THE MODELLING OF ENERGY EFFICIENT DRYING FOR DSM

An Investigation into Energy Use and Energy Efficiency for Industrial Drying Processes
Using Fuzzy Systems

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December 1999

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THESIS SUMMARY

This thesis investigates the modelling of drying processes for the promotion of market-led Demand Side Management (DSM) as applied to the UK Public Electricity Suppliers.

A review of DSM in the electricity supply industry is provided, together with a discussion of the relevant drivers supporting market-led DSM and energy services (ES). The potential opportunities for ES in a fully deregulated energy market are outlined. It is suggested that targeted industrial sector energy efficiency schemes offer significant opportunity for long term customer and supplier benefit. On a process level, industrial drying is highlighted as offering significant scope for the application of energy services.

Drying is an energy-intensive process used widely throughout industry. The results of an energy survey suggest that 17.7 per cent of total UK industrial energy use derives from drying processes. Comparison with published work indicates that energy use for drying shows an increasing trend against a background of reducing overall industrial energy use.

Airless drying is highlighted as offering potential energy saving and production benefits to industry. To this end, a comprehensive review of the novel airless drying technology and its background theory is made. Advantages and disadvantages of airless operation are defined and the limited market penetration of airless drying is identified, as are the key opportunities for energy saving. Limited literature has been found which details the modelling of energy use for airless drying.

A review of drying theory and previous modelling work is made in an attempt to model energy consumption for drying processes. The history of drying models is presented as well as a discussion of the different approaches taken and their relative merits. The viability of deriving energy use from empirical drying data is examined.

Adaptive neuro fuzzy inference systems (ANFIS) are successfully applied to the modelling of drying rates for 3 drying technologies, namely convective air, heat pump and airless drying. The ANFIS systems are then integrated into a novel energy services model for the prediction of relative drying times, energy cost and atmospheric carbon dioxide emission levels. The author believes that this work constitutes the first to use fuzzy systems for the modelling of drying performance as an energy services approach to DSM.

To gain an insight into the 'real world' use of energy for drying, this thesis presents a unique first-order energy audit of every ceramic sanitaryware manufacturing site in the UK. Previously unknown patterns of energy use are highlighted. Supplementary comments on the timing and use of drying systems are also made. The limitations of such large scope energy surveys are discussed.

KEYWORDS : Airless Drying, Modelling, Fuzzy Systems, Energy Efficiency

ACKNOWLEDGEMENTS

I would like to thank my supervisor Dr T.N. Oliver for his invaluable contributions and unstinting support throughout the project.

Experimental work was made possible through extensive co-operation with the Aston University MEE technicians. As such, I would like to thank Joe Thomas, Brian Harrison, Alan Evitts, Jim Jeffs and Dave Farmer. Joe was a good friend and will be sadly missed.

I would like to thank Thomas Stubbing of Heat-Win UK Ltd for up-to-date information on airless drying, and C.D.S Drying Systems Ltd, Stoke-on-Trent, for valuable information on dryer construction and operation. I am indebted to all UK sanitaryware manufacturers for their time and patience during surveying. For the supply of raw testing material, I would like to thank Allied Insulators, Stoke-on-Trent, UK.

I am grateful to Dr M. Booth and his team at Energy Services UK Ltd for their time and suggestions, their financial support and the lone of monitoring equipment.

I would like to extend my thanks to Glen Steer and Robert Harper for their advice on DSM, their sense of humour and their coffee making abilities.

Finally, I would like to thank the Engineering and Physical Sciences Research Council (EPSRC) for financial funding throughout the project.

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GLOSSARY OF TERMS

Adaptive Neuro Fuzzy Inference System (ANFIS). A system based on fuzzy logic which learns its rules from training data. 'Neuro' implies the use of Artificial Neural Networks (ANN) in the learning stage.

Artificial Neural Network (ANN). A system based on a complex layered interconnection of simple neurons. Designed to mimic the connectivity and simple functionality of the brain. Capable of self-learning.

Coefficient of Performance (COP). Measurement of performance relating to a heat pump or refrigeration system. Usually defined as the ratio of useful heat output to input work. The nature of the heat pump system often results in CoP values greater than unity.

Demand Side Management (DSM). A broad term for electric load management applying to utility actions, programs, and designs for the purpose of lowering system peaks and reducing energy consumption by the consumer as well as the utility [Pansini and Smalling, 'Guide to Electric Load Management', PennWell, 1998].

DGEGS (Director General of Electricity and Gas Supply). Title given to the industry regulator for the electricity and gas industries. Appointed from 1998 to the present day. Current DGEGS: Callum McCarthy.

DGES (Director General of Electricity Supply). Title given to the Electricity Industry regulator from privatisation in 1990 to deregulation and the open energy market. DGES from 1990-1998: Professor Stephen Littlechild.

Distribution Use of System (DUoS). The charge made by Public Electricity Suppliers (PES) for the distribution of electricity from the Grid Supply Points to the consumer. DUoS is based on the RPI-X pricing formula and is heavily regulated.

Electricity Supply Industry (ESI). The hierarchy of companies involved in the generation, transmission, supply and distribution of electricity.

Energy Services (ES), or market-led Demand Side Management. Generally recognised as the offering of expert advice on energy use and energy saving technologies to industry and commerce. Can form an essential part of a customer-focused approach to network load management (DSM) and/or as a method of securing long-term energy supply contracts.

Fuzzy Inference System (FIS). A set of fuzzy rules that convert inputs to outputs.

Fuzzy Logic (FL). Has a dual meaning. a) Multivalued logic where everything is a matter of degree and membership. b) Reasoning with fuzzy sets or fuzzy rules.

Green House Gas (GHG). Gas liberated from the combustion of fossil fuels which contribute to global warming through the atmospheric 'green house effect'. The most common GHGs are carbon dioxide, methane and nitrous oxide.

Moisture Loss Method. The calculation of total drying energy derived from the average moisture loss during drying.

OFFER (Office of Electricity Regulation). Independent regulatory body set in place to oversee the privatisation and regulation of the Electricity Supply Industry (ESI). Now supplanted by OFGEM.

OFGEM (Office of Gas and Electricity Markets). The independent regulatory body formed from the merger of the Electricity Supply Industry regulator (OFFER) and the Gas Supply Industry regulator (OFGAS). Designed to oversee regulation and control of the open energy market.

Public Electricity Supplier (PES). The old Regional Electricity Companies (RECs) renamed at the time of deregulation in the supply and distribution businesses (circa 1998).

Regional Electricity Company (REC). The old Area Electricity Boards renamed after the division and privatisation of the Central Electricity Generating Board (CEGB).

Specific Energy Consumption (SEC). The calculation of total energy use per unit mass of product, per unit mass of moisture removed or per piece. Units: kJ/kg, kJ/piece etc.

Specific Moisture Extraction Rate (SMER). A measurement of performance for heat pump dehumidification dryers. Stated as the mass of water extracted per unit of electricity consumed. Units: kg kWh^{-1}.

Supply Side Management (SSM). Management of electricity supply to satisfy demand. SSM actions typically involve increased generation capacity and network reinforcement.

NOTATION

Principal Symbols

A	Area [m^2]
C	Moisture concentration
C_p	Specific heat at constant pressure [kJ/kg K]
D	Coefficient of Diffusion [m^2/s]
D_o	Arrhenius factor [m^2/s]
E	Specific energy [kJ/kg]
E_o	Activation energy [kJ/mol]
H_{ss}	Saturation humidity of drying gas at surface drying temperature, T_s [kg/kg]
H_v	Latent heat of water at ambient temperature [kJ/kg]
K_p	Drying coefficient on a partial pressure basis [g/s m^2 MPa]
K_H	Drying coefficient per unit humidity difference [g/s m^2]
N	Electrical power [kW]
R	Ideal gas constant [kJ/mol K]
rh	Relative humidity [%]
T	Temperature [K]
W	Mass [kg]
X	Moisture content [%]
Y, H	Humidity [kg water/kg dry air]
h	Enthalpy [kJ/kg]
h_c	Heat transfer coefficient by convection [W/m^2 K]
h_t	Total heat transfer coefficient [W/m^2 K]
k	Isentropic compression coefficient
p	Pressure [MPa]
q	Heat energy [kJ]
t	Time [s]
x	Material depth [m]
η, e	Efficiency [%]
λ	Latent heat of evaporation [kJ/kg]
μ	Fluid velocity [m/s^2]
θ	Average in-dryer residence time [s]
ξ	Elevation [m]

Subscript Symbols

air	Air
cb	Combustion

e	Electrical energy
eh	Electrical heater
F	Fan
g	Gas
m	Mechanical
p	Product
s	Saturation conditions
shs	Superheated steam
t	Total
therm., th.	Thermal
wat.	Water
wwb	Wet weight basis
dwb	Dry weight basis

CHAPTER 1

INTRODUCTION

Introduction

Drying is an important industrial process which consumes a significant proportion of total industrial energy. In the UK, drying processes are used widely throughout industry, particularly in the energy-intensive chemical, paper and building materials sectors. The high energy consumption associated with drying results in high energy costs and significant, environmentally damaging emissions of greenhouse gases.

Production systems rely heavily on drying processes. Drying often forms the most lengthy stage in the manufacturing process, dictating the timing and efficiency of production schedules. A failure in the drying stage can form a bottleneck by reducing the flow of production. Moreover, many industries rely on drying as a key determinant of product quality.

UK electricity utilities are currently working to reduce the energy consumption of industrial users; helping consumers reduce energy costs whilst meeting increasingly stringent environmental regulations. A reduction in industrial energy use has additional benefits for the energy utilities, including extensions in the operating life of electricity distribution networks. Modern drying technologies now offer the potential to reduce energy consumption, energy costs and atmospheric emissions whilst providing benefits such as faster drying times and reductions in the floor area needed for drying operations.

The work in this thesis is sponsored by Midlands Electricity plc and Energy Services UK Ltd. To date, Midlands Electricity has commissioned extensive research into the industrial use of energy. The research presented in this thesis highlights drying as a process which offers potentially significant benefits to both customer and utility as an integral part of an energy services approach to demand side management (DSM).

Aims and Objectives

The aims and objectives of this thesis are,

- To provide a review of the UK electricity supply industry and the evolution of demand side management (DSM).
- To examine the driving forces behind the application of DSM and energy services to drying processes.
- To investigate airless drying as a potential process for the application of energy services.
- To model and compare the potential energy and cost benefits derived from the use of airless drying.

- To present an accurate user-profile of drying systems within a UK industrial sector.

The work in this thesis is targeted at energy managers, process engineers, research establishments, Public Electricity Suppliers and energy services companies. It is hoped that this work will provoke discussion on the use of energy for industrial drying, the methods by which energy is accounted for and the potential for reduced energy consumption.

Thesis Structure

The following section provides a chapter-by-chapter appraisal of work included within this thesis. Each summary includes the central arguments and important results found from research presented within each chapter.

Chapter 1

Chapter 1 introduces the aims, objectives and background to the research.

Chapter 2

Chapter 2 introduces demand side management (DSM) and the importance of drying processes for the application of energy services. The first section provides a background to the thesis; discussing DSM and regulation in the United Kingdom electricity industry, as well as the influence of European Directives on atmospheric emissions.

From a discussion on the regulatory state of the electricity supply industry (ESI), the chapter focuses on the driving forces behind DSM and the need for energy services within a fully deregulated energy market.

It is argued that drying processes are a potentially important area for the application of energy services in UK industry. Airless drying is highlighted as a novel drying process offering a wide range of energy and production benefits.

Chapter 3

Airless drying offers the potential for significant energy savings in combination with benefits such as reduced lead-time, improved product quality and smaller drying enclosures. Chapter 3 introduces the novel airless drying technology and provides a discussion of its history and operational features. The proposed mechanisms supporting reduced energy consumption and drying times are discussed, and current research in the area is highlighted.

The potential for energy economy is defined, including the use of mechanical vapour re-compression. Attention is also drawn to the lack of fundamental understanding behind airless drying theory and the underlying problems and limitations of airless operation.

Chapter 3 argues that airless operation offers significant benefits to industry, yet work indicates that market penetration is currently low. Furthermore, the potential sector-wide energy savings achievable from airless operation are unknown. No work was found describing the use of airless drying as an integral part of energy services.

Chapter 4

Energy use for drying in UK industry is significant, yet rarely monitored. Chapter 4 calculates the total use of energy for UK industrial drying in 1994 using the 'moisture loss' method of assessment.

The benefits of large-scale energy surveys are defined, as are historical trends in energy use. Previous attempts to survey industry-wide energy use for drying are discussed, highlighting the survey methods and assumptions used. Little commonality has been found to exist between surveys.

As part of the new survey, comments are made on the accuracy of production figures, moisture loss values and the assessment of thermal efficiencies for drying. The new assessment indicates that 17.7 % to 19.3 % of total UK industrial energy consumption is used for drying operations.

Chapter 5

Modelling of drying processes is an important step towards understanding the prevailing heat and mass transfer mechanisms which occur during drying. Chapter 5 introduces basic drying theory and its history. The potential benefits of modelling are discussed, as are the modelling processes used. Material characteristics are highlighted as having significant importance for the modelling of drying.

The remainder of chapter 5 discusses the advent of Artificial Intelligence (AI) techniques for the modelling of drying. Neural networks are explained and previous modelling work using neural nets is examined. Chapter 5 argues that the use of adaptive neuro fuzzy inference systems will provide a suitable modelling scheme for assessing drying rates and energy for drying.

Chapter 6

Chapter 6 describes the unique use of adaptive neuro fuzzy inference systems (ANFISs) to model drying rates for 3 drying technologies: convective air, airless and heat pump drying. Modelling objectives are defined and the choice of ceramic clay as the test material is discussed.

Experimental procedures are described, as well as details of model construction. Model verification suggests a high degree of accuracy with errors rarely exceeding ± 3 %. The inversion point is derived from extrapolated air and airless drying data, suggesting an inversion temperature of 220 °C.

Chapter 7

Chapter 7 describes the development of a fuzzy software tool for the prediction of energy consumption, energy cost and carbon dioxide emissions. Consideration is given to the use of SEC values for the derivation of thermal efficiency and comment is passed on the assumptions made within each of the models.

The supporting theory behind heat pump drying is discussed and the operation of mechanical vapour re-compression is detailed. Model validation is achieved using a brief case study for the drying of electro-porcelain insulators. Results suggest that airless drying demonstrates significant advantages over standard convective air drying.

Chapter 8

Chapter 8 presents the results from a survey of energy use for drying in the UK sanitaryware sector. The overriding purpose of the study is to gain a unique insight into the use of drying systems throughout an industry. The audit is believed to be the first to survey a complete UK industrial sector.

An introduction to the ceramics industry and its current economic climate is given. Sanitaryware manufacturing processes are described and previous literature on energy use for sanitaryware drying is discussed. Results of the new survey are presented along with discussion of the assumptions made. An interesting insight is given into the operational procedures followed for 'real world' drying processes.

Chapter 9

Chapter 9 discusses the salient points of interest arising from work presented within the thesis.

Chapter 10

Chapter 10 presents concluding remarks to the thesis and details proposals for future work.

CHAPTER 2

INDUSTRIAL DRYING AND DSM

Introduction

From 1990 to 1998 the United Kingdom electricity industry underwent a rapid transformation from a public utility to a hierarchy of privatised companies. The transition from a natural monopoly to an open-market structure has resulted in increased competition, with 29 companies currently vying for the supply of electricity to industrial, commercial and domestic customers [216].

In response to growing competition, the Public Electricity Suppliers (PESs) are investigating schemes for market-led demand side management (DSM) and energy services (ES) [231]. Full deregulation of the energy market now offers the RECs an opportunity to provide 'total energy' packages for the supply of electricity and gas to industrial consumers. Market-led DSM, and more specifically ES, provide a method of achieving long-term energy contracts by supplying customers with additional services, including expert advice on energy use and energy efficient technologies.

The advent of energy services allows PESs to target those industrial sectors and processes which offer the potential for reduced energy consumption, thus benefiting the customer and the environment. Drying is acknowledged as a widely used and energy-intensive process with significant opportunity for energy savings.

This chapter summarises the development of the UK's privatised electricity industry and examines the drivers behind DSM and the use of energy services as a method for reducing energy consumption for drying processes.

Demand Side Management

Demand side management (DSM) was conceived in the early 1980s in response to the changing economic and environmental needs of the United States following the first oil crisis in 1974 [231]. From the mid-to-late 1970s, US energy utilities witnessed a slowing growth in domestic electricity demand. Increasing competition within the energy markets and the introduction of instruments to limit environmental pollution led to over-capacity and loss of sales on excess electricity. The resulting economic climate forced price reductions across the US electricity networks. Essentially, DSM provided a more accurate method of predicting network demand than previous supply side approaches.

Prior to demand side considerations, the United States ESI was selling energy using supply side measures (SSM); routinely increasing generating capacity and upgrading networks to meet an unconstrained post-war electricity demand. Marketing effort within the utilities was directed at load growth, with load levelling appearing to be the only demand side activity used primarily for the promotion of off-peak energy use [231]. Unless applications consuming electrical power were vulnerable to fuel switching technologies, energy efficiency was seen as a significant threat to revenues [32].

The definition of DSM has changed continuously from its conception to the present day. In 1995 DSM was defined as

> 'A methodology through which a Regional Electricity Company (REC) can directly intervene in the customers' use of electricity in order to optimise the load curve'
>
> [203].

Clearly this traditional view of DSM suggests a one-sided arrangement, whereby the energy utility takes an active interest in the end-use of electricity with little regard for the customer. The current view taken by experts, however, suggests DSM as a

> '..broad term for electric load management applying to utility actions, programs, and designs for the purpose of lowering system peaks and reducing energy consumption by the consumer as well as the utility'
>
> [105]

With this definition, the concept of DSM has expanded from direct intervention to a wider scope of measures, encompassing both customers' needs and general network load management. Steer suggests that demand side investment by the utilities as an attempt to optimise network load can involve energy efficient measures [123]. Moreover, it is often possible to achieve greater efficiency gains from investing in demand side activities than in electricity production and transmission (supply side).

Shaping objective	**Aims**	**Potential activities**
Conservation	• Overall demand reduction • Reduced environmental pollution • Primary fuel conservation	• Energy efficiency programmes
Peak demand reduction (peak clipping)	• Reduced short-term high demand • Defer network re-enforcement	• Focused energy efficiency programmes • Interruption of supply
Demand relocation (peak shifting)	• Load levelling/valley filling • Reduced short-term high demand • Optimising transformer efficiencies	• Energy storage options
Demand control	• Accurate control of customer demand • Optimising network utilisation	• Intelligent metering/switching
Load growth (valley filling)	• Promotion of consumption • Optimising network utilisation	• Tariff structures • Fuel switching technologies

Table 2.0 DSM load shaping objectives [113] [123]

Optimising Network Load

The original purpose of DSM was to instigate demand reduction programmes in North America [113]. Analysis of distribution at transformer level highlights the opportunity to shift or increase load as part of a DSM approach to network management [123]. Ultimately DSM schemes may follow a combination of objectives and activities, including increased energy efficiency at the point of electricity use. Table 2.0 presents the alternative demand shaping options found in literature.

DSM and Energy Efficiency in the UK

The implementation and success of DSM within the UK is limited in comparison to the US. The prime reasons for this are differences in regulatory regimes [38].

DSM in the US is an essential part of least cost planning (LCP) strategies instigated by the regulatory authorities. A public electricity supplier must demonstrate all lowest cost options for the supply of electricity to customers, with the outcomes frequently favouring energy efficient DSM options. LCP has also been extended to account for environmental costs and the societal benefits arising for the use of electricity. With most DSM projects favouring demand reduction, the benefits gained over supply side measures become even more pronounced.

The study and application of DSM in the UK has been driven by complicated regulatory, political and market issues.

Regulation in the electricity industry has several aims, including

- Protection of consumers' interests (electricity prices and secure supply)
- Promotion of competition for electricity supply
- Reduced environmental impact (energy efficiency across all sectors).

[17]

The industry regulator's prime concern is the promotion of competition in the best interests of consumers [38]. Although energy efficiency measures are part of these interests, the price of electricity is the dominating factor.

Examination of literature on DSM suggests that two features are central to energy efficiency issues, namely

1. Electricity pricing regulations,
2. Current and future environmental legislation.

[123] [17] [113] [36]

In order to gain an understanding of DSM drivers, the following sections discuss pricing and environmental regulation in the electricity supply industry. A brief background to the industry is provided, as is a history of environmental legislation.

The UK Electricity Industry

Prior to privatisation, the generation and transmission of electricity was undertaken by the nationalised Central Electricity Generating Board (CEGB). The responsibility for local supply and distribution of electricity belonged to the twelve Area Electricity Boards operating in defined geographical regions throughout England and Wales.

Privatisation occurred for a variety of reasons, both economic and political. Essentially, the purpose of privatisation was to eliminate the inefficiencies inherent within the publicly owned CEGB, whilst introducing competition for the generation and supply of electricity to industrial and domestic consumers. Furthermore, privatisation was used as an instrument to ensure the secure supply of electricity to satisfy customer demand.

Secondary goals of privatisation were also introduced. These included the protection of consumers' interests and the promotion of energy efficiency.

The political forces behind privatisation are contentious, although it has been suggested that privatisation was introduced as a method of

- reducing Union power,
- creating share carrying stakeholders,
- generating revenue for the Government,
- shifting decision making to the private sector.

[41] [151]

Regardless of motives, privatisation brought about a sea change in the structure of the electricity supply industry (ESI). The vertically integrated CEGB and Area Boards were sectioned off into their component parts allowing for the separation of the generation, transmission and supply/distribution businesses. Generation was divided into two directly competing companies, Powergen and National Power, with a third company, Nuclear Electric, overseeing the UK's nuclear generating capacity. Bulk transmission of electricity from generation voltage levels (400 kV or 275 kV in England and Wales) down to the Grid Supply Points was renamed the National Grid Company (NGC) and the 12 Area Electricity Boards were re-titled as the Regional Electricity Companies (RECs). The hierarchical structure of the ESI, as of 1998, is given in figure 2.0.

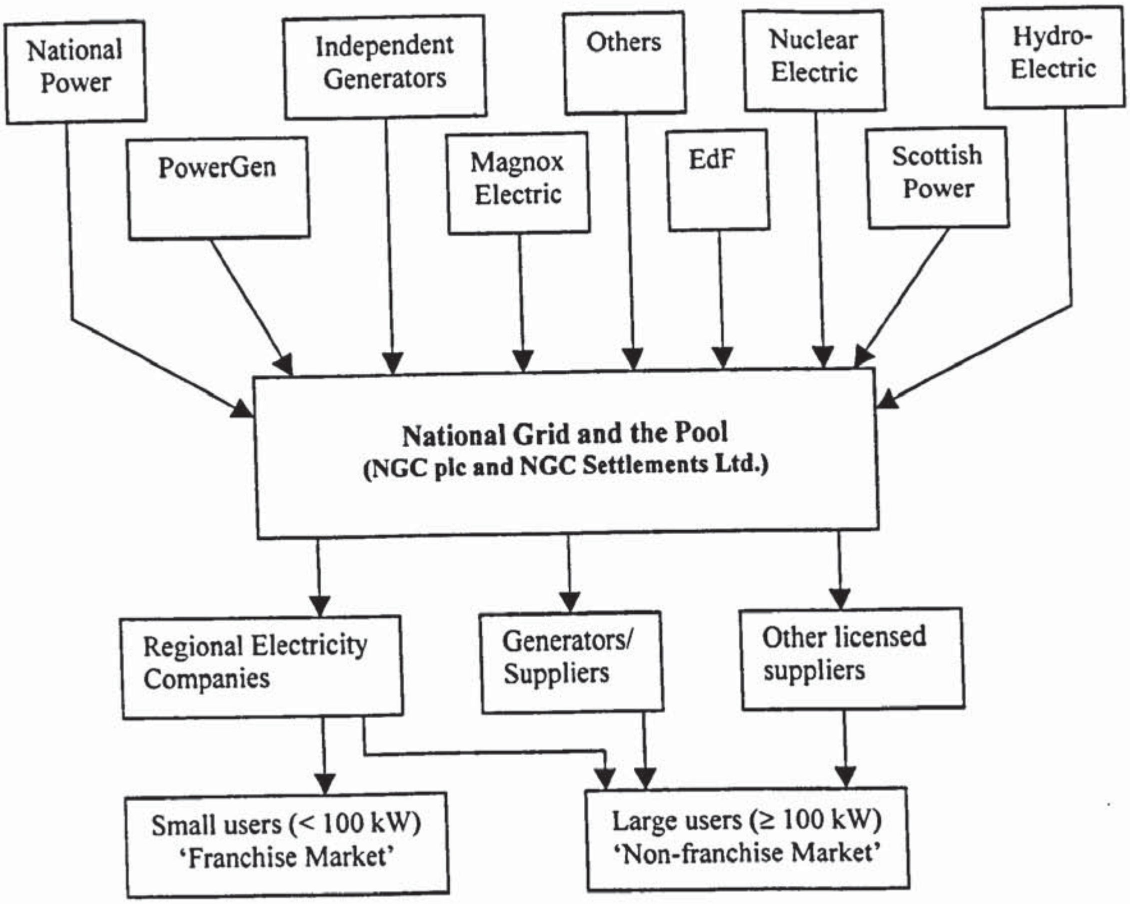


Figure 2.0 Structure of the electricity industry in England and Wales (1998) [192]

Of the four electricity businesses, supply and distribution have seen the greatest change under competition [123]. Between 1991 and 1998 the RECs had a monopoly on franchise supply: acting as sole suppliers (first-tier suppliers) to customers in their own geographical area with a peak demand less than 100 kW. From 1991 the 55,000 UK based customers with a demand of 100 kW or greater were allowed the free choice of supply, whether it be from a rival REC, a generator or an independent supplier [221].

