamber dryers dominated the UK industry, with direct, indirect and dehumidifier systems being utilised. Space heating techniques were used by some manufacturers. Drying times were long, and industrialists indicated that reject rates up to 70% were common due to poor quality drying.

Energy figures were calculated from industrial data. Total SEC values were estimated at 100 GJ/t, which were considerably higher than 50 GJ/t suggest in 1990. There was considerable deviation between published sources of the estimated total energy consumption within the industry. Limited data concerning the energy utilisation of drying equipment was examined due to a lack of industrial monitoring. A chamber dryer audited consumed 0.8

GJ/t, representing a thermal efficiency of 69%. A spray dryer analysed consumed 3.16 GJ/t operating with an efficiency of about 16%. Investigation of processes were complicated further due to rewetting of products, mixing and additional drying phases.

A study of the complete industry was not accurate due to limited information. However, equipment analysed during the study gave a good indication of achievable targets.

Overview of the Ceramics Industry

Table 10.1 summarises the findings of this study for energy consumed in 1994-95.

SECTOR	TOTAL ENERGY MILLION GJ	DRYING ENERGY MILLION GJ	PROPORTION OF TOTAL ENERGY FOR DRYING %
Tableware	7.2	3.11	43
Sanitaryware	3.7	0.52	14
Tiles	1.8	0.43	24
Electrical Ceramics	0.9	0.02[1]	2[1]
TOTAL	13.6	4.07	

Note 1 : Figures based upon limited industrial data

Table 10.1 - Summary of ceramics survey

Figures 10.1 and 10.2 show the proportion of the total and drying energy consumed by the product groups.

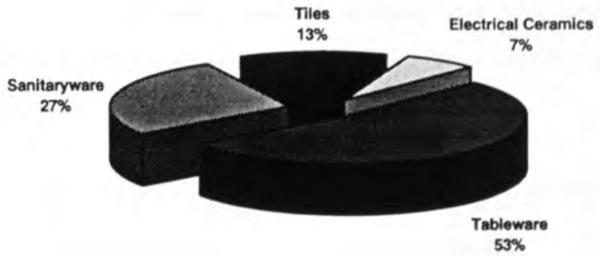


Figure 10.1 - Proportion of total energy consumed

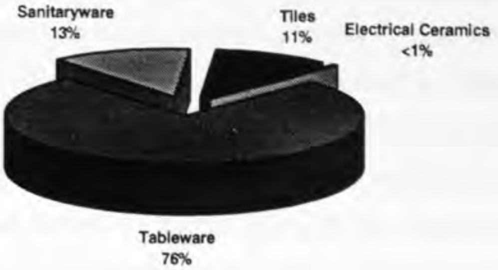


Figure 10.2 - Proportion of drying energy consumed

Figures 10.1 and 10.2 show that the largest proportion of energy is consumed within the tableware sector, representing 53 % of the total and 76 % of the drying energy. The figures reflect the percentage of total energy consumed within the tableware sector for drying processes.

It was suggested that the largest savings could be achieved by implementing energy efficiency concepts within the tableware industry, although the potential for energy saving measurers should not be overlooked within other sectors, especially tiles. Further investigation into electrical ceramics is required for an accurate assessment of potential savings.

Table 10.2 shows a comparison of previous studies. The energy consumed for ceramics production and that utilised for drying has not varied significantly over the last decade. This survey showed that 4.1 million GJ were consumed in 1995, representing 30% of the total energy. A large proportion of industry contacted during this study were using equipment that was up to 30 years old. Many operators were not concerned with energy utilisation, with main objectives being focused on quality and productivity. Many companies did not monitor their drying equipment, and several contacted during the study were unaware of the energy utilisation or efficiency of their plant. New techniques such as isostatic pressing have been introduced although the proportion of the total output manufactured by these techniques is small and it has had very little impact on the total energy consumed.

YEAR	TOTAL ENERGY MILLION GJ	DRYING ENERGY MILLION GJ	REFERENCE
1978	-	4.1	[16]
1978	14.8	4.5 (30.6%)	[131]
1980	14.1	4.3 (30.5%)	[124]
1990	6.9	1.5 (22%)	[132]
1995	13.6	4.1 (30%)	This Study

Note : Figures in brackets are proportion of total energy

Table 10.2 - Previous studies of the ceramics industry

Energy efficient technologies have been analysed describing applications and potential energy savings. Many examples in the form of case studies highlight benefits. Topics addressed included heat recovery, slip preparation, vacuum casting, and improved dryer design. Heat recovery systems are less developed than other industrial sectors such as the brick industry. Figures have shown that there is a large potential for this energy saving technique within the tableware industry, where only an estimated 1% of the total energy presently used is derived from waste heat. Energy savings in the order of 50 to 60% of the total could be realised, representing 2.3 million GJ/year and a reduction in emissions of 0.2 million tonnes of CO_2 based upon 1995 figures. Improved dryer designs could product significant energy savings, although the magnitude is largely dependant upon the original installation. Savings in the order of 10 to 50% of the total energy have been suggested.

Electrical energy savings techniques have also been described including infra-red, radiofrequency and microwave drying, and heat pump dehumidification. Significant energy savings have been highlighted. IR systems for tiles offering improved SEC and reduced drying times in comparison to traditional techniques have been discussed. Energy savings of 1.4 million GJ/year have been suggested as feasible if microwave/vacuum techniques are implemented in the tableware industry. Energy savings in the order of 45 to 80% by implementing heat pump dehumidifier systems have been described. Additional comments have been made in specific cases concerning improvements in product quality, working conditions and productivity.

Building Materials

A detailed examination of the energy utilisation and efficiency of drying processes within additional ceramics subsectors has been performed and is described in Chapter 5. The industrial product groups investigated included bricks, refractories, plasterboard and abrasives.

BRICKS

The UK clay brick manufacturing industry has been examined. Published figures showed that the brick industry has decreased in size and is directly related to the slump in the UK building industry during the 1990s. The production of common bricks has fallen significantly over the last decade, with competition from light weight concrete bricks being an influencing factor.

A survey showed that the proportion by weight of bricks manufactured by the stiff plastic and semi dry processes have decreased significantly over the last decade, while production methods employing extruded and soft mud techniques have increased.

Industrial figures showed that the total energy requirements for drying and firing varied between 0.79 and 8.85 GJ/tonne in 1994. Furthermore, the use of intermittent kilns significantly increases the firing and drying specific energy consumption. In 1994 an estimated 16.6 million GJ of energy was consumed for the manufacture of 2858.4 million bricks (6614.1 x 10^3 tonnes). Figures show that average SEC for drying and firing have increased by 6.5% per weight of bricks produced since the 1980s. The operation of plant at less than full capacity due to the declining market may have contributed to this trend.

Calculations have been performed using data from manufacturers. Tunnel dryers were found to be more efficient than chamber kilns and extruded processed bricks consumed less energy than soft mud bricks, 0.74 GJ/tonne and 1.89 GJ/tonne respectively. Thermal efficiencies varied from 26% for a chamber dryer and up to 67% for tunnel dryers. No information was revealed concerning the quantity of equipment utilised or the degree of waste heat used in the UK. The lack of waste heat information hindered an exact estimation of drying energy consumption.

An estimated 8.02 million GJ of energy was consumed for drying processes, representing 48% of the total sector energy consumption. The figure quoted assumed no waste heat recovery. Data from industry showed that heat recovery from the kiln cooling zone for dryer heat input was widely practised, although the extent of utilisation was indeterminable. Comparison of drying and combined drying and firing figures showed that waste heat recovery was widely practised in the fletton brick industry.

Several scenarios were developed and results showed that if all dryers in the UK derived 85% of their energy from waste heat drying SEC values of 0.18-0.52 GJ/tonne were achievable, i.e. an energy saving of approximately 75% in comparison to not using waste heat. Data implies a possible energy saving of between 0.3 and 0.9 GJ/t, equivalent to 2.6 to 6 million GJ/year and a reduction in CO_2 emissions of up to 0.54 million tonnes based upon 1994 figures.

Average figures revealed an overall drying energy consumption of 4.6 million GJ in 1994, representing 28% of the total conventional fuel consumed.

Calculations performed showed that energy recovery from kiln exhaust would provide significant savings in drying energy consumption, however the corrosive nature of the gasses and capital costs hindered widespread application. The benefits of using heat recovery systems on dryer exhausts, dehumidifier drying systems, and improving dryer control and process integration was shown to provide energy saving benefits, while in cases addition rewards of quality and productivity could be achieved. Energy savings in the order of 60% have been highlighted as achievable by implementing waste heat and dehumidifier systems, while up to an estimated 20% could be realised by improving dryer control and design. Comments were made concerning the developments of airless drying systems using a super heated steam medium and possible energy savings discussed.

REFRACTORIES

Drying processes within the refractoiries industry have been examined. Analysis of published figures showed that production of refractory products fell by 69% between 1978 and 1990, although production only decreased slightly between 1985 and 1990.

A survey showed that refractory products are commonly dried in tunnel or chamber systems, with initial material moisture content varying from about 5-15%, and <1% after drying. Drying temperatures vary from 50-90°C.

Examination of previous literature demonstrated that a survey of the refractory industry has not been conducted since 1978.

Industrial energy data and published sources of production estimated 0.475 million tonnes of refractory products were manufactured in 1990, consuming an estimated 5.275 million GJ. Thus suggesting a total energy SEC of 12.94 GJ/tonne. Comparison to 1978 figures showed that total SEC values have increased by approximately 8%. The movement to the manufacture of high performance products and the low utilisation of equipment has attributed to this trend.

Energy consumption for drying processes have been calculated using data from industry. A drying SEC value of 4 GJ/tonne was estimated, with a typical drying efficiency of 24%. Comparison of the findings with previous studies has shown that drying SEC has doubled since 1978. However, figures vary by up to 3 times for surveys conducted the same year. The accuracy of past figures is thus questionable.

Using calculated SEC figures and production data from published sources an estimated 1.6 million GJ was consumed for drying processes, representing 31.5% of the total energy consumed in 1990. Total SEC values have only increased slightly, unlike drying SEC which has doubled in comparison to surveys conducted in 1978. This suggests that savings have been implemented for the kilning stages of refractory manufacture, although drying now consumes a larger proportion of the total energy than in 1978.

Complete analysis of the energy utilisation within the refractory industry has been hindered by the lack of co-operation from manufacturers. Major firms regarded information on fuel and power consumption as commercially sensitive, although sufficient data was collected regarding typical drying SEC figures. Information relating to the degree of implementation of heat recovery systems, ranges of SEC values, quantity and type of equipment in use, fuel type and exact product specification would enable a more accurate assessment of the industry to be made.

PLASTERBOARD

The energy utilisation and efficiency of drying processes within the plasterboard industry has been examined. Investigation of published figures showed that the production of plasterboard is forecast to increase during the 1990s, after decreasing slightly during the 1980s. Furthermore the production of plasterboard was described by many manufacturers as a very energy intensive process requiring an estimated 22.7 GJ/m^2.

A literature survey showed that overall energy consumption figures relating to plasterboard manufacture are not published for the UK. Subsequently, analysis of the energy consumption for drying processes within the industry is not conducted on a regular basis.

Industrial data showed that continuous tunnel dryers dominated the industry. Calculations performed using industrial data estimated that conventional gas fired tunnel dryers consume 2953 kJ/kg water removed, yielding a thermal efficiency of 71%. For a 9.5 mm board containing 3.5 kg/m^2 of water, 11.46 MJ/m^2 of energy is consumed for drying, including 1.13 MJ for drying raw materials.

An estimated 2.33 million GJ was consumed for drying processes, representing 50.5% of the total energy consumed in 1994. Comparison of the finding of this study with previous surveys showed that the energy efficiency of drying equipment has improved over the last decade, a reduction of approximately 46% since 1981. Improvements in energy utilisation were attributed to improved burner design, improved dryer control through use of cooling air jets to reduce calcination, the implementation of IR board temperature monitoring, and condition monitoring of equipment.

This survey showed that heat recovery is practised within the industry. Air/air heat exchangers are commonly used to supply heat from the initial zones of the kiln to subsequent sections. The high thermal efficiency of equipment demonstrates the benefits of implementing heat recovery systems.

The lack of information from manufacturers regarding the production of cove material has hindered the analysis of energy utilisation. Cove dryers analysed during the study consumed more energy than plasterboard equipment, typically about 3265 kJ/kg water removed. The energy consumed in cove manufacture may be significant.

Various electrical drying techniques have been investigated for plasterboard drying. RF heating is used to a limited extent for the drying of high value decorative cove. The application of RF, microwave and direct resistance electric heating cannot be economically justified for large scale implementation in the UK.

ABRASIVES

Drying processes for the manufacture of coated and vitrified abrasives have been examined. Published sources and contact with trade organisations estimated that 12.87 million m^2 of coated abrasives was manufactured in the UK in 1995, and 10273 tonnes of vitrified abrasives were manufactured in 1990. The production of vitrified abrasives was deemed not to have changed significantly over the last five years.

A survey showed that chamber and tunnel systems are used within the abrasives industry for the drying of bonded/vitrified and coated abrasives respectively. Many of the systems investigated were over 30 years old. The drying of raw materials varied significantly depending upon the product mix. Little evidence of the energy monitoring of raw material drying was uncovered during this survey.

The efficiency of drying processes varied from 14% for drying coated abrasives to 79% for a microwave system drying vitrified wheels. Energy consumed for drying only represented about 6.8 - 7.3% of the total SEC. The low SEC was attributed to the low initial moisture content of the material entering the drying phase.

Using average SEC values and production figures an estimated 9.35 TJ of energy was consumed for drying processes in 1995, representing 7.3% of the total energy consumed within the sector. Comparison to previous studies showed that the energy used for drying had not changed significantly over the last decade.

Microwave drying systems were used to a limited extent for drying bonded/vitrified ware. Savings in the order of 6420 GJ/year could be realised if microwave technology was implemented by the industry. Although the unit cost of electricity is high in comparison to fossil fuels, calculations showed that microwave systems are still more economical due to the high thermal efficiency (typically 70-79%). Implementation is hindered by large capital costs.

Timber Industry

Drying processes within the timber industry were investigated. A literature survey showed that there is little published data concerning the present state of the industry; production trends, equipment utilisation and operators views. Proceeding the energy survey a comprehensive study of the industry and analysis of equipment and product utilisation was conducted.

Comparison of results to a survey conducted in 1981 showed that the timber drying industry in the UK has changed remarkably over the last 20 years. The demand for wood products has increased since the late seventies and it has been predicted that demand will increase further over the next decade. The production of home-grown timber has doubled UK since 1976 representing over 7 million cubic meters of timber. The Forestry Commission has estimated that the amount of home-grown timber will increase further and could reach 20 million cubic meters in 2026.

116 companies were identified during the survey as operating kilning facilities in the UK, representing 467 individual kilns with an estimated total capacity of 19,902m^3. The number of kiln operators has decreased by 60% since 1978 and less sawn timber is presently produced in the UK, a reduction of 58% since 1978. Figures showed that there has been a reduction of 44% in the volume of timber dried in the UK since 1978.

It is envisaged by industrialists that the introduction of new British Standards, especially BS4978 concerning the drying of softwood for constructional purposes, will lead to an increase in the amount of timber dried in the UK. The study showed that a substantial number of kilns (58%) are operated by timber merchants and sawmillers. 44% of companies dry hardwood, 24% softwood and the remainder process both. More companies are drying softwoods in 1995 than in the 1970's. 70% of companies dry timber for their own use or resale, 7% deal with only contract work, while 23% operate in both streams.

The types of equipment in operated in 1995 were analysed. 55% of kilns identified were indirect heat/vent chamber type, 12% were direct heat/vent, 28% dehumidifiers, 4% vacuum, while under 1% were progressive. There has been an increase in the number of vacuum kilns operated in the UK. The proportion of kilns of the heat/vent type has decreased during the last 20 years, whereas the proportion of dehumidifiers has increased. The number of single, low volume dehumidifiers installed during this period has been quite significant. There has been no major investment in progressive kilns in the UK. Dehumidifier, indirect heat/vent, and vacuum kilns are most commonly used for processing hardwood. It was found that progressive kilns were not utilised for drying hardwood in the UK.

Fuel utilisation was also examined showing that there has been a reduction in the number of kilns using oil and wood fuel since the 1970's, with a greater number of kilns using electricity and gas. The increase in use of dehumidifiers in respect to heat/vent type kilns has been an influencing factor. Currently about 90% of kilns in the UK are using wood, oil and electricity as fuel. Gas, although having increased in use since the 1970's, only supplies 10% of kiln installations. In capacity terms, 37% of the total capacity uses wood as a fuel, 29% oil, 21% are electricity, and 13% gas. The largest proportion of the total capacity, 63% are indirect heat/vent type kilns. 10% direct heat/vent kilns, 21% dehumidifiers and 6% progressive. Vacuum kilns having only small capacities in relation to other kiln types represent less than 1%. The proportion of the total capacity provided by dehumidifiers has increased by 300% since 1978.

It was discovered that the number of kilns per operator varies widely from a single unit to 28. Indirect heat/vent kilns are commonly operated in groups of three or more, using a centralised boiler system. Dehumidifiers are often smaller and single units are quite widespread. Vacuum kilns are commonly found in pairs. The number of kilns of brick/concrete construction has reduced from 56% in 1978 to 22% in 1995. The utilisation of aluminium, steel and wood kilns has increased. Steel constructed kilns using ex-cargo transportation containers are common amongst small single dehumidifier units. The survey showed that there has been an increase in the number of kilns using overhead fans since the 1970's, presently 53% of the total. The increase in the number of dehumidifier units has probably influenced this trend.

Due to the lack of data concerning drying within the timber industry during the last decade the age of equipment was examined to investigate the rate of change and any specific trend in equipment installation. 49% of dehumidifier kilns are 0-5 years old, and 66% of vacuum kilns were installed 5-10 years ago. This reflects the development, demonstration and utilisation of these equipment types over the last 20 years. Results have shown that 48% of direct and 45% of indirect heat/vent kilns are 21+ years old. Kilns constructed from aluminium and steel have become abundant in the last 10 years. Wood construction is also currently popular probably owing to its low capital cost and ease of erection. Brick/Concrete kilns are not commonly constructed nowadays, with 80% of brick/concrete kilns being 21+ years old.

86% of kilns in use in 1995 were of UK origin. Foreign competition penetrating the UK kiln market has increased substantially over the last 15 years. Foreign equipment only representing 1% of the total number of kilns in 1978. 100% of kilns surveyed were automatically controlled, a large proportion of which were using measurements taken from wet and dry bulb temperature within the kiln. 289 kilns out of a total 467 (62%) used oven sampling methods of monitoring the timber during drying. Hand held moisture probes were used on 48% of kilns, while only 12% of kilns had on-line moisture probes installed during operation. Several operators utilised two or more control methods.

The results of the industry survey were correlated with energy assessments of equipment presently utilised in the UK. A complete review was made of the trends in energy utilisation and equipment operational characteristics with reference to energy efficiency and good operating practices.

A literature survey showed that many researchers have examined the energy requirements for moisture removal from timber. Many of these studies are very general in nature and details of machine type, timber species, and moisture content changes were not disclosed. Furthermore, examination of past studies has shown that evaluation of the energy utilisation of a kiln with respect to the form of heating and fuel type has not been conducted.

Investigation of past studies showed that the energy consumption for the removal of water from timber varied considerably from 1.1 MJ/kg to 21.1 MJ/kg. Dehumidifiers were found to consume less energy per kg of water removed in comparison to conventional methods. Energy savings upto 89% were shown in comparison to an inefficient chamber kiln. The study has shown that that there was no evidence to suggest that savings in energy were achieved by using vacuum kilns rather than conventional methods. Vacuum kilns only represent a small proportion of the capacity in the UK and thus are insignificant in comparison to other kilning methods.

Energy utilisation data was obtained by directly contacting and monitoring industry. The survey showed that there is a lack of energy monitoring of kiln equipment in the UK. Newer kilns were found to have sufficient instrumentation for the analysis of energy utilisation, however figures were rarely examined. Insufficient data was obtained to allow an analysis of the effects on the energy required for moisture removal from timber at a moisture content below the fibre saturation point.

Calculations based on industrial data showed that electric drying systems, especially dehumidifiers, were very energy efficient, typically over 50%. However, the unit cost of electricity offset the advantage of using these techniques in comparison to conventional fossil fuel kilns. Electric kilns offer additional benefits such as no emissions, improved product quality due to controllable heating, less maintenance and lower capital costs.

The study demonstrated that the energy requirement to remove moisture varied from 1.51 MJ/kg for a dehumidifier drying softwood to 21.78 MJ/kg for an indirect gas fired chamber kiln drying hardwood. Dehumidifiers use more energy for removing moisture from hardwood than softwood in comparison to studies conducted in the 1970's. In comparison to previous studies the chamber kilns analysed consumed a similar quantity of energy for drying hardwood, although softwoods required on average more.

Data from manufacturers showed that the energy consumption of a timber kiln varied considerably and was dependant upon many factors such as; species, kiln type, form of heating, moisture content change, and outside climate conditions. A comprehensive literature survey examined previous studies concerning energy utilisation for drying timber in the UK. Results showed that the total energy consumption for drying processes in the UK has not been examined since 1982. Furthermore, comparison of previous energy studies showed no correlation, with some work for similar years varying by a factor of 7. The accuracy and validity of previous studies is questionable.

It was estimated that 0.63 PJ of energy was consumed for timber drying in 1994-95. Comparison with previous studies showed that the total energy consumption for the drying of timber in the UK has fallen since the 1970's. Moreover, the total energy consumed per unit volume of timber dried has decreased by an estimated 14% during the last 20 years. The closure of old inefficient and dated equipment and the utilisation of energy efficient dehumidifier kilns is the most probable cause for this trend.

Introduction of new British Standards relating to the drying of softwoods were estimated to have little affect on the total energy consumption for drying in the timber industry. An increase in total consumption of less than 2% was estimated from average energy figures.

It is estimated that significant saving can be achieved by air drying hardwood before kilning. Saving of 23% of the total energy can be achieved by air-drying hardwood, reducing the moisture content by 10% from 40-30% before kilning. Saving of 50% can be achieved by air-drying hardwood from green to 30% moisture content. Other economic factors such as storage, work in progress and additional labour costs need to be addressed in order to implement air drying techniques. Calculations showed that only a slight decrease in the total drying energy consumption is achieved by reducing the moisture content of softwood before kilning.

It was estimated that in 1973 95% of the total energy was used by heat/vent kilns. In 1995 the study showed that 77% of the total energy was consumed by indirect heat/vent kilns, 10% by dehumidifiers, 9% direct heat/vent kilns with progressive and vacuum kilns utilising the remainder. Figures showed that less energy per unit volume of wood was used for drying hardwood in 1994-95 in comparison to 1973 figures. However, there have been no realistic saving in the energy required to dry softwood.