Regulation

Although fully privatised by 1991, the ESI was placed under a complex regulatory framework determined by an independent, albeit Government appointed regulator operating through the Office of Electricity Regulation (OFFER). Essentially, regulatory rules apply to all businesses in the ESI with the monopoly areas of transmission and distribution coming under the strongest forms of regulation [123]. The following sections discuss regulation as applied to supply and distribution. Special emphasis is placed on the regulatory implications for DSM and energy efficiency. The author believes that discussion of regulation in generation and transmission is beyond the scope of this thesis.

Regulation and the RECs

RECs provide two specific services to the consumer, namely the supply and distribution of electricity. Supply refers to the sale of electricity and distribution covers the physical connection of the consumer to the electricity network. In the context of the RECs, regulation has been used to foster an open and fair trading environment whilst enforcing free-market competition for supply and distribution between utilities. Further important regulatory agendas include the protection of the poor and environmental concerns [123].

The overriding aim of regulation is to protect customers by limiting the maximum revenue made on electricity sales. Regulation for both supply and distribution is performed using a number of measures including volume drivers and revenue price caps. Of these methods, the 'RPI minus X' pricing formula constitutes the principal form of control [214]. The equation is given as,

$$Y = RPI - X$$

where RPI is the retail prices index and X is an 'efficiency factor'.

Controls prevent the average price, Y, from increasing more than a given value of X below the rate of inflation as measured by the retail price index.

Supply was treated as a partial monopoly from privatisation onwards [192] [123]. As such, franchise supply was subject to an average price cap on revenue per kWh. Control of the supply business treats the RPI-X formula in a similar manner to distribution with one key difference: only the supply business' added costs and margins are limited by the formula, allowing the uncontrollable costs to be passed through to the customer.

As a supplement to the RPI price cap there is a volume driver on the supply business that currently relates only 25 % of remaining allowed revenue for every kWh sold.

The RPI-X control for distribution applies to the tariff charged for the transfer of electricity across the network, also known as the 'distribution use of system' charge (DUoS). Distribution charges account for a significantly higher proportion of customer bills and utility profits. As such distribution is subject to stricter regulatory controls. For each individual REC, OFFER limits the amount of revenue generated per kWh distributed to all customers attached to LV and HV sections of the network [212].

In addition to price controls, a volume driver of 50 % relates revenue for every kWh of electricity distributed.

Regulation and DSM

The use of price controls and volume drivers has a direct effect on the potential for DSM measures and, on the whole, is conducive to the promotion of energy economy.

Prior to the implementation of a volume driver, supply businesses were allowed to relate all revenues generated from electricity sales. Costs remained largely independent of units sold and therefore an artificial incentive existed to increase sales.

Under current controls, supply businesses are allowed to keep the revenue gains generated from energy efficient operation. The customer ultimately benefits because future electricity prices reflect past and future improvements in efficiency. It can be argued that the key benefit of price regulation is the strong incentive to minimise costs and eliminate inefficiencies, thus providing an increase in profits.

DSM considerations form an important part of distribution price control. Distribution businesses assess potential DSM measures against possible lost revenue from a corresponding reduction in distributed units. The implementation of a 50 % volume driver halves these losses, thus making the DSM option more attractive. Furthermore, current regulations allow distribution to double the proportion of revenue generated from efficiency savings on network losses.

Standards of Performance (SoP) are an additional regulation for the supply business. SoP are overseen by the Energy Saving Trust (EST) which dictates that an allowance equal to £1 per customer per annum for 4 years is allocated for expenditure on energy efficiency schemes. With over 25 million customers in England, Scotland and Wales, this equates to approximately £100 million for energy efficient measures, including DSM if applicable.

The drivers behind Standards of Performance are essentially two-fold, namely

- the reduction of energy use by the customer, and
- in response to the regulator's accountability for the ESI's environmental impact

Environmental legislation is becoming an increasing driving force behind energy efficiency from generation of electricity to its end-use. The following section provides a background to international legislation and its impact on the UK electricity supply industry.

Environmental Legislation

Background

Since the late 1970s there has been increasing international concern about the long-term effects of global atmospheric pollution on climate change, economic welfare and the standard of life [175]. The emissions which have caused most concern are the greenhouse gases (GHGs) of which sulphur dioxide, nitrogen oxide, methane and carbon dioxide are the main constituents. Of all the GHGs, carbon dioxide (CO_2) is the most significant of the anthropogenic additions and the most important contributor the effects of global warming [53]. The increase in CO_2 levels has been driven by two factors: increased burning of fossil fuels and the effects of de-forestation [175].

Sector	1980	1990	1995	2000*
Power stations	58	54	44	36
Transport	25	34	34	38
Domestic	23	22	22	23
Services	9	8	9	9
Refineries	6	5	6	5
Industry/agriculture	43	37	34	38
Land use changes	n/a	8	8	8
Total (IPCC basis)	n/a	168	156	158

* Estimated figures from [189]

Table 2.1 Carbon dioxide emissions in the United Kingdom (Mt CO_2)

In 1990, the United Kingdom released an estimated 614 Mt CO_2 into the atmosphere, accounting for approximately 81 % of total UK GHG contributions, or an equivalent 2 % of global greenhouse gas emissions [193]. In 1994, the Government predicted that without energy saving intervention schemes, emissions would rise by 44 Mt CO_2 between 1990 and 2000 [188] [189]. Table 2.1 and figure 2.1 present the predicted CO_2 emissions trend for the UK's main sectors covering 1980 to 1995. The data presented includes a forecast for the year 2000 [189].

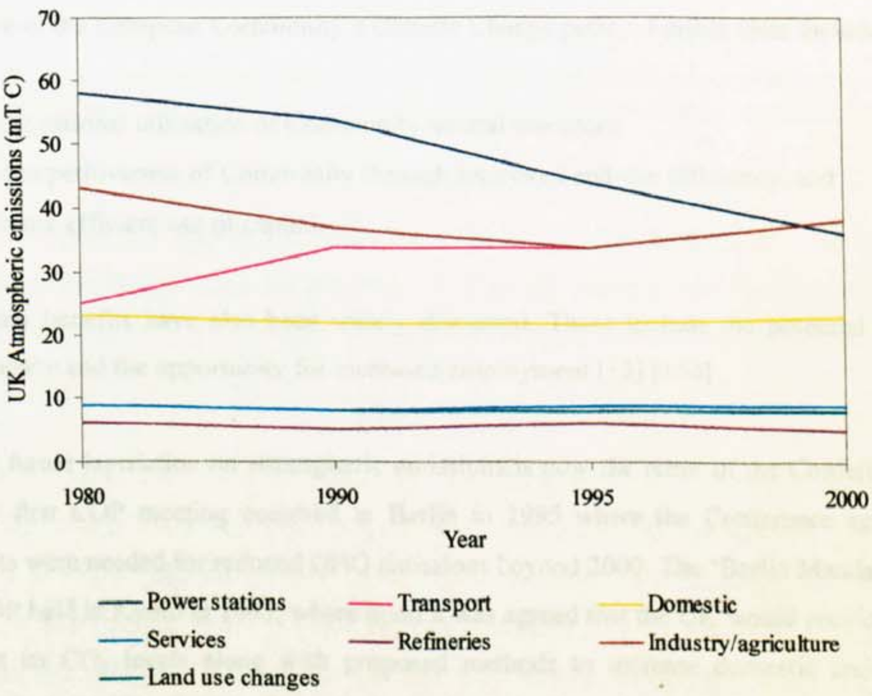


Figure 2.1 Carbon dioxide emissions in the United Kingdom

Figure 2.1 demonstrates the significant reductions in CO_2 emissions made by the electricity industry between 1980 and 1995. Indeed, it is claimed that the efforts of the ESI accounted for more than three quarters of the reduction in UK carbon dioxide emissions over the period 1990 to 1997 [193] [190].

European Legislation

European Community (EC) concern about global climate shifts can be documented from the mid 1980s when a number of non-binding resolutions called for measures to limit atmospheric emission levels. The first formalised agreement on emission levels was endorsed in 1990 under the EC's Climate Change Policy. This policy commits European Union members, including the UK, to the stabilisation of carbon dioxide emissions at 1990 levels by the year 2000.

The first binding legal instrument to limit international atmospheric emissions was the UN Framework Convention on Climate Change, signed by 154 states and the EU at the 1992 "Earth Summit" held in Rio de Janeiro. By the middle of 1993, the convention had been ratified by 169 countries.

In addition to the UN Framework Convention, the EC commenced a separate programme in 1990 aimed at facilitating a reduction in CO_2 emissions through the use of energy efficiency measures. The programme's strategy is based on the premise that reduced energy consumption through increased energy efficiency and fuel-switching is the most effective method of limiting CO_2 discharge.

It must be noted that the reduction of global warming effects through stabilised CO_2 emissions is not the sole objective of the European Community's Climate Change policy. Further aims include,

- the rational utilisation of Community natural resources,
- competitiveness of Community through improved end-use efficiency, and
- more efficient use of capital.

Supplementary benefits have also been widely discussed. These include the potential social benefits of energy efficiency and the opportunity for increased employment [13] [150].

Current and future legislation on atmospheric emissions is now the remit of the Conference of the Parties (COP). The first COP meeting occurred in Berlin in 1995 where the Conference agreed that stronger commitments were needed for reduced GHG emissions beyond 2000. The 'Berlin Mandate' was adopted in the third COP held in Kyoto in 1997, where upon it was agreed that the UK would provide a further 12.5 % reduction in its CO_2 levels along with proposed methods to increase domestic and industrial energy efficiency schemes. The British Government independently committed itself to further reductions in emission levels aimed at achieving discharge levels 20 % lower than 1990 levels by the year 2010 .

Environmental Legislation and the UK's ESI

Environmental legislation in the United Kingdom has been increasingly dictated by its membership of the EU . To ameliorate the damaging environmental impact of energy use and GHG emissions, the EU has specifically targeted energy efficiency as the 'cornerstone' of its efforts [112]. As a result, energy efficiency on both the supply side and demand side of the ESI has now become a key objective for UK atmospheric emission and energy policies. This is reflected in part by the adoption of Standards of Performance by the supply businesses.

As part of the attempt to target CO_2 levels and meet international emission requirements, the EC have proposed a Directive aimed at establishing the importance of increased energy efficiency and reduced energy use. The draft Directive appeared in 1995 and required that gas and electricity companies within the EU adopt a series of new structured planning techniques. Included within these new techniques is the adoption of Integrated Resource Planning, which provides the energy utilities with an opportunity to reduce national atmospheric emissions whilst following programmes of demand side management.

Integrated Resource Planning

Integrated Resource Planning (IRP) has the potential to become an important driving force in the growth of energy services and DSM in the UK electricity industry. Along with the European SAVE II and Joule Thermie programmes, IRP supports energy efficiency at the point of end-use [123]. Under IRP regulations, energy distribution utilities throughout the EU member states will be required to de-couple the volume of commodity sales from profits, thereby gaining benefit from increased energy efficiency at the point of use. The EC's desire to promote energy services is underlined by their statement that,

> "gaining a return from energy efficiency investment is central to the distribution utilities embracing their new role as energy service providers and not simply 'commodity' sellers."
>
> [35]

Clearly the EU hopes that the end result is a European energy distribution system which demonstrates an interest in energy efficiency measures and investment on the demand side. Furthermore, increased energy efficiency will reduce the EU's significant dependence on imported fuels whilst promoting competitiveness in the Europe-wide electricity industry.

It is important to note that IRP does not solely promote demand side energy efficiency schemes at the expense of supply side measures. Electricity utilities undertaking IRP are allowed to evaluate investment opportunities on the supply side against those on the demand side. Moreover, IRP mechanisms should guarantee that distribution utilities following DSM programmes do not lose revenue. Overall, energy companies are encouraged to follow a series of IRP requirements including,

- the informing of consumers on rational energy choices and the competitive price of energy,
- provision of consumer incentives to carry out energy efficiency investments,
- the implementation of DSM programmes targeted at low income energy users,
- investment in energy efficiency through third party financing.

The ultimate aim of IRP is a reduction in Europe-wide energy intensity by 1.5 % per year.

At the time of writing (June 1999), the UK Electricity industry is not obliged to comply with IRP procedures when putting forward investment in the distribution networks [123]. Furthermore, there are currently no operating mechanisms which allow the recovery of revenue through energy efficiency investments. However, it is thought that the UK ESI will eventually undertake IRP policy albeit in a modified form which considers the current structure and operation of the industry [192] [123].

It bears repeating that Integrated Resource Planning in the UK will force the electricity industry to undertake a range of programmes designed to deliver more efficient use of energy by the consumer [193]. However, electricity suppliers in the UK are already duty bound to promote the efficient use of energy. Thus, the adoption of IRP requirements will only serve to strongly encourage existing UK demand side energy efficient schemes [111].

Competition and Deregulation in the UK Energy Market

In 1992 European Directives were set in place with the aim of achieving an Internal Energy Market. Briefly stated, the Directives' objectives are,

- Unbundling of generation, transmission and distribution
- The free choice of supplier
- Third party access to transmission and distribution
- Encourage competition in energy supply.

[111]

The majority of these objectives have been addressed in the UK by privatisation and the subsequent regulatory regimes. Deregulation marks one of the final step towards an open energy market.

Deregulation

Franchise supply underwent a programme of deregulation between 1998 and 1999. The prime reason for deregulation was to offer customers a free choice of energy supplier, allowing for the selection of the most suitable and competitive package of prices and services [221].

The start of deregulation occurred on the 14th September 1998, promoting competition across England and Wales. Literature from OFFER suggests that a name change accompanied the programme of deregulation; Regional Electricity Companies now becoming Public Electricity Suppliers (PESs). Figure 2.2 charts the rapid rate at which the franchise supply market has opened to free-choice [221] [220] [219] [218] [217] [213].

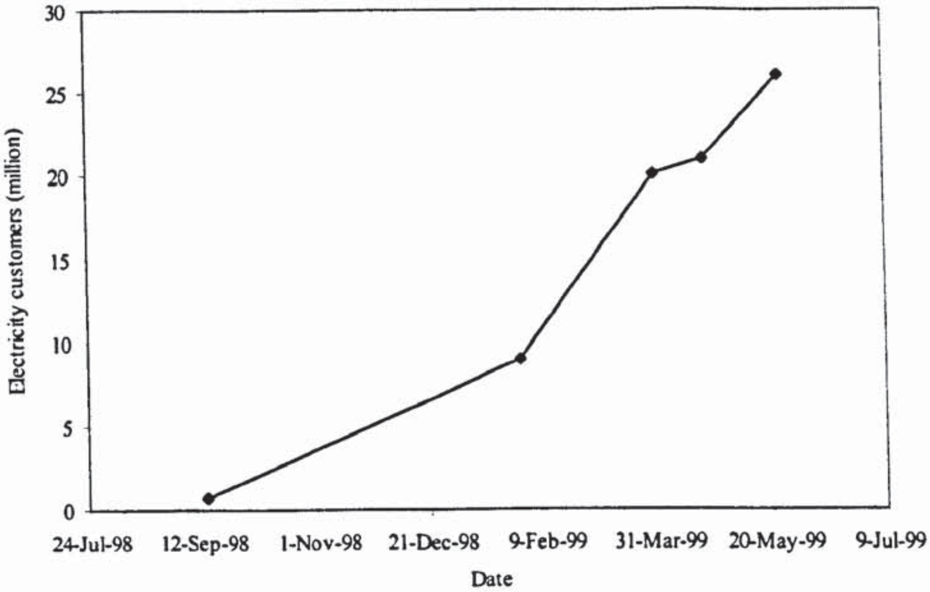


Figure 2.2 Deregulation in the UK electricity supply business

Although suppliers can now compete for the supply of electricity to all customers on a nationwide basis, the PESs still have a regulatory duty as first tier suppliers in their official franchise area. Suppliers competing outside their original boundaries are known as second-tier suppliers.

Competitive environment : Electricity and Gas

The free choice of electricity supply also extends to gas. Consumers can now choose their energy supplier, with gas utilities now capable of supplying electricity and vice versa. Third parties can also offer energy for sale. As of April 1999, over 29 suppliers of gas and electricity were registered to hold energy supply licenses [216].

The advent of a single energy market has profound repercussions for both competition and DSM. Up to May 1999, more than 4.5 million gas and 1.5 million electricity consumers had exercised their right to choose a different supplier. It has been estimated that customers are switching electricity and gas suppliers at a rate of 100,000 and 40,000 per week respectively [213]. Table 2.2 provides a list of implications for prospective DSM measures.

Competition and DSM
• Separation of Supply and Distribution • Increased price competition • Bundled 'total energy' packages • Attempts at product differentiation

Table 2.2 Competition and DSM

The future application of DSM is made potentially difficult by the separation of PESs into component businesses. The new regulator for electricity and gas supply (DGEGS) intends to separate supply and distribution in an attempt to increase market competition and to offer further customer protection. OFFER states that,

> '..present integration of distribution and supply is likely to protect dominant suppliers to the disadvantage of customers and competitors'
>
> [215]

To prevent the unfair treatment of other suppliers, it was suggested that no channels of communication exist between the two businesses. With most DSM measures requiring shared information from supply and distribution, initial statements suggested that DSM had no future founding. Nevertheless, reference to recent literature indicates that mechanisms of communication will be allowed for the purpose of highlighting potential areas for DSM [222].

Price Competition and Total Energy Packages

The electricity suppliers' initial response to free-market competition was to adopt fierce pricing policies. Although aggressive pricing is still used in an attempt to maintain market share, suppliers are moving away from price competition for two main reasons.

1. current supply prices are dictated by generation costs, which are expected to rise,
2. the regulatory framework restricts cost reduction strategies.

[123] [69]

With diminished revenue there is little scope for a supplier to achieve competitive advantage on price alone [123]. Product differentiation is now viewed as an innovative method of gaining competitive advantage.

Companies which successfully achieve product differentiation provide themselves with barriers against competition [68] [153] [109]. However, electricity supply is traditionally seen as a commodity market in which little or no product differentiation is possible [32]. One solution to this problem is the inclusion of a customer-focused energy services component, through which the supplier provides additional services in conjunction with the sale of energy.

DSM provides an opportunity to offer expertise on energy efficiency and energy saving technology as part of a long-term energy supply contract. Essentially, DSM has changed to market-led DSM, or energy services (ES) [231].

DSM and Energy Services

Public Electricity Suppliers have started to realise the potential benefits in assisting the customer to save energy. Schemes undertaken in the US suggest that DSM investments have proved both cost-effective and useful for increasing customer satisfaction [231].

As with traditional DSM, the driving forces behind ES are legislative, technical and increasingly commercial. Redford states that the technical objectives of traditional DSM were a combination of factors, the main aims of which were to

> 'Seek maximum advantage through satisfying regulatory / national objectives for energy efficiency whilst achieving peak reduction and energy service objectives'.
>
> [111]

It can be argued that the move from peak shifting and load reduction considerations to a customer focused approach has changed the overriding goal of DSM; essentially switching the objective to the provision of the best possible support to the customer in the rational use of energy and power [123]. Redford suggests that the technical objectives of market-led DSM are now,

- differentiation of the 'energy product' between suppliers, and in competition with alternative fuels, and
- targeting the most profitable and/or achievable energy savings or other benefits.

[111] [32].

Customer-focused energy services can be wide-ranging and varied, yet they all derive from the simple fact that customers often have little specialist knowledge and experience in energy management [123] [38] [113]. Furthermore, unlike energy utilities, companies often lack the resources and manpower to commit to energy management schemes. Companies are also more likely to take a short-term view on energy conservation [9]. Fletcher and Redford suggest that energy efficient operation is further constrained by the competition for capital, demanding delivery schedules, a conservative attitude and a lack of responsibility for energy management [44].

The scope of energy services is varied [185]. Examples include information on emerging energy efficient technologies and practices, the loan of energy monitoring equipment and personnel, and the opportunity to arrange third party financing for the purchase of energy efficient equipment [173]. Table 2.3 suggests the potential benefits of energy services for both utility and customer.

Utility	Customer
• Locking in customers to long-term energy contracts • Understanding / meeting customers' needs • Increased understanding of end-use technologies • Understanding of customer practices / decision processes • Anticipate shifts in demand • Rapid response to changes in demand • Understand profitability of customers • Peak demand manipulation • Energy and cost efficiency for customer service	• Improved energy efficiency • Third party financing • Lower production costs • Improved working environment • Satisfying of industry standards • Product quality improvements

Sources: [32] [44]

Table 2.3 Customer and utility benefits from market-led DSM

Energy services also offers societal and economic benefits, including

- lower consumption of resources
- reduced cost of energy supply.

The provision of energy services signifies a paradigm shift from the PESs' previous role of selling kilowatts to the building of supply chain relationships with the customer [32].

To fully capitalise on the potential for market-led DSM, energy utilities need to gain a fundamental appreciation of the merits of energy services as a method of securing long term profitability [123]. As part of this fundamental appreciation, PESs need to understand the individual component energy demands which constitute overall demand [32]. Individual demands include the nature of lighting, heating, refrigeration and motive loads across a range of industrial sectors and processes. More importantly, the REC needs to satisfy customer demand in a cost-effective manner.

Energy services should account for customers' total energy use, thus allowing the energy supplier to target processes which derive the majority of their primary energy from the burning of fossil fuels. Applications include drying processes, space heating and steam raising. Of these processes, drying presents a significant opportunity for energy saving and efficiency.

<u>**Potential for Industrial Drying and Energy Services**</u>

The drying process is probably the most common unit operation in industry [66] [67]. Almost every product in the foodstuffs, pharmaceuticals and timber sectors undergoes some form of drying, whilst the energy-intensive chemical, paper and building materials sectors rely heavily on the extensive use of moisture removal processes.

It can be argued that industrial drying is the most energy-intensive of the manufacturing processes [191]. As of 1976, no accurate estimation of UK industrial evaporative load had been established [110], although a more recent paper by Blythin estimates that in excess of 30 Mt of water are removed annually within the UK [12]. Assuming an average latent heat of evaporation of 2350 $kJ/kg_{wat.}$, the UK energy demand for drying would therefore total an estimated 7×10^{10} MJ per annum.

Essentially, it is the energy-intensive nature of drying coupled to its common application throughout industry which results in drying processes accounting for a large proportion of overall industrial energy use [191]. It has been estimated that industrial drying processes in the UK consume between 12 per cent and 18 per cent of total industrial energy [56] [67] [7], and somewhere in the order of 10 per cent of energy use in Russia and the main industrial sectors throughout Europe [4] [80]. With the majority of dryers generating heat from the combustion of fossil fuels, drying processes have a clearly defined impact on national carbon dioxide emission levels and the overall demand for energy resources.

Scope for Energy Services

An industrial process does not necessarily lend itself to energy services solely because it consumes a significant amount of energy. There must also exist a clear opportunity for a reduction in energy use, atmospheric emissions or the possibility of some other benefit to both energy supplier and energy user. More importantly, ES should be directed at measures which are effective for the rational use of energy in the long-term; particularly process plant with a significantly long operating life [123].

Figure 2.3 indicates the prioritisation of activities for industrial DSM measures as determined by the Swiss Electricity Industry's 'Working Group on DSM' [231]. Industrial process heating, including drying, is clearly identified as offering a first tier opportunity for the application of market-led DSM.

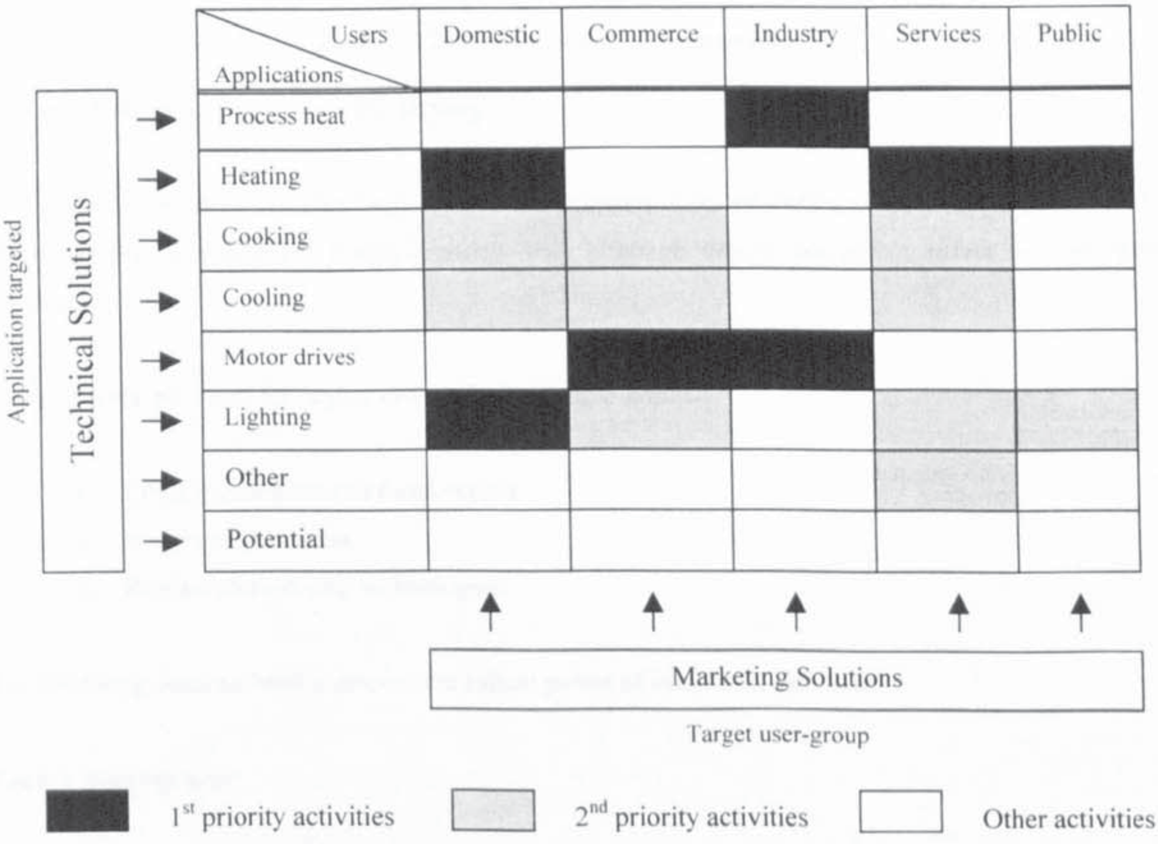


Figure 2.3 Market-led industrial DSM options [231]

RECs have traditionally targeted energy services at drying in the attempt to promote the penetration of electroheat technologies [56]. The fundamental aim was to claim a greater share of the industrial heating and drying market for the electricity utilities. PESs still retain an interest in the application of electroheat, although they are also showing interest in fossil fuel fired drying technologies for the application of market-led DSM [184].

The application of energy services to drying processes requires a comprehensive knowledge of existing drying technologies as well as the more innovative drying systems available. Research suggests that PESs need to build competencies in three areas of drying technology, namely

- fuel switching to electroheat technologies,
- Integrated drying systems
- Conventional and innovative drying systems.

Table 2.4 provides a list of drying technologies based on the above categories.

Electroheat Technologies	**Integrated Systems**	**Novel drying**	**Conventional drying**
• Infra red (IR) • Microwave • Radio frequency (RF) • Heat pump	• Dual fuel drying • Airless drying (with MVR)	• Airless drying • Dual fuel drying	• Convective air • Indirect air drying • Freeze drying

Table 2.4 Drying technologies by category [99]

Reduced Energy Consumption for Drying

Drying processes consist of two basic factors: the material under process and the drying equipment. Both factors exhibit potential for reduced energy use, although drying equipment offers a much greater opportunity.

Energy saving activities for drying can be divided into 3 groups.

1. Energy management/housekeeping
2. Integrated processes
3. Replacement drying technologies.

The following sections briefly discuss the salient points of interest in each area.

Energy Management

Energy Management is the structured practice of minimising consumption and therefore reducing supply requirement [12]. Energy efficiency can be enhanced in 5 ways.

- Proper insulation of the drying chamber to prevent unwanted heat losses
- Careful control of inlet/exhaust air enthalpies
- Heat recovery from the exhaust to pre-heat the fresh inlet air.
- Drying at the highest allowable temperature
- Avoidance of over-drying.

[56] [5] [120] [110] [75]

Energy audits are an essential part of continuing energy management, and can be used to quickly identify opportunities for energy conservation [102]. On-going analysis of energy use is labour intensive and may require the co-operation of suppliers or energy services companies. Energy load management systems are often used in supervisory and control roles [45].

Integrated Processes

Smith suggests that industrial processes such as drying may consume considerably more energy than is necessary due to disaggregation of processes [120]. A careful study of energy use for each process step should highlight procedures which demonstrate disaggregated energy use.

The benefits of process integration include,

- Reduced primary energy consumption
- Increased flexibility of batch processes
- Improved understanding of process
- Increased profitability and productivity
- Enhanced competitive position of domestic manufacturing base.

[45]

Replacement Technologies

The potential for energy conservation by design and operating changes in drying is significant [191]. Retiring old equipment in favour of new has the following advantages,

- Incorporated heat recovery
- Technical improvements (CPU instrumentation and control)
- Optimised dryer operation (CFD designed gas flow regimes)
- Optimised dryer design i.e. minimal footprint, effective insulation
- Controlled variable speed exhaust fans
- Improved product quality.

[101] [110]

After general housekeeping measures, the installation of new equipment will lead to the greatest gains in energy efficiency [12]. Even accounting for the capital costs involved, substantial economics can sometimes be made from changing dryers [110].

Although like-for-like dryer replacement will yield energy savings, a greater energy economy can often be derived from the use of new or innovative drying regimes. Table 2.5 provides a description of 3 novel drying techniques.

Drying technology	Description
Airless drying	Replacement of air with superheated vapours. Benefits include, • significant energy savings • high drying rates • solvent recovery • enhanced product quality
Dual fuel drying	A combination of dielectric heating and convection drying. Benefits include, • faster drying times • lower energy consumption
Heat pump drying	Drying energy derived from compressor work operating in a closed heat pump cycle. Benefits include, • cost effective drying • no atmospheric emissions • enhanced product quality

Table 2.5 Energy saving replacement technologies

Of the drying technologies given in table 2.5, airless drying offers the greatest range of potential benefits as part of an energy services approach to DSM.

Summary

This chapter has discussed the drivers behind DSM and the potential role that drying processes have within energy services.

It has been concluded that the greatest energy savings derive from the replacement of older drying technology with modern efficient designs. Chapter 3 introduces airless drying technology which offers the potential for reduced energy use, faster drying times and improved product quality.

CHAPTER 3

AIRLESS DRYING

Introduction

The majority of today's industrial dryers rely on mature technologies, developed and improved over decades of operation. Despite this, industry shows an ongoing interest in any novel drying concept which can provide benefits to the user, particularly in the areas of improved product quality, profitability and reduced production lead-times. Masters [91] suggests that innovative drying technologies must satisfy four performance criteria prior to acceptance by industry, including,

- the ability to address and solve a particular drying problem
- scale-up potential
- give an added value element to the process
- be compatible with health, safety and environmental protection ideals.

Airless drying has been identified as an innovative drying technology with the potential to demonstrate a wide range of benefits including reduced energy consumption and faster drying times. Numerous researchers and authors highlight airless drying as a successful replacement for traditional convective air drying systems [117] [98] [145] [29] [8], suggesting it is the single most important breakthrough in the area of high efficiency drying. Indeed, as industrial air dryers approach their theoretical maximum efficiency, superheated steam drying offers the single greatest opportunity to reduce energy costs further.

The market penetration of airless drying in the UK is currently low, albeit showing an increasing trend [26] [24]. Subsequently, a significant opportunity currently exists for Regional Electricity Companies (RECs) to market superheated steam drying within UK industrial sectors. As part of an energy services approach to demand side management (DSM), energy utilities can provide expert advice on the installation, operation and the suitability of airless drying, whilst providing long-term production and cost benefits to the customer.

This chapter describes the airless drying technology, its development and its potential application for DSM and energy services (ES) measures.

Airless Drying

Airless drying is a process in which the product is dried using a gaseous medium other than air. The drying gas used within an airless system is always the superheated vapour of the solvent to be removed from the product. With the vast majority of drying applications dealing with water removal, it is commonly assumed that airless drying uses superheated steam as the de facto drying medium. References have been found pertaining to drying using organic solvents such as n-butanol, benzine [20] and naphtha [157], although these processes remain rare [99].

Three principal advantages are claimed for airless drying over conventional air drying, namely

1. reduced drying times
2. increased energy efficiency
3. improved product quality.

It is the opportunity to increase drying rates and save energy which has fuelled research into airless drying. With drying processes frequently acting as energy-intensive bottleneck operations [98] [27], any process which can reduce costs and/or lead-times will provide a manufacturer with an economic edge over competitors [117]. Additionally, the continual pursuit of decreasing environmental emissions provides an extra stimulus for further research into airless drying and its mechanisms [164]. To understand the reasons for energy saving and rapid drying cycles, the author considers it necessary to explore the underlying history and theory of airless drying.

History and Development

Superheated steam drying is still approached by many within industry as a novel drying technique, yet the concept of drying in an airless atmosphere is now approximately 100 years old. Nevertheless, research suggests that airless drying has only become a patented technology in recent years [224] [225].

Hausbrand is generally credited as the 'father' of airless drying after his seminal publication in 1898 [55]. The first published diagram of his conceptual dryer, presented in figure 3.0, illustrates the fundamental operational characteristics of batch steam drying. A flow of steam is continually re-heated and passed over the product using a re-circulation fan. Any excess steam evolved from the product is vented through a simple exhaust vent.

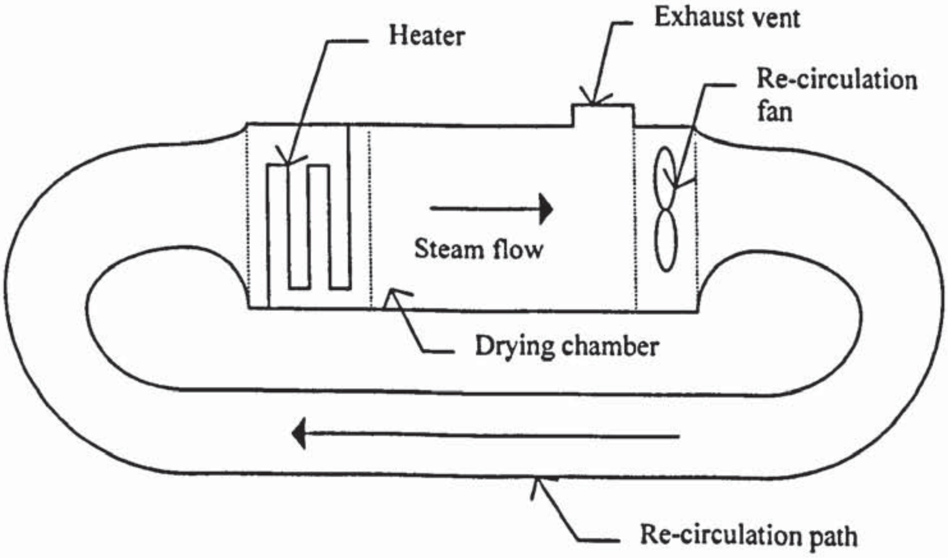


Figure 3.0 Hausbrand's concept steam atmosphere dryer [55]

The history of airless drying can be traced from Hausbrand through Fleissner (1927) [42] and his design of an airless drying process for the dehydration of coal. Fleissner's design used pressurised superheated steam at 1.2 MPa. The pressure was rapidly reduced to below atmospheric causing the internal moisture to flash to steam. Thompson (1955) [152] and Lane and Stern (1956) [79] used an airless tray dryer to process fine particulate solids. In the 1950s atmospheric steam dryers were operated commercially in the Federal Republic of Germany according to Kollman (1961) [76].

Research into airless drying theory and its applications was initially conducted from the 1950s onwards. Yoshida and Hoydo (1966) [167] investigated the drying of foods and Luikov (1966) tested cellulose pellets in superheated steam conditions [83]. Mikhailov (1962) published a 200 page book entitled "Superheated Steam Drying" in the Russian language. This suggested that airless drying and its associated technologies had a much larger following in ex-USSR than western developed countries [99]. Wimmerstedt and Hager performed an extensive literature survey, concluding that in excess of 300 papers have been published on the subject of steam drying. It was noted that industrial interest in steam drying increased after the first oil crisis of 1973 [164]. A report by Mujumdar provides a brief history of drying under airless conditions [99].

Patented Airless Drying

Airless drying in its patented form extends from 1988 when Thomas J. Stubbing of Warwick Heat-Win Ltd, England, applied as UK patent holder and licensee of the airless drying technology. Successful patent applications were made for both batch and continuous dryer operation in 1988 and 1994 respectively [224] [225]. At the time of writing (March 1999), patents have been raised in 50 countries including the USA, Japan, Australia and Germany.

From the 1980s to the present day, Stubbing has been the most active and prolific publisher of literature on the subject of airless drying. Table 3.0 provides a summary of Stubbing's work in chronological order. Clearly, the development of patented airless drying has been promoted in four specific areas of interest: dryer configuration, dryer technologies, materials tested and other.

Stubbing's early work concentrated on a successful pre-production Airless Tumble Dryer (ATD) for the laundry industry [11], although the majority of reported airless dryer configurations are for general batch operation. The advent of the continuous airless dryer system is relatively recent. To date continuous airless drying has been demonstrated with varying success for the drying of towelling, chopped orange peel, magnesium hydroxide filler cake and the drying of industrial waste by-products [26] [127] [144].

Stubbing has gradually expanded the range of materials to which airless drying has been applied. Initial material studies concentrated on laundry, a reflection of Stubbing's own background. Although papers citing the possible application of airless drying to paper [145], waste disposal [144], biomass processing [139] and the drying of wood [129] have been identified, the majority of Stubbing's work to date concentrates on the drying of ceramics. From October 1994 to December 1996, CERAM Research conducted the only known trial of patented airless drying to have been completed in the UK ceramics industry [126] [180] [181] [182] [183] [184].

Description	Development area	Dates
Dryer configuration	ATD	1988 – 1989
	Batch	1989 – 1998
	Continuous	1995 – 1998
	Pre-heat	1998
Supporting technology	Multi-effect drying	1993 – 1998
	General exhaust recovery	1990 – 1991
	Process water heating	1988 – 1998
	MVR	1993 – 1998
Materials investigated	Laundry	1988 – 1997
	Ceramics	1989 – 1998
	Paper	1990 – 1994
	Waste	1992
	Biomass	1994 – 1995
	Wood	1997
Others	Dryer construction	1994 – 1998
	Energy efficiency	1988 – 1998
	Financial savings	1988 – 1998
	Time savings	1989 – 1998
	Atmospheric emissions	1989 – 1992
	Condensation effects	1995 – 1996
	Market analysis	1997 - 1998

Table 3.0 Development of patented airless drying

The energy efficiency benefits and financial savings offered by airless drying have been promoted from the advent of the first ATD. However, the use of airless drying as a method for reducing processing time was only suggested from 1990 onwards [106]. A brief mention is made of reduced atmospheric carbon dioxide emissions through the use of airless drying, yet no work on this area can be detailed beyond 1992 [143].

Continuous Airless Drying

Chamber drying is limited to applications which process fragile, delicate, large or batched goods. With continuous dryers accounting for 90 per cent of total world-wide dryer sales, an opportunity clearly exists to develop and market an airless unit based on continuous operation [133]. However, operation under airless conditions precludes the ingress of air, suggesting that an open-to-atmosphere continuous system would prove difficult to engineer. Even so, Stubbing and Ceramic Drying Systems Ltd, UK, have developed a patented system for continuous superheated steam drying [224].

Continuous airless drying is a direct out-growth of the batch drying technology. Two initial dryer configurations were proposed by Stubbing; each design using a different method for maintaining an air tight seal [132]. The designs were,

1. A horizontal tunnel dryer with pallet-isolating partitions
2. A tunnel dryer with a sloping warm-up zone and an elevated airless drying chamber.

The author's direct contact with Stubbing, and a supporting literature search, suggests that development has followed the latter concept, which makes use of a steam-air stratification layer to prevent the ingress of air [127].

Essentially, air ingress into the continuous dryer can be prevented by elevating the drying chamber above the level of the product inlet, as demonstrated in figure 3.1. The stratification layer at the steam-air interface arises due to the significantly different densities existing between superheated steam and air. For example, ambient air at 15 °C (0.1 MPa) has a density of 0.82 kg/m^3; a factor of 1.56 higher than that of superheated steam at 150 °C (0.1 MPa). The end result is a sufficiently stable manometric seal which will tolerate the disturbance and possible mixing of gases which may occur as a result of a product passing into the dryer [127] [133] [132] [26].

Details of an energy saving adaptation to continuous airless dryer operation have recently been published by Stubbing. The inclusion of a 'post-dryer' system has been described as offering further savings in energy efficiency [128]. The system enables final moisture removal using airless dryer exhaust to heat incoming ambient air. As far as the author is aware, the validity of such a system has not been theoretically, or practically, demonstrated.

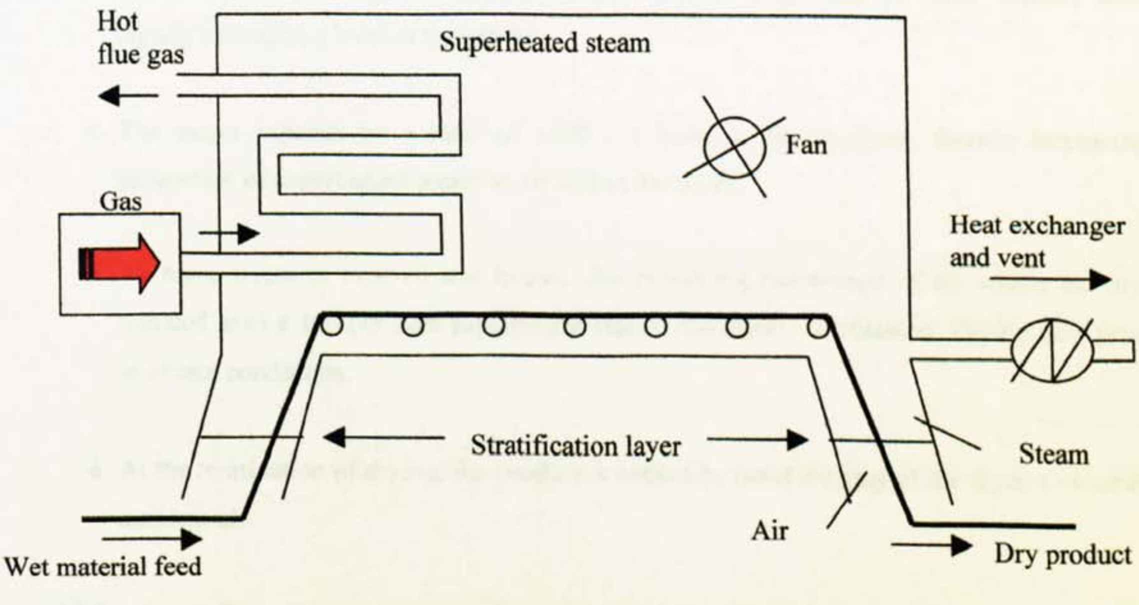


Figure 3.1 Simplified schematic of a continuous airless dryer

Airless Dryer Operation

As with conventional air drying systems, airless dryers are classified as either direct or indirect depending upon the method in which the drying gas interacts with the solid to be dried. Direct dryers, or contact dryers, are considered fully airless in their operation because the drying gas provides both the heating and the means to remove moisture after evaporation. The basic schematic layout of a direct airless batch dryer is given in figure 3.2.

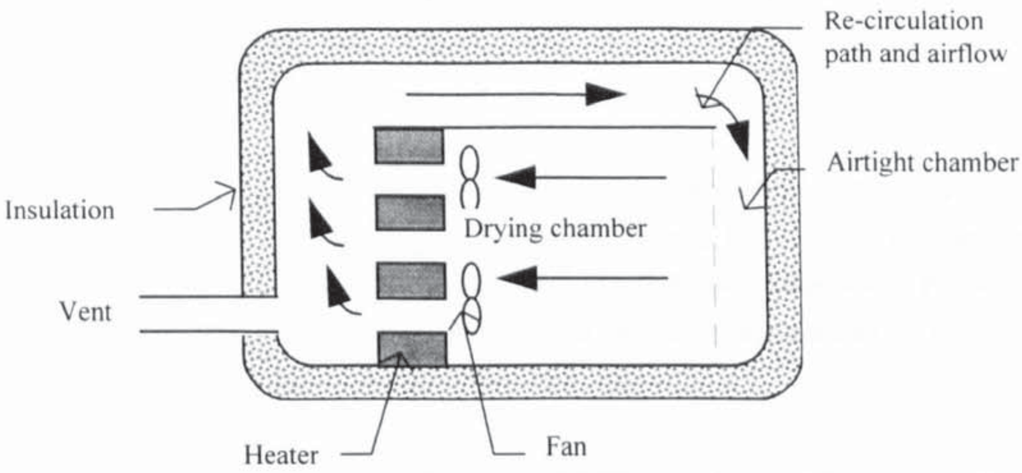


Figure 3.2 Simple outline of an airless dryer

The operating cycle of an airless dryer can be sub-divided into six stages.

1. Air in the dryer is heated and re-circulated using an internally located heater and fan.

2. The increasingly hot air expands and part of its volume is vented to exhaust.

3. The wet solid increases in temperature and releases a quantity of water vapour, which is rapidly heated to a level of superheat.

4. The steam expands by a ratio of 1690 : 1 from its liquid phase, thereby increasing the proportion of superheated steam to air within the dryer.

5. As more steam is evolved and heated, the remaining percentage of air within the dryer is reduced until a 100 per cent superheated steam atmosphere is obtained. Drying now proceeds in airless conditions.

6. At the termination of drying, the product is cooled by rapid purging of the dryer's volume with ambient air.

A humidifier, normally a direct steam injection unit, is often used to achieve rapid warm-up whilst also providing controlled suppression of evaporation at the start of drying. During the cycle, an airless unit will frequently operate at a slight positive pressure to prevent air ingress.

The control system needed to operate airless drying is relatively simple when compared to standard air drying, requiring only the monitoring and control of off-heater vapour temperature [8] [138] [50].

Benefits of Airless Operation

The use of airless drying in industry is well documented, yet literature detailing the process mechanisms and theory appears limited. Indeed, there remains a lack of understanding in to the fundamental mechanisms involved in the airless drying process [10].

Björk and Rasmuson suggest that the relationship between the moisture equilibrium of a product and superheated steam has not been sufficiently investigated [10]. Going further, they indicate that the relationship is actually a function of the superheated steam's activity and temperature, as well as the material under process. Tarnawski and Klepaczka researched the steam impingement drying of paper, stating that the effects of the drying medium are relatively little known [148].

A paper by Wimmerstedt and Hager in 1996 attempts to describe the heat and mass transfer processes in addition to the equilibrium, capillarity and sorption phenomena occurring in porous materials during the steam drying process [164]. Mujumdar [99] and Beeby and Potter [8] provide detailed summaries of superheated steam drying theory, methods and technologies. Beeby and Potter provide simple equations for heat and mass transfer but do not elaborate upon them.

Regardless of previous attempts to model and simulate steam drying, the ability of airless drying to reduce drying time, save energy and simplify solvent recovery when compared to air drying have proved consistent over differing product types and different dryer configurations. The following sections briefly discuss the purported mechanisms which result in faster drying times and reduced energy consumption from the use of airless drying.

Reduced Drying Times

Direct air drying and superheated steam drying display some commonality: both gases behave as heat and mass transfer media within the drying process, supplying the heat of evaporation and the means to carry the evaporate away from the product surface. Moreover, heat transfer during air and steam drying is primarily due to the temperature difference which exists between the drying medium and the solid under process. A study conducted by Björk and Rasmuson suggests that the activities of water in air and water in superheated steam are identical [10].

Despite the similarities, airless drying has frequently demonstrated dramatic reductions in in-dryer residence time. Covington suggests that drying of fibrous fuels in a steam atmosphere can be three times quicker than in conventional air drying [29]. Schwartze commented that, on the basis of the transfer area, the drying of wool fibre mats proceeded at higher drying rates during airless drying when compared with typical air drying conditions [117].

An extensive trial of airless drying in the UK ceramics industry was conducted between 1993 and 1996 [180] [179]. The project was undertaken by CERAM Research in collaboration with C.D.S Projects Ltd (dryer manufacturer), Warwick Heat-Win Ltd (airless drying patent holders), EA Technology (research and development organisation) and a number of ceramics manufacturers. A summary of the project's results are given in table 3.1.