Due to the limited data available from industry it has been suggested that implementation of good house keeping measures could produce significant saving in the timber industry. Demonstration schemes and technical information describing energy saving techniques could be beneficial. The energy monitoring of equipment provides essential information and produces targets that can be the focus for the implementation of energy efficient measures. Information from kiln operators has demonstrated that very little monitoring occurs within the UK timber industry. Better monitor of equipment can lead to improved control providing additional benefits of improved quality, reducing drying times as well as reducing energy costs.

Research and development concepts have been addressed. It has been revealed that heat exchangers for heat recovery systems, work on the variation of kiln air flow and fan utilisation, together with burner design could produce significant saving. Energy savings of 0.7 to 0.9 MJ/kg water removed have been reported for implementing heat recovery systems, while variable fan speed drives could save up to 3.5 MJ/kg water removed.

Paper Industry

Drying processes within the paper industry have been examined with reference to newsprint, writing, tissue, and packaging paper. Paper is a widely used commodity and users are demanding increases in product quality while maintaining costs.

Figure from published sources showed that in 1993 an estimated 5.3 million tonnes of paper was produced by 88 mills operating 198 paper machines. The number of paper mills has decreased significantly over the last 20 years.

Information from trade organisations demonstrated that the variation of the total energy used within the paper industry has corresponded to changes in total industrial consumption, decreasing over the last 20 years. The UK paper industry consumes an estimated 105.72 x 10^9 MJ of energy a year, representing 5% of the total UK industrial consumption.

Comparison of published estimates of the total SEC of individual paper types has shown that savings have been made, however, figures show that average SEC values have not changed significantly since the 1980s. Data from trade organisations demonstrated that the production of paper has increased over the last 10 years, recovering from a depression during the 1970s. Significant increases in production have been noted in the manufacture of printing paper, newsprint and case material.

Information from industry has shown that drum type dryer sections dominate the industry. Yankee, IR and air flotation equipment represents less than an estimated 15% of the total. Many researchers have estimated the energy/steam consumption characteristics of dryer sections and a literature survey showed a large variation in figures.

Various projects have demonstrated the effectiveness and potential energy savings by recovering heat from the dryer section and improved felt press sections. Developing technologies have been discussed including press drying, direct gas heated cylinders, impulse and high temperature drying. Dry forming, the use of induction heating for moisture profiling and drying using superheated steam have been examined. Comments were made concerning the potential of energy savings by the implementation of these technologies.

A survey has been conducted estimating the operating characteristics and energy utilisation of 192 dryer sections. The energy required to produce steam has been addressed, and typical efficiencies of 68-92% have been revealed for conventional boilers and 50-60% for CHP units. Over 52% of mills currently use CHP for power/heat production.

Data from industry showed that moisture contents vary from 75-88% and between 45-63% onto and after the press respectively. Final end moisture corresponds to the end use of the product and vary between 4-9%. Paper machine speed and web width varied considerably. Age of equipment, layout of plant, product type and specification were influencing factors. Packaging material and board were commonly processed in smaller webs in comparison to writing paper, tissue and newsprint.

Results of the survey showed that the energy consumption of dryer sections varied considerably. Steam consumption ranged from 1.16-2.31 kg steam/kg product produced and 1.11-2.46 kg steam/kg water removed (weighted average figures). Yankee dryers consumed the least steam per kg of water removed, and product produced. Dryers processing packaging material consumed the largest amount of energy at 2.46 kg steam/kg water, although writing paper consumed the largest amount of energy at 2.31 kg steam/kg product produced. Newsprint machines were found to be the most energy efficient at 56.7%. The manufacture of case material was the least efficient at 38%. Limited data regarding the operation of Yankee machines hindered analysis of their energy characteristics.

Comparison of energy utilisation figures with past studies showed that average steam consumption for conventional dryers were higher for present equipment. Comparison of newsprint machines to previous estimates showed that there has been little change in steam consumption requirements per mass of water removed. However, present equipment consumed less energy per mass of product produced. Improved press techniques was attributed to these findings.

Dryer sections were found to consume up to nearly twice the amount of energy required to remove water from the web than previous estimations. Advances in boiler design and heat recovery systems contradicts the comparison and questions the validity of previous studies. The variation of the energy required per kg of product of current dryer sections showed less variation in comparison to previous studies. Air flotation dryers were found to consume least energy per kg of water removed, although limited information was available. The closure of smaller, inefficient plants may have contributed to these findings.

A literature survey showed that few studies have been conducted regarding estimation of the energy consumption for drying within the UK paper industry. Discrepancies were found when comparing previous estimates. This study estimated that 25×10^9 MJ was consumed for drying processes within the paper industry, representing 23% of the total energy consumed in 1993.

Comparison of results with previous studies showed that the proportion of energy used for the drying of newsprint and writing paper has increased since the 1980s. Increases in production were attributed to this trend. The extent of energy saving measures were demonstrated by the reduction in the proportion of drying energy used to manufacture tissue and case material, whereas production had remained constant and increased respectively.

Comparison of previous studies estimating the proportion of the total energy consumed in the paper industry for drying demonstrated that a figures varied widely and the variance has hindered analysis of an energy trend. The accuracy and validity of previous statistics is questionable. The decreasing proportion of the total energy used for drying suggests that energy saving measures may have been implemented for drying processes and are effective.

The advances in dryer technology and the implementation of efficient systems will lead to future saving in energy consumption for drying in the paper industry. Comments have been made concerning developing technologies such as heat recovery, press drying, direct heated cylinders, impulse drying, high temperature drying, dry forming, induction moisture profiling and the application of superheated steam methods.

Modelling of Drying Characteristics Using Artificial Neural Networks

Chapters 8 and 9 describe the modelling of two drying systems using neural network, and the application of the results to control principles, process optimisation and parameter measurement.

Background

The theoretical principles of neural networks are discussed in Chapter 8 together with a brief introduction to the modelling of drying.

Analysis of literature and discussion with experts within the field has demonstrated that drying is not well understood due to the complexity of the simultaneous transfers of heat, mass and momentum during the process. The history of the modelling of drying has been described with reference to the purpose and potential benefits. Escalating energy costs and more intense competition provides the impetus for continued efforts in improving dryer efficiency, a methodology that relies on an accurate process model.

A comprehensive literature review has shown that many researchers have investigated the modelling of drying. Limitations and problems associated with traditional mathematical techniques using simultaneous heat and mass transfer equations have been addressed. Techniques such as empirical calculation based upon experimental data, irreversible thermodynamics and finite element analysis have been applied. Traditional techniques are hindered by the need for time consuming, expensive experiments, or theories are limited by simplifying assumptions often made in order to enable a tractable solution.

Theoretical principles of neural networks have been investigated including details of design, neural structures, development and verification procedures. Analysis of current literature showed that there has been a large increase in research into neural networks and many industrial applications have been demonstrated successfully. Neural networks offer a convenient platform for capturing the non-linear and dynamics inherent in a non-linear system. Drying processes are commonly non-linear and are thus potential systems for the application of neural modelling techniques. Furthermore, neural models could be applied as the model component in a predictive control system, for optimisation of a process, or evaluating data from secondary control parameters.

There has been little research regarding the application of neural networks for the modelling of drying processes. Studies describing the modelling of paper drying and grain drying have been reviewed. Comments regarding parameters, development and testing of the models produced have been described. Faults of models previously developed included the use of impractical training data which may be inappropriate in describing the mulit-dimensional space, or lacked details concerning consistency of training data or accuracy of the model produced.

There is potentially a large range of applications of neural network within the field of drying processes which have remained undeveloped. Information from industrial experts, manufacturers and academics within the field suggested that neural networks have not previously been applied to an industrial drying system in the UK.

Chapter 9 describes the neural network modelling of microwave and convective drying characteristics of paper coated gypsum cove material.

Comments have been made concerning the selection of a drying system. Points assessed included the nature of the model and application, product quality, data acquisition, material properties required and the characteristics of different heating processes. A paper coated gypsum cove material subjected to microwave and convection heating mediums was selected due to the diverse range of product and drying characteristics. The decision was made to develop a model with parameters which will have direct meaning to general industrial engineers. Thus the modelling of kinetics was not implemented and parameters such as temperatures and air flow rates were used. The inclusion of quality terms within the model was an important aim.

Literature and experimental analysis of the chemical properties of gypsum has been examined. It was concluded from previous work that gypsum was very heat sensitive and its physical properties changed markedly with chemical phase. Temperature STA and dielectric properties were experimentally analysed to gain an understanding of the drying characteristics.

The results of temperature phase STA tests and investigation of the dielectric properties of gypsum with respect to moisture and temperature have been described. Brief comments have been made on the findings of these tests and the influence on the heating characteristics of gypsum, including mass loss and product quality defects. Results showed that the gypsum cove was extremely heat sensitive and accurate control of the drying process was required to prevent the loss of bound moisture. Furthermore, results suggested that the physical form of the gypsum had a direct affect on the chemical-phase and drying characteristics thus highlighting the inefficiency of a generalised model. The STA analysis showed distinct phase changes;

Removal of free water	35-130°C	Formation of hemihydrate	130-140 °C
Formation of soluble anhydrite	160-180°C	Formation of non-soluble anhydrite	200°C

Dielectric properties showed typical characteristics with loss factor increasing with rising product moisture content. Loss factor was found to be dependent upon the gypsums chemical phase, decreasing upon formation of the hemihydrate while remaining significantly higher in the anhydrate and dihydrate states. Analysis of the magnitude of the loss factor and penetration depth has been described highlighting that gypsum is susceptible to electromagnetic microwave energy during all phase states. Furthermore, results showed that gypsum was calcinated using microwave energy thus contradicting previous literature which suggested that the heating was self limiting upon the removal of all free moisture.

The theoretical principle of microwave and convective heating and traditional modelling techniques have been briefly discussed highlighting the complexity, application and problems of traditional methods.

The microwave experimental set-up has been described including equipment utilised, parameters studied, and procedures conducted. General experimental drying characteristics have been examined and related to theoretical principles of the process and the influence of material properties. Comments were made concerning product quality in the form of paper burning, bubbling and calcination during microwave heating.

The development of neural networks to model weight loss, and product quality (burn and bubbling) have been described including details of network architecture, training and verification using experimental data. A three input model using parameters of magnetron power (0-6kW), product free moisture content (0-60g) and time (0-1500s) was implemented. Two and three layer back-propagation networks using Tan and Log transfer functions with between 8 - 10 neurons in the hidden layer were constructed. A Levenberg-Marquardt training algorithm, an approximation of Newton's method, was utilised in each case.

Results showed that the networks were capable of simulating the microwave drying characteristics to a high degree of accuracy. Errors up to 6% and 7.5% were encountered when modelling moisture loss and paper bubbling respectively. However, errors of up to 20% were encountered when modelling paper burning. It was noted that the accuracy of the experimental data severely influenced the accuracy of the model produced. Methods to improve accuracy have been addressed including further training, analysis of data and refinements to experimental methods.

The modelling of the convection drying of gypsum has been described. Previous studies relating to hot air drying were reviewed highlighting techniques, findings and accuracy of results. Experimental analysis has been conducted and comments made concerning equipment utilised, methods and parameters involved. A four dimensional input model was successfully implemented using neural networks to model moisture loss and temperature characteristics during convective drying. Input parameters included product moisture (20-30g), air temperature (100-160°C), circulating air speed (35-75 Hz variable frequency) and time (0-6000s). Two and three layer back-propagation networks with Tan and Log transfer functions and between 8 - 10 neurons in the hidden layer were implemented. Radial basis structures were tested but problems were encountered due to computer memory. A Levenberg-Marquardt training algorithm was used in each case and network inputs for the temperature network were scaled using a factor of 170.

The neural models produced were capable of predicting product weight to an accuracy of 0.5%, while temperature generally within 5°C. The models clearly showed that the network was capable of predicting the underlying characteristics of the data although a high degree noise was present in the raw information.

The work conducted has shown that artificial neural networks offer a convenient platform for capturing the non-linearity and dynamics inherent in drying systems. Results have shown that the neural models could achieve a high degree of accuracy within the parameter ranges analysed. Furthermore, the work has demonstrated that model development times are short, straightforward and require only a basic knowledge of the system under investigation. Construction times of under a week were achieved upon collection of sufficient data. Times could be reduced substantially by the application of unsupervised learning and the development of multifunctional software.

CHAPTER 11

PROPOSALS FOR FUTURE WORK

tion

conclusions drawn in Chapter 10 it can be seen that the work conducted has produced data and ated concepts which potentially offer a wide variety of benefits for industrialists and scope for further efforts.

pter describes proposals for future work associated with the application of results, development of ideas xpansion of the methodology used within other areas. The proposals for future work have been divided e associated with energy utilisation, and the development and application of neural networks for the g and control of drying processes.

Jtilisation and Efficiency of Industrial Drying Processes

ion of Additional Industrial Sectors

f the investigation of energy utilisation within the ceramics, building, paper and timber sectors showed t changes in comparison to previous studies and to the present industrial views of energy usage.

ete understanding of the utilisation of energy for drying processes, together with examination of y available is essential for the fundamental application of energy efficient measures, processes and Future plans using previous figures from data collected in the 1970s will undoubtedly produce c, inaccurate targets.

used extensively in many industrial sectors. The energy trend update, described in Chapter 3, analysed s. Further investigation into other sectors could be performed. This could take the form of specific reas e.g. the drying of malt or processes such as paint drying. The analysis demonstrated that a t proportion of energy used in the textile, food and chemicals industry is used in drying processes. investigation of these sectors would provide a more comprehensive view of industrial energy utilisation n the potential targets for the implementation of energy efficient schemes and technology transfer.

industries process data is commercially sensitive and an alternative means of information acquisition required if a comprehensive picture of the industry is to be obtained. Slightly different approaches to ection may be necessary, especially within the chemicals industry. The use of company personnel to collect process data concerning energy utilisation and provide 'generalised' figures based upon these readings may solve this problem.

The analysis of industrial applications showed that many systems commonly lacked instrumentation and sufficient data was not readily attainable to enable an energy balance of the machine to be performed. This problem was especially apparent in areas where steam heating is used, as in the textile industry. A survey conducted as part of this work showed that many industrialists were unwilling to spend capital on instrumentation due to the lack of information regarding the benefits of monitoring dryer systems. An awareness campaign highlighting the benefits of monitoring may provide a long term source of energy data. However, a shorter term method would be to offer incentives such as free or subsidised monitoring equipment and technical advice regarding efficiency based upon readings thus encouraging users to install instrumentation. The latter scheme would ensure specific equipment or product types are monitored within the sectors under analysis.

Analysis of the Trend in Energy Utilisation

During the study figures of overall energy consumption and SEC of processes were compared with previous studies conducted in the 1970s and the trends in energy utilisation and efficiency were examined. Results of the study conducted showed significant changes since previous surveys and in several cases a trend comparison was impractical.

The wide variety of techniques utilised and methods applied in the past have hampered the analysis of energy consumption trends and the changes in equipment thermal efficiency. Utilisation of a consistent method for analysing energy trends as described in this work would eliminate this problem and enable direct comparison.

Energy utilisation and SEC figures could be up-dated on a regular basis provided established industrial contacts were maintained. The regular analysis of the energy efficiency and utilisation of drying equipment would allow not only the trend in consumption to be monitored, but also provide an indication of the effectiveness of energy efficient measures, technology and process changes. Additional benefits would be the assessment of the introduction of new standards or regulation concerning drying, either through product specification requirements or legalisation of pollution control affecting specific equipment types.

An up-to-date assessment of energy utilisation would allow concepts of be focused, adjusted and reveal targets for technology development or further investigation. Information would benefit schemes run by bodies, such as the Energy Saving Trust, enabling the focusing of technical and financial support.

The Economic Aspects of Energy Efficiency

Energy efficiency in drying, as in most other areas, usually requires capital investment. This investment can be considered worthwhile if the resulting cost savings are sufficiently attractive. The cost of energy saving equipment is highly specific to each application and in many cases can only be established by a detailed design study. Additional benefits such as improved productivity, product quality, and environmental gains may provide justification for implementation of new technology as well as energy savings.

This project has focused on the energy savings and utilisation of equipment and practices. Brief reference has been made to economic or financial gains and the cost of the implementation of efficient measures. Future work could examine the economic aspects of;

- The cost of energy efficient measures. This covers a wide range of potential areas from the application of instrumentation for data collection and capital costs on a manufacturers level, to the organisational finance required for information collection, literature and project management of industrial awareness schemes.

- Savings possible through the implementation of processes, both in the form of process costing, capital outlay, and effectiveness of practices. The aspects of energy utilisation, and additional benefits such as manpower resources, productivity, and quality could be examined.

The economic aspects of energy efficiency schemes, whether involving technological investment or just good practices, would provide fundamental advice and support technical information for persuading industrial users to implement new concepts.

There is little published material concerning industrial views on the justification of energy efficient measures. Industrialists contacted during this study highlighted that the procedures and decisions made in implementing new technology varied considerably depending upon the nature of the company and product area. A study of the logistics behind the selection process and key decisions made by industrialists concerning energy efficiency would ensure information was available and aimed at the right personnel.

The take up of proven technologies within industry is commonly slow. Demonstration projects and case study information has been used in the past to promote new technologies and describe economic gains for specific implementations. However, for measures to be effective information is required concerning the investment prospects of projects, the size of permissible capital investment and expected paybacks. Case studies concerning the financial and management intervention during implementation of processes may provide the backbone for project appraisal within other companies in the same product area or other sectors.

Factors such as human resource relations require consideration if the implementation of new technology, or changing of the processes, to become more energy efficient involves loss of workforce, responsibility or knowledge skills.

Production of a Tool to Analyse Energy Efficient Implementations

Information presented in this thesis could be used to form a computational tool to assess energy efficiency and address the best possible measures likely to effective energy savings with regard to equipment or changes to operating practice or processes.

The tool may analyse;

- Operating equipment, processes and products,
- Size of capital investment, predicted rate of return on investment, and other financial issues,
- Parameters such as factory space, process integration, and restrictions on fuels, emissions etc.

The system could use a technology database combining new, developing and proven technologies, operating conditions and energy targets. The database would be comprised of industrial data from competitors within the field and other sectors allowing technology transfer and setting realistic best practice targets. Options could also address the effects on product quality, productivity, working condition and process integration within the present system.

The system would depend upon the successful completion of an economic examination of energy efficient measures, and an understanding of the effect and probable implementation of new technologies on present industrial practices.

The system in a basic form may provide case study information developed from industrial data relating a variety of product/equipment utilisation and target SEC values. It could form an interactive best practice target generator based upon the current systems and practices, and enable comparison to the present industrial processes and achievable targets.

Application of Energy Data to Demand Side Management (DSM)

The project has described energy utilisation of process equipment. However, little reference was made to operating cycles or trends in equipment utilisation regarding load profiles, or, with the exception of timber drying, the specific primary energy consumption in terms of fuel type.

Further work could analyse the energy load profiling of equipment and examine details of batch and continuous processes, times and magnitude of production. Information of this nature combined with an assessment of production trends and types of equipment utilised could form the basis of a demand side management (DSM) study.

Combined with energy saving measures and implementation of technology DSM could lead to more effective energy distribution and eliminate the requirement to run inefficient power generation equipment to meet peak load demands.

Neural Network Modelling of Drying Characteristics and Control

On an academic development level the application of neural networks to the modelling of drying process characteristics has been very successful. An aim for future work would be to demonstrate to both manufacturers of control equipment and users that the technique is cost effective, reliable, and has benefits over traditional systems. Efficiency improvements concerning both design, development and application require quantifying. This progressive development is essential for the widespread implementation of neural networks within the field of drying systems.

Development of Neural Model

The work performed demonstrated that neural networks could be used to model drying characteristics. Developments of this study could involve;

- Production of a more complex model involving a larger input matrix. Additional parameters could include atmospheric conditions, such as humidity, and the effects of external temperature, thus accounting for winter and summer working conditions. Exact parameters and ranges are dependant on the specific application. The experimental drying rig constructed for data acquisition for convective drying could easily be modified to simulate partial or full air recirculation with a humid atmosphere. Developing a model with more parameters would require substantially more input data for training and test purposes. However, work is currently progressing to develop a tool to predict the dimensional space of functions and hence reduce the matrix of training data required to produce a viable solution [89].

- Historical or on-line data from an industrial machine could be used as a training set. Information from an industrial source may reveal problems associated with the consistency, accuracy and signal noise components.

- The neural network developed during this study was specifically for the drying of paper coated gypsum cove in either a microwave field or convective drying atmosphere. The design and conception of additional models of other materials could easily be achievable provided training information could be obtained.

Application to Control Theory

Neural network systems have been employed as the model component in predictive control applications. However, a neural model has not been reported for application to a drying process. This could be achieved by using the neural network as the model component in a software control package inplace of traditional mathematical techniques. The following may be analysed;

- The effective economic savings due to the reduction in development time from using neural techniques,
- The accuracy of the neural model in comparison to conventional techniques, including assessment of the nature of any errors,
- Any further benefits or problems associated with the implementation of neural networks within a drying control system.

The views of manufacturers and users are also an important factor in effectively developing and marketing the technique. Communication and the availability of information demonstrating the system and highlighting its benefits will require examination.

The drying neural model could be adapted to use on-line training. The would entail the system retraining the model based upon current operating conditions on a regular basis. This phenomena would enable the model to adjust to any changes in drying or machine operating characteristics, such as slight changes in product specification or machine aging with time. The traditional models would require substantial redevelopment if these variable factors were not predicted during initial development of the model.

Modelling Using an Alternative Format

For a single operating system producing a variety of products a range of models could be developed. The system could take the form of a block orientated design where neural model blocks could be interchangeable, e.g. a product and machine mixed system, allowing for changes in production, additional heating or a varied product. This development may allow a more flexible system to be developed, although careful consideration is needed in block training and the ranges of parameters.

Neural networks could be used to model specific parameters which affect the drying characteristics of a product during processing. e.g. in the case of microwave and radio-frequency heating, the dielectric properties, which in many products vary with temperature, moisture and density. The models could be incorporated within traditional proven modelling techniques to simulate a single or set of parameters. Development times may be reduced since less data and training is required in comparison to the whole system.

Conclusions

This chapter has described details of the application of results and detailed proposals for future work.

The analysis of additional sectors has been described together with the examination of trends in energy usage, economic aspects and the possible application of data to DSM. A tool for the assessment of energy efficiency concepts, both capital projects and measures has been proposed.

Future developments in the use of neural networks for the modelling of drying characteristics has been described, including alternative modelling formats and the application of neural techniques to the control of drying processes.

CHAPTER 12

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APPENDIX A

DRYER MANUFACTURERS QUESTIONNAIRE

Company details

Is your company :

- A manufacturer of drying equipment
- An installer of drying equipment
- Both manufacturer and installer

No. of Employees at this site ....

Types of Machine

Which of the following dryer types does your company Manufacture/install;

Cylinder

- Rotary
- Indirect
- Steam-tube
- Cascading

Shelf/Tunnel

- Shelf
- Rotating shelf
- Turbo tray
- Tunnel
- Belt/oven
- Impingement
- Dielectric/IR
- Moving bed
- Package
- Filter-dryer
- Freeze
- Solar

- *Spray*

Belt/Band

- Belt
- Band
- Perforated band
- Plate

Paddle

- Double cone
- Conical
- Horizontal/vertical
- Vertical pan

Pneumatic

- Pneumatic conveying
- Flash
- Spouted bed

Multistage

- Combinations of more than one dryer type

Fluid Bed

- Fluid bed
- Fluid bed granulator
- Vibrated fluid bed
- Torbed
- Centrifugal

- *Stenter*

Drum

- Drum
- Rotary filter

Mechanical

- Press
- Centrifuges

- *Other Dryer*

Type............................

Classification of Product Group

In which product sector(s) do you market your equipment;

- Food and beverages
- Tobacco
- Textiles
- Leather
- Wood and wood products
- Pulp, paper and paper products
- Chemicals and pharmaceuticals
- Minerals (e.g. Ceramics)
- Other sector

....

Nature of Product Feed stock

Which feed stock types do your dryers process;

- Gasses

Solids:

- Free flowing powder
- Sticky particles
- Granules
- Pellets
- Sheets
- Blocks and pre-finished goods
- Solution or slurry
- Other..........................

Installations

Which is the most common equipment installation;

- Complete drying system
- Retrofit system
- Upgrade old systems
- Supplying parts for customer commissioning

Further Information

Would your company be willing to provide further information concerning drying equipment with respect to energy consumption and efficiency.

- Yes
- No

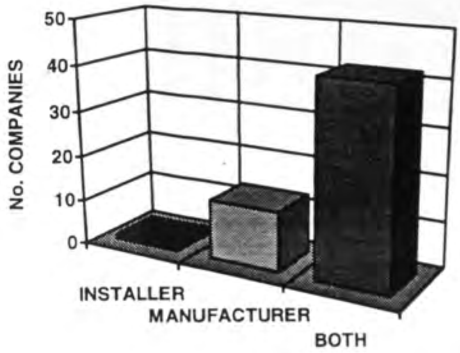
If YES who can we contact: Name..

Tel. No.....................................

DRYING QUESTIONNAIRE SUMMARY

The following data is a summary of the results obtained from the responses provided by manufacturers and installers of drying equipment.

A return rate of 35% yielded 70 questionnaires. 60 sources providing valuable data with the remainder having no direct connection to drying equipment manufacture and/or installation.



Type of Company

Many companies involved with drying equipment were engaged in design, construction and installation of equipment. Results indicated that manufacturers that did not install equipment were involved with only a small consortium of installers.

Number of Employees

Employees ranged from 3 to 100+. A total of 3031 gave an average of 51 employees per company. Results showed that the size of the company did not relate to the range of products offered.

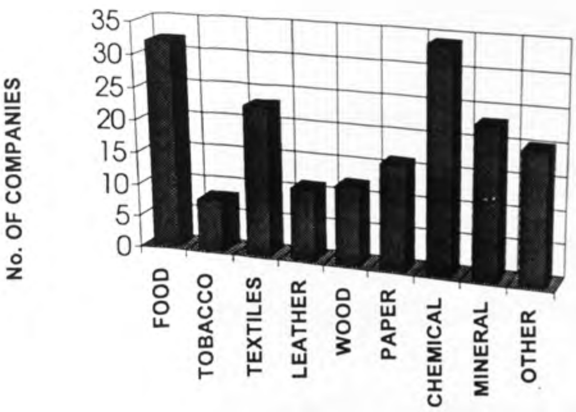
Type of Machine

Numeric values indicate number of companies manufacturing/installing equipment.

Cylinder	
Rotary	17
Indirect	3
Steam-tube	7
Cascading	5
Shelf/Tunnel	
Shelf	6
Rotating shelf	3
Turbo tray	4
Tunnel	22
Oven	21
Impingement	6
Dielectric/IR	10
Moving bed	5
Package	0
Filter-dryer	7
Freeze	2
Solar	0
Belt/Band	
Belt	13
Band	11
Perforated band	8
Plate	1
Paddle	
Double cone	3
Conical	3
Horizontal/vertical Paddle	6
Vertical pan	4
Spray	9
Pneumatic	
Pneumatic conveying	7
Flash	9
Spouted bed	1
Fluid Bed	
Fluid bed	10
Fluid bed granulator	5
Vibrated fluid bed	8
Torbed	0
Centrifugal	2
Stenter	6
Multistage	
Combinations of more than one dryer type	11
Drum	
Drum	5
Rotary filter	1
Mechanical	
Press	2
Centrifuges	7
Other Dryer	18

The most common 'Other' equipment included heat-pumps and dehumidifiers, air knifes and ultraviolet units.

Product Grouping



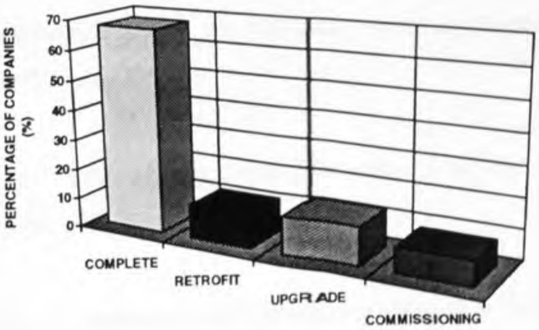
A large proportion of equipment manufacturers and installers were involved with the food, chemical and pharmaceutical industrial sectors. Due to the nature of equipment and/or industrial sector size, results indicated that industries such as the tobacco, paper and wood were supplied by only a small proportion of drying equipment companies.

Nature of Product Feed

Four companies manufactured and/or installed equipment to dry gasses. The remainder were involved with the drying of solids. The nature of the product feed stock was directly related to the equipment type. e.g. Sheet feed stock for a company manufacturing cylinder dryers etc.

Type of Installation

Complete drying systems were the most common installation offered by over 65% of respondents. Many companies offered facilities for upgrading systems or retrofit equipment installation.



Further Information

78% of the replies expressed that they were willing to provide further information concerning drying equipment with respect to energy consumption and efficiency.

APPENDIX B

RESEARCH PUBLICATIONS

This Appendix contains research papers published during the course of the project. The following papers were produced (The latter two are not included due to size and format);

- Jay, S, Oliver, T.N. Current Energy Trends for Industrial Drying Processes in the United Kingdom. 29th Universities Power Engineering Conference, Galway, 14-16 September, 1994.
- Jay, S, Oliver, T.N. Energy Consumption for Industrial Drying Processes in the United Kingdom. 9th International Drying Symposium, Gold Coast, Australia, August 1-4, 1994.
- Jay, S, Oliver, T.N. The Potential for Electrotechnologies in the Ceramics Industry. 30th Universities Power Engineering Conference, London, 5-7 September, 1995.
- Jay, S, Oliver, T.N. Artificial Neural Networks : Dryer Process Modelling and Control. International Congress on Electricity Applications, Birmingham, 16-20 June, 1996.
- Jay, S, Oliver, T.N, Booth, M, Jackson, S. Electrotechnologies in the Ceramics Industry. International Congress on Electricity Applications, Birmingham, 16-20 June, 1996.
- Jay, S, Oliver, T.N. Modelling and Control of Drying Processes Using Neural Networks. 10th International Drying Symposium, Krakow, Poland, 30 July - 2 August, 1996.
- Jay, S, Oliver, T.N. Timber Drying : Trends in Energy Consumption and Equipment Utilisation Within the UK Timber Industry. 10th International Drying Symposium, Krakow, Poland, 30 July - 2 August, 1996.
- Jay, S, Oliver, T.N, Evans, N, Hamlyn, M. Dielectric Properties of Gypsum at Microwave Frequencies and their Influence on Microwave Heating. International Conference on Microwave and High Frequency Heating, Cambridge, 1995.
- Jay, S, Oliver, T.N. Timber Drying : A Survey of the Timber Drying Installations in the United Kingdom. ISBN 1-85449-201-2. Midlands Electricity, Halesowen, Birmingham, 1996.
- Jay, S, Oliver, T.N. Is the Kilning Market Drying Up?. Timber Trades Journal. Vol. 378. No. 6214. November 1996.

CURRENT ENERGY TRENDS FOR INDUSTRIAL DRYING PROCESSES IN THE UNITED KINGDOM

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ABSTRACT

Industrial drying is a major user of energy in the UK. This paper discusses the past techniques used for energy estimation and reveals that no common approach has been taken. Little comparison can be made between studies, and as up-to-date auditing does not take place on a regular basis analysis of the changes in drying energy consumption at a national level are difficult.

Details presented here based upon a methodology proposed by Baker and Reay [6] show an increase in energy consumption for drying during the period 1978 to 1990. At the same time industrial energy usage has fallen.

Previous studies may have under-estimated the percentage of industrial energy used for drying. Results suggest this figure may be as high as 20% or 9×10^4 GWh of load nationally, representing a consumption of over 3×10^{11} MJ in 1990.

INTRODUCTION

Energy is an important commodity used widely throughout both the industrial and public domain. Audits of energy production and consumption are carried out periodically [1], [9].

Many investigators have studied energy consumption for specific industrial unit operations. Drying is one such industrial unit operation and past studies have indicated that drying is widely employed in a large number of UK industries and is a major consumer of energy. Over the last two decades results from many published surveys have claimed that drying is a major energy consumer [2] - [8], [10]. Analysis of the trends and current consumption of energy for industrial drying is an important quantity.

- *A greater in-depth estimation of the energy use in industry.* When combined with other values, leads to an overall view of energy consumption. Demand and supply networks can be planned and maintained to meet industrial requirements. Data may assist public utilities in the field of Demand Side Management techniques.
- *Areas for potential energy conservation can be investigated.* These can be machine, process or product specific. Results may lead to a reduction in energy costs, increased production, and a more environmentally friendly drying process.

The latter is an important factor when considering the variations in energy prices. Other factors such as legislation on pollution, working conditions and safety have become more stringent during the last decade.

Drying energy auditing and estimations of consumption is not a regular topic for examination. Published results have been examined. Regular auditing and updating does not take place.

The last published estimation for the UK industry in 1981 [6], apart from an overall report for the chemical industry [8], is now thirteen years old. Industrial energy consumption has shown a decrease during the last decade [1], [2], [9]. These trends, as shown in Figure 1.0, emphasise the need for regular analysis of the energy consumption in industrial drying.

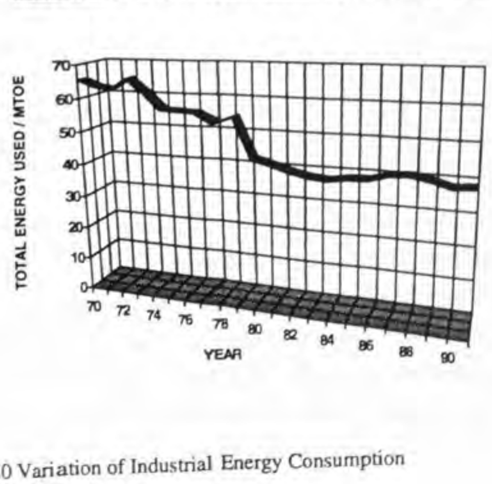


Figure 1.0 Variation of Industrial Energy Consumption

PAST STUDIES INTO DRYING ENERGY CONSUMPTION

Two general methods have been used in the past to estimate the energy consumption in industrial drying;

- Product based - Consideration of a wide range of products in various industrial sectors.
- Process based - Audits of various machines/processes for a variety of products, or industrial groups.

Previous audits have been based upon production figures, and have related energy requirements to the amount of moisture removed during processing [4], [5]. These surveys are flawed due to the exclusion of energy required for motive power (Pumps, fans etc.), the energy required for sensible heating of the product, losses from the machine, and machine inefficiencies.

Work by Baker and Reay [6] accounted for machine characteristics; energy consumption was based upon production figures for a variety of products from certain industrial sectors, relating production values to a product specific energy usage figure.

Other energy estimates have involved large scale industrial audits of specific sectors [3], [7], [8]. These methods involve an excessive amount of effort, and accuracy can not be assured.

All techniques used product or industrial group classification as basis for analysis. Selection was most commonly based upon overall sector energy consumption. This eliminated minority groups which could overall consume a substantial amount of energy. Moreover, all techniques assumed a set machine thermal efficiency, defined as the fraction of heat supplied that is actually required to evaporate the moisture. Drying processes can vary between about 25 and 50% [12] or more, and assuming an average value would have induced errors. Work by Wilmshurst [7] which assumed a weighted average was probably the most accurate, although the calculation considered few product groups.

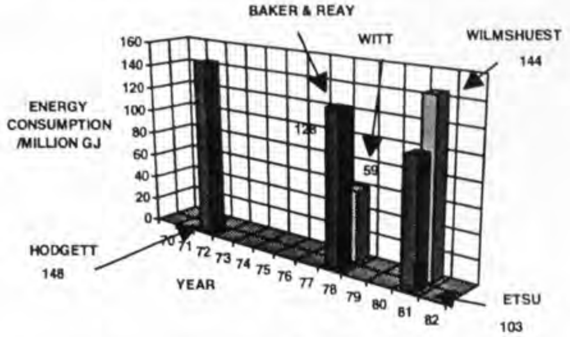
Figure 2.0 shows a comparison of five published surveys. The lack of a common approach makes comparison of data and examination of energy trends difficult. It must be noted that the comparison in Figure 2.0 does not take into account the method of analysis. Results by Hodgett [5] and Witt [4] were based on moisture measurement, whereas the others were product or industrial sector based. However, the results show that comparison of the energy estimates produce no definite trend. Moreover, results for the same year were found to vary by a factor of two.

ENERGY CONSUMPTION UPDATE

Selection of a Research Methodology

As part of this investigation it was necessary to develop a methodology to examine the trend in energy consumption over the last decade. Two factors restricted the selection of technique;

- Methods excluding machine and product characteristics, &
- Problems associated with large scale auditing.



ENERGY CONSUMPTION IN UK INDUSTRY

Figure 2.0 Energy Consumption in the UK for surveys studied

The former was considered inaccurate, while the latter involved an excessive amount of effort. The methodology suggested and utilised by Baker and Reay [6] was selected for the energy trend estimation. Updating the work involved recalculations using new production figures. Although the figures have inaccuracies the data and method are sufficient for a trend analysis.

Collection of Data

Baker and Reay [6] grouped industries into six sectors;

- Food and agriculture,
- Chemicals,
- Textiles,
- Paper,
- Ceramics and Building Material, &
- Timber.

In each sector various products were selected, and production figures used with a unit usage value to yield an overall figure for drying energy consumption. Estimates were made concerning scope of products analysed and overall sector size. Consumption figures were adjusted accordingly. The specific moisture extraction rates (SMER) of Baker and Reay [6] were utilised. The following correction factors allowing for limited product analysis were used directly from the original methodology;

- Food and agriculture - 90% energy accounted,
- Chemicals - 65% energy accounted,

Energy consumption adjustment relating to product quantity was not applied to the paper, printing and stationary industry, or ceramics and building material sectors.

Baker and Reays study was for the year 1978. A re-estimation every two years was considered appropriate for a general trend analysis, upto the year 1990. Availability of production data for all products was a limiting factor.

Various sources of information were used including statistical books of production, and the Government Business Monitor series. Trade organisations were consulted concerning production figures of specific products which were not published. Production figures which were not available were based upon production indexes and several by-products (e.g. Brewers spent grain) estimated by comparison with the original process or product.

Energy figures for overall timber production were not available due to the original source [9] changing the category of energy sectors. The exclusion of timber from the whole trend estimate was unavoidable due to the missing data. The consumption for timber was thus subtracted from the 1978 total.

DISCUSSION

Table 1.0 compares energy used for drying with total energy consumed in the sectors studied.

Overall Analysis

Figure 3.0 shows the variation of drying energy consumption as a percentage of the total energy used for the years 1978 to 1990.

It can be seen that the energy consumption for drying processes has increased when compared with the total industrial energy usage.

Figure 4.0 shows the variation of total industrial energy consumption over the last decade. The figure shows a gradual decrease in the total amount of energy used by the industrial sectors considered. The decrease appears to be greatest around the early eighties, and energy consumption levelled off by about 1986.

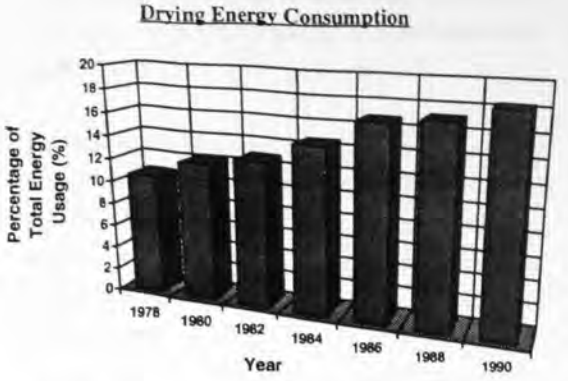


Figure 3.0 Trend in drying energy consumption in omparison to overall usage.

During the late seventies and early eighties there was an abundance of schemes, mostly the result of Energy Technology Support Unit [11] and other Government bodies, promoting energy efficiency. These projects involved education and movement towards more efficient processing and energy management. The downward trend in energy consumption for industry could be a direct result of these schemes, or just general techniques of improved production methods and energy awareness due to developing technologies in the eighties. The decline in manufacturing base could also be an attributing factor.

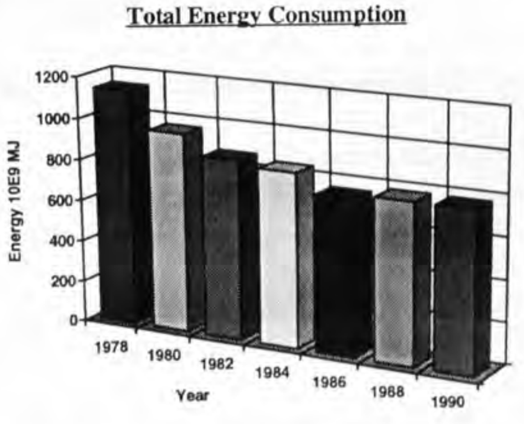


Figure 4.0 Total Industrial Energy Consumption.

Although the total energy consumption has decreased, the proportion of energy used for drying processes has increased. Results obtained suggest that schemes for improved drying efficiency, and energy conservation have not been effective in the long term.

Sector Analysis

Although several sectors analysed showed a decreasing drying energy consumption, the majority rose dramatically. Large consumers of energy for drying were the paper, printing and stationary, food and agriculture and chemical industries. The ceramics and building materials and textile industries used significantly less energy for drying.

Most sectors showed trends of decreasing drying energy consumption during the early eighties. This phenomena could have been the result of effective energy efficiency schemes and programmes, and/or development of new improved technology which may have produced more energy efficient systems. The food and agriculture industry was the only exception, showing an increasing energy consumption. The size and need for increased production due to population development may have contributed to this factor.

In the latter part of the decade, drying energy usage rose dramatically for the food and paper, printing and stationary industries. The chemical and textile industries consumption stayed relatively constant, whereas the ceramics and building sector decreased. In all sectors the total consumption of energy decreased, the greatest rate being during the early eighties. Results indicate that even though the consumption of energy for drying has decreased during the last decade, the decrease does not correspond with the reduction in total energy usage. i.e. the proportion of energy used for drying in comparison with the total has increased. The ceramic and building industry is an exception to this trend, with the drying energy consumption decreasing at a comparable rate to the total.

Accuracy of Updated Energy Estimate

Various problems were discovered during data collection and calculation using the methodology proposed by Baker and Reay [6]. The most probable areas for error included;

- Use of a constant specific energy system over the whole period studied. The unit figures were developed in 1978 and changes in production processes, improvements in machine operational characteristics and energy efficiency will adjust the figures. However, there is still a considerable amount of old process plant, and set standard production methods employed in all of the sectors considered, giving justification to application of the unit figures to new production levels. Errors were probably small.

- Sources of production figures varied considerably. Both energy usage and production data were affected. Sources were selected that were nearest to the figures stated by Baker and Reay [6] in 1978, thus reducing the errors to a minimum.

- Several products were grouped together within certain sectors in the original analysis. Present production data was unavailable for individual items within some groups. Errors would have occurred by estimating the proportions of each component.

- Baker and Reay [6] estimated and applied correction factors to the limited range of products analysed in each sector to obtain an overall value. Errors would have occurred if these estimates were inaccurate, or a large energy contributing product had been excluded. The nature of this error was hard to determine.

Resent production data was not available thus limiting the extent of the study to 1990. There has been a recession during the last four years which will have affected production. The trend in energy usage for drying processes during the early 1990's may be different from that revealed by the analysis.

The authors are presently conducting an greater in-depth study of energy consumption for drying processes. Methodology is based upon an equipment approach which may yield an up-to-date accurate energy value.

CONCLUSIONS

This paper has described details of published investigations into energy consumption for industrial drying in the UK, and has revealed that no common approach has been taken. The lack of up-to-date auditing has made analysis of trends difficult.

An estimation of the energy usage for drying in industry based upon a methodology proposed by Baker and Reay [6] has revealed that the total energy consumption for drying has increased over the period 1978 to 1990. Results from investigation of five sectors suggest that this could be as high as 20% of the total industrial consumption.

Moreover the total industrial energy usage has decreased from about 1140 to 780 x 10^9 MJ. Comparison of the total energy consumption for the five sectors with that of all industrial sectors revealed the sectors studied only represented 50% of overall industrial consumption. Based upon this evidence the energy consumed in drying in UK industry could have been in excess of 3×10^{11} MJ in 1990. i.e. 9×10^4 GWh of load nationally.

ACKNOWLEDGEMENT

This work is supported by the United Kingdom Science and Engineering Research Council and by Midlands Electricity plc, Halesowen, West Midlands, UK.