Sub-sector of the ceramics industry	Product	Drying time for standard drying (hrs)	Drying time for airless drying (hrs)	Saving (%)
Heavy clay	Brick specials	60	24	60
	Perforated bricks	48	20	58
	Roof tiles (250 mm^2)	192	72	62
Sanitaryware	Single cast ware	14	5	64
	Stuck on rim closets	72	12	83
	Fire clay sinks/ channels	96	16	83
	Plaster moulds	60-80	12	80-85
Refractories	Insulating bricks	90	35	61
	Perforated bricks	120	43	64
Insulation products	Slabs	90-140	48	46-65
	Pipe sections	36	8-12	66-77
Electro porcelain insulators	Hollow & solid core products	60-90	20-30	66
Tableware	Plaster moulds	30-48	8	73-83
Colours and glazes	Colours and glazes	16	8	50

Source: CERAM Research, EA Technology [180] [181] [182] [183] [184].

Table 3.1 Savings in ceramics process times using airless drying

It is clear that overall drying times were significantly reduced in all drying trials. In general, reductions between 46 per cent and 85 per cent were achieved, with the thicker cross-sectioned items experiencing a larger proportional change in drying time over the thinner section products [180].

Although the general mechanisms and characteristics of airless drying are similar to standard air drying, some fundamental differences exist [8]. In practice the overall drying rate can be faster or slower in superheated steam depending on many factors, including the amount of condensation occurring during 'start-up', whether the steam temperature is above or below the inversion temperature and the nature of material being dried [8].

The following mechanisms have been cited as prime reasons for faster drying under airless conditions [8] [130] [99] [79].

- The temperature difference and, hence, the heat transfer rate between the solid and superheated steam is greater than that for standard air drying.

- Superheated steam has a greater thermal conductivity than air at the same temperature. The result is an associated increase in the coefficient of heat transfer.

- The effects of condensation and radiation increase heat transfer rates during steam drying.

- Superheated steam has a lower dynamic viscosity than air at the same temperature. The combination of lower viscosity with higher drying gas temperatures leads to improved moisture migration throughout the product.

- The evaporation rate of water in superheated steam is higher at the solid's surface than in dry/humid air at same temperature. Essentially, the use of superheated steam avoids the stagnant, saturated boundary layer of air at the product's surface experienced during conventional drying.

- Even temperature distribution in the dryer leads to uniform drying during airless operation.

The mechanisms which affect airless drying rates can be divided into studies of heat and mass transfer. The following sections briefly elaborate on the requirements for faster drying rates and the existence of the inversion temperature.

Heat Transfer

Assuming that material enters a dryer at a temperature below that of superheated steam or air, a transfer of heat will occur from the gas to the solid with the rate of transfer proportional to the difference in temperatures. During airless drying at atmospheric pressure the solid dries at the steam's saturation temperature of 100 °C. The rate of heat transfer therefore depends upon the degree of superheat used.

In air drying the solid dries at the wet-bulb temperature which, for the most part, is significantly lower than 100 °C. Without a sufficient degree of superheat during steam drying, an opportunity therefore exists for faster heat transfer rates during air drying [83]. The situation is complicated further by the existence of two additional heat transfer mechanisms which occur during steam drying, namely condensation effects and gas radiation.

If the degree of superheat is low, a potential exists for the steam to condense on the solid with the associated rapid heat transfer which accompanies the condensation effect [136] [164]. Although condensation promotes heat transfer to the product, in most situations it is to be avoided; presenting as it does an extra drying load and the potential to damage products. The effects of condensation can be easily ameliorated by the pre-heating of products.

Research work has been found which indicates that airless drying occurs by the mechanisms of forced convective heat transfer and radiation effects, rather than the sole mechanism of convective heat transfer found in air drying [164] [104]. Nishimura et al examined the effects of gas radiation on the evaporation of moisture into a laminar stream of superheated steam [104]. The nature of superheated steam as a 'radiation participating' medium was modelled, concluding that the inclusion of a parameter for radiation lowers the temperature of the main steam stream whilst increasing the total heat transfer flux at the water surface.

Both the effects of condensation and radiation transfer are significantly reduced when drying in standard air conditions. The author has found only one paper that details the behaviour of superheated steam as a radiation participating gas. Until further published evidence becomes available, the author is cautious in assuming the significance of radiative heat transfer during airless drying.

As drying proceeds, the drying rate becomes increasingly dependent on the transport of moisture from the product's core to its surface. It is claimed that airless drying offers further benefits during the mass transfer dependent drying stage [131].

Mass Transfer

A survey of literature suggests the principal reason for rapid drying in airless conditions is due to the increased mobility of moisture throughout the product. Constant rate drying in atmospheric superheated steam proceeds at 100 °C, compared to a typical 50 °C for low-temperature air drying. The corresponding dynamic viscosity of water at 100 °C is 2.8×10^{-4} $kgm^{-1}s^{-1}$, significantly lower than a viscosity of 5.44×10^{-4} $kgm^{-1}s^{-1}$ for water at 50 °C. This reduced dynamic viscosity results is a more rapid diffusion of moisture throughout the product and a faster drying rate.

Toei et al. demonstrated that the constant rate period during superheated steam drying continued longer than for air drying [154], suggesting that moisture is more mobile under airless conditions [8]. Luikov indicated that larger moisture diffusion coefficients were a direct result of increased drying gas temperature [83].

In addition to enhanced internal moisture diffusivity, literature suggests that airless drying benefits from increased evaporation rates at the solid-gas interface. Tarnawski et al claim that the process of moisture 'pick-up' from a material is different in air than in steam although no intimation is given as to the reason for this [149].

In conventional air drying, mass transfer is impeded by a saturated layer of relatively stagnant air occurring at the solid-air boundary. Moisture evaporated at the surface must undergo binary diffusion through this stagnant layer to reach the bulk flow of drying gas. The lower density and dynamic viscosity of superheated steam, and the elimination of air under airless conditions, results in a resistance-free uptake of evaporate into the bulk gas flow [131] [8]. Wimmerstedt and Hager [164] and Beeby and Potter [8] suggest that external mass transfer in airless drying is simply a function of the pressure difference between the main steam flow and the evaporate, rather than the boundary diffusion mechanism occurring in air drying. Chu et al. [20] and Wenzel and White (1951) indicate that a negligible degree of superheat is needed to provide sufficient pressure difference for mass transfer.

Overall, the relative performance of airless drying depends upon the material being dried. The identification of inversion temperature allows the engineer to determine the preferential temperature for drying in air or superheated steam.

The Inversion Temperature

In 1970, Yoshida and Hoydo measured the evaporation rates of water into air and superheated steam. Comparing the results at constant gas velocity yielded the 'inversion temperature', or the gas temperature above which superheated steam gives a preferential drying rate over air drying.

Studies comparing airless drying to standard drying have since noted the existence of a temperature limit below which drying in air occurs at a faster rate than in steam [166] [130] [99]. Inversion temperature appears to vary with the type of material under test. Figure 3.3 illustrates the inversion temperature for the impingement drying of paper [148].

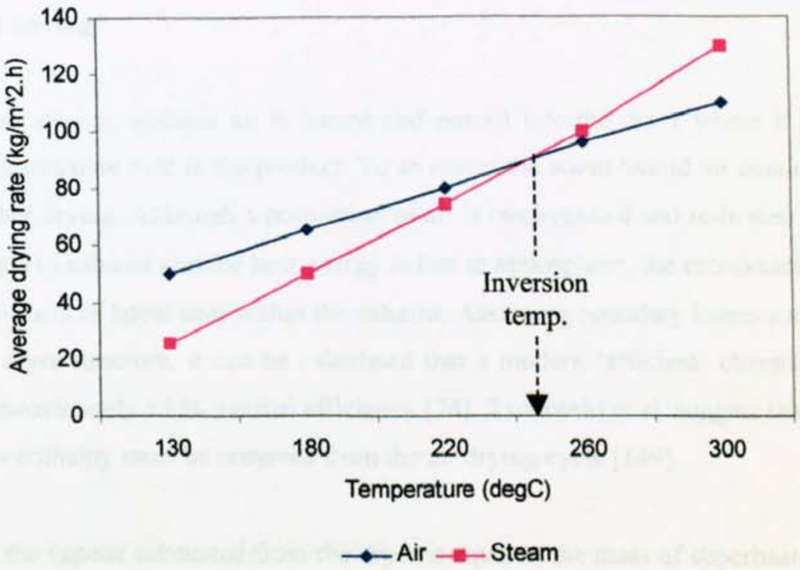


Figure 3.3 Inversion temperature for air and superheated steam drying

Yoshida and Hoydo investigated the drying of foods and subsequently verified inversion temperature, which they recorded as approximately 175 °C [167]. A study on the impingement drying of paper by Tarnawski and Klepaczka indicates that only the use of steam above 245 °C gives a higher drying rate than air drying at similar temperatures (Figure 3.3) [148]. It is suggested that the lower kinematic viscosity of steam and the drop in Reynolds number (Re) in air above 200 °C are the main influences on inversion temperature. Nishimura et al. found that the inversion temperature for the evaporation of free water varied between 150 °C and 170 °C [104].

A search of literature suggests that the airless drying of large cast ceramic and gypsum products demonstrates significantly increased drying rates at steam temperatures as low as 120 °C and 130 °C [180] [178].

Reduced Energy Consumption

'Energy efficiency' was initially championed as the key advantage over standard air drying. However, with relatively low energy prices and an increasing value placed on product quality and production lead-times, it can be argued that airless drying's main advantage is now recognised as the reduction in drying time. Nevertheless, the ability to combine reduced drying times with significant energy cost savings is beneficial for the use of airless drying as a potential process for the application of DSM.

In comparison with air, drying in superheated steam creates many possibilities for energy conservation [149] [99] [139] [140]. Energy savings arise for three fundamental reasons,

1. Drying time is reduced leading to a lower specific energy consumption. Overall electricity demand is also reduced for motor driven applications e.g. re-circulation and burner fans
2. Airless drying intrinsically operates more efficiently than air drying
3. Thermal energy in the airless dryer's exhaust is capable of being recovered economically.

Intrinsic Energy Savings

In conventional air drying, ambient air is heated and passed into the dryer where it undergoes heat and mass transfer with moisture held in the product. To an extent the warm humid air coming off the product is incapable of further drying. Although a proportion of air is re-circulated and re-heated for drying duty, the majority is directed to exhaust and the heat energy is lost to atmosphere: the economics of energy recovery preventing the re-claim of latent heat within the exhaust. Assuming boundary losses and sensible heating of the product and dryer structure, it can be calculated that a modern 'efficient' chamber air dryer will not operate above approximately 55 % thermal efficiency [74]. Tarnawski et al. suggest that more than 67 % of heat showing low enthalpy must be removed from the air drying cycle [149].

In airless drying the vapour exhausted from the dryer is equal to the mass of superheated steam evaporated from the product. The steam used for drying is simply re-heated and re-circulated within the dryer, resulting in a lower net energy requirement and better energy economy when compared to air drying.

The replacement of air with superheated steam has further energy benefits. Superheated steam has a higher specific heat capacity (C_p) than air at the same temperature. As such a lower mass flow rate is required for a given transfer of thermal energy [147]. To illustrate the benefits, table 3.2 provides a comparison between air and steam at 200 °C.

	Specific heat capacity, C_p (kJ/kg K)	**Ratio to $C_{p\,air}$**
Air	1.0465	1
Superheated steam	1.9750	1.89

Table 3.2 Specific heat capacity for air and steam at 200 °C, 0.1 MPa

For this particular case, an associated reduction in mass flow rate has the effect of lowering fan power duty by 52 per cent for a given thermal enthalpy.

Energy Analysis: Air Drying vs. Airless Drying

Energy use for drying processes depends upon many factors including material type, drying gas temperature and drying time. As such no general model of energy consumption can be derived for air or superheated steam drying.

Tarnawski et al. performed an energy analysis on the use of air and superheated steam for the impingement drying of paper webs [149]. Table 3.3 compares the results for gas temperatures and velocities of 300 °C and 60 ms^{-1} respectively. The effects of condensation in the heat-up period were not considered and recuperation of heat from the dryers' discharge was not taken into account.

Items	Unit	Drying media	
		Steam	Air
Total demand of heat for drying, q_r	kJ/m^2	934.7	913.2
Power for driving the recirculation fan, N_F	kW	1.1	1.7
Electric heater power demand, N_{eh}	kW	16	73.4
Electric energy demand for drying, N_e	kW	17.1	75.1
Specific energy demand for drying, E_t	$kJ/kg_{wat.}$	4132	17558
Thermal efficiency, *e*	%	47.0	9.0

Table 3.3 Paper drying air with superheated steam and air (t =300 °C) [149]

Table 3.3 suggests that switching to superheated steam incurs several benefits, including

- a 35 % reduction in fan power,
- a 76 % decrease in specific energy demand,
- a 5 times increase in thermal efficiency.

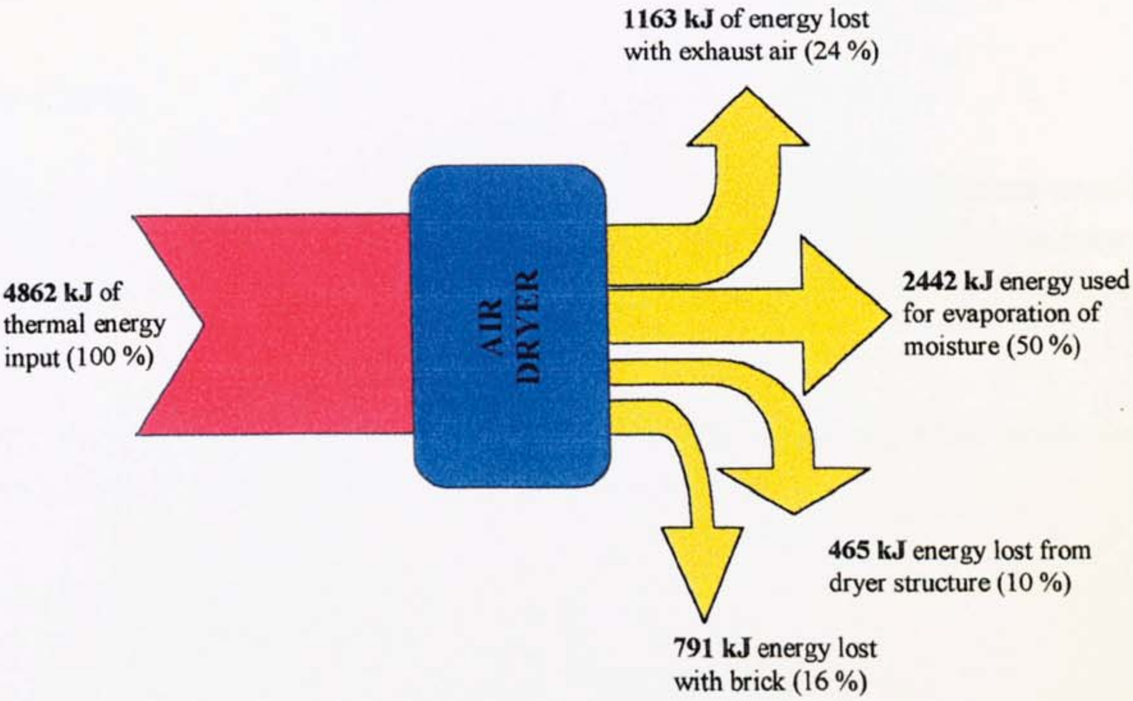
Thermal energy use	Conventional drying		Airless Drying	
	kJ	%	kJ	%
Energy withdrawn with bricks, etc.	791	16	1164	24
Energy to evaporate 1 kg of water	2442	50	2442	50
Energy losses from dryer structure	465	10	233	5
Energy lost with exhaust air	1163	24	n/a	0
Gross thermal energy use	4,861	100	3839	79
Recycling potential	n/a	n/a	2442	50
Net thermal energy use	**4,861**	**100**	**1397**	**29**

Table 3.4 Energy use comparison (brick drying) [143]

Stubbing presented an assessment of energy use for the removal of 1 kg of moisture from a house brick using air and superheated steam [143]. Table 3.4 compares the approximate amounts of thermal energy required. An 'efficient' conventional unit is assumed for all air drying calculations.

Figures 3.4(a) and 3.4(b) present the data given in table 3.4 as Sankey diagrams.

(a)



(b)

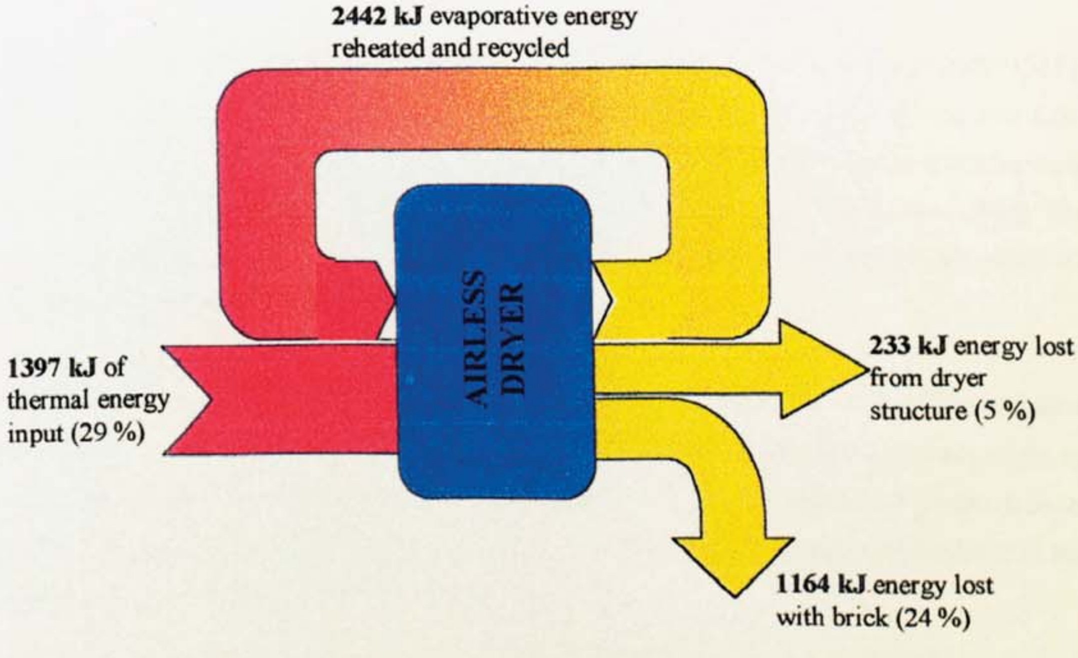


Figure 3.4 Sankey diagrams: air drying (a) and superheated steam drying (b) of brick

Overall, the total specific energy input for airless drying is 1023 $kJ/kg_{wat.}$ less than for air drying, corresponding to a 21 % reduction. Translation of these values to theoretical drying efficiencies gives 64 % for superheated steam drying and 50 % for air drying. No assessment of relative electrical power consumption has been included within Stubbing's work.

In addition to the relative efficiency of airless operation, superheated steam drying offers the possibility of almost 100 per cent closure of the energy cycle from the recovery of latent heat energy in the exhaust. Re-claim of latent heat can realise substantial energy cost savings if the recovered energy is utilised elsewhere [117].

Heat Recovery

It has been stated earlier that the exhaust gas from airless drying is 100 per cent superheated steam. Pure superheated vapour can be economically condensed at its saturation temperature and the latent heat recovered. For superheated steam, the latent heat constitutes approximately 84 % of its total enthalpy content.

Ultimately, the method of energy recovery depends upon the dryer configuration and the specific need for energy re-claim. The most common options found in literature include,

- Hot water production
- Process steam production
- Space heating
- Heating for second-stage drying (or multi-effect drying)
- Steam compression (MVR) followed by re-use within the airless drying process.

Literature has been found which describes all of these methods of energy re-claim [50] [131] [135] [99]. Stubbing suggests that the dryer's superheated steam exhaust can be condensed on one side of a heat exchanger to produce approximately eight times its own weight of boiling water or a greater weight of 'less hot' water. Examples including the supply of hot water for showers have been cited [223]. Similarly, the exhaust steam can be condensed in a heater battery to heat a supply of ambient air within a secondary conventional drying processes [50].

As an alternative, steam quality can be upgraded using an open heat pump cycle and re-introduced in to the airless dryer as a supplementary method of superheating steam. Essentially, the heat pump cycle uses a mechanical compressor to increase the steam's pressure with an associated rise in saturation temperature, T_s. The resulting increase in T_s allows the steam's enthalpy to be economically transferred back into the drying process by means of a heat exchanger.

Literature suggests that the use of mechanical compression, or Mechanical Vapour Re-compression (MVR), is of particular interest to the energy utilities [99] [184] [63]. The combination of airless drying with MVR provides an opportunity to promote energy efficiency and help the consumer reduce overall energy costs. Moreover, the use of MVR decreases the reliance on fossil fuel combustion, therefore decreasing atmospheric carbon dioxide emissions and creating a 'cleaner' process at the point of energy use. The following section briefly describes the operation of MVR within an airless drying process.

Mechanical Vapour Recompression (MVR)

Vapour compression is widely used within continuous evaporators [99]. However, the use of vapour compression in relation to drying systems is considerably more recent. The paper and pulp industries were amongst the first to embrace the MVR technology for drying, a direct result of the considerable energy requirement for evaporation of moisture from both the pulp and paper web during forming [106].

Wimmerstedt and Hager found reports from the 1980s detailing two commercial drying installations operating with MVR: a sugar beet dryer based in France and a Swedish Exergy dryer used for the processing of peat [164]. The use of exhaust steam in an MVR system, or as a supply for multi-stage cascade drying, is not mentioned by Stubbing until the end of 1993 [142].

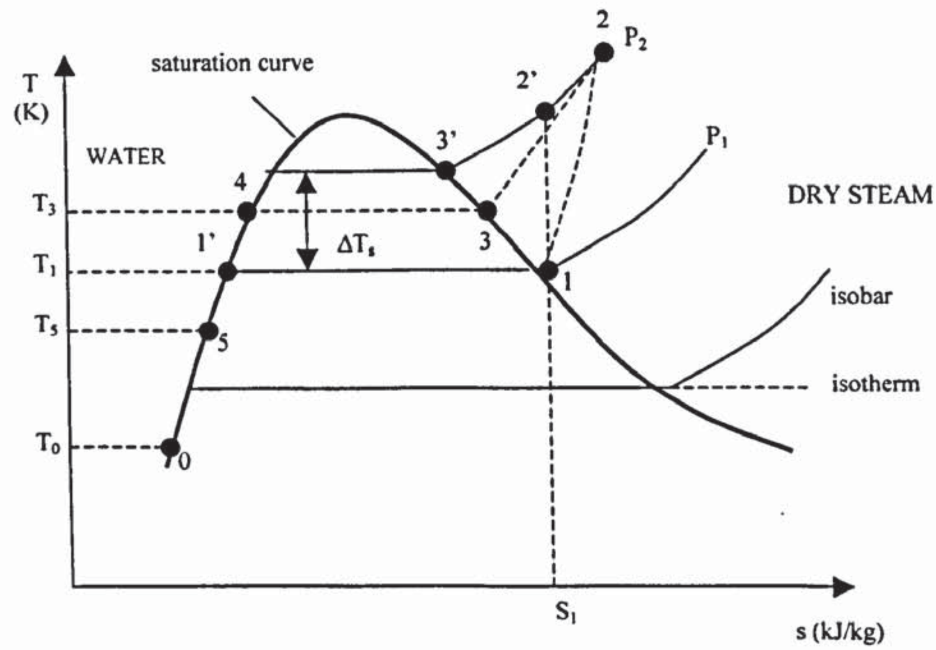


Figure 3.5 T – s diagram (mechanical vapour recompression)

Figure 3.5 gives the temperature-entropy (T-s) analysis for steam compression. Point 1 characterises the condition of steam leaving the dryer and entering the compressor, assuming that pressure and temperature losses in the compressor inlet are negligible [208]. The compressor then raises the pressure from P_1 to P_2. Compression is polytropic and gives a steam output characteristic defined at point 2. Point 2' indicates ideal, adiabatic and reversible compression at constant entropy S_1.

To maximise heat transfer within the evaporator (dryer), the compressor's output must be de-superheated using water injection [108] [208]. Ideally steam conditions will be brought to point 3', although losses in the compressor result in a de-superheated state at point 3. Assuming that differences between 3 and 3' can be neglected, the 'compressor ΔT_s' can be defined as,

$$\Delta T_s = T_{3'} - T_1$$

The value of ΔT_s is decided from product characteristics and the drying regimes and temperatures required.

If a compression system is working within specific design limits, the amount of energy, or electrical power, required to drive the system will remain considerably less than the recoverable heat value in the vapour [208] [86]. As such an economic value may be gained. Chapter 7 provides a detailed analysis of electrical energy use for MVR as part of an energy services tool for the modelling of drying processes.