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TABLE 1.0 *SUMMARY OF DRYING AND TOTAL ENERGY ESTIMATION.*

INDUSTRIAL SECTOR	**YEAR** 10e9 MJ							
	1978		**1980**		**1982**		**1984**	
	DRYING ENERGY	**TOTAL ENERGY**	**DRYING ENERGY**	**TOTAL ENERGY**	**DRYING ENERGY**	**TOTAL ENERGY**	**DRYING ENERGY**	**TOTAL ENERGY**
FOOD AND AGRICULT.	35.42	286.44	37.80	197.71	39.29	173.34	41.40	168.38
CHEMICALS	23.00	461.80	21.29	435.74	20.44	420.23	24.06	404.30
TEXTILES	7.30	127.77	5.96	98.33	5.18	84.51	6.00	78.40
PAPER	44.83	137.16	43.29	116.37	38.57	90.20	42.81	91.16
CERAMICS/BUILD. MAT.	10.40	127.76	8.76	114.89	7.11	99.70	7.84	100.23
TOTAL	**120.9**	**1140.9**	**117.1**	**963.0**	**110.6**	**867.9**	**122.1**	**842.4**
PERCENTAGE OF TOTAL	**10.6 %**		**12.1 %**		**12.7 %**		**14.4 %**	

INDUSTRIAL SECTOR	**YEAR** 10e9 MJ					
	1986		**1988**		**1990**	
	DRYING ENERGY	**TOTAL ENERGY**	**DRYING ENERGY**	**TOTAL ENERGY**	**DRYING ENERGY**	**TOTAL ENERGY**
FOOD AND AGRICULT.	40.79	167.86	38.89	168.49	42.06	172.82
CHEMICALS	25.34	338.15	26.62	352.3	26.62	354.60
TEXTILES	5.73	52.12	5.91	54.75	5.16	49.48
PAPER	46.15	91.80	52.55	93.90	58.92	102.44
CERAMICS/BUILD. MAT.	7.69	105.08	8.67	108.35	8.38	96.64
TOTAL	**125.7**	**755.0**	**132.6**	**777.7**	**141.1**	**778.9**
PERCENTAGE OF TOTAL	**16.6 %**		**17.0 %**		**18.1 %**	

ENERGY CONSUMPTION FOR INDUSTRIAL DRYING PROCESSES IN THE UNITED KINGDOM

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Department of Mechanical & Electrical Engineering,
Aston University, Aston Triangle, Birmingham. UK.

ABSTRACT

Industrial drying is a major user of energy in the UK. This paper discusses the past techniques used for energy estimation and reveals that no common approach has been taken. Little comparison can be made between studies, and as up-to-date auditing does not take place on a regular basis analysis of the changes in drying energy consumption at a national level are difficult.

Details presented here based upon a methodology proposed by Baker and Reay (6) show an increase in energy consumption for drying during the period 1978 to 1990. At the same time industrial energy usage has fallen.

Previous studies may have under-estimated the percentage of industrial energy used for drying. Results suggest this figure may be as high as 20% or 9×10^4 GWh of load nationally, representing a consumption of over 3×10^{11} MJ in 1990.

Energy is an important commodity used widely throughout both the industrial and public domain. Audits of energy production and consumption are carried out periodically (1), (9).

Many investigators have studied energy consumption for specific industrial unit operations. Drying is one such industrial unit operation and past studies have indicated that drying is widely employed in a large number of UK industries and is a major consumer of energy. Over the last two decades results from many published surveys have claimed that drying is a major energy consumer (2) - (8), (10). Analysis of the trends and current consumption of energy for industrial drying is an important quantity.

- *A greater in-depth estimation of the energy use in industry.* When combined with other values, leads to an overall view of energy consumption. Demand and supply networks can be planned and maintained to meet industrial requirements. Data may assist public utilities in the field of Demand Side Management techniques.

- *Areas for potential energy conservation can be investigated.* These can be machine, process or product specific. Results may lead to a reduction in energy costs, increased production, and a more environmentally friendly drying process.

The latter is an important factor when considering the variations in energy prices. Other factors such as legislation on pollution, working conditions and safety have become more stringent during the last decade.

Drying energy auditing and estimations of consumption is not a regular topic for examination. Published results have been examined. Regular auditing and updating does not take place.

The last published estimation for the UK industry in 1981 (6), apart from an overall report for the chemical industry (8), is now thirteen years old. Industrial energy consumption has shown a decrease during the last decade (1), (2), (9). These trends, as shown in Figure 1.0, emphasise the need for regular analysis of the energy consumption in industrial drying.

PAST STUDIES INTO DRYING ENERGY CONSUMPTION

Investigation has shown that no common approach has been taken to estimate the energy consumption in industrial drying. Two general methods have been used in the past;

- Product based - Consideration of a wide range of products in various industrial sectors.

- Process based - Audits of various machines/processes for a variety of products, or industrial groups.

Previous audits have been based upon production figures, and have related energy requirements to the amount of moisture removed during processing (4), (5). These surveys are flawed because;

- Exclusion of energy required for motive power (Pumps, fans etc.),

- Exclusions of energy required to heat the product, losses from the machine, and machine inefficiencies,
- Assumption of a set machine thermal efficiency.

Work by Baker and Reay (6) accounted for machine characteristics; energy consumption was based upon production figures for a variety of products from certain industrial sectors, relating production values to a product specific energy usage figure.

Other energy estimates have involved large scale industrial audits of specific sectors (3), (7), (8). These methods involve an excessive amount of effort, and accuracy can not be assured.

Figure 2.0 shows a comparison of five published surveys. The lack of a common approach makes comparison of data and examination of energy trends difficult. It must be noted that the comparison in Figure 2.0 does not take into account the method of analysis. Results by Hodgett (5) and Witt (4) were based on moisture measurement, whereas the others were product or industrial sector based. However, the results show that comparison of the energy estimates produce no definite trend. Moreover, results for the same year were found to vary by a factor of two.

ENERGY CONSUMPTION UPDATE

Selection of a Research Methodology

As part of this investigation it was necessary to develop a methodology to examine the trend in energy consumption over the last decade. Two factors restricted the selection of technique;

- Methods excluding machine and product characteristics, &
- Problems associated with large scale auditing.

The former was considered inaccurate, while the latter involved an excessive amount of effort. The methodology suggested and utilised by Baker and Reay (6) was selected for the energy trend estimation. Updating the work involved recalculations using new production figures. Although the figures have inaccuracies the data and method are sufficient for a trend analysis.

Collection of Data

Baker and Reay (6) grouped industries into six sectors;

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- Textiles,
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Table 1.0 compares energy used for drying with total energy consumed in the sectors studied.

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Figure 3.0 shows the variation of drying energy consumption as a percentage of the total energy used for the years 1978 to 1990.

It can be seen that the energy consumption for drying processes has increased when compared with the total industrial energy usage.

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Sector Analysis

Figures 5.0 to 14.0 show the energy variation for the five sectors examined. The drying energy and total energy variation are shown for each sector during the period 1978 to 1990.

Although several sectors analysed showed a decreasing drying energy consumption, the majority rose dramatically. Large consumers of energy for drying were the paper, printing and stationary, food and agriculture and chemical industries. The ceramics and building materials and textile industries used significantly less energy for drying.

Most sectors showed trends of decreasing drying energy consumption during the early eighties. This phenomena could have been the result of effective energy efficiency schemes and programmes, and/or development of new improved technology which may have produced more energy efficient systems. The food and agriculture industry was the only exception, showing an increasing energy consumption. The size and need for increased production due to population development may have contributed to this factor.

In the latter part of the decade, drying energy usage rose dramatically for the food and paper, printing and stationary industries. The chemical and textile industries consumption stayed relatively constant, whereas the ceramics and building sector decreased. In all sectors the total consumption of energy decreased, the greatest rate being during the early eighties. Results indicate that even though the consumption of energy for drying has decreased during the last decade, the decrease does not correspond with the reduction in total energy usage. i.e. the proportion of energy used for drying in comparison with the total has increased. The ceramic and building industry is an exception to this trend, with the drying energy consumption decreasing at a comparable rate to the total.

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ACKNOWLEDGEMENT

This work is supported by the United Kingdom Science and Engineering Research Council and by Midlands Electricity plc, Halesowen, West Midlands, UK.

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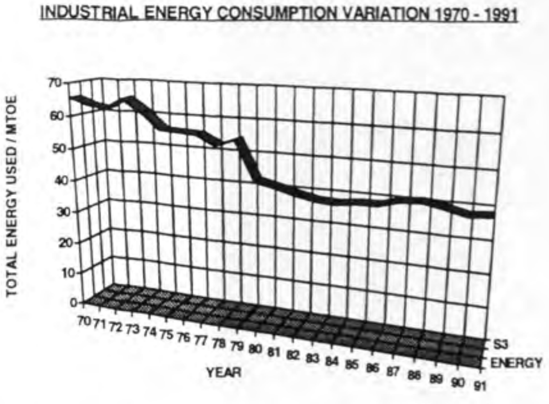

Figure 1.0 Variation of Industrial Energy Consumption

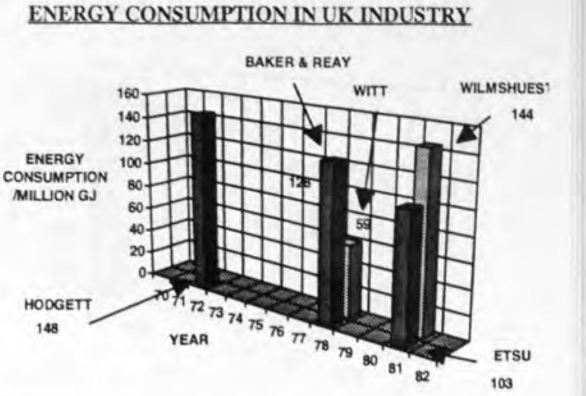

Figure 2.0 Energy Consumption in the UK for surveys studied

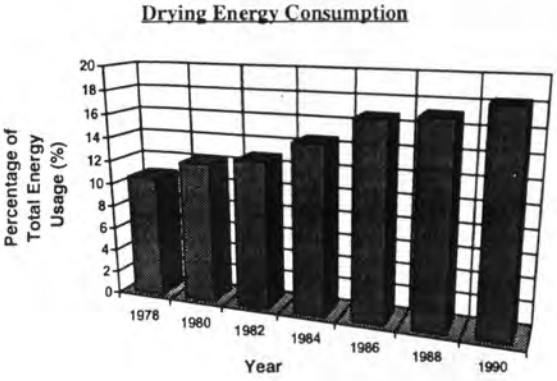

Figure 3.0 Trend in drying energy consumption in comparison to overall usage.

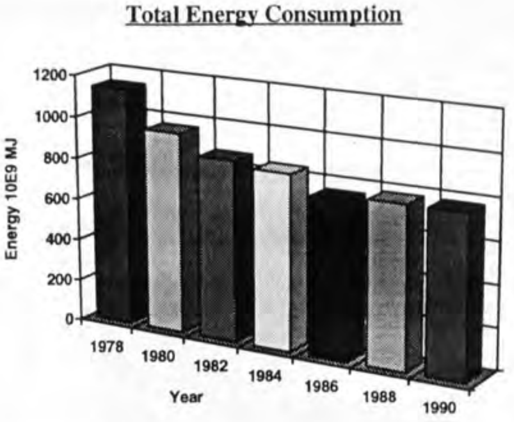

Figure 4.0 Total Industrial Energy Consumption.

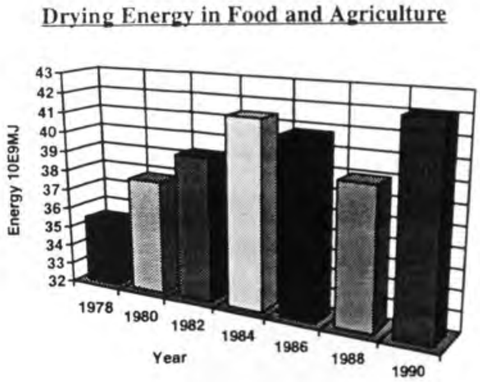

Figure 5.0 Energy for drying in the food and agriculture industry.

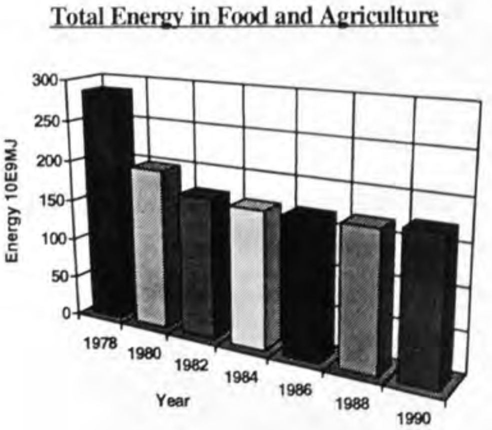

Figure 6.0 Total energy consumption in the food and agriculture industry.

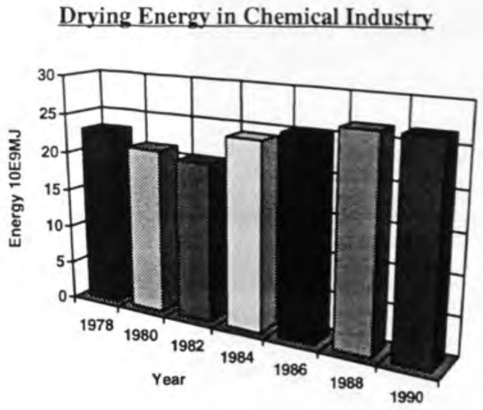

Figure 7.0 Energy for drying in the chemical industry.

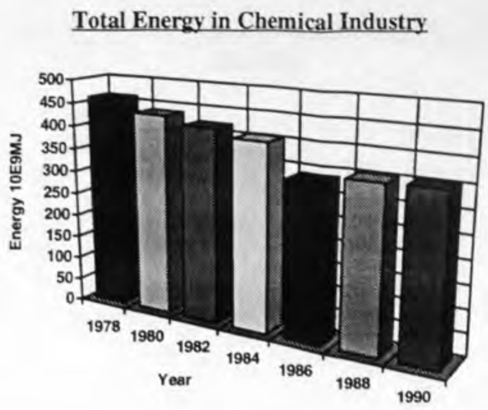

Figure 8.0 Total energy consumption in the Chemical industry.

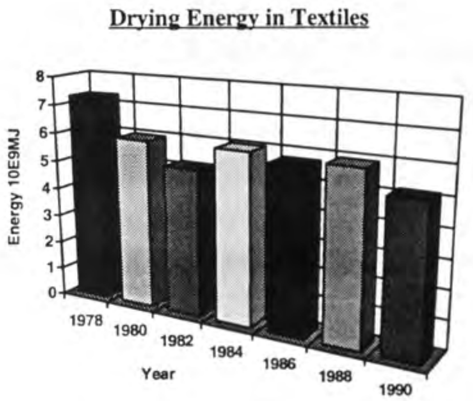

Figure 9.0 Drying energy consumption in the textile industry.

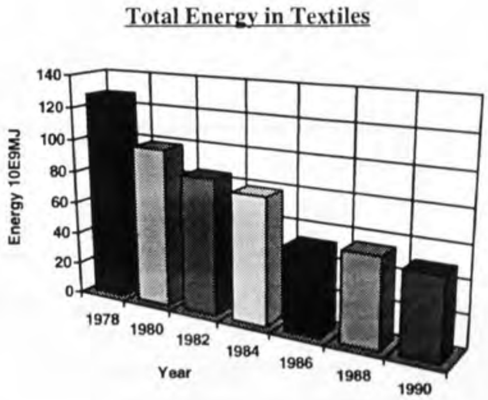

Figure 10.0 Total energy consumption in the textile industry.

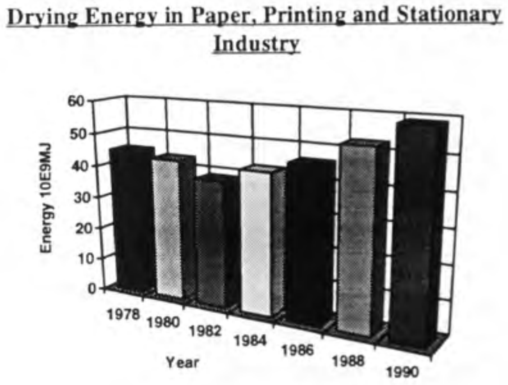

Figure 11.0 Drying energy consumption in the paper, printing and stationary industry.

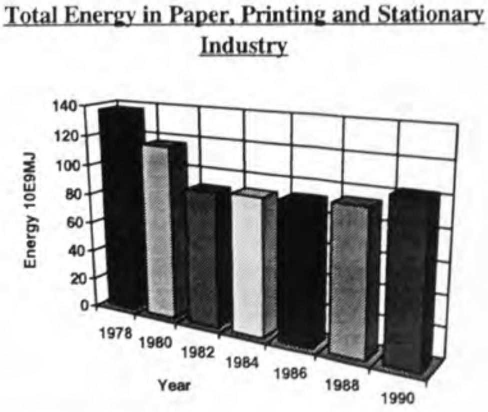

Figure 12.0 Total energy consumption in the paper, printing and stationary industry.

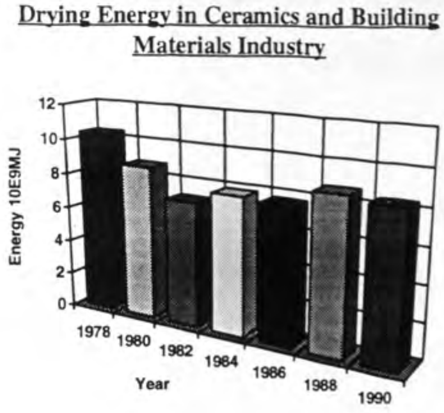

Figure 13.0 Drying energy consumption in the ceramics and building materials industry.

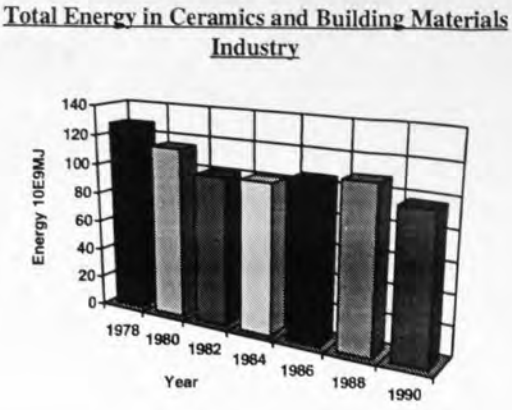

Figure 14.0 Total energy consumption in the ceramics and building materials industry.

Table 1.0 Summary of drying and total energy estimation.

INDUSTRIAL SECTOR	**YEAR** 10e9 MJ							
	1978		**1980**		**1082**		**1984**	
	DRYING ENERGY	**TOTAL ENERGY**	**DRYING ENERGY**	**TOTAL ENERGY**	**DRYING ENERGY**	**TOTAL ENERGY**	**DRYING ENERGY**	**TOTAL ENERGY**
FOOD AND AGRICULT.	35.42	286.44	37.80	197.71	39.29	173.34	41.40	168.38
CHEMICALS	23.00	461.80	21.29	435.74	20.44	420.23	24.06	404.30
TEXTILES	7.30	127.77	5.96	98.33	5.18	84.51	6.00	78.40
PAPER	44.83	137.16	43.29	116.37	38.57	90.20	42.81	91.16
CERAMICS/BUILD. MAT.	10.40	127.76	8.76	114.89	7.11	99.70	7.84	100.23
TOTAL	**120.96**	**1140.94**	**117.11**	**963.04**	**110.61**	**867.99**	**122.1253**	**842.46**
PERCENTAGE OF TOTAL	**10.60 %**		**12.16 %**		**12.74 %**		**14.49 %**	

INDUSTRIAL SECTOR	**YEAR** 10e9 MJ					
	1986		**1988**		**1990**	
	DRYING ENERGY	**TOTAL ENERGY**	**DRYING ENERGY**	**TOTAL ENERGY**	**DRYING ENERGY**	**TOTAL ENERGY**
FOOD AND AGRICULT.	40.79	167.86	38.89	168.49	42.06	172.82
CHEMICALS	25.34	338.15	26.62	352.3	26.62	354.60
TEXTILES	5.73	52.12	5.91	54.75	5.16	49.48
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CERAMICS/BUILD. MAT.	7.69	105.08	8.67	108.35	8.38	96.64
TOTAL	**125.72**	**755.01**	**132.65**	**777.79**	**141.15**	**778.98**
PERCENTAGE OF TOTAL	**16.65 %**		**17.05 %**		**18.19 %**	

THE POTENTIAL FOR ELECTROTECHNOLOGIES IN THE CERAMICS INDUSTRY

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ABSTRACT

Energy is a very important commodity used widely throughout the industrial and public domain. Drying is a common unit operation and the lack of up-to-date surveys has inhibited analysis of the trends in energy usage.

This paper discusses the energy consumption for drying processes within the ceramics sector. Product processes are investigated and the results of present and predicted future energy trends are revealed. The effectiveness of energy efficiency programmes are addressed and a comparison is made between Government energy targets and the general performance of past and present equipment within the ceramics industry. Comments are made concerning areas for potential improved process technology using electrical techniques. Case study examples are summarised emphasising the potential for improved energy efficiency, and other key factors such as improved productivity and product quality.

The analysis of the operational characteristics of machines and common practices will assist in the planning and maintenance of fuel supply networks and lead to a greater understanding of fuel utilisation vital for the successful application of demand side management techniques.

INTRODUCTION

The pottery industry is one of Britain's traditional industries and world famous names such as Wedgwood, Royal Doulton and Royal Worcester have been around for over 200 years. The principle subsections of the ceramics industry are;

- Tableware - China, Porcelain, Earthenware, and Stoneware,
- Sanitaryware,
- Wall and floor tiles, &
- Electrical and engineering ceramics.

Other products include refractories, abrasives and non-metallic mineral products such as plaster board and cement, which will not be considered here.

The UK ceramics industry is diverse, with a broad range of products being made by 1500 companies, employing over 20000 people [1].

Stoke-on-Trent is the main region containing 90% of the industry. A decade ago the sector consisted of many small traditional style potteries, but recently has become more concentrated.

Production levels have remained fairly constant with slight increases in tableware production and decreased output from the tile industry. The level of production is not expected to change significantly during the next decade, although stronger competition is expected from the Far East utilising cheaper fuel and labour.

The majority of ceramic manufactures produce their products from slip; an aqueous suspension of clay, filler and flux with a solids content of around 70%. Forming technologies vary significantly according to the type, size and shape of the product, but traditional craft skills are highly important [2]. A diagram showing typical ceramics process flow is shown in Figure 1.0.

Three different forming processes have been identified;

- Drying the slip to form a powder which is then pressed, (e.g. tiles)
- Squeeze water out of the slip to produce a dense plastic body which can be moulded; extruded, or shaped on plaster formers or hydraulic presses, (e.g. flatware), or in the case of electrical ceramic products machined.
- Casting the slip in a plaster mould which then absorbs water from the slip, depositing a layer of clay on the inside surface of the mould. (e.g. sanitaryware)

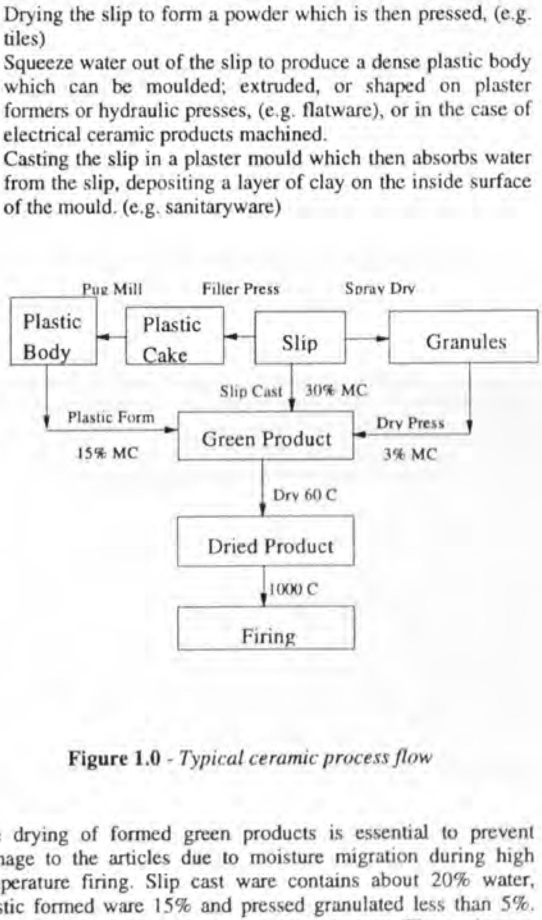

Figure 1.0 - *Typical ceramic process flow*

The drying of formed green products is essential to prevent damage to the articles due to moisture migration during high temperature firing. Slip cast ware contains about 20% water, plastic formed ware 15% and pressed granulated less than 5%. Plaster moulds also require drying prior to reuse. The equipment used for drying varies considerably depending upon the product. Granulate pressed products which have been formed from dried slip particles (usually incorporating a spray drier), require very short drying times and is even incorporated into the firing cycle. Green products formed by other routes contain too much water and separate drying operations are required.

Drying time and temperature is dependant upon product moisture content and thickness. Controlled reduction of the ambient humidity to avoid cracking is essential. Drying ware in the mould presents further problems with plaster dehydrate formation limiting drying temperature. Dryers are generally continuous using turntables or conveyors to move the ware through a heated chamber. For larger products, such as sanitaryware, intermittent dryers are often used. In many cases open shop drying is practised, in which the whole area is heated to dry the product which is left on racks.

ENERGY CONSUMPTION FOR DRYING PROCESSES

The energy consumption for ceramic manufacture can vary considerably from one plant to another according to the products made and types of equipment utilised [3].

In 1980 14.13×10^6 GJ was used in the ceramics industry [2], of which 4.3×10^6 GJ was used for drying and space heating (30.4% of the total energy for drying). In 1990 the total energy consumption (excluding electrical/technical ceramics) was 8.4×10^6 GJ [1], where 15 to 40% of energy in the sanitaryware and table -ware was used for drying and only 5-10% of energy was for drying in the manufacture of tiles.

Various sources of literature [3], [4] remark that the equipment used for drying pottery articles before firing is often primitive and relatively energy-inefficient, mainly because the cost of energy has traditionally been low compared with other production costs.

Table 1.0 shows a comparison of the specific energy consumption (Total energy) for the subsectors under investigation.

No current data has been published concerning technical and electrical ceramics.

Table 2.0 shows a comparison of the drying energy component.

Over the past years the pottery industry has made significant energy savings which have been achieved through improved management and housekeeping, reorganisation and closing of older, obsolete plant. Technologies such as improved burners, retrofit equipment and heat recovery systems have reduced specific energy consumption's. Savings have also been made through the movement away from steam raising to direct fuelled equipment for space heating and drying. The tables show a drastic decrease in the total SEC used for the production of ceramic ware. However, it must be noted that the 1990 figures do not include energy for space heating. Energy values, especially in the sanitaryware sector where open shop drying is widely practised, may have inaccuracies. Furthermore, 1990 figures are based upon a European study and for some technologies, e.g. tiles where traditional techniques still dominate over the more efficient roller methods, data may have been influenced by foreign processes.

Tableware total SEC figures appear to be especially low in 1990. The averaged values in the 1990 study are perhaps not comparable to bone china production in 1980, which is the most energy intensive process in the tableware sector.

Drying SEC's have decreased during the last decade (Table 2.0). It has been suggested in 1980 that improved drying methods and controls could produce savings in excess of 30% on the amount of energy used for drying in 1980 [2]. Instrumentation and other factors such as preventing over drying and optimising drying air recirculation could improve energy efficiency. Figures shown in the table have decreased nearly 90% for some processes over the last decade. However, comparison of 1990 to 1995 estimates, conducted by the author in certain sectors, have revealed discrepancies. For example monitoring was conducted on behalf of the author [10] at a leading tile manufacturer yielding an energy breakdown of; Spray drying (0.86GJ/t) - common to both processes, Traditional methods (0.4GJ/t), and Roller methods (0.2GJ/t). The 1990 figure obtained from the European study probably relates to the most modern roller installations in Italy, the leading European component, thus not reflecting typical UK practices.

Further surveys are being conducted examining the tableware and sanitaryware sectors. Additional sectors connected to the ceramics sectors such as refractories, abrasives, bricks and building materials are also under investigation.

It has been suggested that further savings of 5% for tiles, 30% for Tableware and 20% for sanitary of the drying SEC could be achieved based upon a study in 1990 [1].

Various energy efficient technologies have been highlighted [1], [2], [3] as potential ways of reducing energy consumption;

- Use of waste heat,
- Direct heating to replace steam,
- Controlled dehumidification, &
- Fast drying (including Infrared and microwave).

ELECTROTECHNOLOGIES FOR DRYING PROCESSES

Manufacturers are prepared to invest in new technologies if the gains in productivity and energy efficiency give paybacks on the investment within at least five years and, more commonly, around two years. These gains are acceptable only if there is no degradation in product quality. Increases in productivity, decreases in staffing levels due to automation and environmental gains may in many cases influence the investment over energy savings.

It is highlighted in Caddett analysis series report No.12 [5] that high levels of energy efficiency can be achieved with heat delivered by electromagnetic energy directly to the solid or the moisture in the solid, thereby avoiding the need to heat a stream of drying air.

The main electrotechnologies for drying applicable in the ceramics industry are;

- Infra-red,
- Radiofrequency,
- Microwave, &
- Heatpump dehumidification (including waste heat recovery).

Many sources are available describing these techniques; design and operation, and only the application within the ceramics sector and possible energy savings will be emphasised here.

The considerable non-energy benefits of electrically heated systems, particularly the vastly reduced drying times, can also be extremely valuable and give rise to short payback periods. Many of the examples quoted were situations where the electrical technique replaced an older less efficient type of dryer, which may be considerably different than those available today.

Infra-red Techniques

A combination of sources can be combined to emit a broad spectrum of infra-red radiation (IR). The oven design have to be customised to match the absorption bands of the product to optimise heating. IR radiation cannot penetrate ceramic bodies and so only the surface is heated, the core of the product is heated by conduction from the surface. The method is ideally suited to thin items such as tiles. Although gas IR units electric offer improved response times and eliminates problems of combustion products.

IR heating can easily be retrofitted to existing dryers by bolting on simple panel-shaped emitters at suitable points.

Trials conducted by Centro Ceramico of Bologan [5] have compared fast single layer roller drying and infrared roller drying. The results are summarised in Table 3.0.

	FAST DRYER	INFRARED DRYER
CYCLE TIME (mins.)	40 to 140	5 to 10
TEMPERATURE (°C)	100 to 240	180 to 200
SEC (GJ/t)	0.3 to 0.4	0.2 to 0.4

Table 3.0 - *Comparison of fast and IR dryers for tiles*

The study demonstrated that IR drying was more energy efficient and reliable in comparison to conventional techniques.

IR dryers are already used for tile production, although they have not penetrated UK markets. The tableware and sanitaryware markets are potential processes although the uptake of IR technology is limited. IR/vacuum techniques for drying sanitaryware have been demonstrated, with drying times being reduced from 24 hours to 2 hours with no detrimental effects on product quality [5].

Table 4.0 shows a typical energy balance for an IR dryer and conventional fast dryer.

100% ENERGY INPUT	FAST DRYER	IR DRYER
EVAPORATION OF WATER	36%	35%
MATERIAL	8%	33%
EXHAUST AIR	30%	14%
HEAT DISPERSED	26%	18%

Table 4.0 - *Energy balance for IR and conventional dryer*

Radio Frequency and Microwave Drying

Dielectric heating is a generic term for heating with an alternating electric field of high frequency (between 1MHz and 2.45GHz). Frequencies below 300 MHz are called radio frequency (RF), those above 300 MHz, microwaves. The two systems differ in the way the energy is applied, RF by a series of electrodes, while microwave is through a wave guide. Heat is delivered directly to the solid or to the moisture in the solid, thereby removing the need for to heat a stream of drying air.

Various applications in the ceramics industry have been documented;

Oda, Woods and Foster [12] descibe work involving the drying of ceramic 'green bodies'. Chabinsky and Eves [13] comment further on the drying of ceramic forms including the processing of ceramic ware in gypsum moulds during slpip casting. They describe relatively new applications where the time for mould release has been cur from 24 to 7 hours by microwave treatment, increasing throughput and reducing the need for mould drying between casts.

Microwave drying of cast enamel ware has reported energy savings of 73% and a payback of only 1.3 years. The short payback is due to increased production and savings in labour costs as much as energy savings [5].

Microwave/vacuum drying systems have been installed for the processing of slip casting techniques once the slip has been drained from the plaster cast. Microwaves are used for the initial hardening and then combined with vacuum moisture removal in a second stage. After the product is removed from the mould, the empty mould undergoes a further period of microwave/vacuum conditioning before returning to the casting station [6]. Figure 2.0 shows a typical installation.

Figure 2.0 - A *microwave unit at a slip casting facility*

Although these technologies are very efficient at the point of use, the efficiency of generation varies, 60% for microwave heating and 50% for RF. Considering this point microwave systems offer benefits including; reduced drying times, fewer moulds required (and hence energy for mould reconditioning/production), increased mould life, reduced space heating requirements for the casting shop, and increased productivity.

A ceramics company installing such a system in the UK drying slip cast lamp bases found that the specific energy requirement for 1Kg of ware reduced from 13.49MJ to 3.64MJ. [6] Another slip casting company manufacturing slip-cast ware [7] has reported a 90% reduction in energy costs, increased throughput of 150% and a payback time of 18 months for an atmospheric 10.5kW microwave unit.

Cast earthenware products in the UK amounts to approximately 620000 pieces/week [6]. The majority of these pieces are dried using open shop systems, gas heated castings and cabinet dryers. If, however, the microwave/vacuum drying technology was used, the potential energy savings on cast earthenware production alone would be 314TJ/year. (or £893000/year based on natural gas at £2.84/GJ).

If the total replication potential in the cast china tableware and giftware sectors of the UK industry were realised, savings of at least 1412TJ/year would be expected.

The application of microwave systems have been discouraged due to the large capital cost of installations, this combined with the relatively short life of magnetrons (approx. 2500 hours) has slowed the response from industry although the processes is technically feasible. Demonstrations in Italy with the drying of sanitaryware have achieved cycle times of 3 to 4 hours, incomparison with up to 48 hours for conventional methods.

Heatpump Dehumidification

In a traditional chamber dryer, large volumes of air are heated, passed over the product and then vented. Although heat recovery systems are available to recycle energy they are not widely utilised. Dehumidification systems are more energy efficient than conventional chambers because they are totally closed. Water is removed in a refrigerated heat exchanger which cools the air below its dew point releasing its latent heat. The hot exchanger in the refrigerant cycle heats the air in the chamber.

Communication with various ceramic manufacturers in the UK [10] revealed that the implementation of heatpumps within the UK ceramics industry has become wide spread, unlike other electrotechnologies.

A UK tableware manufacture has claimed that drying times have been reduced to one third with energy savings of 80%. [1]. Furthermore results published by CERAM Research suggest energy savings of 75% in comparison to direct gas-fired and steam heated chambers for plaster mould drying [3]. CADDETT studies [5] of applying heatpump dehumidification in the pottery industry has achieved cost savings of 45-50%, while reducing drying time by 20%.

A company manufacturing decorative plaster mouldings [8] have obtained a 90% reduction in drying time, 50% increase in throughput, a consistent product quality, with a pay back of only seven months by replacing their existing oven with an electric heatpump dryer. An electrical ceramic manufacturer also using heat pump drying techniques [9] has reduced drying times from four weeks to 15 days and reduced product reject rates by around 60%. Further applications include a pottery replacing an oil fired dryer with a heatpumps reduced their energy consumption by 45%, cut their drying time by 30%, reduced rejects by 10% and doubled production.

Process integration of heatpump technology must be considered since it is fundamentally a batch process. Savings may not be achievable in continuous flow process situations, such as the tile industry.

A simple and cost effective form of heat pump is mechanical vapour recompression (MVR). Although not applicable to most dryers, it can be used where superheated steam is used as the drying medium. In this technique the exhaust steam is adiabatically compressed, causing it to become hotter but without causing condensation. After recompression, the steam is suitable for reuse as the drying medium. No known applications are currently in operation within the UK ceramics industry, although tests have been performed drying bricks. CERAM research/EA Technology are currently building a prototype low-pressure superheated steam dryer for the ceramics industry incorporating MVR heat recovery [11].

Implementation of Electrical Processes

Many studies [1], [2], [3], [10] have revealed that few companies are able to relate fully their energy consumption to production variables such as output tonnage. This is largely because the output is traditionally measured in pieces rather than weight. Furthermore, many companies do not monitor their equipment and are hence unaware of the energy consumption characteristics of their processes.

Results summarised here emphasis that electrical drying techniques show outstanding promises in comparison to conventional methods, although their uptake within the UK ceramics industry is slow. Many barriers such as risk assessment, capital investment justification have to be assessed, together with the technical aspects of monitoring and implementation of a project which many smaller companies will not be capable of conducting. The Energy Efficiency Office offer a range of guides and projects from Energy Consumption Guides to New Practice Projects describing installations and energy efficient technologies are well documented. However further emphasis must be placed upon the need for monitoring and targeting to control energy use and plan improvements in the efficiency of the energy used. This assessment of machine operational performance will give a clearer picture of where energy is consumed within the ceramics sector, and reveal potential areas for improved efficiency and targets for the application of new technology and effective demonstration projects.

With energy utilities now looking at least cost planning/demand side management options it has been suggested [1] that in the future utilities will help finance energy efficiency investments, inparticular where the investment defends their market share against competitors.

ACKNOWLEDGEMENT

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SECTOR	SPECIFIC ENERGY CONSUMPTION GJ/t		
	1980[2]	1990[2] PREDICTED	1990[1]
PORCELAIN	212.5	139.5	70
EARTHENWARE	42.9	25.9	10
GLAZED TILES	13.3	8.3	9
UNGLAZED TILES	9.7	6.4	6
SANITARYWARE	44.0	29.1	30
ELECTRICAL CERAMICS	77.1	55.4	≈50

Table 1.0 - *Total specific energy consumption (SEC) for ceramic sectors*

SECTOR	SPECIFIC ENERGY CONSUMPTION (DRYING) GJ/t			
	1980[2]	1990[1]	1995[10]	REDUCTION FROM 1980 TO 1990 (%)
PORCELAIN	84.5 (40%)	20 (30%)	n.a.	76
EARTHENWARE	10.2 (24%)	3 (30%)	n.a.	70
GLAZED TILES	3.8 (29%)	0.5 (6%)	1.1	86
UNGLAZED TILES	4.2 (44%)	0.5 (8%)	1.2	88
SANITARYWARE	15.1 (34%)	6 (22%)	n.a.	60
ELECTRICAL CERAMICS	43.0 (55.8%)	n.a.	0.8	-

Note :
n.a. denotes figures not available, & Figures in brackets show percentage of the total energy consumption

Table 2.0 - *Drying specific energy consumption*

Electrotechnology Applications in the Ceramics Industry

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ABSTRACT

This paper discusses energy usage for drying and kilning processes within the ceramics sector. Electrical technologies for drying processes are examined including infra-red, microwave, radiofrequency and heat pump dehumidification techniques. Electric firing systems are also examined highlighting the application of electrotechnologies for decoration firing and new developments in fast glost firing. Comments are made concerning areas for potential improved process technology using electrical techniques. Case study examples are summarised emphasising the potential for improved energy efficiency, and other key factors such as improved productivity and product quality.

Cet article traite de l'utilisation de l'nergie dans les processus de schage et de cuisson employs par l'industrie cramique. Les technologies lectriques appliques aux processus de schage sont tudies, ainsi que la dshumidification par infrarouge, micro-ondes, radiofrquence et pompe chaleur. Les systmes lectriques de cuisson sont analyss et commentent l'application des lectrotechnologies la dcoration au four, ainsi que les nouveaux dveloppements raliss au niveau de la cuisson en mail rapide. Cet article propose des commentaires sur les secteurs d'application potentiels de la technologie employant des procds lectriques. Des exemples d'tudes de cas sont rsums et mettent en vidence les possibilits d'optimisation du rendement nergtique et d'autes facteurs cls tels que l'amlioeration de la productivitt et de la qualit du produit.

INTRODUCTION

The ceramics sector is one of Britain's traditional industries and world famous names such as Wedgwood, Royal Doulton and Royal Worcester have been established for over 200 years. The principle subsections of the ceramics industry are; tableware (china, porcelain, earthenware, and stoneware), sanitaryware, wall and floor tiles, & electrical and engineering ceramics. The UK ceramics industry is diverse, with a broad range of products being made by 1500 companies, employing over 20000 people.[1] Stoke-on-Trent in the Midlands is the main region containing 90% of the industry.

The majority of ceramic manufacturers produce their products from slip; an aqueous suspension of clay, filler and flux with a solids content of around 70%. Forming technologies vary significantly according to the type, size and shape of the product. The clay product is then dried to become rigid and undergoes various firing stages depending upon the nature of the product (Figure 1).

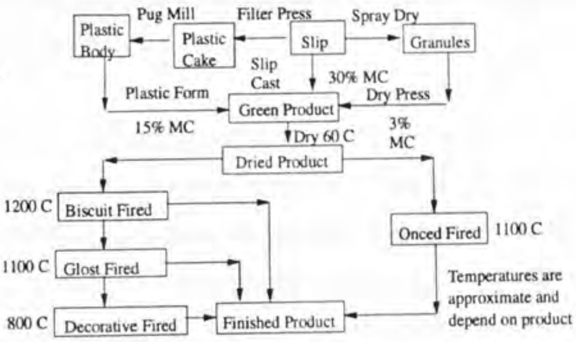

Figure 1 - Typical ceramic tableware manufacture process

Drying time and temperature are dependant upon moisture content and thickness. Controlled reduction of the ambient humidity to avoid cracking is essential. Dryers are generally continuous using turntables or conveyors to move ware through a heated chamber. In many cases open shop drying is practised. The whole area is heated to dry the product which is left on racks in the work area.

Firing, decoration and glazing can take place in a variety of ways. Firing of tiles, sanitaryware and the cheapest tableware can be carried out in one operation. More commonly, there is a first biscuit firing to increase the strength of the product. Glaze is commonly applied (and sometimes decoration) prior to glost firing. Decoration is usually added at this stage which is fixed by the decoration firing. Firings are carried out in continuous or intermittent kilns. In traditional tunnel kilns the ware is transported through the firing regime supported by refractory furniture on kiln cars. Roller hearth kilns convey the ware with a minimum of kiln furniture by using ceramic rollers. A large reduction in firing time is gained by using this technology, commonly known as fast firing.

ENERGY UTILISATION

The energy consumption for ceramic manufacturing can vary considerably according to the products made and types of equipment utilised.[2] In 1980 14.13 x 10^6 GJ was used in the ceramics industry as a whole,[3] of which 30% of the total energy was used for drying and 56% for firing operations. In 1990 the total energy consumption (excluding electrical/technical ceramics) was 8.4 x 10^6 GJ.[1] Table 1 shows the energy consumption for the subsectors under investigation.

ENERGY GJ/t	DRYING			KILNING	
	1980[3]	1990[1]	1995	1980[3]	1990[1]
PORCELAIN	84.5 (40%)	20 (30%)	47.3	113 (53%)	48
EARTHENWARE	10.2 (24%)	3 (30%)	n.a.	30.1 (70%)	5
GLAZED TILES	3.8 (29%)	0.5 (6%)	1.1	7.7 (58%)	4.8
UNGLAZED TILES	4.2 (44%)	0.5 (8%)	1.2	4.9 (50%)	3
SANITARYWARE	15.1 (34%)	6 (22%)	2.3	27.3 (62.1%)	20
ELECTRICAL CERAMICS	43.0 (55.8%)	n.a.	0.8	30.3 (39.4%)	n.a.

Note : n.a. denotes figures not available, & Figures in brackets show percentage of the total energy consumption

Table 1 - Drying/Kilning energy consumption

Over the past years the ceramics industry has made significant energy savings which have been achieved through improved management and housekeeping, reorganisation and closing of older, obsolete plant. Technologies such as improved burners, retrofit equipment and heat recovery systems have led to significant improvements in energy efficiency. Savings have also been made through the movement away from indirect steam raising, to direct fuelled equipment for space heating and drying. The ceramics industry energy consumption as a whole comprises 20% electricity and 80% fossil fuels, mainly gas. It has been estimated that less than 4% of the energy used for firing is supplied by electricity.

ELECTROTECHNOLOGIES IN THE CERAMICS SECTOR

Manufacturers are prepared to invest in new technologies if the gains in productivity and energy efficiency give paybacks on the investment within at least five years, but more commonly within two years. These gains are acceptable only if there is no degradation in product quality. Increases in productivity, decreases in staffing levels due to automation and environmental gains may in many cases be the major influence in the investment.

ELECTROTECHNOLOGIES FOR DRYING

The main electrotechnologies for drying applicable in the ceramics industry are; Infra-red, Radiofrequency, Microwave, & Heatpump dehumidification (including waste heat recovery).

Infra-red Techniques

A combination of sources can be combined to emit a broad spectrum of infra-red radiation (IR). The oven designs have to be customised to match the absorption bands of the product to optimise heating. IR radiation cannot penetrate ceramic bodies and so only the surface is heated, the core of the product is heated by conduction from the surface. The method is ideally suited to thin items such as tiles. Electric IR units offer improved response times over gas systems and eliminate problems of combustion products. IR heating can easily be retrofitted to existing dryers by fitting simple panel-shaped emitters at suitable points. Trials conducted by Centro Ceramico of Bologna have compared fast single layer roller drying and infrared roller drying.[4] The results are summarised in Table 2.

	FAST	INFRARED
CYCLE TIME (mins.)	40 to 140	5 to 10
TEMPERATURE (°C)	100 to 240	180 to 200
SEC (GJ/t)	0.3 to 0.4	0.2 to 0.4

Table 2 - Comparison of fast and IR dryers for tiles

The study demonstrated that IR drying was more energy efficient and required less maintenance in comparison to conventional techniques. IR dryers are already used for tile production, although they have not penetrated UK markets. The tableware and sanitaryware sectors are potential areas for the application of IR techniques although the uptake of IR technology is limited. IR/vacuum techniques for drying sanitaryware have been demonstrated, with drying times being reduced from 24 hours to 2 hours with no detrimental effects on product quality.[4] Infra-red heating has been applied by Portmeirion Potteries for maintaining the glostware at the correct handling temperatures for the application of decorative transfers. The application of this controllable form of heating has enabled quality levels to be maintained.