Airless Drying: Further Benefits

It has been suggested in literature that product quality can be improved through the use of airless drying [8]. Recent trials have been conducted on the airless drying of plaster moulds in the UK ceramics industry. Results indicate that mould life can be doubled from 110 casts per mould up to 250 casts per mould by superheated steam drying at 130 °C [178]. Additional benefits noted include,

- A 50 % reduction in annual gypsum bills
- Reduced waste disposal
- Reduce labour for mould making
- Halved mould replacement costs
- Significantly reduced floor space for mould drying.

Covington noted that tests on kraft wood pulp drying show at least the same quality as air drying [29].

Other widely reported benefits of airless drying include,

- Elimination of fire and explosion hazards
- No oxidative damage
- Compact dryer size and reduced floor area for drying.

[8] [50]

It is reported here for the first time that airless drying has a beneficial role in increasing production capacity by highlighting sub-standard product quality [24]. For the drying of delicate materials, such as vitreous ceramics, the rigorous airless drying schedule causes flawed products to fail during drying rather than at the later, more costly, down-stream firing stage. Failed products can then be removed, allowing greater capacity in the post-dryer inspection, spraying and kilning sections. As yet, no statistical data on failure rates or assessments of potential increase in capacity have been published.

Potential Problems with Airless Drying

The primary problem in airless drying is the exposure of temperature sensitive materials to superheated steam. More specifically, products which cannot tolerate drying temperatures of 100 °C or higher should not be considered for airless drying. Furthermore, products which can tolerate high steam temperatures are frequently found to fail as a result of excessively rapid drying rates and over-pressure inside the material.

For such materials, a system of evaporation suppression is needed during the dryer start-up stage. Evaporation suppression is achieved through the use humidification units, which result in the increased complexity of the dryer's control system, the capital cost of the dryer and, ultimately, the length of the drying cycle.

The unwanted effects of condensation during dryer warm-up have been alluded to previously. It bears repeating that condensation on products must be eliminated to provide satisfactory product quality and to maintain dryer load and drying time at a minimum. Drying trials conducted by CERAM Research noted that highly hygroscopic ceramic insulation blocks easily re-absorb moisture from their environment [181]. Blocks placed at the periphery of the airless dryer were exposed to steam with a low degree of superheat. During drying, the steam cooled and condensed resulting in under-drying of the blocks.

In practice, it is important to note that the dryer's exhaust may prove 'dusty' as a result of particulates entrained within the steam. If this were the case, some form of gas cleansing would be required. To ameliorate this effect in practical MVR systems, the re-compressed vapour is often condensed in a heat battery with clean steam being liberated on the opposite side of the device. The heat exchanger may be placed inside the dryer or as a product feed pre-heater.

Table 3.5 provides a checklist of potential problems and possible solutions facing the user of airless drying.

Problem	Result	Solution
Temperature sensitive material	• Cracking and deformation • Blistering • Discolouration and browning	n/a
Drying rate sensitive material	• Cracking, deformation and pinholing	• Evap. suppression • Lower steam temperature
Condensation	• Warping and deformation • Under-drying	• Material pre-heating • Evap. suppression
Differential drying in material stacks	• Under-drying • Cracking	• Investigate integrity of dryer insulation • Alter product loading
Under loading of dryer	• Extended drying times • Condensation effects	• Steam injection
Air ingress	• Extended drying times • Condensation effects	• Investigate sealing arrangements

Table 3.5 Potential problems with airless drying

<u>Airless Drying for Industrial DSM</u>

Industrialists and experts working in the field of drying are unified in their opinion as to the importance of moisture removal in terms of its economics, environmental factors and energy usage [91] [98]. Despite this, Mujumdar found that little market penetration for steam drying has occurred [99]. Beeby and Potter note that drying in superheated steam or superheated solvent vapour has been accepted for a long time but practised very little [8].

Current Market Penetration

Overall, the commercial use of airless drying plant is severely limited in its applications throughout the world. At the time of writing (March 1999), the author is aware of only 3 currently operational superheated steam batch dryers based within the UK. Internationally, airless drying has been found to be successful in several industrial processes dating back as far as the late 1970s but, as yet, has been limited to special opportunities [164]. Examples of its application include the steam drying of pulp, bark and hog fuel in Sweden; pulverised coal in Australia the former Eastern block countries of the USSR and GDR and also South Africa. Textiles drying in India has been documented [99].

Pilot schemes found in literature include the drying of peat in Finland, the drying of wood and particle board in the USA, France and Finland. Other investigative studies within the area of industrial steam drying have been recognised and documented [199]. It has been demonstrated that airless drying is a feasible process option for the textile industry [117]. Countries furthering industry research into superheated steam drying include Australia, Austria, Canada, China, Finland, France, Germany, India, Japan, Sweden, UK, USA & USSR [99].

To the best of the author's knowledge, Baker and Reay have produced the only known qualitative penetration survey of supporting energy saving technologies relating to airless drying in the UK [7]. Table 3.6 summarises the conclusions of the survey.

Development	Potential Energy Savings 10^9 MJ/yr	Penetration rate
Heat recovery from exhaust (without heat pump)	1	High
Heat pumps (closed cycle) (Superheated steam drying)	9	Medium
Vapour compression	26	Low
Better instrumentation and control	4	High
Optimal design/operation	11	High
Better dewatering of feed	5	High
Dry forming of paper	13	Low/Medium

Table 3.6 Estimated industrial penetration of airless drying (UK, 1980) [7]

Although this survey is dismissed by the authors as "a guess of the degree of penetration" for energy saving developments, it nonetheless serves as an indication of possible future trends in market penetration. As of 1980, airless drying and its associated vapour compression technology had low-to-medium penetration yet offered potentially substantial combined energy savings in the order of 35×10^9 MJ per annum.

An industrial market clearly exists for the proven airless drying technology [24] [137]. Initial analysis by Stubbing recognises both 'natural' and 'new' growth areas for continuous airless drying [132]. 'Natural' growth areas include replacement of conventional drying systems whereas 'new' areas are dictated by increasing legislative regulations on environmental areas and renewable energy sources. Essentially, both types of growth offer potential opportunities for the application of airless drying as part of a DSM or energy services programme.

Application to DSM and ES

A thorough search of literature indicates no current research detailing the use of airless drying as an integral part of a demand side management or energy services scheme. Furthermore, of the work that exists, no information has been found which describes a framework for comparing traditional drying methods with airless drying.

The author believes that a significant opportunity exists for a detailed comparison between airless drying and conventional drying methods for the purposes of assessing energy and production benefits. Such a model would have the ability to provide basic data on the salient differences between drying technologies in terms of energy use, energy cost, drying time and atmospheric emissions.

Summary

In summary in can be stated that airless drying is a proven but still maturing technology, showing marked benefits over conventional air drying systems [29]. This chapter has briefly discussed the history, development and potential savings in drying time and energy consumption that can be offered to UK industry through the adoption of airless drying. Despite such apparent advantages, penetration in to the industrial sector is limited and the potential savings from industry-wide adoption of airless drying are unknown.

To gain an appreciation of the potential energy savings offered by airless drying, the author believes it necessary to determine current energy use for industrial drying in the United Kingdom. Chapter 4 describes previous attempts to estimate energy use for drying and provides the results of a new survey.

CHAPTER 4

ENERGY USE FOR DRYING IN UK INDUSTRY

Introduction

Energy efficiency is not a new concept to industry. The energy crises of the early and late 1970s provided an incentive to reduce fuel consumption, allowing the industrial energy user to combine lower production costs with protection against future fluctuations in energy price. To a certain degree the low energy prices of the late 1980s and 1990s have eliminated the strive for energy efficient operation started in the 1970s. Although modern drying equipment is often better designed and more energy efficient than its 70s counterpart, industry often eschews energy efficient operation in favour of increased product quality and lower production lead-times [62] [110].

Mounting social awareness of environmental issues and increasing 'green' legislation are now forcing European industry to meet specified atmospheric emission standards and conform to Best Practice Programmes. As such, energy use and energy efficiency form two important areas for the continuing survival and competitiveness of UK industry.

Previous estimations of energy use for drying on a national scale have used different calculation methodologies and assumptions, resulting in little commonality between individual surveys. This chapter presents the results of a new survey for the use of energy in United Kingdom industrial drying processes. Based on a 'moisture loss' method of analysis, an estimate of total energy use for drying in 8 broadly defined industrial sectors has been completed. The author believes this survey to be the first in 22 years to use the 'moisture loss' method for the assessment of energy consumption in drying processes. Furthermore, it is suggested that the moisture loss method offers the greatest potential for the modelling of Demand Side Management (DSM) measures.

Purpose of the Study

Regular monitoring of energy use for drying is important. The use of energy for drying operations in the UK shows a continuing increase against a background of falling total industrial energy use; thus highlighting the lack of research in energy efficiency for drying processes [63]. Audits of national energy use for drying serve multiple purposes, including

- Indication of potential trends in energy use for drying
- Identification of those UK industries which use a large proportion of the total energy demand for drying
- Insight and understanding into the factors which dictate overall energy efficiencies for drying processes.

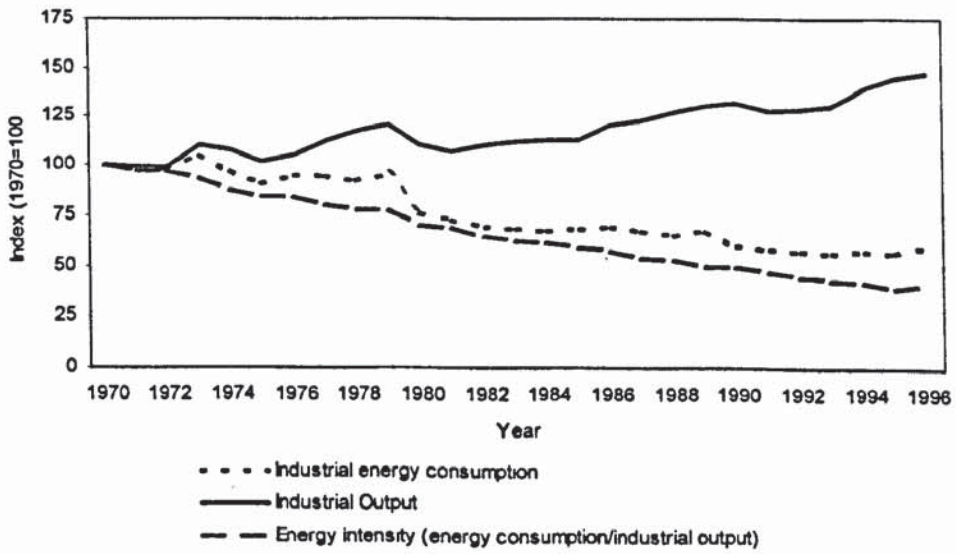
Ultimately, energy audits are essential prerequisites for the effective management of energy use [63]. On a commercial level, energy utilities can use national energy surveys as a valuable tool to identify potential targets for the application of demand side management (DSM) measures and energy services. A model of industrial energy use for drying can be discretised by sub-sector, thus providing an opportunity for the planning of energy saving schemes. Furthermore, analysis of industry-wide trends in energy consumption offer indications of future energy demand on the supply and distribution networks for gas and electricity.

Trends in Industrial Energy Consumption

Total industrial energy usage figures are published regularly [206] [207], albeit energy audits specific to industrial sectors remain infrequent and irregular. A literature search suggests that the last published industry-wide energy audits were those of Jay (1996) [63], Baker and Reay (1983) [7], Hodgett [57] and a review of drying, evaporation and distillation processes undertaken by ETSU (1981) [198]. Table 4.0 summarises the calculated total industrial energy use for these four audits.

Study	Ref.	Year(s) covered	Industrial energy use (PJ)
Hodgett	[57]	1976	3240
ETSU	[198]	1981	1887
Baker and Reay	[7]	1982	1103
Jay	[63]	1978 to 1990	779 to 1141

Table 4.0 Industrial energy use in the UK (1976 – 1990)



Source : Department of Trade and Industry, Office for National Statistics

Figure 4.0 Industrial energy consumption and industrial output, 1970 to 1996 [187]

Total energy use in industry has fallen over the past decade [63] [187]. Before the late 1980s, industry was the single largest consumer of energy in Britain. By 1997 industrial energy use had been overtaken by the transport and domestic sectors; a result of fuel switching, structural change in industry and an increase in the energy efficiency of manufacturing [187]. The Department of Trade and Industry (DTI) suggest that industrial energy intensity (energy consumption per unit output) and energy use have varied with industrial production output as illustrated in figure 4.0 [187].

It is impossible to infer from figure 4.0 whether energy intensity is falling uniformly across industrial sub-sectors and, more importantly, whether energy use is decreasing equally between industrial processes. Indeed, as part of a survey investigating energy use for drying, Jay highlights an increasing trend in energy use for drying. Energy use for drying has increased from 120 PJ to 141 PJ over the years 1970 to 1991 (figure 4.1). This compares to a decrease in total industrial energy consumption from 1140 PJ to 778 PJ in the same period [63] [66] [67].

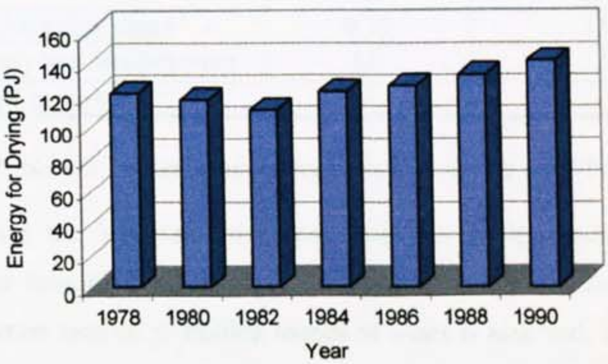


Figure 4.1 Variation in energy use for drying between 1978 and 1990 [63].

Previous Studies of Energy Use for Drying

The author has identified six references pertaining to energy use for industrial drying, thus indicating the limited number of specific energy audits for drying processes. Table 4.1 presents the results of those surveys researched, covering a range of years from 1976 to 1990.

Study	Ref.	Year(s) covered	Drying energy	Drying energy as proportion of total industrial energy use
Hodgett	[57]	1976	148 PJ	6.0 %
Witt	[165]	1977	61.5 TJ	n/a
ETSU	[198]	1981	103.8 PJ	5.5 %
Baker and Reay	[7]	1982	128 PJ	11.6 %
Wilmshurst	[163]	1989	144.1 PJ	8.3 %
Jay	[67]	1978 to 1990	141.15 PJ	18.19 %

Table 4.1 Past estimations of energy use for industrial drying in the UK

A frequently quoted paper by Hodgett estimates that 6 % of total industrial energy consumed in the UK is used for drying processes [57]. Hodgett's method of assessment analysed 14 material groups for average moisture loss and annual production rates. It was subsequently estimated that 17.4 million tonnes of moisture was removed by evaporation in UK industry for 1976. Table 4.2 gives a detailed breakdown of Hodgett's results.

Material	Annual Production (× 10^6 tonnes)	Average moisture content drop (%)	Water removed (× 10^6 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
Fertilisers	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 china clay pipes	0.75	15	0.11
Tiles, pottery and sanitaryware	1.0	15	0.15
Total for 14 materials	-	-	17.4

Table 4.2 Water removed by industrial drying in 1976 (after Hodgett [57])

Hodgett recognises the important omissions from his survey, including products from the chemical, pharmaceutical or foodstuffs industries. To account for the exclusion of these three industrial sectors, a total UK evaporation load of 30 million tonnes of water is assumed. The accuracy of the survey is further limited due to Hodgett's assumption of a nominal 50 % dryer efficiency, giving a final energy consumption figure of 148 PJ for drying processes, or 6 % of all the prime energy used in industry. Nevertheless, Hodgett goes on to identify 6 % as a 'very approximate guess', suggesting that this figure does not fully indicate the true proportion of industrial energy used in drying.

A similar 'moisture loss' analysis to that of Hodgett's is produced by Witt, who suggests that the mass of water removed through evaporation in the UK is of the order of 24.1 million tonnes [165]. Witt, however, fails to include any assessment for energy or plant efficiencies. Moreover, Witt does not identify those products which are assessed and, more importantly, those products which have been omitted from the analysis.

ETSU published a report investigating energy use for drying in 12 industrial sectors [198]. It is suggested from this document that 103.8 PJ of energy was used for drying processes in 1981. This figure constituted 5.5 % of total industrial demand in that year. It is important to note that only industrial sectors with energy consumption exceeding 2.0 PJ per annum are analysed.

Wilmshurst used ETSU's report as a base study for a more far reaching energy audit [163] [198]. The resulting study estimated a total energy consumption for drying of 144.1 PJ. This corresponds to a figure of 8 % of total industrial energy used for drying in 1981, an increase of 2 % over that of ETSU's estimate. As with previous studies, only sectors with a significant energy consumption were analysed: in this case sectors with energy consumption above 0.1 PJ pa. In addition, dryer efficiencies are rated uniformly at 35% and only energy in the form of heat is included in the calculations. No motive energies such as fan work or product conveyance are provided.

Baker and Reay [7] published a paper analysing energy usage for drying in selected UK industrial sectors. Overall production levels and annual energy figures for six industrial sectors are presented and the corresponding Specific Energy Consumption (SEC) figures are calculated. The resulting total suggests a figure of 11.6 % of total industrial energy used for drying, almost twice that of Hodgett's estimation. It must be noted, however, that energy consumption figures used by Baker and Reay are sourced from international data and can be criticised for being not typical of UK drying processes [63]. Furthermore, Baker and Reay do not provide information on their data collection methodologies, or detail on any products or sectors which may have been excluded from their survey.

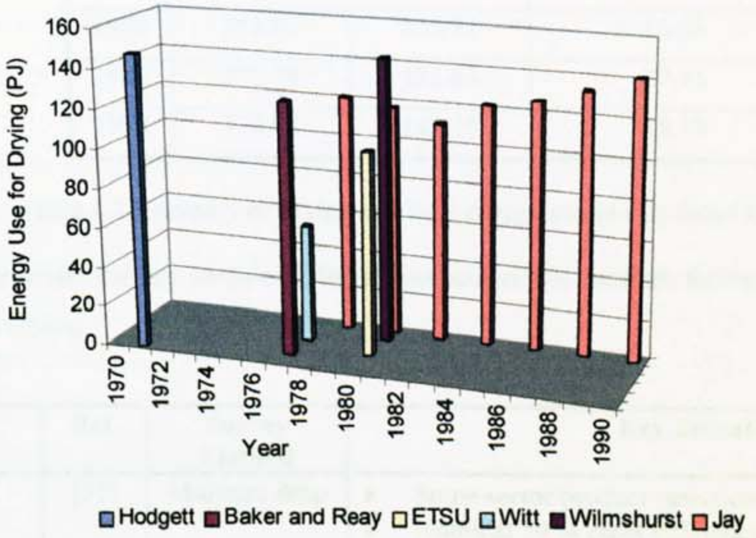


Figure 4.2 Historical use of energy for drying processes in the UK

The most recent survey of energy use for industrial drying has been completed by Jay, who provides an updated analysis for energy use from 1978 to 1990 using the Specific Energy Consumption (SEC) method followed by Baker and Reay [63] [7]. As an extension to the survey, Jay presents a comprehensive breakdown of energy use for industrial drying processes in the UK's ceramics, brick, abrasives, plasterboard, timber and paper industries. The results for total energy use, given in table 4.3, are based on a preliminary trend analysis from 1978 figures, followed by a re-estimation using production figures at 2 year intervals. Jay highlights the constraints of the survey by acknowledging the limited availability of production figures for some years and the exclusion of the timber industry as a whole. The resulting figures from Jay's work are compared to the results of previous energy surveys in figure 4.2 [57] [165] [198] [7].

Infrequent energy monitoring has resulted in a lack of analytical continuity between surveys, with each surveyor using different data sources and assumptions. Moreover, the difficulty in comparing energy surveys like-for-like is exacerbated by the use of two distinctly different methods for compiling and presenting energy figures, namely the

- **Specific Energy Consumption** (SEC) method - The calculation of total drying energy use per unit mass of product, or per unit mass of moisture removed.

- **Moisture Loss method** - The calculation of total drying energy derived from sectorial production figures and the average drop in moisture content during drying.

Year	Total energy use (PJ)	Energy use for drying (PJ)	Energy use as a proportion of total (%)
1978	1140.94	120.96	10.6
1980	963.04	117.11	12.16
1982	867.99	110.61	12.74
1984	842.46	122.13	14.49
1986	755.01	125.72	16.65
1988	777.79	132.65	17.05
1990	778.98	141.15	18.19

Table 4.3 Summary of drying and total energy use as calculated by Jay [63]

Table 4.4 summarises the key omissions, limitations and survey methods followed by past assessments of energy use for drying.

Survey	Ref.	Survey Method	Key limitations
Hodgett	[57]	Moisture drop	• Some sector/product omissions • Nominal 50 % plant efficiency assumed • No assessment of motive power etc.
Witt	[165]	Moisture drop	• No assessment of plant efficiency
ETSU	[198]	SEC	• Only sectors with annual consumption over 2 PJ assessed
Baker and Reay	[7]	SEC	• Non UK-specific data used • No data collection methodology disclosed
Wilmshurst	[163]	SEC	• Plant efficiency rated uniformly at 35 % • Only sectors with annual consumption over 0.1 PJ assessed
Jay	[63]	SEC	• Exclusion of the timber industry

Table 4.4 Energy use for drying: limitations of previous surveys

Historically, the SEC method of assessment has proved the most popular. The ready availability of national production statistics and total energy consumption figures enables the SEC method to provide a tenable estimate of energy use for drying in the UK. In theory, SEC values afford easy comparison between similar surveys, allowing the researcher to compare industrial processes like-for-like across sectors and between sub-sectors. Unfortunately, past studies based on the SEC methodology have failed to fully disclose the source of data and assumed efficiencies, whilst also ignoring some sectors which consume below 1.0 or 2.0 PJ per annum [63] [198] [163].

The different approaches taken by the moisture loss and SEC methods mean that they remain fundamentally incomparable to each other. Previous attempts at the moisture loss calculation have been passed off as an 'approximate guess' [57] or have estimated a total evaporative load whilst ignoring dryer efficiency and certain industrial sub-sectors [165]. In contrast, the SEC methods appear to have been significantly more rigorous in their surveying; a fact which is arguably displayed in their consistently higher estimation of energy use for drying.

Although past SEC-based surveys appear to have been more rigorous, it is the opinion of the author that the moisture loss method yields the greatest potential for the modelling of DSM measures. Overall, the SEC method followed by Jay, and Baker and Reay, offers the advantage of seamlessly including dryer efficiencies in the final energy figures. However, the ability to model individual efficiencies within a moisture loss based survey provides a more flexible tool for the estimation of potential sector-wide energy savings through the use of DSM and energy services.

It is the author's belief that the works of Hodgett and Witt offer scope for improvement and refinement, thereby providing a more sound comparison between the moisture loss and the previous SEC methods of energy survey. The remainder of this chapter details a new assessment of UK energy consumption for industrial drying processes in 1994: believed by the author to be the first 'moisture loss' based survey for twenty two years. Calculations are based upon the methodology first adopted by Hodgett [57].

<u>A Re-estimation of Energy Consumption for Drying in the UK</u>

Data was collected in five stages,

1. Obtaining recent production figures including the Chemical, Pharmaceutical and Food industries previously omitted by Hodgett.

2. Evaluation of product moisture losses during drying.

3. Division of each product group into sub-groups and evaluation of drying systems currently used within those sectors.

4. Assessment of typical thermal efficiencies for each individual drying system.

5. Calculation of total moisture removed and total drying energy used.

Overall industrial energy figures were sourced from UK, European and OECD data on energy trends and energy consumption [206] [187] [204] [207] [205] [228] [230]. Results were compiled into the eight broad industrial sectors as given in table 4.5.

Industrial sector	Industrial UK Energy Consumption, 1994 (PJ)
Paper and Board	117.5
Ceramics and Building Materials	203.3
Food and Agriculture	163.7
Textiles	58.5
Timber	2.2
Chemicals and Pharmaceuticals	656.9
Other Industry	443.5
Iron and Steel	323.4
Total	**1969**

Table 4.5 Total energy consumption by UK industry, 1994

As with previous surveys, the most energy-intensive sectors are identified as the Iron, Steel, Ceramics and Building Materials and the Chemicals and Pharmaceuticals industries. Overall UK industrial energy consumption was estimated to be 1969 PJ in 1994; 1271 PJ lower than calculated by Hodgett in 1976.

Energy Use for Drying

For this survey, UK industry was divided into 9 sub-sectors comprising of 55 product areas. Product types were selected from previous energy surveys and industrial energy consumption data [63] [163] [198] [7] [165] [57]. With the exception of surface air-knife drying, no significant drying operations were found to operate in the iron and steel sectors [210] [194]. The iron and steel sectors were therefore omitted from the final survey results.

Total industrial production figures for individual product areas were derived from indexes of production, Government agencies and national energy committees [211] [25] [226] [201] [202] [227] [229]. Values for average product moisture losses were formed from previous surveys, trade organisations and literature searches [57] [195].