Radio Frequency and Microwave Drying

Dielectric heating is a generic term for heating with an alternating electric field of high frequency (between 1MHz and 2.45GHz). Frequencies below 300 MHz are called radio frequency (RF), those above 300 MHz, microwaves. The two systems differ in the way the energy is applied, RF by a series of electrodes, while microwave is through a wave guide. Heat is generated directly within the solid or the moisture in the solid, thereby removing the need to heat a stream of drying air.

A microwave/vacuum drying system has been installed at Goodson Lighting for the heating of slip in a process following drainage from the plaster mould. Microwaves are used for the initial hardening and then combined with sub-atmospheric pressure moisture removal in a second stage. After product removal the empty mould undergoes a further period of microwave/vacuum conditioning before returning to the casting station.[5] Drying times were reduced from 20 hours to under 15 minutes, allowing an increase in production capacity. Due to the nature of the microwave system precise control was achieved allowing Goodson to program the heat input into every product base, improving quality and reducing energy costs. The application of reduced pressure enables the drying process to operate at lower temperatures. Consequently the life of gypsum moulds has been increased by up to five times, reducing the number of moulds required by 83%. Even working at 50% capacity an annual energy saving of 5 TJ was realised, with total benefits valued at more than £168000, achieving a payback within three years. Cast earthenware products in the UK amounts to approximately 620000 pieces/week.[5] The majority of these pieces are dried using open shop systems, gas heated castings and cabinet dryers. If, however, the microwave/vacuum drying technology was used, the potential energy savings on cast earthenware production alone would be 314TJ/year (or £893000/year based on natural gas at £2.84/GJ).

Heatpump Dehumidification

In a traditional chamber dryer, large volumes of air are heated, passed over the product and then vented. Although heat recovery systems are available to recycle energy they are not widely utilised. Dehumidification systems are more energy efficient than conventional chambers because they are totally closed. Water is removed in a refrigerated heat exchanger which cools the air below its dew point releasing its latent heat. The hot exchanger in the refrigerant cycle heats the air in the chamber.

A heatpump dehumidification unit installed at Steelite International, a tableware manufacturer, replaced a gas fired 'in-kiln' drying process. Rejects were reduced by over 90% to under 0.5%, producing an annual saving valued at over £8000. The system was capable of handling 6000 cups overnight, removing 512 kgs of water in a 16 hour cycle. The dehumidifier enabled greater utilisation of the kiln, and reduced the floor space required when using a 'in-kiln' drying process. The introduction of dehumidifiers at Portmeirion Potteries has reduced plaster mould drying times from 72 hours to between 24 and 48 hours. This cut in drying time of up to 66% has generated annual savings valued at £30000 for an investment of only £20000. Control of the drying atmosphere using the dehumidifier resulted in the production of high quality moulds which was reflected in the reduction of rejects further down the production line. Working conditions were also improved.

ELECTROTECHNOLOGIES FOR FIRING

Table 3 shows the fuel utilisation of kilns.[6]

	Intermittent		Continuous	
TYPE OF KILN	Electricity	Gas	Electricity	Gas
Biscuit	12 %	88 %	8 %	92 %
Glost	67 %	33 %	11 %	89 %
Decoration	98 %	2 %	52 %	48 %

Table 3 - Percentage of fuels used in for firing

Table 3 reflects the current utilisation of electricity as a fuel for firing processes. Electricity is a refined fuel and commands a premium price. However the adoption of an electric process may result in a lower energy cost per unit of production due to an advantage in primary energy efficiency. 'Clean' electric processing may also improve quality and provide better working conditions. The introduction of environmental pollution regulations will enhance the application of electric kilns.

Kilns fired by electricity are commonly used for the final stages of processing, as reflected in Table 3. Electric kilns offer a high degree of control giving maximum yield during final firing of high value ware. It has been revealed that electric kilns give an advantage of a clean non-turbulent atmosphere, free from combustion products, with obvious quality benefits.

A new fast fired decorating kiln installed at Royal Worcester has increased productivity, reduced energy consumption by 48% and produced annual savings of £122000 with an investment payback time of less than three years. The new electric kiln, which carries bone china on a welded steel mesh belt, allows fast heat-up times, flexibility in firing cycles and high levels of energy efficiency. The continuous kiln unit allowed a reduction of work in progress due to the switch from a batch process. A similar electric rotary kiln has been installed at Rose of England, a manufacturer of high quality china beakers, replacing three intermittent units. The kiln has cut production lead times by 41% and reduced energy costs by 47%.

A new electric fast-fire glost kiln installed by M R Hadida Limited has reduced firing cycle times for bone china bathroom accessories from ten hours to two. This new process also cut firing costs by 70% enabling Hadida to produce higher quality products and increase daily production output by almost 600%. The unit is of a low thermal mass compact design with a floor space of only $28m^2$. The rapid response of the kiln has enabled Hadida to plan operations with Midlands Electricity to greatly reduce daytime electricity consumption by using lower cost night-time units for automatic warm up and programming daytime operation to avoid or reduce peak rate charges. The increased flexibility and control system of the new kiln allowed Hadida to achieve additional production capacity by using the kiln at both decorating and glost firing temperature. The kiln has achieved major quality gains by cutting transfer times from glazing to final firing, and has resulted in a significant reduction in surface dust contamination, thus improving product quality and miminising rejects.

Midlands Electricity in collaboration with Ceram Research has developed a new fast-fire kiln for glost firing. The 150kW silicon carbide element kiln capable of 1400°C has six zones, with four heating sections. The kiln is lined with low thermal mass refractory and ware is transported on ceramic chain driven rollers with heating elements above and below the conveyor. The kiln has a rapid heat up time and firing cycles have been reduced to as low as 30 minutes. Exceptional quality has been achieved during testing using unleaded glaze formulations developed for MEB by Ceram Research.

New and novel systems are currently under development including a 90kW microwave assisted gas firing process at EA Technology, and microwave kilning using a prototype 17kW, $1m^3$ unit at Staffordshire University.

CONCLUSIONS

The energy aspects and application of electrotechnologies for drying and firing within the ceramics industry have been discussed. Comments concerning areas for potential improved process technology using electrical techniques and the scope for research and development have been revealed. Case study examples have highlighted that electrical techniques can provide competitive benefits such as improved product quality, productivity and environmental aspects in comparison to conventional techniques.

ACKNOWLEDGEMENT

This work is supported by the United Kingdom Engineering and Physical Science Research Council and by Midlands Electricity plc, Halesowen, West Midlands, UK.

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Artificial Neural Networks :
Dryer Process Modelling And Control

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ABSTRACT

It has been shown that improved understanding and control of drying processes can lead to savings in energy, together with increased production throughput and enhanced product quality. Drying is still not well understood and normal computational modelling techniques have been hampered by the sheer complexity of the processes. Artificial neural networks offer a convenient platform for capturing the non-linearity and dynamics inherent in drying systems. This paper discusses the neural network modelling of the microwave drying of gypsum cove material. The experimental analysis is described together with development of the model architecture. The model's ability to predict moisture loss characteristics, including a measure of product quality, are revealed highlighting the accuracy of the applied technique. Comments are made concerning application of the model within the fields of control and of equipment evaluation.

Il a été démontré que la compréhension et le contrôle des processus de séchage peut permettre de réaliser des économies d'énergie et d'optimiser la productivité et la qualité des produits fabriqués. Le séchage n'est pas entierèment résolu et le développement des techniques ordinaires de modelage informatique a été ralenti par la complexité intrinsèque des processus. Les réseaux neuronaux artificiels offrent une plan d'analyse idéal de la non linéarité et des caractéristiques dynamiques inheréntes aux systèmes de séchage. Cet article commente le modelage par réseau neuronal du processus de séchage par micro-ondes des corniches en gypse. Il décrit l'analyse expérimentale ainsi que le développement de l'architecture de modelage. La capacité de prédiction des caractéristiques de perte d'humidité par modelage et la méthode de détermination de la qualité du produit y sont révélées, soulignant le précision de la technique employée. L'article commente l'application du modelage aux domaines du contrôle et de l'evaluation de l'équipement.

INTRODUCTION

INDUSTRIAL DRYING

Industrial drying is an energy intensive operation, consuming an estimated 3 x 10^{11} MJ of energy annually in the UK.[1] In recent years advances in drying have been achieved.[2] However drying is still not well understood (meaning that good phenomenological models may not be readily available), due mainly to the complexity involved in the simultaneous transfers of heat, mass and momentum during the process. Modelling has increased our knowledge, but many models are complex and in many cases require data that is either unavailable or outdated. Escalating energy costs and more intense competition provide the impetus for continued efforts in improving drying efficiency.

CONTROL AND MODELLING OF INDUSTRIAL DRYING

Until the advent of process computers, manual and automatic feedback systems were the most commonly used methods for drying control.[3] Many of these techniques are still in operation in older plants. The availability of process computers and advances in sensor technology have increased the use of control systems combining feedforward and feedback loops. Control of drying processes is an important factor which is directly related to an understanding of the drying system. A poorly controlled process is likely to be wasteful, both in terms of energy and inferior quality product. An understanding of the process will enable both the control and design of a dryer to be optimised, enhancing product quality, maximising throughput rates and minimising energy costs. Many systems are still based upon empirical data obtained from a vast number of experimental tests, scaling up of small scale tests and past design experience.

Feedforward control techniques have superseded feedback systems where there is a significant time lag between a control change being made to an input and its effect being felt on the outputs. Feedforward control depends upon having an accurate mathematical model of the system. Drying systems, like most industrial processes are very complex and sufficiently accurate models do not exist.[3] Due to the non-linear dynamic nature of drying processes linear based modelling and control methods are unsuitable. The characteristics of drying may vary because of changing raw materials properties, gradual changes in process equipment and changes in environmental variables.

NEURAL NETWORKS FOR MODELLING AND CONTROL

An approach that has evolved as a powerful computational technique in the past few years is artificial neural networks.[4,5] In chemical engineering neural networks have been applied to solve problems of fault diagnosis, sensor data interpretation, prediction of dryer performance and process control.[4,5,6]

A variety of neural network configurations and training algorithms have been developed over the past 20 years.[5] Multilayer perception architectures have been successfully applied to many modelling processes. These networks have one input layer, two or more hidden layers and an output layer. The number of neurons used in the hidden layers is one of the architectural parameters. Many articles have been published describing neural network configurations and architectures.[5, 8]

Pao, Bhat and McAvoy, Psichogios, and Ydstie, are among many researchers who have investigated the use of neural networks in process control.[4] Several types of neurocontrol architectures have been employed by researchers in the past and many of these require on-line training. Such training is feasible if it is fast and inexpensive, but in many cases on-line training will disrupt the normal operating environment and may even raise some safety concerns.

Over the past 12 years, model predictive control has become the standard procedure for control using a process model. In this architecture, an on-line model of the process is used to predict the outcome of future control actions. This paper describes work aimed at developing and evaluating a neural model of a drying system, with the possible applications to control and investigation of the process.

APPLICATION OF NEURAL NETWORKS TO A MICROWAVE DRYING SYSTEM

An industrial 4kW $1m^3$ multimode microwave unit was selected as the drying equipment. Tests were carried out using 100mm lengths of Gyproc cove. Although presently not commercially processed using microwaves, paper coated gypsum cove was chosen due to its availability, drying characteristics (including quality terms) and ability to be laden with a measurable quantity of water.

The dielectric properties and thermal-physical characteristics of the cove material have been examined demonstrating that it is very susceptible to microwaves, especially at high moisture contents.[9] Furthermore, careful control of the drying process (even using conventional methods) is essential due to the thermal sensitivity of the gypsum material. Excessive drying will result in the loss of the water of hydration forming the hemihyrate; a material with a marked change in structure and overall strength characteristics.

Optimising the energy efficiency of a machine and maximising product throughput may adversely affect product quality. It was essential that the model analysing the drying system should include some form of quality terms in its output. In an industrial situation there may be many parameters that effect the characteristics of the system, however a three input model was selected for initial investigation. The objectives were to evaluate the ability of a neural network to model a drying system, including a representation of product quality. Figure 1 shows the parameters studied.

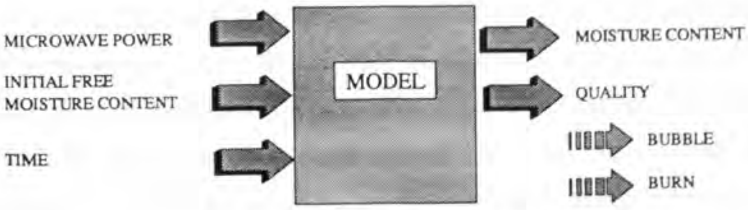

Fig. 1 - Model parameters

The cavity was modified and an electronic data-logging balance installed allowing the product weight to be recorded throughout the drying process. Samples of gypsum were soaked in water and allowed to reach an equilibrium moisture content. Drying characteristics were analysed for samples with moisture contents between 0g and 60g of added water, subjected to input magnetron powers of between 0 and 100% (4kW). Product quality defects were noted using a video camera with digital timing facility. Results were transferred directly to a PC version of MATLAB, where a third of the data was retained for model verification, and the neural networks developed. A backpropagation architecture network using a Levenberg-Marquardt approximation was utilised. Three separate networks were produced modelling moisture loss, paper bubbling and burning characteristics.

RESULTS AND DISCUSSION

MOISTURE LOSS

The drying curves (mass loss with time) obtained when paper coated gypsum cove was subjected to a microwave field showed typical drying characteristics, i.e. heating phase, constant drying phase, and falling rate period. The exact shape of the curve was found to be dependant upon the initial moisture content and magnetron power setting. Figures 2 and 3 show a comparison of network output to non-training test data for high and low power levels respectively.

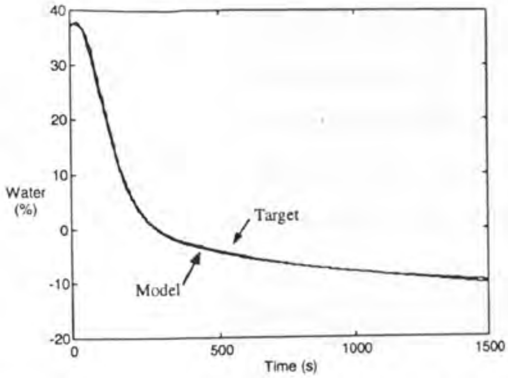

Fig. 2 - *Comparison between model and experimental data for low power*

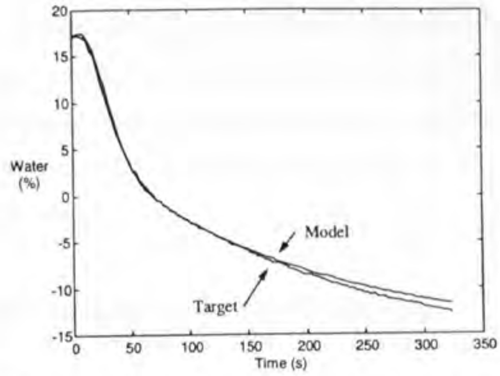

Fig. 3 - *Comparison between model and experimental data for high power*

Figures 2 and 3 show that the neural model constructed was capable of simulating the water loss drying curves of paper coated gypsum cove subjected to microwave heating within the parameter range analysed. Although small errors were encountered during the initial and final stages of drying the model could easily predict the point of zero free moisture content.

PRODUCT QUALITY

Paper bubbling occurred during microwave heating trials and was attributed to the paper coating being less porous than the gypsum core. The water was removed from the core due to internal pressure and temperature gradients being established during heating. As this water was removed, especially during the liquid movement phase that proceeds the constant drying period, the porosity of the paper was insufficient to allow the volume of moisture to migrate through the coating. Paper deformation due to the coating being forced away from the gypsum core thus occurred. Furthermore, due to the bubbling occurring during the initial stages of heating, the time for deformation to occur was not analysed. Paper shrinkage may have also contributed to the movement of the paper away from the central gypsum body. Since any form of paper deformation cannot be tolerated on a standard production line a model was produced to predict if any bubbling will occur. Figure 4 shows a plot of the experimental data obtained.

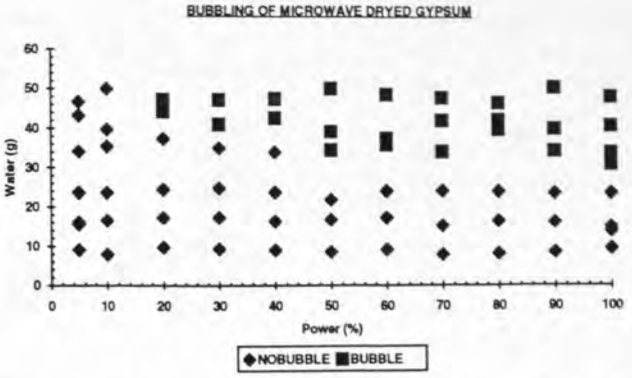

Fig. 4 - *Experimental data showing bubble deformation as a function of magnetron power and added water*

Various networks were assessed. A two layer structure with tangent and logsigmoid transfer functions was the most successful. Eight neurons formed the hidden layer and a sumsquared error (indication of the fit of the network output to training data) of 0.00037 was obtained after only 55 training epochs. Testing of the network with non-training data proved that the model could predict the likelyhood of paper deformation due to bubbling to a high degree of accuracy. Tables 1 and 2 show some typical results.

Table 2 shows that the model is capable of predicting the bubble characteristics for non-training data.

Training Data	Network Output
0	0.0000
0	0.0003
1.0000	1.0000
1.0000	1.0000
0	0.0000
1.0000	0.9807

Table 1 - *Comparison of the network output for modelling the training data*

Test Data Target	Network Output
0	0.0000
0	0.0002
1.0000	0.9249
1.0000	1.0000
0	0.0000
1.0000	0.9987

Table 2 - *Comparison of the network output for modelling of non-training data*

Burning of the paper coating the gypsum core occurred during microwave heating. The time to burn and dependence on the power level was attributed to the rate of removal of moisture from the body. Figure 5 shows a scatter diagram of the water content verses the time for initial burning for various microwave power levels.

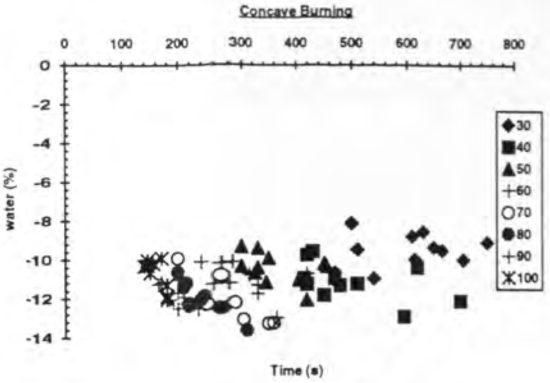

Fig. 5 - *Time and moisture group plot for concave burning*

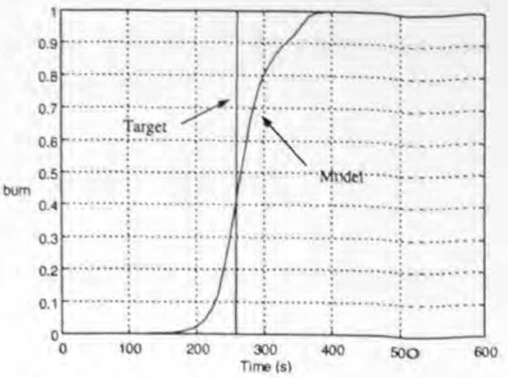

Fig.6 - *Comparison between model and non-training experimental data*

A three layer architecture (Tan-Log-Log) with 8 and 10 hidden neurons respectively was implemented. The network underwent 225 training epochs. Figure 6 shows a comparison of the network output when presented with non-training data, (where 1 represents burning, and 0 no burn). Although the models capability of predicting the time for burning in comparison to non-training experimental data resulted in some errors as high as 15%, most tests were within 4% of the target. The noise level and lack of training data was the most probable cause of the error. Further tests may have resulted in a more accurate representation of the burn phenomena. However, burning only occurred at a moisture content of below zero free-moisture, and hence was not considered important to warrant further investigation.

CONCLUSIONS

Artificial neural networks offer a convenient platform for capturing the non-linearity and dynamics inherent in drying systems. A neural network model was constructed capable of simulating the water loss drying characteristics of paper coated gypsum cove subjected to microwave energy to a high degree of accuracy. Furthermore, two quality terms notably, paper burning and bubbling were also investigated and successfully modelled.

The model could be applied as the 'model' component in a predictive control system, or used by engineers to maximise system performance and design by evaluating the response to input variations, without the need to run full scale tests. Further development could expand the technique to examine other parameters which have a direct influence on the drying characteristics of the process. Although the model is specific in nature, neural networks of this kind can be used in 'adaptive' control systems, where the model is retrained using modified data from the process, thus optimising the model to any changing process parameters.[4]

ACKNOWLEDGEMENT

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MODELLING AND CONTROL OF DRYING PROCESSES USING NEURAL NETWORKS

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Key Words : neural networks, modelling, drying

ABSTRACT

It has been shown that improved understanding and control of drying processes can lead to savings in energy, together with increased production throughput and enhanced product quality. Drying is still not well understood and normal computational modelling techniques have been hampered by the sheer complexity of the processes. Artificial neural networks offer a convenient platform for capturing the non-linearity and dynamics inherent in drying systems. This paper discusses the neural network modelling of the microwave and convection drying of gypsum cove material. The experimental analysis is described together with development of the model architecture. The model's ability to predict moisture loss characteristics, including a measure of product quality, are described highlighting the accuracy of the applied technique. Comments are made concerning application of the model within the fields of control and equipment evaluation.

CONTROL AND MODELLING OF INDUSTRIAL DRYING

Industrial drying is an energy intensive operation, consuming an estimated 3 x 10^{11} MJ of energy annually in the UK (Jay, 1994). In recent years advances in drying have been achieved (Robinson, 1992). However drying is still not well understood (meaning that good phenomenological models may not be readily available), due mainly to the complexity involved in the simultaneous transfers of heat, mass and momentum during the process. Modelling has increased our knowledge, but many models are complex and in many cases require data that is either unavailable or outdated. Escalating energy costs and more intense competition provide the impetus for continued efforts in improving drying efficiency.

Until the advent of process computers, manual and automatic feedback systems were the most commonly used methods for drying control (Mercer, 1994). Many of these techniques are still in operation in older plants. The availability of process computers and advances in sensor technology have increased the use of control systems combining feedforward and feedback loops. Control of drying processes is an important factor which is directly related to an understanding of the drying system. A poorly controlled process is likely to be wasteful, both in terms of energy and inferior quality product. An understanding of the process will enable both the control and design of a dryer to be optimised, enhancing product quality, maximising throughput rates and minimising energy costs.

Feedforward control techniques have superseded feedback systems where there is a significant time lag between a control change being made to an input and its effect being felt on the outputs. Feedforward control depends upon having an accurate mathematical model of the system. Drying systems, like most industrial processes are very complex and sufficiently accurate models do not exist (Mercer, 1994). Due to the non-linear dynamic nature of drying processes linear based modelling and control methods are unsuitable. The characteristics of drying may vary because of changing raw materials properties, gradual changes in process equipment and changes in environmental variables.