The assessment of thermal efficiencies for drying is complex. Industrial dryers are often purpose built or modified units derived from standard systems, rendering it impossible to generate a single generic figure for dryer efficiency. The individual performance parameters of each dryer depends on several variables including the material to be dried, dryer configuration, psychrometric conditions and the chosen drying schedule [110]. Subsequently, an accurate energy efficiency figure can only be specific to a dryer which has undergone an energy audit.

Nevertheless, Clegg estimates that 55 % of all applied energy is used for evaporation in dryers [22], whilst Richardson and Jensen indicate typical thermal efficiencies for a variety of direct and indirect dryers as given in table 4.6 [114]. Richardson and Jensen go further, correlating dryer type to dryer application. Calculations within this survey use a combination of average dryer efficiencies from the work of Richardson and Jensen and those derived from Mercer [92], as provided in table 4.7.

		Dryer type	Thermal efficiency (%)	Food and kindred products	Tobacco	Textiles	Timber	Paper and allied products	Chemicals and allied products	Rubber and plastics	Stone, clay, and glass	Electric, gas and sanitary services
DIRECT DRYERS	Batch	Centrifuge	-									
		Fluidised bed	40 - 80									
		Pneumatic	20 - 25									
		Through circulation	-									
		Tray	85	X					X	X		
	Continuous	Centrifuge	-									
		Conveyor	40 - 60	X	X	X		X	X	X	X	X
		Flash	50 - 75	X					X	X		
		Fluidised bed	40 -80	X		X			X	X	X	
		Press	-									
		Rotary	75 - 90	X					X		X	X
		Sheeting	50 -90	X						X		
		Spray	50	X					X	X	X	X
		Through circulation	-	X	X	X			X	X		X
		Tower	20 - 40	X								
		Tray	85	X	X		X		X	X		
		Tunnel	35 - 40	X			X		X	X		
INDIRECT DRYERS	Batch	Agitated pan	90						X			
		Freeze	-	X					X			
		Vacuum rotary	70	X					X			
		Vacuum tray	-	X					X			
	Continuous	Cylinder	90 - 92					X				
		Drum	-	X		X			X	X		
		Rotary	75 - 90	X					X			
		Screw conveyor	-	X					X			
		Vibratory tray	-									
	Misc	Dielectric	60	X		X		X	X			
		Infrared	30 - 60	X		X		X	X			
		Industrial dryer applications										

Table 4.6 Thermal efficiency of dryer types (after [114])

Dryer group and type	Typical SEC (MJ/kg water)	Derived thermal efficiency (%)
Rotary		
Indirect rotary	3.0 – 8.0	31 – 82
Cascading rotary	3.5 – 12.0	21 – 70
Band tray and tunnel		
Cross-circulated tray/oven/band	8.0 – 16.0	15 – 31
Cross-circulated shelf/tunnel	6.0 – 16.0	15 – 41
Through-circulated tray/band	5.0 – 12.0	21 – 49
Vacuum tray/band/plate	3.5 – 8.0	31 - 70
Drum	3.0 – 12.0	21 – 82
Fluidised/spouted bed	3.5 – 8.0	31 – 70
Spray		
Pneumatic conveying/spray	3.5 – 8.0	31 – 70
Two-stage	3.3 – 10.0	41 – 75
Cylinder	3.5 – 10.0	20 – 70
Stentor	5.0 – 12.0	21 – 49

Table 4.7 Dryer efficiencies derived from Mercer [92]

Results

Table 4.8 presents the summarised results of the first 'moisture loss' energy survey in twenty two years. A full set of tabulated results, covering the total 55 product areas, is given in Appendix A. The evaporative latent energy requirement has been assumed to be 2435 kJ/kg of water removed [7].

Industrial Sector	Annual Production (Mt)	Average Moisture Drop (%)	Weight of Water Removed (Mt)	Drying Energy (PJ)	Average Drying Plant Efficiency (%)	Total Drying Energy (PJ)
Paper and Board	9.3	200	18.6	45.9	50.0	91.8
Ceramics and Building Materials	181.4	12	22.2	54.8	69.3	79.0
Food and Agriculture	209.4	11	23.5	57.9	47.1	123.0
Plaster and plasterboard	3.0	20	0.6	1.5	60.0	2.5
Textiles	30.0	30	9.0	22.2	57.3	38.7
Timber	4.6	46	2.1	5.3	55.0	9.6
Chemicals*	13.0	6	0.8	1.9	58.0	3.3
Pharmaceuticals	0.2	3	0.01	0.014	70.0	0.02
Laundry	0.3	50	0.2	0.36	53.0	0.7
					Total	**348.6**

* Limited information on the scope and use of drying processes

Table 4.8 Re-assessment of industrial energy use for drying in the UK.

This survey estimates that 348.6 PJ of energy was consumed by industrial drying processes in 1996, representing 17.7 % of total industrial energy consumption in that year. In agreement with past industrial energy surveys, it is possible to highlight the significant users of energy for drying processes, namely the paper, foodstuffs and building materials sub-sectors.

Both the 'moisture loss' and the SEC methods of energy assessment are difficult to follow with full integrity. As with all previous wide-ranging industrial energy surveys, the accuracy of this new assessment is questionable; with many of the limitations deriving from assumptions that are necessary due to the enormity of such a survey. Furthermore, the model relies heavily on average moisture content values and, more importantly, averaged dryer thermal efficiencies. The former can be criticised for being too general and the latter for being significantly higher than in practice. In an attempt to provide a fair assessment of energy use, thermal efficiencies were taken as averages based on three criteria,

- process volumes in each sub-sector,
- types of dryer used throughout each sub-sector
- typical dryer efficiencies taken from the work of Mercer [92] and Richardson and Jensen [114].

Past surveys have noted significant energy use for drying in the chemicals and allied industries. Unfortunately, the lack of available information about the scope and use of drying processes in these sub-sectors has resulted in spuriously low energy consumption values for drying. Interestingly, Jay [63] noted a similar problem with the chemicals industry, describing the information on drying and manufacturing processes as 'commercially sensitive'.

<u>Summary</u>

It has been made clear that little commonality exists between previous energy audits [63]. However, the requirement for accurate data to support the assessment of DSM and energy services schemes indicates the need for more regular studies of UK energy use. Furthermore, the infrequent nature of energy audits, combined with a falling trend in industrial energy consumption and an increasing trend in energy use for drying, suggest that regular audits will become more important in the future.

The new survey estimates that approximately 350 PJ of energy was used for drying in 1994. Based on the stoichiometric equation for the burning of methane, it can be assumed that 1 kWh of natural gas liberates 0.178 kg of carbon dioxide (see Chapter 7). Excluding the use of electricity, UK drying processes therefore emit an estimated 17.3 Mt CO_2 per year in to the atmosphere. Clearly, any improvement in the operational efficiency of UK industrial drying systems has a direct benefit to the environment. Furthermore, results suggest that the analysis of drying efficiency has an important role in the monitoring, reduction and control of the energy used in drying processes.

Detailed energy studies are useful for identifying potential energy conservation measures at the machine, process, sector and product specific levels [63] [123]. Although industry-wide surveys provide a good indication of energy use across the UK, they provide insufficient detail for use at the product level. To this end, Chapter 8 provides a thorough study of drying energy consumption in the UK sanitaryware industry. Sanitaryware manufacture has been selected because it is,

- an energy-intensive process with significant drying operations.
- regionally concentrated, thereby offering an opportunity to model the effects of demand side management (DSM) and energy services measures on electricity distribution networks.

CHAPTER 5

MODELLING OF DRYING PROCESSES

Introduction

Drying can be defined as,

> 'The removal of moisture from a substance involving the simultaneous transfer of heat to the substance and moisture from the substance, known as a unit operation'.
>
> [51]

Although drying is the oldest unit operation, it still remains one of the least understood and most complex [98]. This complexity is a function of the multifarious variables which apply to each individual drying situation. A material's physical and chemical characteristics, the thermodynamic state of the drying medium and the drying system configuration all impact on the drying mechanisms and drying rates.

This chapter introduces the different areas of modelling which exist for the study of drying processes, including energy use, energy efficiency and drying mechanisms. Basic drying theory is discussed, as is the development of models and simulations to describe convective drying processes. Although drying processes include the removal of volatile solvents, for the purposes of this thesis drying is considered solely as the extraction of water.

Research suggests that the modelling of drying rates and drying coefficients appears frequent in literature. However, the author has found limited published work relating to the modelling of energy use and energy efficiency for drying processes. Moreover, of the work that exists, no information has been found which specifically demonstrates the modelling of drying processes for the application of energy services or demand side management (DSM).

Basic Drying Theory

It was not until the late 19th century that theories relating to drying rates and drying mechanisms were hypothesised. Although it has been stated that drying mechanisms still remain theoretical and incomplete, the advent of increased CPU processing speeds has aided in performing a range of more complex analyses [94].

The modelling of drying mechanisms and systems serves a variety of purposes. It is suggested that accurate modelling will result in improved process control, the most appropriate selection of equipment and the optimal drying regime [63]. Ideally, the real-world application of successful drying models should provide two main benefits:

1. a cost-effective method of reducing energy consumption
2. optimised lead-times and increased productivity.

A comprehensive understanding of the systems which effect drying is an essential pre-requisite for the engineer or production manager aiming to optimise the drying process, however impracticable in its attainment. Nonhebel and Moss acknowledge the ultimate need for explicit and detailed process information but concede that even semi-quantitative prediction of dryer performance from the fundamental physical data available in chemical works is impossible [103]. However, Nonhebel and Moss do suggest four areas to consider when attempting basic drying predictions, namely,

- the nature of heat transfer,
- drying atmosphere conditions,
- the general physical properties of solid-liquid system, and
- properties of the solid.

Across these categories, Nonhebel and Moss note at least 34 parameters which influence the drying process [103]. A literature survey suggests that of these parameters, the following six variables demonstrate the greatest effect on overall drying rate.

- Pressure (humidity) and temperature of the drying gas
- Changes in the partial pressure of the liquid throughout the drying process
- Relative velocity of the drying medium past the drying surface
- The solid's effective surface area
- Agitation of the solid and product supporting method
- Material porosity and hygroscopy.

[103] [125] [108] [74].

The effects of changes in drying variables can be observed from the study of product drying profiles. These profile curves can be used to determine the rate of drying, total drying time and the influence of material characteristics on the drying process.

Drying Rates and Drying Curves

Drying is a combined process, involving the evaporation of a liquid which is held within a solid, followed by the removal of the evaporate from the solid into the bulk flow of the drying air [118]. The drying process itself can be sub-divided into four clearly defined stages or drying rates; the warm-up, constant and first and second falling rates. Table 5.0 indicates drying rates together with their rate-limiting mechanisms.

Period	Drying rate	Rate-limiting mechanism
I	Warm-up	Solid-gas temperature difference
II	Constant rate	Solid-gas temperature difference
III(a)	Falling rate (first)	Internal moisture transport
III(b)	Falling rate (second)	Internal moisture transport

Table 5.0 Drying rates and corresponding rate-limiting mechanisms

Figures 5.0 and 5.1 provide diagrammatic representations of the drying curves for changes in product temperature, moisture loss and evaporation rate over a generalised drying cycle.

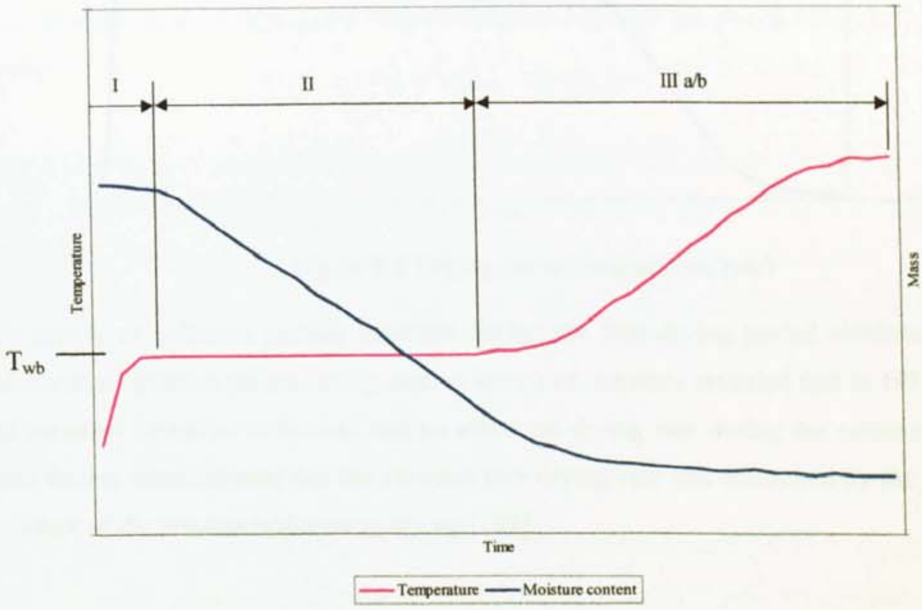


Figure 5.0 Evaporation rate curve

Figure 5.1 indicates that negligible evaporation occurs during the warm-up period (I), which is dominated by transfer of sensible heat from the drying atmosphere to the solid. Warm-up rates are dictated by the size of dryer, type of heating system, the operating temperature and the solid's susceptibility to quality defects resulting from rapid changes in temperature. The warm-up period terminates once the solid's surface temperature approaches the wet-bulb temperature of the drying air and a corresponding increase in evaporation rate occurs.

Assuming that the moisture content is sufficiently high to maintain a wetted solid surface, the drying schedule now enters the constant rate drying period, also known as the first drying period (II). During this period liquid vaporised from the surface of the product is quickly and continually replenished from internal moisture reserves. Evaporation thus commences at a rapid rate, restricted only by the rate at which latent heat can be transferred to the moisture.

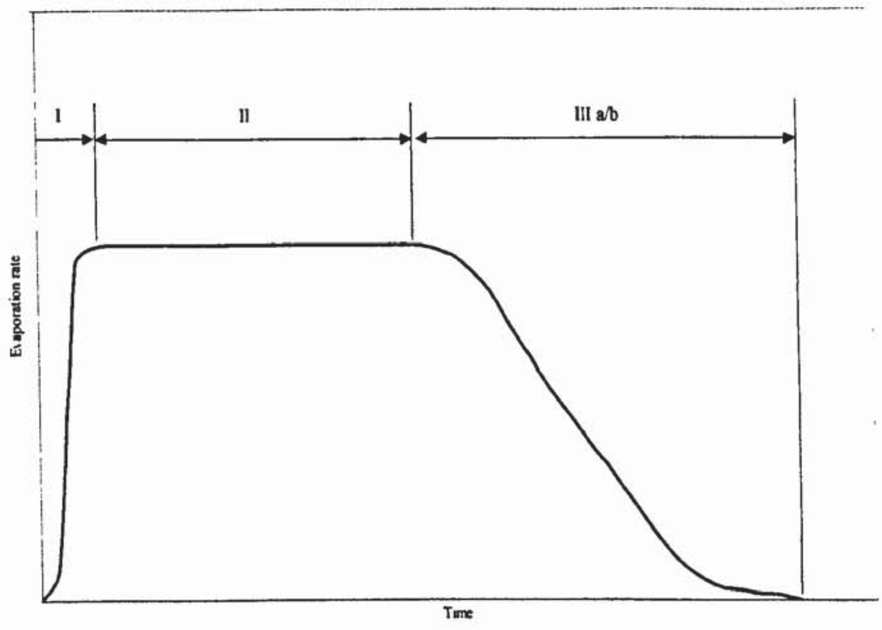


Figure 5.1 Drying curve (evaporation rate)

A ready supply of unbound surface moisture during the first drying period eliminates the influence of internal material variables on the drying rate. A search of literature revealed that in 1933 Sherwood proved internal variables (material variables) had no effect on drying rate during the constant rate period [118]. Nonhebel further demonstrated that the constant rate drying rate was controlled by the rate of heat transfer to the surface of the product undergoing drying [103].

Throughout the constant rate period the solid's surface temperature approximates to the wet-bulb temperature of the drying gas. As indicated in figure 5.1, the drying rate remains constant throughout the period, so long as the thermodynamic state of the drying gas remains constant.

As drying proceeds the moisture content falls and the supply of moisture to the solid's surface becomes discontinuous. Internal moisture levels can no longer maintain a wetted product surface and the drying rate begins to decrease, thus signifying the start of the falling rate drying period (III). The change from constant to falling rate period is characterised by the level of moisture within the solid and is commonly termed the critical moisture content (CMC) or break-point. Research suggests that CMC is not a specific property of a given material, but rather a function of drying rate history, the product's dimensions and temperature, and its internal structure [74].

For most types of material, the falling rate period is an amalgam of two distinctly separate periods; the 'first' and 'second' falling rates. The first falling rate occurs from the end of constant rate drying to a time when the product's surface becomes fully unsaturated and the evaporation front recedes into the interior of the solid; wherein the second falling rate commences. A survey of literature suggests that Sherwood and Lewis first defined the constant and both falling rate periods in 1929 and 1921 respectively [118] [119] [81].

During the first falling period, the drying rate depends on factors effecting both moisture migration to the surface and vapour diffusion into the drying stream. As the evaporation front recedes further into the solid, the drying rate becomes increasingly controlled by the transport of moisture and vapour to the solid's surface. The result is a retardation in drying rate during the second falling period (figure 5.1).

It is important to note that changes between drying periods are seldom as accurately defined as those given in figures 5.0 and 5.1. Furthermore, materials which begin drying at moisture contents below the CMC will exhibit no constant rate drying period. The drying rates are further complicated by the existence of boundary layer effects. Essentially, both heat transfer and the reciprocal mass transfer must occur through a relatively stagnant layer of drying gas which ultimately impedes the drying rate and lengthens the overall drying time.

The total drying time is equal to the sum of the four drying rate periods [108]. To optimise the overall drying time, experts agree that the first objective is to minimise the feed-stock moisture content prior to drying [75] [73]. Subsequently, for those products with a low input moisture content, or high CMC, drying will be dominated by the falling rate periods, thus highlighting material variables as an important factor influencing drying time.

Material Considerations

As alluded to previously, drying mechanisms and rates are highly sensitive to material type [103]. To aide the selection of the appropriate drying mechanisms, materials require classification by structure [2]. Although a number of different classifications for material structure have been found in literature the two most general classifications are found to be

• hygroscopic,		• colloidal
• partially hygroscopic	OR	• capillary-porous bodies
• non-hygroscopic		• colloidal-capillary-porous bodies.

[103] [125] [73] [74],

A more pragmatic approach to materials classification is taken within the chemicals and manufacturing industries, where material is often classified with respect to its feed-form or macro structure. Table 5.1 illustrates the common types of dry solid encountered in industrial drying applications [73].

Perry's extensive experience in the chemicals industries results in a similar classification regime to that given in table 5.1 [108]. As before, classification is made by material feed-form, highlighting the generic product groups as either static, moving, fluidised or dilute.

Material type	Examples	Comments
Crystals	• Inorganic/organic chemicals • Granules	> 1 mm diameter
Porous solids	• Ceramics • Synthetic rubbers	typically hygroscopic in nature
Pastes and sludges	• Foodstuffs • Waste products	
Free flowing powders	• Pigments, stains • Precipitates	< 200 μm diameter
Slurries	• Foodstuffs	
Liquids	• Extracts, emulsions, • straight solutions	

Table 5.1 Classification of materials by feed-form

The non-standard classification and conflicting definitions of material type and moisture retention caused initial difficulties for the analysis of drying processes [2]. A measure for moisture retention was eventually derived using either a 'wet' or 'dry' weight basis. Although the expression of moisture content on a dry weight basis (dwb) proves the most popular for conceptual and mathematical reasons, Baker and Reay suggest that the use of wet weight basis (wwb) is more common in industry [7]. The following equations are used to calculate both definitions of moisture content.

$$\text{M.C.}_{dwb} = \frac{\text{weight of water in product}}{\text{weight of dry matter}} \times 100 \quad [\%]$$

$$\text{M.C.}_{wwb} = \frac{\text{weight of water in product}}{\text{weight of dry matter} + \text{weight of water}} \times 100 \quad [\%]$$

where,

$$\text{M.C.}_{dwb} = \frac{\text{M.C.}_{wwb}}{1 - \text{M.C.}_{wwb}} \qquad \text{M.C.}_{wwb} = \frac{\text{M.C.}_{dwb}}{1 + \text{M.C.}_{dwb}}$$

Figure 6.2 indicates the relationship between moisture content calculated on a wet and dry weight basis. Clearly, for the purposes of dryer design and energy consumption calculations, it is important to agree on a consistent method of describing moisture content. Unless stated otherwise, all work presented in this thesis operates on a dry weight basis.

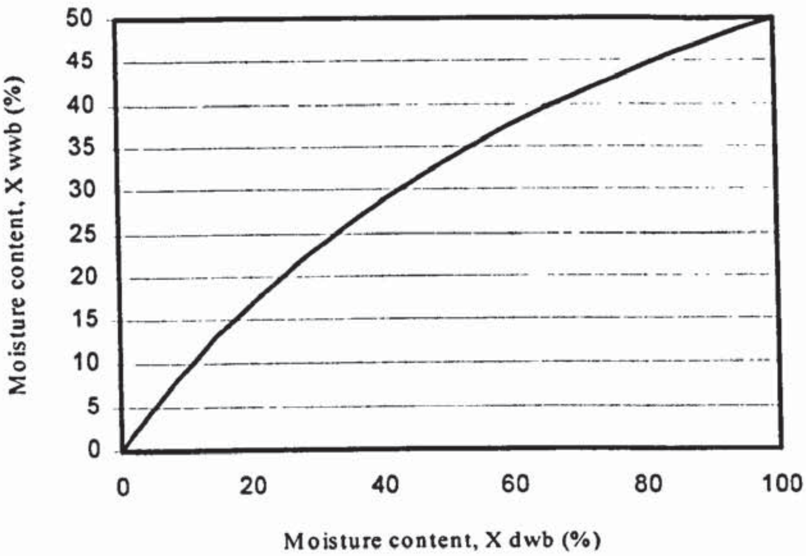


Figure 5.2 Correlation between wet and dry weight basis moisture content

The mechanisms by which moisture is retained within a product determine the length of drying and the ease with which moisture can be extracted [74]. As indicated in table 5.2, moisture retention is facilitated by one or more of four mechanisms: mechanical bonding, chemical bonding, surface moisture and free moisture. Keey suggests that a useful classification of moisture retention follows a scheme derived by Rebinder (1976), which classifies moisture retention mechanisms based on diminishing bond energy [125] [74].

Moisture type	Typical bond energy (J/mol)	Comments
Surface moisture	< 50	• External film resulting from surface tension effects
Unbound or free moisture	< 100	• All moisture in non-hygroscopic solids • Excess moisture above equilibrium moisture content in hygroscopic solids • Exists in the funicular or pendular states
Mechanically bound moisture	> 100	• Capillary bound or absorbed moisture • Movement by diffusion or capillary action • Retained in small pores or cell walls
Chemically bound moisture	3000-5000	• Water of hydration • Chemical absorption

Table 5.2 Types of moisture occurring in solids

Moisture retention plays an important role in drying calculations. When designing a drying system, the engineer is interested in the levels of temperature and humidity required to produce a dry product. To this end the experimental study of changes in moisture content at constant temperatures enables the engineer to derive absorption/desorption isotherms for the process. These isotherms, normally referred to as sorption isotherms, allow for the determination of moisture levels for combinations of temperature and relative humidity [73].

Figure 5.3 presents a generalised sorption isotherm for a hygroscopic porous solid. For any value of relative humidity at a given temperature, it is possible to calculate the equilibrium moisture content for the product.

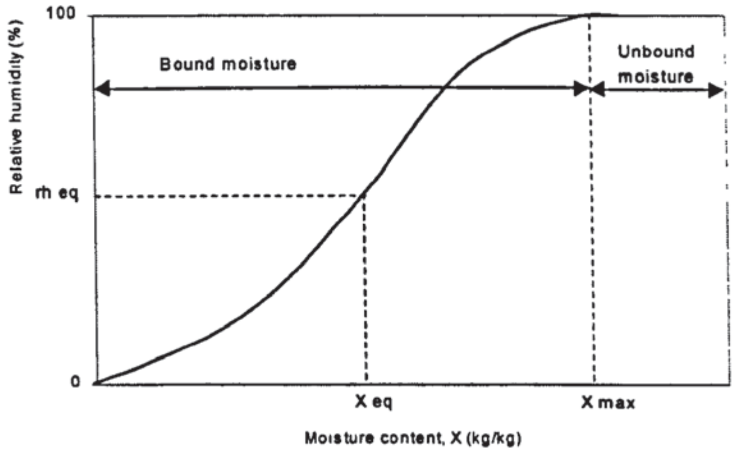


Figure 5.3 Generalised sorption isotherm [125]

Ultimately, the understanding of material variables and drying rates is essential for the classification of the drying mechanisms which occur throughout the drying cycle [3].