NEURAL NETWORKS FOR MODELLING AND CONTROL

An approach that has evolved as a powerful computational technique in the past few years is artificial neural networks (Joseph, 1993, Bishop, 1994). In chemical engineering neural networks have been applied to solve problems of fault diagnosis, sensor data interpretation, prediction of dryer performance, drying characteristics, quality factors during paper drying and process control of degradation dynamics (Joseph, 1993, Bishop, 1994, Huang, 1993, Kaminski, 1995, Jinescu, 1994, Elo, 1993, Strumillo, 1995, Zbicinski, 1996).

A variety of neural network configurations and training algorithms have been developed over the past 20 years (Bishop, 1994). Multilayer perception and radial bases architectures have been successfully applied to many modelling processes. These networks have one input layer, two or more hidden layers and an output layer. The number of neurons used in the hidden layers is one of the architectural parameters. Many articles have been published describing neural network configurations and architectures (Bishop, 1994, Ydstie, 1990).

Pao (Pao, 1989), Bhat and McAvoy (Bhat, 1990), Psichogios (Psichogios, 1991), and Ydstie (Ydstie, 1990), are among many researchers who have investigated the use of neural networks in process control. Several types of neurocontrol architectures have been employed by researchers in the past and many of these require on-line training. Such training is feasible if it is fast and inexpensive, but in many cases on-line training will disrupt the normal operating environment and may even raise some safety concerns.

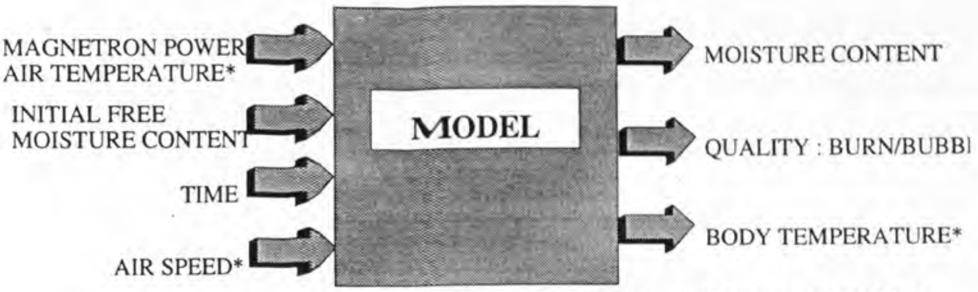
Over the past 12 years, model predictive control has become the standard procedure for control using a process model. In this architecture, an on-line model of the process is used to predict the outcome of future control actions. This paper describes work aimed at developing and evaluating a neural model of a drying system, with the possible applications to control and investigation of the process.

APPLICATION OF NEURAL NETWORKS TO A DRYING SYSTEM

Drying trials were conducted using an industrial 4kW $1m^3$ multimode microwave unit, and a convection tunnel dryer operating between 100-160°C. Tests were carried out using 100mm lengths of Gyproc cove. Although presently not commercially processed using microwaves, paper coated gypsum cove was chosen due to its availability, drying characteristics (including quality terms) and ability to be laden with a measurable quantity of water.

The dielectric properties and thermal-physical characteristics of the cove material have been examined demonstrating that it is very susceptible to microwaves, especially at high moisture contents (Evans, 1995). Furthermore, careful control of the drying process (even using conventional methods) is essential due to the thermal sensitivity of the gypsum material. Excessive drying will result in the loss of the water of hydration forming the hemihyrate; a material with a marked change in structure and overall strength characteristics.

Optimising the energy efficiency of a machine and maximising product throughput may adversely affect product quality. It is essential that the model analysing the drying system should include some form of quality terms in its output. In an industrial situation there may be many parameters that effect the characteristics of the system, however a three and four input model was selected for initial investigation. The objectives were to evaluate the ability of a neural network to model a drying system, including a representation of product quality. Figure 1 shows the parameters studied.



* : CONVECTION DRYING ONLY

Figure 1 - Model parameters

Both drying cavities were modified and an electronic data-logging balance installed allowing the product weight to be recorded throughout the drying process. For the microwave system drying characteristics were analysed for samples with moisture contents between 0g and 60g of added water, subjected to input magnetron powers of between 0 and 100% (4kW). Product quality defects were noted using a video camera with digital timing facility. Convection tests were performed at air temperatures of 100-160°C, air speeds of 35-75 Hz (Variable speed frequency controller) and moisture contents of 20-30 g of added water.

Results were transferred directly to a PC version of MATLAB, where a third of the data was retained for model verification, and the neural networks developed. A backpropagation architecture network using a Levenberg-Marquardt approximation was utilised.

RESULTS AND DISCUSSION

Moisture Loss

The drying curves (mass loss with time) obtained when paper coated gypsum cove was subjected to a microwave field or hot air stream showed typical drying characteristics, i.e. heating phase, constant drying phase, and falling rate period. A three layer architecture (Tan-Log-Log) with 8 and 10 hidden neurons respectively was implemented. Figures 2 and 3 show a comparison of network output to non-training test data for high and low power levels respectively for the microwave trials. Figures 4 and 5 show model and experimental curves for convection drying.

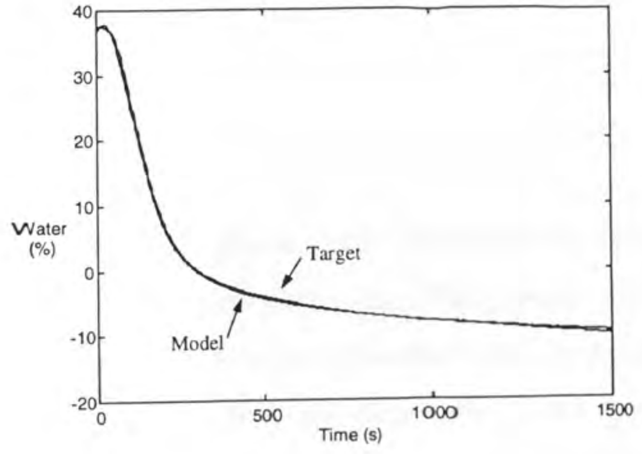


Figure 2 - Comparison between model and experimental data for low power microwave

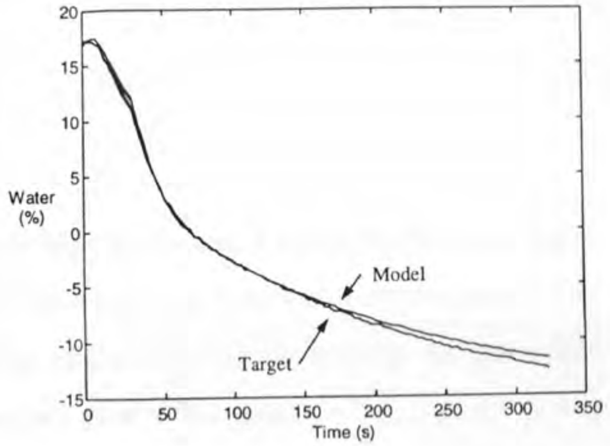


Figure 3 - Comparison between model and experimental data for high power microwave

Figures 2 to 5 show that the neural models constructed were capable of simulating the water loss drying curves of paper coated gypsum cove subjected to microwave heating or convection hot air drying within the parameter range analysed. Although small errors were encountered during the initial and final stages of drying the models could easily predict the point of zero free moisture content.

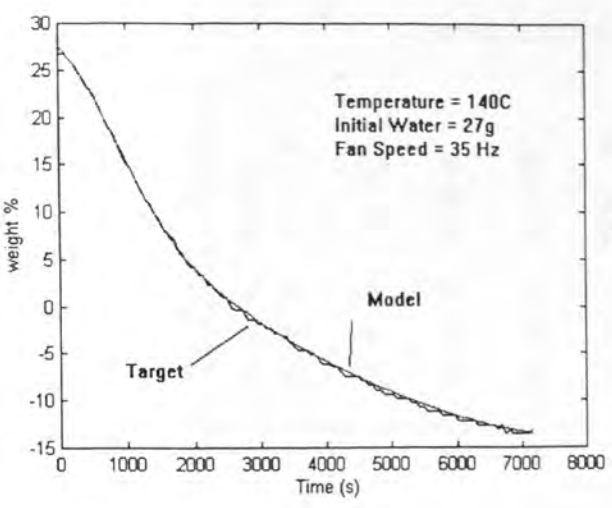


Figure 4 - Model and target for training data set - Convection drying

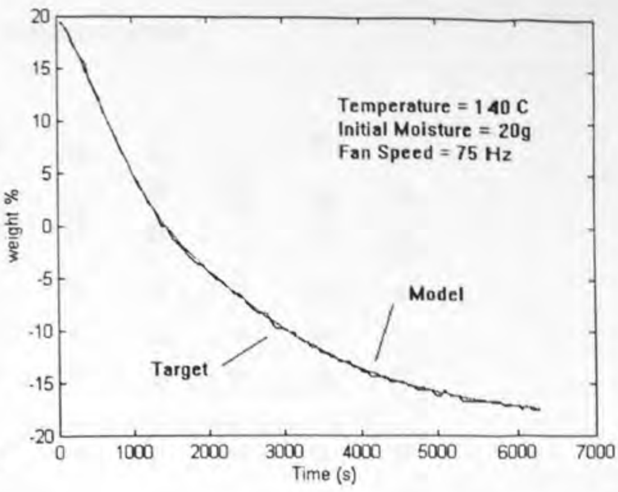


Figure 5 - Model and target for non training data set - Convection drying

Product Quality

Paper bubbling occurred during microwave heating trials and was attributed to the paper coating being less porous than the gypsum core. The water was removed from the core due to internal pressure and temperature gradients being established during heating. As this water was removed, especially during the liquid movement phase that proceeds the constant drying period, the porosity of the paper was insufficient to allow the volume of moisture to migrate through the coating. Paper deformation due to the coating being forced away from the gypsum core thus occurred. Furthermore, due to the bubbling occurring during the initial stages of heating, the time for deformation to occur was not analysed. Paper shrinkage may have also contributed to the movement of the paper away from the central gypsum body. Since any form of paper deformation cannot be tolerated on a standard production line a model was produced to predict if any bubbling will occur. Figure 6 shows a plot of the experimental data obtained.

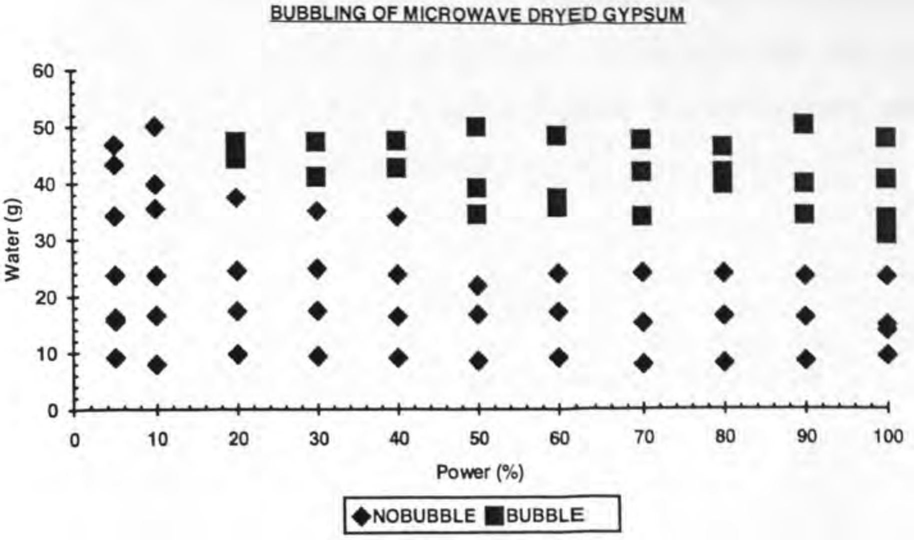


Figure 6 - Experimental data showing bubble deformation as a function of magnetron power and added water

Various networks were assessed. A two layer structure with tangent and logsigmoid transfer functions was the most successful. Eight neurons formed the hidden layer and a sumsquared error (indication of the fit of the network output to training data) of 0.00037 was obtained after only 55 training epochs. Testing of the network with non-training data proved that the model could predict the likelihood of paper deformation due to bubbling to a high degree of accuracy. Tables 1 and 2 show some typical results.

Table 2 shows that the model is capable of predicting the bubble characteristics for non-training data.

Training Data	**Network Output**
0	0.0000
0	0.0003
1.0000	1.0000
1.0000	1.0000
0	0.0000
1.0000	0.9807

Table 1 - Comparison of the network output for modelling the training data

Test Data Target	**Network Output**
0	0.0000
0	0.0002
1.0000	0.9249
1.0000	1.0000
0	0.0000
1.0000	0.9987

Table 2 - Comparison of the network output for modelling of non-training data

Burning of the paper coating the gypsum core occurred during microwave heating. The time to burn and dependence on the power level was attributed to the rate of removal of moisture from the body. Figure 7 shows a scatter diagram of water content verses time for initial burning for various microwave power levels.

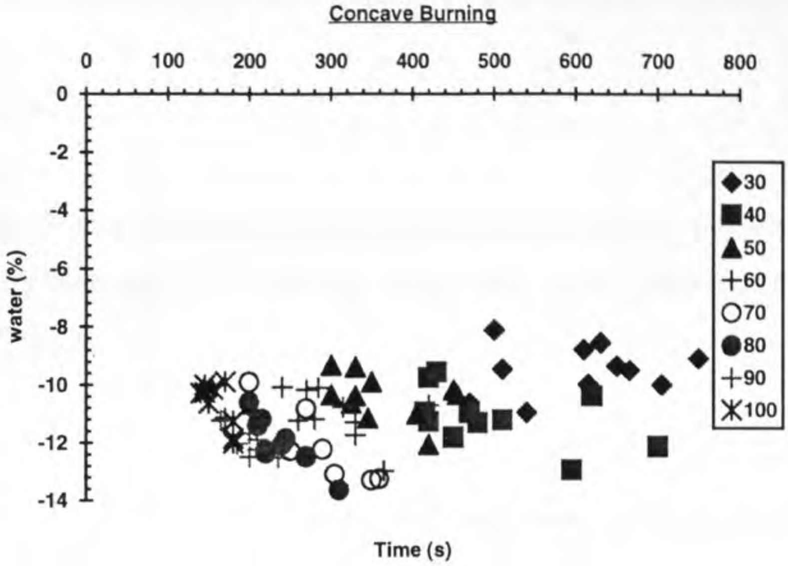


Figure 7 - Time and moisture group plot for concave burning

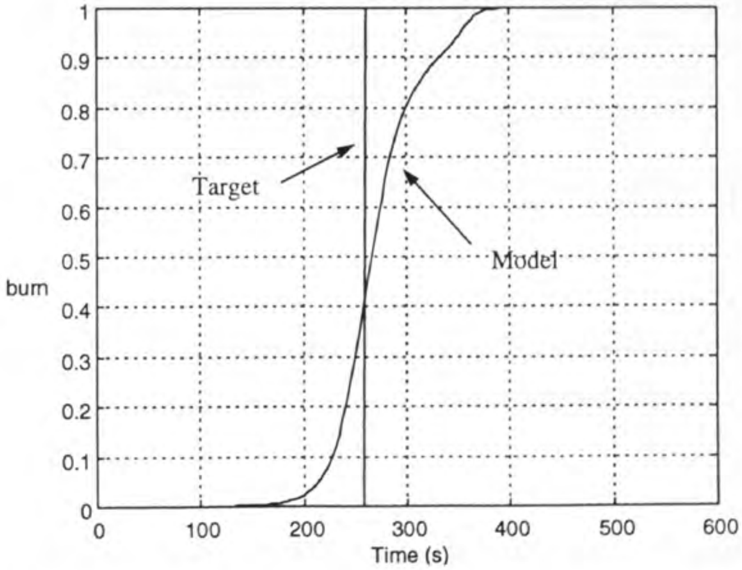


Figure 8 - Comparison between model and non-training experimental data

A three layer architecture (Tan-Log-Log) with 8 and 10 hidden neurons respectively was implemented. The network underwent 225 training epochs. Figure 8 shows a comparison of the network output when presented with non-training data, (where 1 represents burning, and 0 no burn). Although the models capability of predicting the time for burning in comparison to non-training experimental data resulted in some errors as high as 15%, most tests were within 4% of the target. The noise level and lack of training data was the most probable cause of the error. Further tests may have resulted in a more accurate representation of the burn phenomena. However, burning only occurred at a moisture content of below zero free-moisture, and hence was not considered important to warrant further investigation.

Product Temperature

The variation of product temperature was investigated for convection drying of gypsum. Data could not be obtained for microwave drying due to the interference caused by the electromagnetic field.

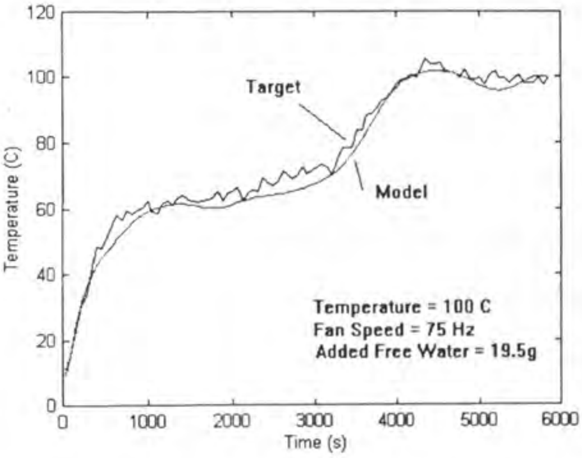


Figure 9 - Comparison of model and target for training data set

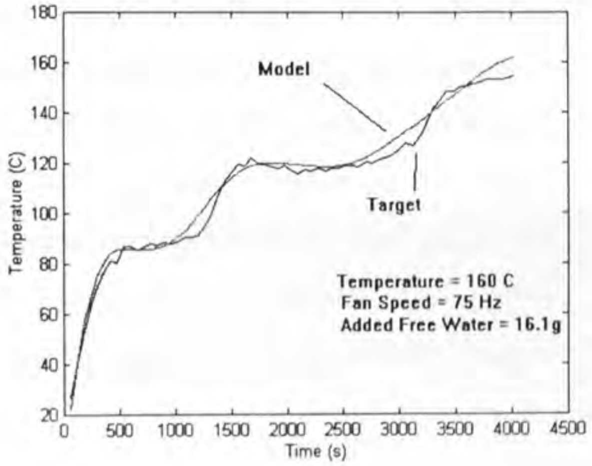


Figure 10 - Comparison of model and target for test data set

Problems of electrical noise were encountered using the fan variable frequency speed controller and a small degree of noise was thus present in the network target data. Initial training using backpropagation techniques proved inaccurate, and a radial base network was utilised. Initial development has only analysed data for a single fan speed, 75 Hz. Figures 9 and 10 show a comparison of model data and experimental target data for training and non-training inputs respectively. Initial results show some error, although general shape characteristics are inherent in the model output. Further work is continuing to develop a four dimensional input network.

CONCLUSIONS

Artificial neural networks offer a convenient platform for capturing the non-linearity and dynamics inherent in drying systems. A neural network model was constructed capable of simulating the water loss drying characteristics of paper coated gypsum cove subjected to microwave energy and a hot air medium to a high degree of accuracy. Furthermore, two quality terms notably, paper burning and bubbling were also investigated and successfully modelled. Initial investigation into the modelling of product temperature characteristics during convection drying has shown promising results and work to develop a four dimensional input is proceeding.

The model could be applied as the 'model' component in a predictive control system, or used by engineers to maximise system performance and design by evaluating the response to input variations, without the need to run full scale tests. Further development could expand the technique to examine other parameters which have a direct influence on the drying characteristics of the process. Although the model is specific in nature, neural networks of this kind can be used in 'adaptive' control systems, where the model is retrained using modified data from the process, thus optimising the model to any changing process parameters (Joseph, 1993).

ACKNOWLEDGEMENT

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TIMBER DRYING : TRENDS IN ENERGY CONSUMPTION AND EQUIPMENT UTILISATION WITHIN THE UK TIMBER INDUSTRY

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Key Words : timber, energy utilisation, drying

ABSTRACT

The benefits gained from using quality kiln dried timber have been recognised and have led to the evolution of a very traditional industry. Developments over the last 50 years have moved away from traditional air drying techniques to the utilisation of kiln drying processes. In an increasingly competitive industry the cost of drying is an important factor.

This paper describes a survey of kiln drying installations within the UK timber industry. This is an area which has remained unexamined for over 15 years. Trends in equipment type are evaluated and comments are made concerning fuel utilisation and products processed. The results of a survey examining the energy efficiency and consumption of drying equipment in the UK are presented. A comparison is made of previous studies and comments made concerning changes in energy utilisation. An estimation of the total energy consumption for drying processes within the UK is described. Results detailing energy consumption for specific equipment and species types and changes over the last 20 years are discussed. Concepts concerning the means of reducing the energy consumption for timber drying are discussed including the effects of air drying and views of UK kiln operators.

THE UK TIMBER INDUSTRY

The forestry products industry is very diverse in nature ranging from management of woodland to the processing of wood and pulp products. Britain's growing domestic markets and expanding supply of high quality timber from British forests has attracted over £100 million of new investment in the processing sector over the last 8 years (FIC, 1994). Furthermore while Britain still remains a relatively small producer compared with the larger softwood producing nations, British processors are able to compete aggressively within large import markets where quality, technological innovation and distance to markets give them the balance of advantage (FIC, 1994).

In 1992 7,052,000m^3 of timber were produced (FIC, 1994). Figure 1 shows the forecast production for the UK forest sector.

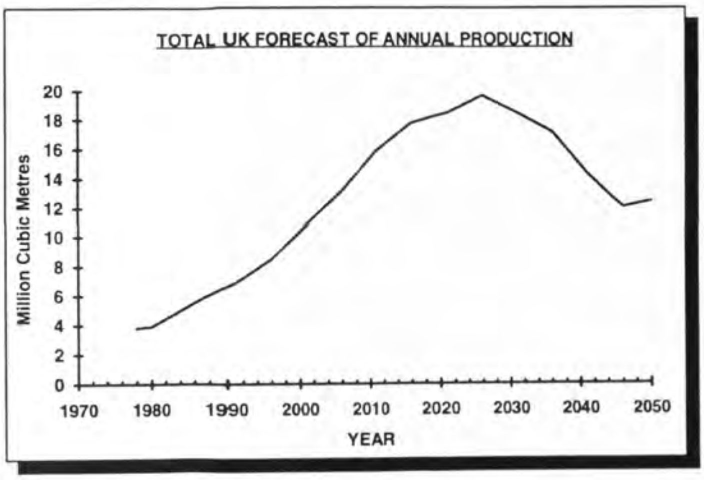

Figure 1 - Total UK forecast of annual production

The demand for wood products has increased since the late seventies, and it has been predicted that demand will increase further over the next decade. The production of home grown timber has doubled in the UK since 1976 representing over 7 million cubic meters of timber. It is predicted that the amount will increase further and could reach 20 million cubic meters in 2026.