The Modelling of Drying Mechanisms

So far this chapter has highlighted drying as a complex, dynamic process involving the simultaneous transfer of heat and mass components. From Sherwood's and Lewis' pioneering work at the start of the century to present-day studies, researchers have postulated mechanisms which attempt to describe the heat and mass components in terms of their physical, thermodynamic and chemical behaviour.

Heat Transfer Theory

To dry a material, heat needs to be supplied to both the solid and liquid phases; the liquid phase subsequently evaporating to leave the dry solid. The transfer of heat energy during drying occurs by one of four mechanisms: convection, conduction, thermal radiation or volumetric electromagnetic heating. Although a combination of mechanisms can exist at any stage during drying, the predominating mechanisms are usually convective or conductive transfer [103]. The work in this thesis concerns itself solely with convective heat transfer.

Convective heat transfer is divided into two mechanisms:

1. heat supplied to the material's surface (external forces)
2. heat transfer from the material's surface to its interior (internal forces).

In the case of commercial dryers external forces are usually facilitated by low pressure fans or distribution cone/fan arrangements providing 'forced' convective heat transfer. Internal forces within a partially dried body are usually due to temperature difference alone, commonly termed 'free' convective heat transfer [74]. The following equation describes generalised external heat transfer to a body during the constant rate drying period [108].

$$\frac{dq}{dt} = h_t A \, \Delta T$$

q	Heat energy [kJ]	T	Temperature [K]
h_t	'Total' heat transfer coefficient [W/m^2 K]	t	Time [s]
A	Solid area [m^2]		

Analysis of this equation indicates that heat transfer rates are dependent on three variables,

- the heat transfer coefficient,
- solid surface area, and
- temperature difference between solid and drying gas.

Assuming that the heat transfer coefficient is at steady state during constant rate drying, and the product surface area remains unchanged, the principal driving mechanism then becomes the solid-gas temperature difference. During the falling rate periods, analysis of heat transfer becomes increasingly redundant as mass transfer and transport mechanisms begin to dictate the overall drying rate.

Moisture Transfer and Transport Theory

The mechanisms which control moisture migration from the solid's internal structure to the bulk flow of the drying gas are mathematically complex. This section provides a brief description of these mechanisms with limited recourse to involved analytical equations. Readers interested in gaining a greater understanding of the mechanisms pertaining to mass transport during drying are urged to reference the following texts [108] [125] [103].

The four classical moisture migration theories discovered in literature are,

- liquid diffusion
- capillary action (liquid phase)
- evaporation - condensation theory (vapour phase)
- moving boundary theory.

Additional mass transfer mechanisms have also been found, as indicated in table 6.3.

Vapour phase transport	Liquid phase transport
Mutual Diffusion	Surface Diffusion
Knudsen Diffusion	Hydrodynamic Flow
Effusion	
Slip Flow	
Hydrodynamic Flow Stefan Diffusion Poiseuille Flow	

Table 5.3 Mass transfer mechanisms [158]

Irreversible thermodynamics approaches to both heat and mass transfer have also been identified [82].

Liquid Diffusion

Lewis and Sherwood suggest that the principal mass transfer mechanism during drying is through the movement of moisture by liquid diffusion [81] [118] [119]. One-dimensional liquid diffusion can be expressed by Fick's second law during the falling rate period,

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2}$$

C	Moisture concentration	D	Coefficient of diffusion [m^2/s]
t	Time [s]	x	Material depth in direction of diffusion [m]

Crank provides solutions to Fick's second law for diffusion is provided for a variety of boundary conditions [30].

Hougen et al. criticise liquid diffusion as being non-specific in its application and suggest that previous work had incorrectly assumed the diffusion coefficient, D, to be constant or linear with respect to temperature [59]. Moreover, it is suggested that incorrect predictions and misinterpretation of empirical observations can result if liquid diffusion theory is applied for liquid and vapour movement. Almubarak, however, states that Fick's second law cannot be excluded entirely [2]. It is suggested that the limitations in liquid diffusion lie in assuming that it is the only mechanism to apply during drying.

It is suggested by Zogzas and Maroulis [172] that Kamei and Shiomi (1937) proved diffusion coefficients display a variance with temperature in an Arrehenius type relationship.

Capillary Theory

Buckingham (1907) is espoused as having formed the fundamentals of capillary theory. Capillary flow is described as having a driving force derived from 'capillary potential' within the solid. The capillary potential is quantified as the pressure difference between the water and air occurring at the air-water interfaces. Figure 5.4 illustrates the effect of capillary action.

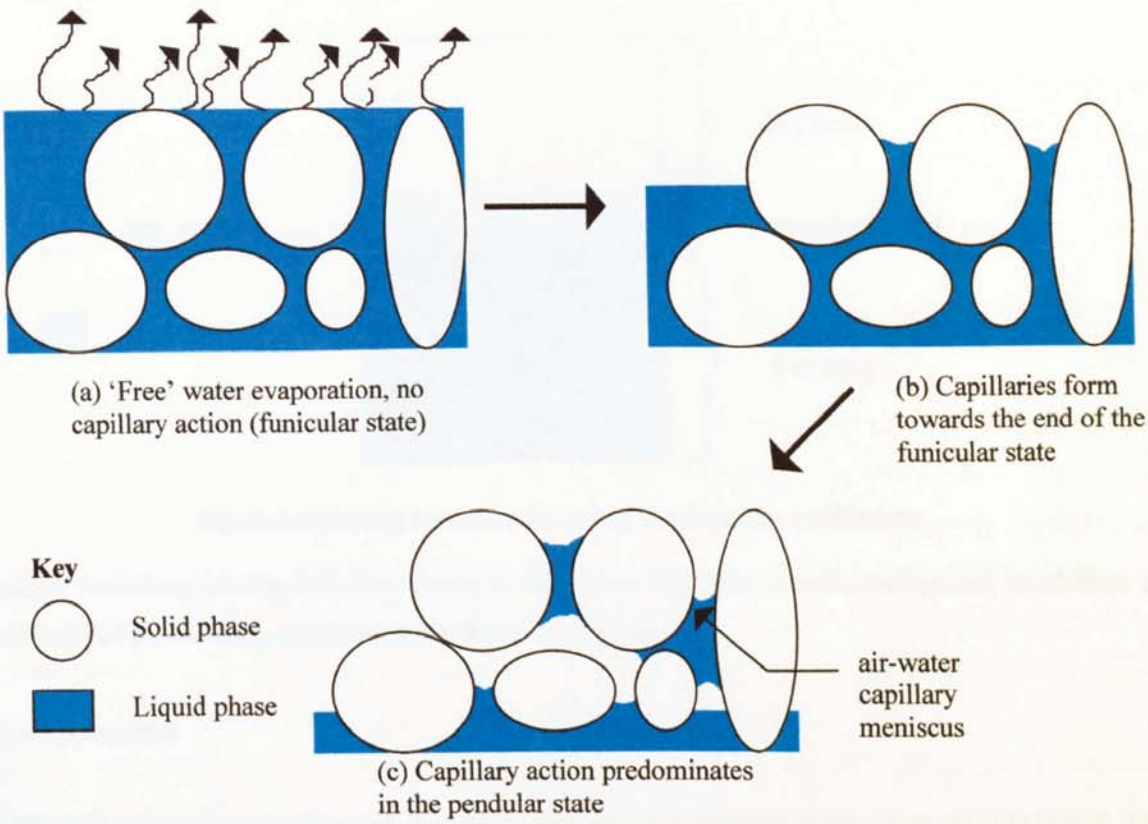


Figure 5.4 Schematic of porous solid containing interconnecting pores and channels.

Capillary action has been reported in partially saturated porous media [18]. Fully saturated media is dominated by evaporation of 'free' water (Figure 5.4a) which is dependent on the temperature of the drying gas. Figure 5.4b signifies the end of constant rate drying and the preliminary formation of capillaries, whilst figure 5.4c indicates the development of capillaries in partially saturated solid. The moisture migration now becomes dictated by capillary potential. Ceaglsk and Kiesling (1940), and Hougen et al. (1940) demonstrated the existence of a capillary mechanism, rather than liquid diffusion, for the drying of granular solids [18] [59].

Evaporation-Condensation Theory

Evaporation-condensation theory assumes moisture migration takes place solely in the gaseous phase. Water evaporates from the hotter side of a pore and condenses on the cold side, thus transferring its latent heat of evaporation. Little information has been found to describe this mechanism. Furthermore, no valid physical meaning can be derived from the implementation of evaporation-condensation mechanisms as limitations exist with such a method [2].

Moving Boundary (Receding Front) Theory

Moving boundary theory is a relatively recent concept, having only been inferred by Luikov in 1966 [83]. Essentially the evaporation plane moves towards the centre of the product as the falling rate progresses. The solid body is thus divided into a gradually increasing dry zone and a gradually decreasing wet zone. Figure 5.6 presents a diagrammatic representation of receding front theory.

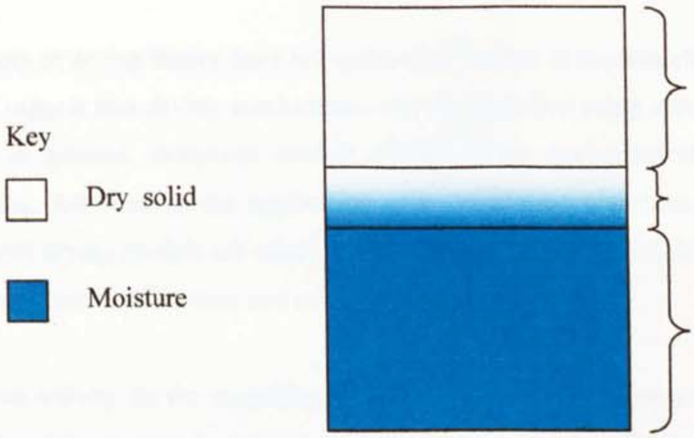


Figure 5.6 Moving boundary (receding front) drying mechanism

Literature describing moving boundary theory is infrequent due to its recent development, in addition to the majority of papers being published in the Russian language.

Other Approaches

In 1977 Whitaker presented a thorough analysis for the drying of granular porous material [159] [160]. The theory attempted to solve momentum, heat and mass transfer equations at the microscopic level, followed by the application of a 'volume average' method to obtain the macroscopic equations. A survey of literature indicates that a significant number of recent modelling work has been based on the theories of Whitaker [61] [96] [97].

An alternative mechanism has been presented by Nonhebel and Moss who present a rigorous analysis of heat and mass transfer with the assumption that heat transfer is by convection only [103]. A dynamic equilibrium is assumed to exist at any instant during the drying process. The resulting equation serves to present a complete heat and mass transfer equilibrium in terms of temperature, partial pressures and humidity driving forces.

$$\frac{dW}{d\theta} = \frac{h_c A(T_g - T_s)}{\lambda} = K_p A(p_s - p_v) = K_H A(H_{ss} - H_g)$$

W	weight of dry solid in dryer [kg]	λ	latent heat of evaporation at surface [kJ/kg]
θ	average residence time [s]	K_p, K_h	drying coefficients [kg/s m^2 MPa] [kg/s m^2]
h_c	heat-transfer coefficient by convection [W/m^2 K]	H_{ss}	saturation humidity of drying gas
A	area of drying surface [m^2]	H_g	humidity of drying gas [kg/kg]
T_g	temperature of drying gas [K]	T_p	temperature of drying surface [K]

Driving forces are further analysed by Nonhebel and Moss, thereby isolating rate equations for the constant and falling rate periods.

Modelling of Mechanisms: Recent Developments

Advances in drying theory have led to increased effort in the modelling of drying processes. Strumillo and Kudra suggest that drying mechanisms can be modelled using either experimental or analytical methods [125]. In general, analytical models are based on mathematical descriptions of the relevant drying processes, followed by the application of a calculation algorithm. A survey of literature suggests that analytical drying models are often non-linear partial differential equations, thereby reflecting the complex non-linear nature of the heat and mass transfer mechanisms.

Research activity for the modelling of drying mechanisms on the macro and micro scale has expanded as a function of the increased computer processing power now available [94]. A number of review articles have been found relating to the application of drying models. Waananen et al. have attempted to classify models for the drying of porous solids [158], whilst Moyne and Perre published a paper summarising the development of modelling for drying mechanisms between 1981 and 1991 [96]. Keey, Almubarak, and Strumillo and Kudra all provide detailed summaries of the development of drying modelling [2] [74] [125].

Spiga and Spiga attempt to present a rigorous solution to heat transfer in two phase porous media and packed beds [122]. The aim of the study is to analyse the dynamic response of a porous media to time varying gas inlet temperatures. The analytical solution is claimed as successful. However, it is noted that no reference is made to practical model considerations such as the method of heat application.

Maroulis et al. proposed an 'externally controlled' drying model using heat and mass transfer coefficients as model parameters [89]. Experimental data was mathematically regressed onto the model to arrive at estimated drying coefficients, which were assigned 'levels of confidence'. Results indicate that the heat and mass transfer coefficients can be estimated, although the heat transfer coefficient cannot be derived.

Zogzas and Maroulis dictate that moisture diffusivity is the most important parameter in the application of drying calculations [172]. Four alternative models on the drying data of three foodstuffs - potato, carrot and apple - are used. Two detailed models and two simple models were derived using varying boundary conditions and assumptions. It is concluded that both the detailed and simple models which assumed constant moisture diffusivity failed in their prediction, whilst those which assumed a temperature based Arrhenius type relationship were deemed satisfactory.

Van der Zanden et al. derived a hydrodynamic model for the prediction of isothermal moisture transport through a partially saturated clay [156]. The diffusion equation used is based on Darcy's Law with the diffusion coefficient as a function of porosity, permeability and pore size distribution. Although transport appears to obey the diffusion equation when compared to experimentally observed values, van der Zanden et al. admit that refinement of the model is required to provide conclusive proof.

Area of Study	Drying discipline	Material	Reference
Generalised equation for the temperature curve	convective drying	moist materials	[78]
Modelling kinetics of moisture content, pressure and temperature	convective drying	gypsum	[84]
Modelling boundary and inertia effects	convective mass transfer	porous media (Foametal)	[155]
Modelling liquid transport	convective drying	macroporous materials	[31]
Modelling relative permeability relations	convective drying	sapwood of pine	[28]
Investigated transport-based models	convective drying	Wood, timber	[147].
Method for calculation of concentration dependence of diffusion coefficient	convective drying	porous media	[116]

Table 5.4 Modelling of drying processes: further examples

Moyne and Perre used Whitaker's three equation model to simulate the heat and mass transfer in a rigid homogeneous porous media [96] [159] [160]. It is assumed that the drying gas exists as a mixture of two phases (water vapour and air), the medium is in thermodynamic equilibrium and the vapour pressure is also given by an equilibrium value. A second paper by Moyne and Perre [97] solved the previously derived model for heat and mass transfers in saturated and unsaturated porous media. It is concluded that, although a satisfactory simulation has been conducted, further model verification is required.

Other examples of drying models have been found in literature. Table 5.4 summarises the area of study, the type of drying and material under investigation.

<u>Modelling of Drying: Difficulties and Limitations</u>

Despite decades of research into modelling, drying remains ill-understood in terms of its exact driving mechanisms [118]. The gradual refinement and improvement of models has helped increased understanding, yet those models which exist remain complex. In many cases essential modelling data is either unavailable, outdated or cannot be predicted [63] [103]. Moreover, reference to past studies indicates that some drying models have not been validated, verified or considered against practical considerations, such as methods of heating.

Although individual mechanisms for mass transfer have been described, more than one mechanism will often contribute to total moisture transport at any given time. Moreover, the contribution of each mechanism may change over the drying cycle [14]. A representative model of drying therefore involves the difficult task of accurately identifying all possible contributing mechanisms [158].

Mathematical drying models can only be derived once a series of relevant mechanisms have been established. It has already been highlighted that analytical drying models take the form of non-linear partial differential equations. Often these equations incorporate variable coefficients, parameters and dimensionless equations which can only be found by numerous time-consuming experimental studies. Solid phase and evaporation coefficients have been highlighted as particularly difficult to derive accurately [74] [63]. Furthermore, the modelling process often presents equations which are difficult to solve, requiring the use of complicated finite element analysis and numerical methods [63] [74] [93] [19].

To allow for a more tractable solution of drying equations, simplifications and assumptions are frequently introduced into drying models [63]. The following assumptions have been found to occur frequently in drying literature,

- Constant air velocity
- No product shrinkage
- Vapour pressure remains in equilibrium
- Constant boundary conditions
- Constant moisture diffusivity
- Constant vapour diffusivity.

Clearly, the greater the number of assumptions made, the more abstract the model becomes from describing general drying and the more the model describes only the situation from which it was derived. Indeed, as drying technology advances and the heat transfer efficiency of dryers improves, a greater dependence is placed upon what is essentially an unpredictable material dependent mass transfer rate. The practical effects are two-fold.

- a material's drying rate can only be determined empirically and cannot be predicted
- experiments must be related to the type of dryer proposed for use.

[103]

Until general and robust drying models become accessible, it can be argued that drying will remain an art rather than a science [63]. The prediction of drying rates, temperature profiles and moisture distributions from analytical 'first-principles' studies currently prove excessively time-consuming and costly for practical industrial application. Ultimately, experimental drying trials are needed to establish accurate and practical drying performance.

Modelling of Energy Use for Drying and DSM

The modelling of drying rates and drying coefficients appears frequently in literature. However the author has found limited published work relating to the modelling of energy use and energy efficiency for drying processes. Moreover, of the work that exists, no information has been found which specifically demonstrates the modelling of drying processes for the application of energy services.

Analysing energy use for drying is complicated. The author suggests that generalised modelling is rare for a number of reasons, including

- the different energy sources available (steam, gas, oil, electroheat),

- the operation of different dryer types (direct, indirect, spray, chamber etc.),
- the number of dryer configurations (dryer size, burner type, motive devices).

On a production basis, it is difficult to model SEC values because dryer output does not often produce objects for which sales or production figures exist [58]. Moreover, drying is not the primary energy consumer in most sectors. As such the need to model energy consumption is low.

Holmes et al. suggest that the diversity of products and the general nature of drying makes it difficult to generalise the types and amounts of energy consumed for industrial drying [58]. It is concluded that exact product specifications have a great influence on the selection of the energy source.

New Modelling Techniques

A need exists for the development of a fast and reliable method of modelling drying processes based on empirical data. Furthermore, the modelling technique developed must be readily adaptable for use as part of an energy services tool. Data should be assimilated rapidly and the model should be open to cost effective up-dating with relevant modelling data.

A search of literature highlights the recent application of Artificial Intelligence techniques, specifically Artificial Neural Networks, for the modelling of drying behaviour. The neural network systems investigated require no formal mathematical modelling or irreversible thermodynamic equations. Models have been derived and instructed purely from empirical data.

Neural Networks

The first neural networks were devised in the mid 1950s, although the practical use of neural networks did not begin until 1980 [161]. Over the past 20 years, artificial neural networks (ANNs), or 'neural nets' (NNs), have evolved into a powerful computational paradigm [70].

Neural networks were developed from the study of information processing in the biological nervous system [63] [146]. Indeed, ANNs were designed as a very simplistic representation of the brain's functionality [162].

Essentially, neural nets are constructed from a large number of simple interconnected processing neurons [16]. Several interconnection structures have been developed with the neuron as the base [146]. Morris suggests that over 50 different network architectures can be found in literature [95]. Figure 5.7 illustrates a simple neuron with input, output and weighting components.

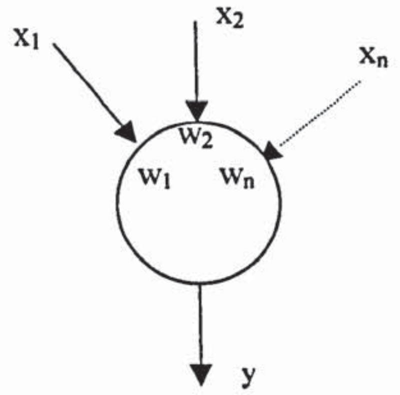


Figure 5.7 Neuron (after Sutton [146])

Each neuron input, x_n, is modified by a weighting, w_n. Weighted inputs are then combined to form a single output, y. For practical networks the output is fanned to the inputs of other neurons held within the next layer. The resulting network can be divided into input layers, hidden layers and output layers. The number of neurons and layers depends upon the complexity of the system being modelled.

Mapping of model inputs to output is achieved through training, which involves the successive presentation of input-output data pairs to the network. Data are scaled prior to input and then propagated forward through the network, where the internal weights are adjusted to minimise the square of input-output error [162] [146]. The author believes that detailed mathematical analysis of training techniques is beyond the remit of this thesis.

The current use of neural networks is extensive, including applications in process control, predictive maintenance, signal processing, quality control, scheduling, image processing, diagnostics, design modelling and analysis [146]. A search of literature highlighted several references for the artificial neural network modelling of drying.

Neural Networks for Drying

The overriding barriers to the widespread use of complex mathematical drying models are cost and the need for expert knowledge. Neural nets have a proven ability to derive accurate models of highly non-linear processes by learning from experimental behaviour.

The benefits of using neural networks for the modelling of drying processes include,

- general learning capability
- avoidance of first-principles models
- reduced development costs
- reduced development time
- potential for adaptive solutions

[16]

Four texts have been found which attempt to model drying processes using neural nets. Table 5.5 summarises modelling goals and the drying regimes studied.

Elo et al. used NNs to analyse the relationship between quality properties of paper and drying conditions, namely heat transfer, pressure difference and drying time [39]. A perception network was used with one hidden layer. Heat transfer and pressure difference were found to exhibit the most significant effects on paper quality.

Material	Dryer type	Modelling objective	Year	Ref.
Paper	Impingement	Material quality	1993	[39]
Poplar planks	Convective air	Global optimisation	1997	[60]
Gypsum coving	Convective air	Drying curves	1996	[63]
Sliced potato, peas, silica gel	Convective air	Drying conditions, quality degradation	1998	[71]

Table 5.5 Neural network modelling of drying systems

Hugget et al. used a combined neural net and generic algorithm to globally optimise a dryer [60], whilst Kaminski and Tomczak examined the use of an integrated NN for the modelling of drying and product degradation [71]. Kaminski and Tomczak suggested that NNs described the drying process "fairly well", but results were not optimal because of complex calculations and the cost of experiments.

Jay successfully used a neural network model for the prediction of drying curves for processing gypsum coving [64] [65]. Modelling data were derived from STA analysis of the coving and empirical measurement of sample temperature and weight in a pilot convective air dryer. One third of the experimental data was used to train the neural net, with the remaining two thirds used for model verification.

Jay also recognises other publications describing the use of NN modelling for drying processes; including the work of Huang and Mujumdar (1993), and Jinescu and Laveric (1994). The University of Lodz, Poland, and the University Politechnia of Bucharest are also highlighted as active in the area of NN modelling for drying processes [63].

Neural Network Limitations

It is important to note that limitations to neural networks exist. These include,

- a continuing risk of overfitting data, thus highlighting unwanted trends within data sets
- a substantial degree of specialised knowledge is required for neural network engineering and programming.
- neural systems are not particularly intuitive from the perspective of the end-user

- good performance is highly dependent upon the interconnection model used and how well it models the problem [146].

Neural nets require specialised programming knowledge and the resultant modelling capabilities are often highly dependent on the network scheme selected. Moreover, when used as part of an energy services tool, an inability to view the modelling process may result in a lack of user confidence by the customer.

A survey of literature highlights an alternative, yet complimentary modelling regime to neural networks. In comparison to neural nets, literature suggests that fuzzy logic proves more adept at modelling systems in which input data is less clearly defined, typically in terms of linguistic variables or approximate numeric data. Furthermore, the modelling process is clearly visible to the end-user. The following section briefly discusses fuzzy logic and its application to the modelling of drying.

Fuzzy Logic and Fuzzy Inference Systems

The concept of fuzzy sets and fuzzy logic operations derives from a seminal paper by Zadeh in 1965 [171]. Zadeh suggested that objects and data within the real physical world do not have precisely defined membership criteria, but are members of fuzzy sets. Essentially, fuzzy sets are a 'class' with a continuum of grades of membership. A fuzzy set can be defined as,

> '.... a membership function mapping the elements of a domain, space, or universe of discourse X to the unit interval [0 1]'
>
> [171]

or mathematically as,

$$A(x)=\begin{cases}1, & \text{if } x\in A\\ 0, & \text{if } x\notin A\end{cases}$$

The development of fuzzy logic was driven by a need for "a conceptual framework which can address the issues of uncertainty and lexical imprecision" [168]. Zadeh suggests that fuzzy logic can be viewed as an extension of classical Aristotelian logic, but is more effective at reasoning with approximate than exact data. Essential characteristics of fuzzy logic include,

- exact reasoning is viewed as a limiting case of approximate reasoning
- everything is a matter of degree
- all logical systems can be fuzzified
- knowledge is interpreted as a collection of elastic fuzzy constraints.