A recent literature survey has shown that no UK based research concerned with the energy used for timber drying or review of current installations have been conducted within the last fourteen years. The last survey of kiln drying installations in the UK was published in 1981 by R.A. Hooks of the Timber Drying Section of TRADA (Hooks, 1981). The 1981 study up-dated the earlier work performed by G.H. Pratt and N.P. Skinner of the Building Research Establishment in 1971 (Pratt & Skinner, 1971).

A survey of the UK timber drying industry has been conducted (Jay & Oliver, 1996). From over 400 contacts within the timber industry 116 companies were found to be operating kilning facilities in the UK (Excluding Northern Ireland) in 1995, representing 467 individual kilns with an estimated capacity of 19902 m^3. The number of kiln operators has decreased by 60% since 1978. Table 1 shows the estimated amount of timber dried and variation over the last 20 years.

Table 1 - Volume of timber dried in 1995

VOLUME DRIED (/000'm^3)	**1973-74**	**1977-78 [5]**	**1994-1995**
Hardwood	472.5	392.5	164.2
Softwood	212.5	167.6	116.9
Both Hard & Softwood	-	-	104.5
Total	*685*	*568.5*	*385.6*

Note.: 12 companies were unable to provide volumetric data relating to their production.

Table 1 shows that there has been a 44% reduction in the volume of timber dried in the UK since 1978. However, there has been an increase in the total consumption since the early 1970s, home production has nearly doubled and imports have increase slightly. Many sources have suggested that imported timber is usually dried in the country of origin (Hooks, 1981), (ETSU, 1985), and data from the study demonstrates this is the situation in the 1990s. It is envisaged that the introduction of new British Standards, especially BS 4978 (British Standard, 1988) concerning the drying of softwood for constructional purposes, will lead to an increase in the amount of timber dried in the UK.

Previous studies have estimated 1210 drying units operating in 1978 (Hooks, 1981) although only 672 kilns were covered by a survey in 1976 (Electricity Council, 1976). Figure 2 and 3 shows the number of kiln facilities surveyed in 1976 and the present study. The reduction in kilning units reflects the declining market for timber drying in the UK.

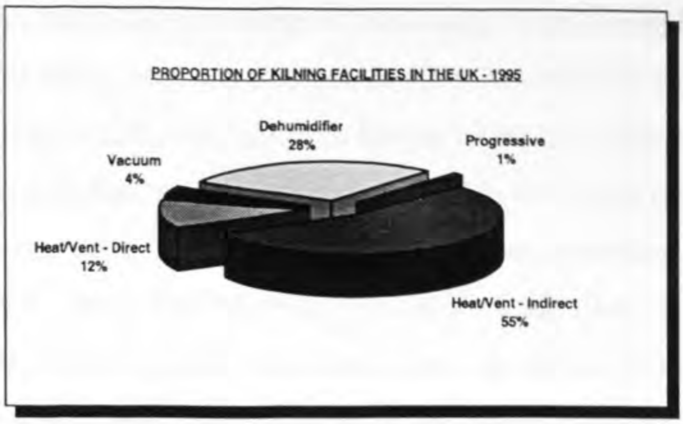

Figure 2 - Equipment type of kilning facilities in the UK (Proportion of total number)- 1995

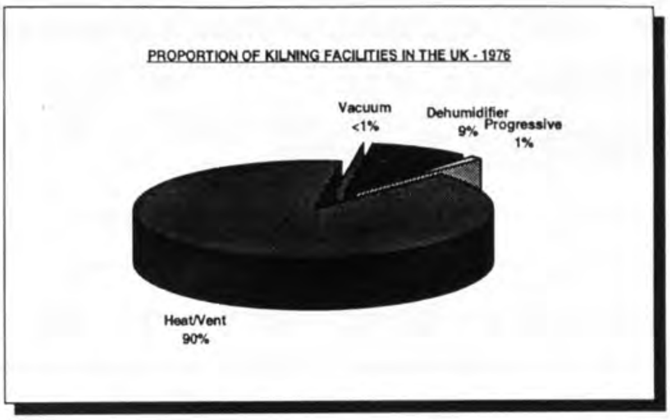

Figure 3 - Equipment type of kilning facilities in the UK (Proportion of total number)- 1976

From Figures 2 & 3 it can be seen that the use of dehumidifiers for drying has increased over the last 20 years, whereas the proportion of heat/vent type kilns has decreased. There has been no major investment in progressive kilns in the UK during the last decade. Discussion with kiln operators revealed that dehumidifiers were currently popular due to their close control of drying characteristics, low capital cost, no centralised steam raising boiler required, and their compact size which suits timber companies with a small throughput.

The application of vacuum kilns in the timber drying industry, like dehumidifiers has also increased over the last 20 years. It was reported that only one was in operation commercially in 1976 (Electricity Council, 1976), while the 1995 survey revealed 18 and a further two vacuum press kilns which were not fully investigated during this study. Manufacturers have reported commercial advantages with this equipment including; added product value due to improved product quality, faster drying times, and improved energy efficiency.

There has been a reduction in the number of kilns using oil and wood fuel since the 1970s, with a greater number using electricity and gas. In 1995 30% of kilns in the UK were using wood, oil and electricity as fuel. Gas, although having increased in use since the 1970s only supplies 10% of kiln installations. In capacity terms, 37% use wood as fuel, 29% oil, 21% electricity and 13% gas. Table 2 shows the number of kilns processing soft, hard and both types of timber. Results show that heat/vent kiln type are the most common with indirect heating as the heat source, either steam/hot water or air/air heat-exchanger system. Dehumidifier, indirect heat/vent, and vacuum kilns are most commonly used for processing hardwood.

Table 2 - Number of each kiln type processing timber types - 1995

WOOD	**HEAT/VENT**		**VACUUM**	**DEHUMIDIFIER**	**PROGRESSIVE**
	INDIRECT	DIRECT			
HARD	82	18	11	95	0
SOFT	45	3	0	9	3
BOTH	128	35	7	29	2
Total	*255*	*56*	*18*	*133*	*5*

The 116 kiln units survey in 1995 represented a total capacity of 19,902m^3, a reduction of approximately 31% since 1976. Figure 4 shows comparison of the capacity of kilns with the type of kiln utilised.

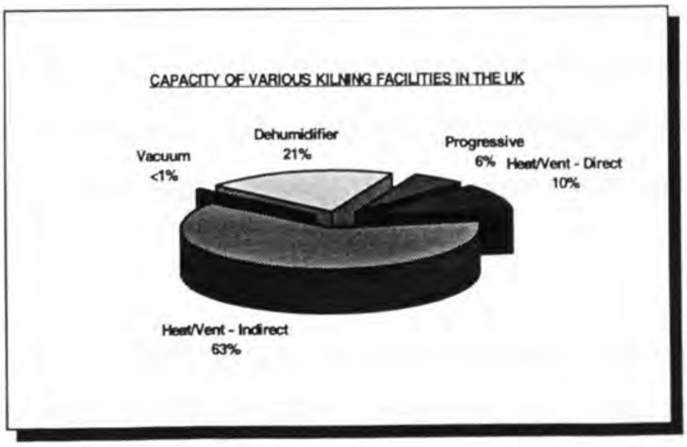

Figure 4 - Proportion of the total capacity for specific kilns types

Results obtained by a survey conducted by TRADA in 1978 (Hooks, 1981) suggested that although their were 210 dehumidifiers operating in the industry at the time, they represented less than 5% of the total UK drying capacity. Results of the 1995 study presented in Figure

11.0 show that dehumidifiers have taken a distinct proportion of the timber drying market share with a capacity of 21% of the total. The total capacity of kiln installations in the UK has decreased by approx. 31% since 1976. However, the number of single units has fallen from 1210 in 1976 to 467 in 1995, a reduction of 61%. This implies that the average individual kiln capacity has increased.

With regards to equipment types, many companies surveyed were not up-to-date with the modern equipment now available for timber drying. Several contacts for instance were not well informed of dehumidifier or vacuum techniques, and some had never heard of dehumidifiers. Many of the companies, although not all, appeared very traditional in their selection of equipment and operational characteristics/control of their kilns. These views will have to change if significant advances in timber drying in the UK are to proceed.

ENERGY UTILISATION WITHIN THE UK TIMBER INDUSTRY

Many studies have investigated the nature of kilns and the principles have been thoroughly researched and documented e.g. (Jay & Oliver, 1996), (Pratt, 1986). Further work has also been carried out involving energy studies of specific kiln equipment e.g. (Hanson, 1988), (Anon, 1985). These studies are mostly specific in nature and no reference was found relating to energy utilisation and efficiency of the whole timber drying industry in the UK.

Kiln drying is the most energy intensive process in the manufacture of timber products. The amount of energy used for drying depends on a number of factors; the amount of water evaporated being by far the most dominant, with dryer design, ambient air conditions, maintenance of equipment and drying procedures all having an important bearing (Comstock, 1975).

Communication with the timber industry revealed that energy monitoring of timber drying installations was not common practice. Most kilns in the UK lacked instrumentation to monitor fuel consumption, although automatic systems for temperature and humidity control have become more popular over the last decade (Jay & Oliver, 1996). Many operators based their drying costs on typical market averages or manufacturers design or commissioning data. Only a small proportion of the kiln users contacted during a recent survey of the industry (Jay & Oliver, 1996) held sufficient data to analyse general energy characteristics. Table 3 shows the average values of energy consumption for the kilns analysed and a comparison with previous studies.

Table 3 - Comparison of average energy consumption values

DRYER TYPE	**FUEL**	**DIRECT/ INDIRECT**	**SPECIES**	**AVERAGE MJ/kg Water Removed 1995**	**AVERAGE Thermal Efficiency (%) 1995**	**MJ/kg Water Removed (PREVIOUS STUDIES)**
Chamber	Oil	Direct	Hard	7.53	34	Hard 6.7-21.1 Soft 3.3-4.2
			Soft	13.7	19	
		Indirect	Hard	-	-	
			Soft	6.1	42	
	Gas	Direct	Hard	12.4	21	
			Soft	-	-	
		Indirect	Hard	14.7	17	
			Soft	5.6	46	
	Elec	-	Soft	4.7	55	
Vacuum	Gas	-	Hard	4.3	59	General 2.9-5.0
			Soft	6.5	40	
	Oil	-	Hard	10.6	24	
			Soft	-	-	
Dehumid -ifier	Elec	-	Hard	4.9	52	1.1-2.9
			Soft	1.5	172	1.6-4.4

Table 3 shows a large variation of energy requirements for specific kiln types. The energy required to remove the water from the timber varied from 1.51 MJ/kg for a dehumidifier drying softwood to 21.78 MJ/kg for an indirect gas fired chamber kiln drying hardwood.

Many sources of literature (Hansom, 1988), (Pratt, 1986) have suggested that water is more easily removed from softwoods in comparison to hardwoods due to difference in structure of the two species. From the energy view point, with the exception of gas fired chamber kilns and dehumidifiers, comparison of the results have found no evidence to back these suggestions.

The energy utilisation of vacuum kilns in comparison to past studies appears to be similar, requiring about 4 MJ of energy to remove 1 kg of water. The installation of vacuum kilns in the timber drying industry has increased over the last 20 years, and 89% of the present units are less than 10 years old (Jay & Oliver, 1996). However vacuum kilns only represent a very small proportion (4%) of the present number of kilns and less than 1% of the timber drying capacity. The lack of wide spread application of this kiln type has probably slowed development and adjustment of kiln schedules which may reduce drying times, maximising productivity, reducing drying costs and hence energy consumption. The energy benefits of using vacuum kilns for timber drying have been questioned by many researchers (Hansom, 1988), (Brazier, 1991). Results shown in Table 3 suggest that generally vacuum kilns are no more efficient than chamber kilns. The lack of detailed information relating to timber species, type of kiln heating, load volume, atmospheric conditions, and drying schedule have hindered an exact comparison of previous studies.

Figures in Table 3 show that the present energy utilisation of dehumidifiers drying hardwood is greater than that revealed in past studies. However data for softwood drying showed a marked reduction in energy requirements, although limited information was available. Pratt (Simpson, 1983) found that the energy consumption in dehumidifier drying ranged from 15 to over 50% less than in conventional kiln drying depending on species. Chech and Pfaff (Simpsom, 1983) also found energy reductions of over 50%. Results of the present study also agree with these findings, with energy consumption reductions of 89% in comparison to an inefficient chamber kiln processing hardwood. The average values displayed in Table 3 show clearly that dehumidifier kilns are the most energy efficient type of timber dryer, requiring on average only 4.9 MJ/kg of water removed and 1.5 MJ/kg for drying hardwood and softwood respectively.

Chamber kilns represent the largest proportion (67%) of the current timber drying installations in the UK, and 73% of the capacity. Table 3 shows that energy utilisation for drying hardwoods is similar and softwoods high in comparison to previous studies. Electric heating is efficient but is offset by the unit cost of the fuel. However, electric kilns offer additional benefits such as low emissions, improved product quality due to controllable heating, less maintenance and lower capital costs.

TOTAL ENERGY CONSUMPTION FOR TIMBER DRYING IN THE UNITED KINGDOM

The total energy consumption of timber drying processes in the UK has not been examined for over 15 years (Jay & Oliver, 1996). The methodology and data used for evaluating timber drying energy consumption in the past is questionable and figures of limited nature were uncovered during a comprehensive literature survey.

Figures 5 and 6 show the variation of the total and drying energy consumption over the last 25 years. Although the energy used for drying has decreased during the last 20 years, the proportion of the total has only fallen slightly.

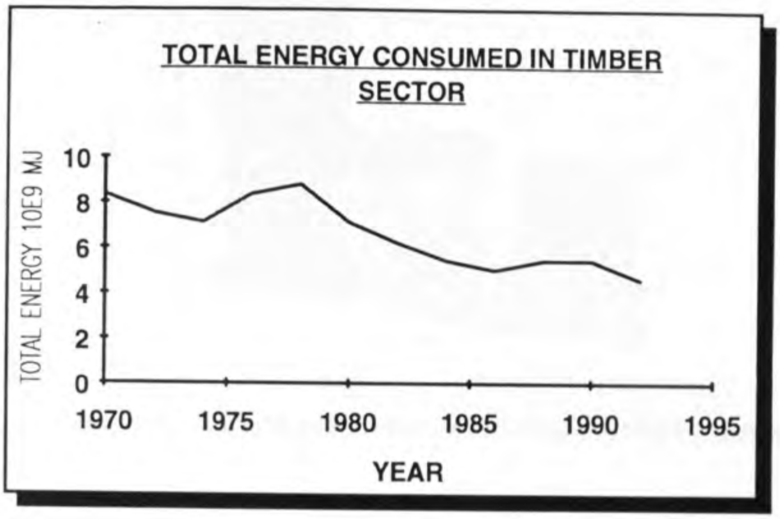

Figure 5 - Total energy consumption

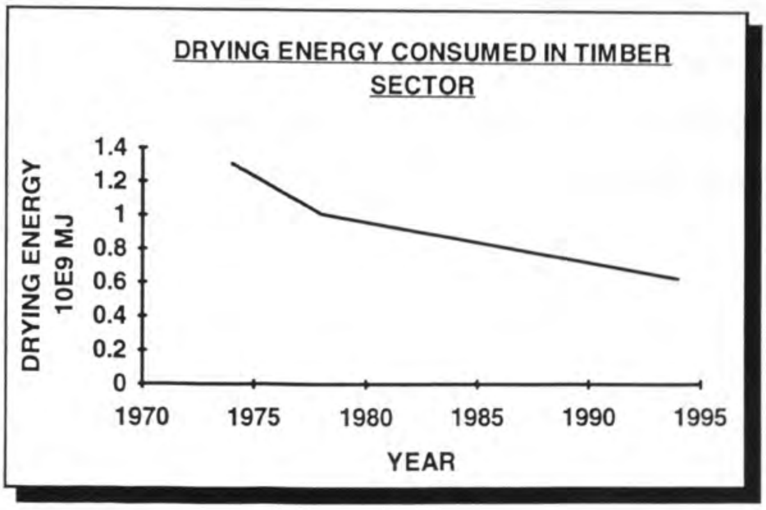

Figure 6 - Drying energy consumption

Figure 7 shows the variation of the total energy consumption for timber drying as a proportion of the volume of wood processed.

Energy utilised for drying a cubic meter of timber has decreased since the 1970s, although only slightly during the last decade. The declining use of conventional heat/vent kilns and introduction of energy efficient dehumidifier units over the past 20 years (Jay & Oliver, 1996) has resulted in this overall reduction in energy consumption. There is further scope for greater energy savings by implementing dehumidifier units for timber drying.

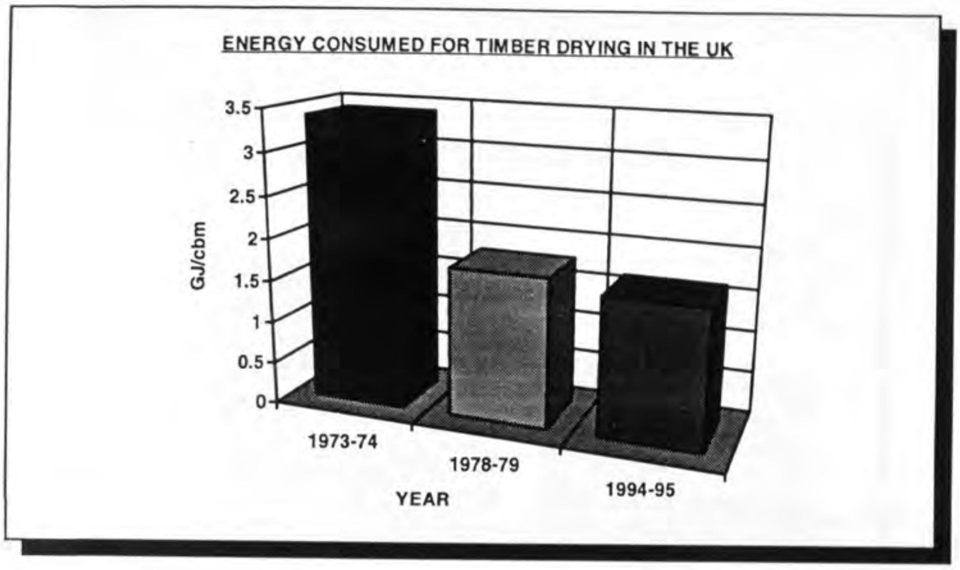

Figure 7 - Energy consumption for timber drying (GJ/m^3)

Figure 8 shows the proportion for energy utilised by each kiln type for timber drying in 1995. The comparison shows that dehumidifiers use a significantly smaller amount of energy per volume of timber produced than other conventional kilns. The variation of energy for softwood and hardwood drying with respect to the volume of timber produced in the UK is shown in Figure 9.

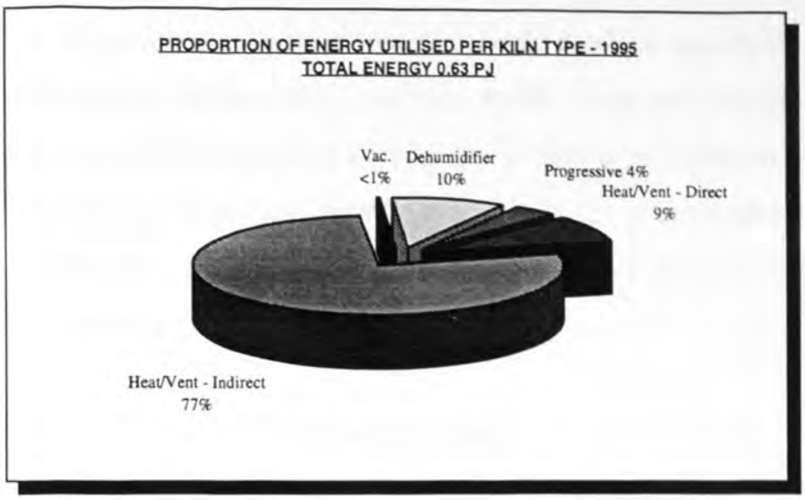

Figure 8 - Proportion of energy utilised by specific kiln types for 1995

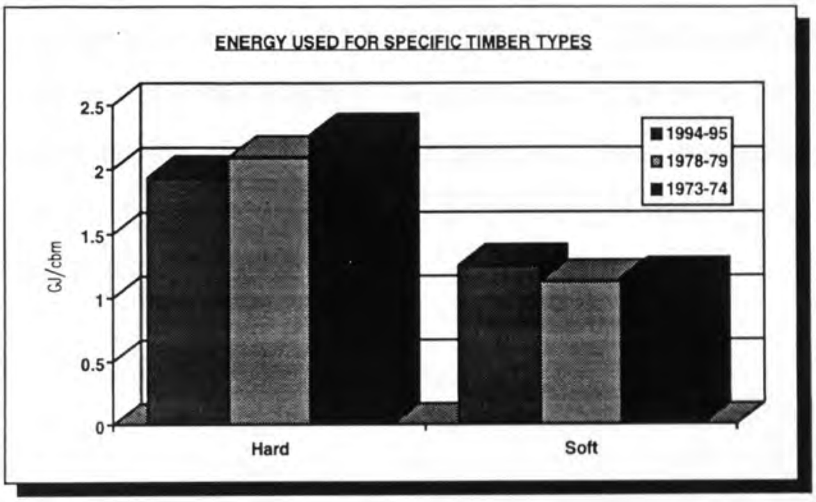

Figure 9 - Energy utilised per cubic meter for the drying of hardwood and softwood

Figure 9 shows that the energy required to dry a cubic meter of hardwood has fallen during the last 20 years. However, there have been no realistic savings in the energy required to dry softwood since 1978.

Communication with kiln operators revealed that hardwoods are commonly air dried prior to drying to reduce kilning times and improve product quality. However, not all sites contacted (Jay & Oliver, 1996) airdried hardwoods to 30% moisture content. The energy savings achievable by implementing air drying methods are substantial. An energy saving of over 23% of the total consumption can be made by reducing the initial moisture content of hardwood by 10% from 40 to 30%, and savings of nearly 50% by air-drying from 80 to 30% prior to kilning.

Implementation of good house keeping measures could produce significant energy savings in the timber industry. Demonstration schemes could improve energy awareness by highlighting new methods and developing technology. Targeting information would allow kiln operators to assess their equipment and provide a goal in terms of achievable energy savings. Research and development of heat exchangers for heat recovery systems and burner design could also produce significant savings.

CONCLUSIONS

Timber kiln operators contacted during this study revealed that monitoring of the energy consumption of drying equipment is not conducted on a regular basis. There is thus little impetus for kiln operators to improve the energy efficiency of their equipment. The energy monitoring of equipment provides essential information and produces targets that can be the focus for the implementation of energy efficient measures. Better monitoring of equipment can lead to improved control providing additional benefits of improved quality, reducing drying times as well as reducing energy costs.

ACKNOWLEDGEMENT

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