[77] [168] [88]

The author believes that a full account of fuzzy mathematics and philosophy is beyond the scope of this thesis. For further information, the reader is directed to the following texts [107] [77] [49] [168] [87] [37] [88] [169] [170] [171].

Fuzzy Inference and Modelling

A fuzzy model is essentially a black box in which input data is mapped to output data. Fuzzy inference is simply the process of mapping using fuzzy logic, or classifying objects which are separated by unclear boundaries in which membership is not 'black and white', but a matter of degree. Fuzzy systems have gained increasing popularity in engineering over the past few decades, finding a large variety of applications in control theory, pattern recognition, power systems and expert prediction systems [115] .

Before discussing the inference process, the author believes that a brief explanation of membership functions, fuzzy operators and fuzzy rules is necessary.

A membership function (MF) is a curve which defines how the input space maps to membership values between 0 and 1. MFs are assigned to all inputs and outputs, and the chosen MF should reflect the appropriate relationship. Curve types typically include step functions, bell curves, gaussian curves, triangular and sigmoidal functions.

Fuzzy logic operators are a superset of standard boolean logic [115]. As with classic logic, the relationship between inputs can be defined as AND, OR and NOT operations. Under fuzzy operation, these logical operators translate to the respective 'min', 'max' and 'additive complement' of the membership functions for a given input. Fuzzy rules use conditional statements to link inputs to outputs. Statements are typically in the form IF-THEN.

Figure 5.8 gives a diagrammatic representation of the inference process.

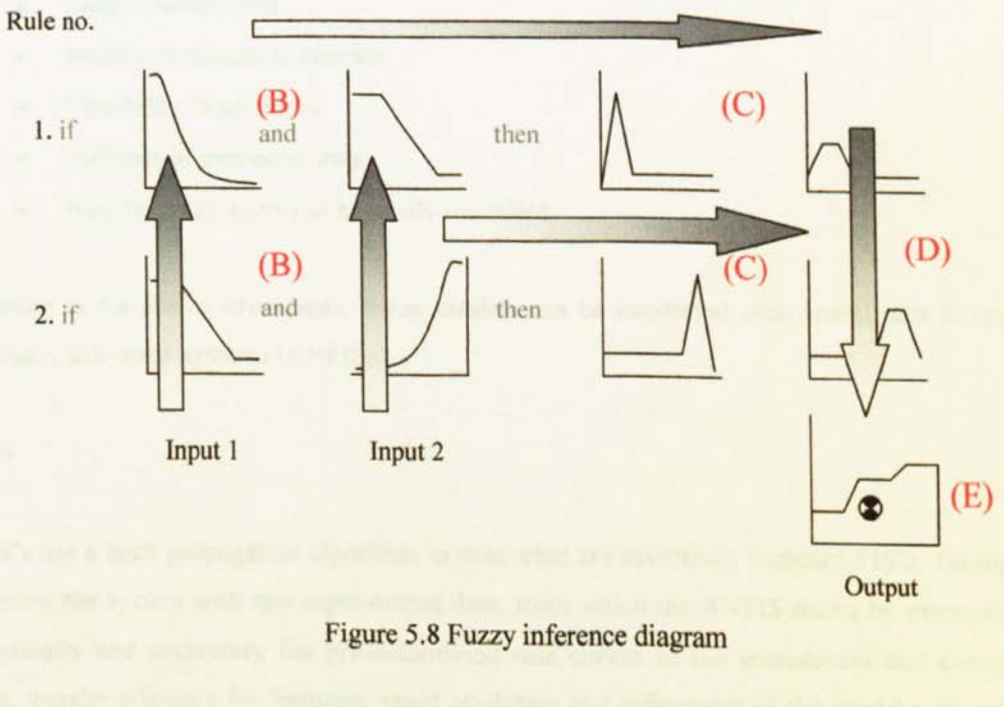


Figure 5.8 Fuzzy inference diagram

The fuzzy inference process can be divided into 5 clearly defined stages:

1. Fuzzification of inputs
2. Application of fuzzy operators
3. Application of implication method
4. Aggregation of all outputs
5. Defuzzification of outputs.

Raw inputs (antecedents) are always precise numerical values within the universe of discourse; the fuzzy input is its degree of membership of the antecedent. For most practical situations, fuzzification of the input simply requires allocation of an MF and the corresponding function evaluation [115]. Operators are introduced if two or more inputs exist within a single rule (B). All antecedents are operated on and a single truth value is passed to the output function.

Implication occurs for each fuzzy rule. The implication process takes the truth values from the antecedents and defines the output set (consequent) as given by the output membership function (C). After implication, the individual rule sets are added together in the aggregation stage (D) ready for defuzzification.

Defuzzification takes the fuzzy output set and evaluates it to leave a single output number (E). The most popular defuzzification method is centroid calculation which returns the weighted centre point of the area given by the fuzzy output curve.

The overall calculation time for fuzzy inference is negligible. Other benefits to fuzzy systems include,

- Cheap and fast construction
- Easy to understand
- Intuitively simple to operate
- Flexibility in up-dating
- Tolerant of imprecise data
- Non-linear systems can be easily modelled.

In addition to the above advantages, fuzzy models can be combined with neural nets to create adaptive neuro fuzzy inference systems (ANFISs).

ANFIS

ANFIS's use a back propagation algorithm to tune what are essentially standard FIS's. Tuning is achieved by training the system with raw input-output data, from which the ANFIS learns by example. The system automatically and accurately fits pre-determined rule curves to the antecedents and consequent of the system, thereby allowing for frequent, rapid up-dating and refinement of the model with newly acquired data.

Fuzzy Systems and Drying

Only limited applications of fuzzy logic to drying systems have been found in literature. Kosko indicates that one electronics manufacturer, Hitachi Corporation Japan, have used a fuzzy system for the control of domestic dryers [77]. On an academic level, Baker and Lababidi have used a fuzzy system as a base for an expert dryer selection system [6].

No references have been found which detail the use of fuzzy systems for the prediction of drying characteristics and drying conditions. Furthermore, no literature was uncovered which uses FL within an energy services model.

Empirical modelling data from drying trials contains inherent approximations and errors, and therefore cannot be classified as 'exact'. The author suggests that fuzzy logic and, more specifically, adaptive neuro fuzzy inference systems offer significant opportunity for the modelling of drying characteristics. A suitable ANFIS should demonstrate the combined advantages of both fuzzy logic and neural nets, namely rapid, cost-effective and intuitive construction with accurate modelling capabilities.

Chapter 6 attempts to model 3 drying technologies using ANFIS. To the best of the author's knowledge this is the first documented use of FISs for the modelling of drying behaviour.

CHAPTER 6

FUZZY LOGIC MODELLING OF DRYING PROCESSES

Introduction

The set objectives for drying models are numerous, yet research suggests that very few models are derived for the sole purpose of assessing energy consumption or energy efficiency. Moreover, a thorough search of literature reveals no previous attempts to model drying processes for the purposes of energy services or DSM schemes.

Development of models to describe the drying of different materials have been the topic of research in many fields for several decades [164]. Chapter 5 indicated that past predictions of drying rates and overall drying times have been achieved using a variety of methods, including the use of irreversible thermodynamics, the numerical solution of non-linear drying equations and the use of neural networks.

The author has identified a potential application for the use of a fuzzy inference system (FIS) as a tool to predict drying rates and, hence, drying times. This chapter describes the use of empirical data to construct a fuzzy model for the assessment of three drying technologies, namely standard air drying, airless drying and heat pump dehumidification drying.

It is the author's belief that the work presented in this chapter is the first to investigate the modelling of drying rates and drying times using a fuzzy logic inference system. Furthermore, a survey of literature suggests that this work is the first to give a direct three-way comparison between standard convective air drying, heat pump drying and the novel airless drying technology in the context of an investigation into energy services and DSM.

Material Selection: Electro-porcelain Insulators

Before introducing the fuzzy logic modelling of drying rates, the choice of clay ceramic as the test material is discussed.

Clay ceramic has been selected for a number of reasons,

- Ceramic products often require lengthy drying times. A potential therefore exists for substantially reduced lead times resulting from the application of the airless drying technology.

- The drying of ceramics and building materials in the UK is an energy-intensive industry, consuming an estimated 79 PJ annually, or 23 % of all drying energy [48]. The application of energy efficient drying techniques therefore offers potential for lower energy consumption and the possibility of reduced carbon dioxide emissions.

- Ninety per cent of all UK ceramics manufacture is regionally concentrated in the Stoke-on-Trent area. The potential therefore exists to target DSM and energy services between similar industrial sub-sectors on the same electricity distribution networks.

On a product level, electro-porcelain insulators have been chosen over other types of ceramic ware for the following reasons,

- Electrical insulators require some of the longest drying times of any ceramic product, typically in excess of 14 days. The potential benefits of using the rapid, energy efficient airless drying technology could be considerable.

- Insulator ceramic is formed using extrusion technology. The output material is in a physically homogeneous and manageable form allowing for reproducibility of drying trials.

Electrical Insulation Ceramics

Electrical ceramics are a sub-set of the fine porcelain sector and, by definition, cover the class of products designed for the insulation of electrical current. Depending upon end-use, electrical porcelains are typically divided into high- and low-voltage designs. General applications include overhead power distribution, electrical machinery and telecommunication transmission networks [100].

Production Cycle (Ribbed Insulators)

Electrical ceramics are produced from either a plastic mixture or by slip casting techniques. Plastic forming is generally preferred for its speed and associated lower labour costs [15].

Once the raw materials have been blunged into a uniform homogeneous mixture, the clay is de-aired using a vacuum pug and then extruded to the required diameter billet. Suitable billets are then turned on vertical lathes from where they are passed to the ageing, dressing and drying processes. After drying the shapes are cleaned, glazed and fired to give a final saleable product. The case study presented at the end of chapter 6 provides a more detailed analysis of the current drying practice for electro-porcelain.

Six billets of raw material were provided for experimental testing purposes. Each billet measured approximately 380 mm height, 152 mm diameter with an average mass of 10 kg. Figure 6.0 illustrates a section of raw clay billet and figure 6.1 provides an example of a finished product.

Figure 6.0 Extruded clay billet

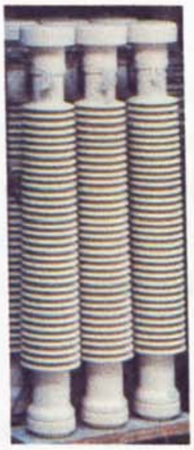


Figure 6.1 Finished ribbed insulator [179]

Modelling Objectives

The objectives of this modelling exercise were three-fold,

1. to derive accurate drying times and drying rates from empirical drying data
2. to demonstrate fuzzy systems as a robust, reliable method of predicting drying rate
3. to use the resulting fuzzy system as a key process in the development of an energy services tool.

In providing a framework for the fuzzification of data, it is necessary to define a number of boundary conditions, including

- modelling objectives
- number of model antecedents and consequents
- input range of the antecedents
- type of fuzzy inference system used (Mamdani or Sugeno)
- number and type of membership functions (MF)
- experimental constants/controls.

As highlighted during the remainder of chapter 6, a number of the above boundary conditions are dictated by the software package used for this work.

Drying Variables (Antecedents) and Model Outputs (Consequents)

Input data for experimental drying investigations can be divided into three categories. Data is either,

(i) measurable and controllable
(ii) measurable and uncontrollable
(iii) immeasurable and uncontrollable. [125]

To provide a realistic and practical model for the prediction of drying rates, it is necessary to use input variables which are both measurable and readily controllable in an industrial situation. Previous drying models found in literature have used a variety of input variables, including gas temperature, humidity, gas velocity and other material characteristics [63] [117]. Nonetheless, contact with the UK's sanitaryware industry indicates that air temperature and relative humidity are the fundamental control variables when drying ceramic ware.

As such, a two input model is assumed for convective air and heat pump drying: the inputs are defined as 'air temperature' and 'relative humidity'. For airless drying, the fundamental control variable is the degree of steam superheat [50]. A one input model is therefore assumed for airless drying. Figure 6.2 and figure 6.3 provide simple 'black box' block representations of both model schemes.

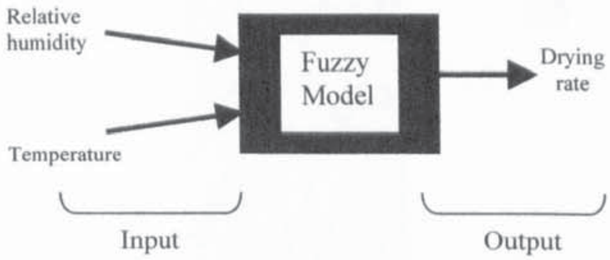


Figure 6.2 Block representation of fuzzy drying model for convective air drying and heat pump drying

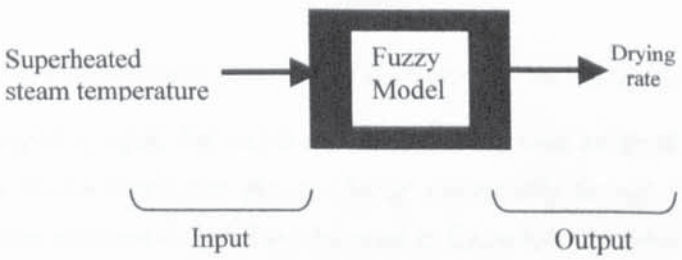


Figure 6.3 Block representation of fuzzy drying model for airless drying

All three models output 'overall drying rate', defined as the rate of mass loss per unit area of material ($g/m^2/s$). Previous studies have taken drying rate independently of product surface area [63]. Although these studies remain valid, the inclusion of surface area allows comparison between drying rates for differently shaped solids and different materials. Texts have been found which favour area-dependent evaporation rates [125] [117][103].

Determination of Control Moisture Content

A set of controlled drying tests were undertaken for each batch of raw material. The purpose for establishing an experimental control is two-fold,

- to determine true dry weight moisture content
- to ensure a constant starting moisture content, thereby guaranteeing uniform thermal load throughout drying trials.

A literature search indicates that no British Standard exists for the determination of moisture content for electrical ceramics. It was subsequently decided to derive a suitable drying regime by experimentation.

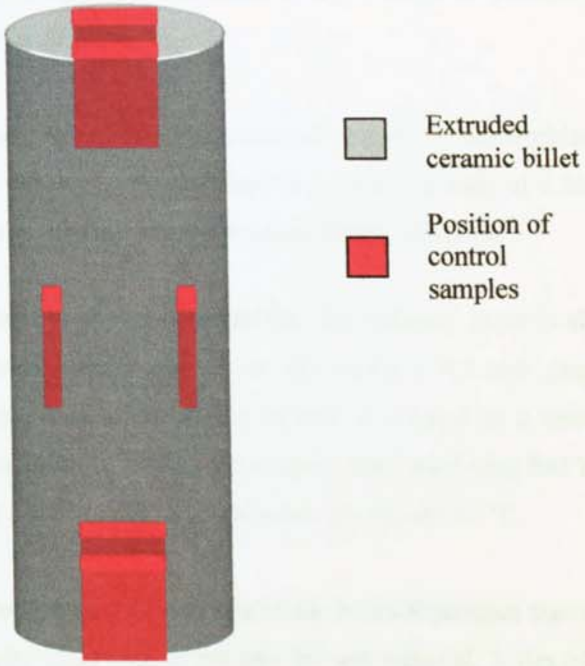


Figure 6.4 Segmentation of ceramic billet for controlled determination of moisture content

Six 'wet' samples of equal dimension and mass (0.1 kg) were weighed to a resolution of 100 mg. To ensure that moisture distribution did not change significantly throughout the extruded billet, samples were taken from different locations as illustrated in figure 6.4. The remainder of the billet was used for drying trials.

Batch no.	Drying trial	Average moisture content over batch* (% dwb)
1	Convective air	29
2	Convective air	30
3	Convective air	30
4	Heat pump	30
5	Heat pump	29
6	Airless	31
	Overall average	**29.8**

* 6 samples per batch (figure 6.4)

Table 6.0 Averaged control moisture contents

Control samples were dried in a hot-box oven for 8 hours at 80 °C followed by a further 16 hours at 105 °C. The samples were then re-weighed at 30 minutes intervals until no variation in mass was measured between 3 consecutive readings. The average control moisture content across the 6 batches was taken as 29.8 % dwb, as illustrated in table 6.0.

Sample Preparation

All clay billets were double wrapped in tarpaulin sheeting and stored away from direct sunlight throughout the period of testing. Billets were inverted every 3 days to prevent uneven moisture distribution resulting from the effects of gravity.

To maximise load cell resolution and to optimise raw materials supply, it was decided to set a standard sample dimension of 80 mm × 60 mm × 25 mm, corresponding to a wet mass of 0.222 kg. This sample size was deemed sufficiently large to provide a representative drying schedule.

Sample preparation was standardised to ensure repeatability. Immediately prior to all drying trials, the clay extrusions were removed from storage and cut to size using a 0.5 mm gauge wire and steel template. Wet samples were weighed on an electronic balance calibrated to a resolution of 100 mg. Samples were re-weighed on completion of drying. To ensure complete drying had been achieved, dry samples were weighed again after a further 4 hours of hot-box drying at 105 °C.

A standardised procedure was adopted for the insertion of the internal product thermocouple. A 2 mm gauge rod was used to force a cavity of 26 mm length into the wet material. A flexible thermocouple of negligible mass was inserted 40 mm into the cavity, thus positioning its hot junction at the product's centre point, as illustrated in figure 6.7.

<u>Convective Air Drying of Electrical Ceramic</u>

An investigation into the manufacture of sanitaryware, tableware and bricks suggests that clay products are rarely dried at air temperatures above 80 °C; excessive drying temperatures resulting in deformation and reduced product quality. In many cases products are simply left to dry at factory room temperature, or at a slightly higher 40 °C during open-shop drying. Humidity levels were found to vary from 'no control' to 40 % rh.

To follow industrial drying practice as closely as possible, it was decided to dry samples over a temperature range matching that found in industry. Temperature set-points were chosen from 30 °C to 90 °C rising in steps of 10 °C. Humidity control ranged from 'no control' to 40 % rh in steps of 10 %. To simulate the effects of open-atmosphere drying, a single set of drying trials was conducted using no temperature or humidity control. Three samples were dried at each combination of temperature and humidity, resulting in the total drying of 105 samples over a time period of more than 3000 hours.

Experimental Set-up

Air drying trials were conducted in a modified laboratory scale convective dryer [63]. A longitudinal cross section of the drying unit is given in figure 6.5. Figure 6.6 presents an image of the drying unit and control system.

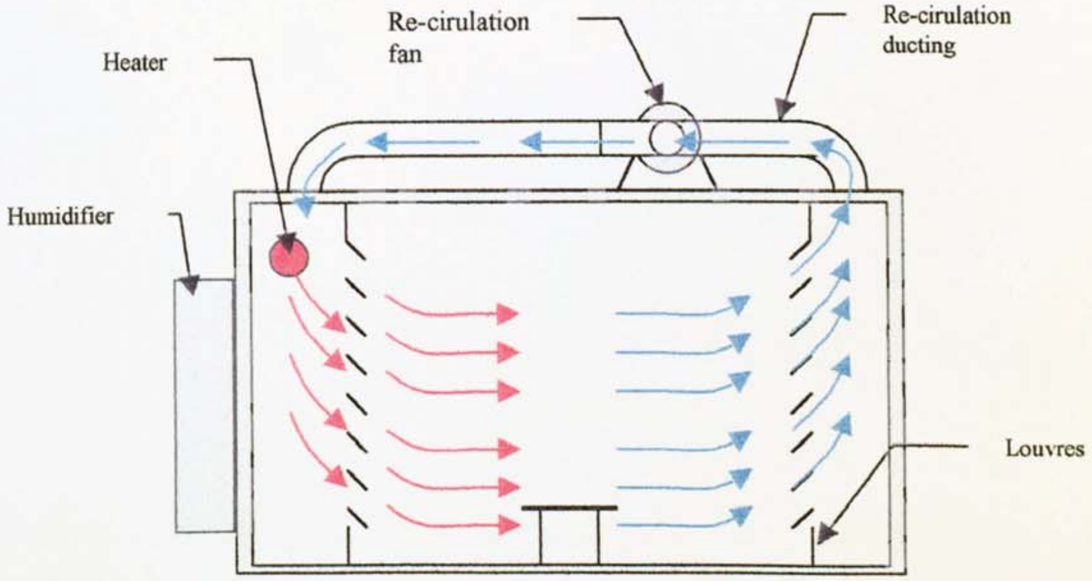


Figure 6.5 Air dryer cross-section

Air is continually circulated throughout the chamber using a fan located in the re-circulation path of the dryer. The fan forces air over an 9 kW electric heating element and into the drying chamber where an array of louvres is used to direct air flow over the product.

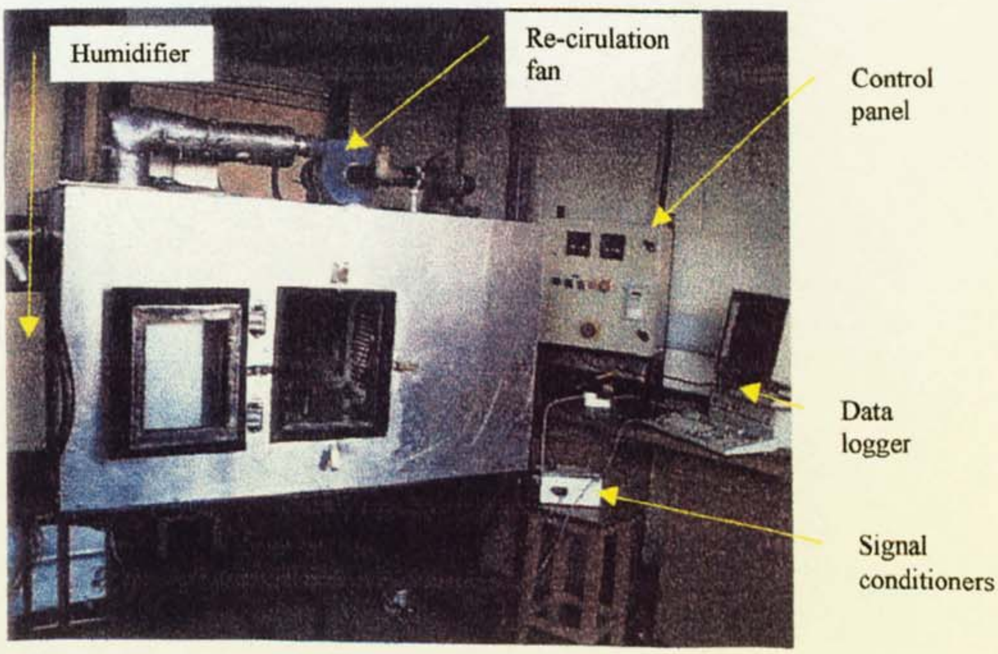


Figure 6.6 Air dryer

Air flow is directed over the product to the exhaust side of the dryer, where a proportion is vented to atmosphere and the remainder is returned to the heater for further drying duty. Control of air temperature is maintained using a K-type thermocouple linked to a Eurotherm PID control unit (0–200 °C range). For all trials, the control thermocouple was suspended at a horizontal distance of 25 mm from the product's leading edge, as illustrated in figure 6.7.

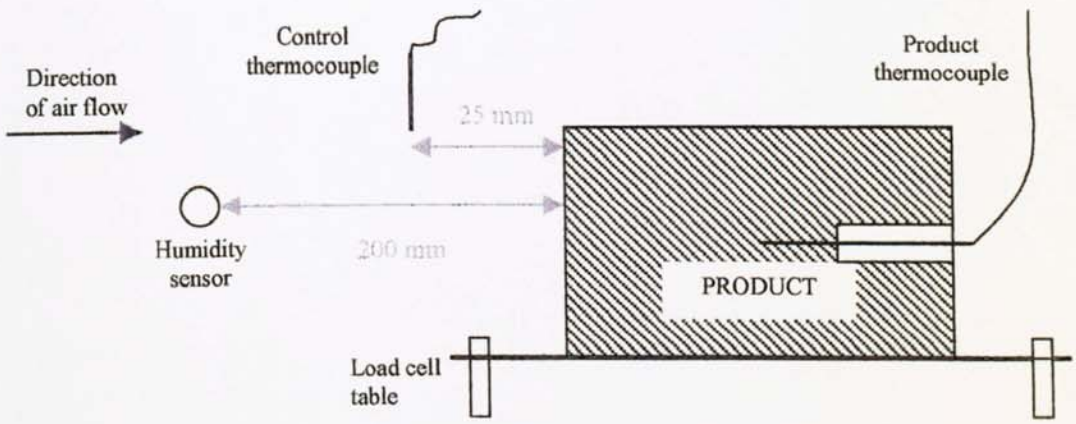


Figure 6.7 Humidity and thermocouple sensor locations

Pre-determined humidity levels were maintained using a Howden AirConMatic TS240 steam injection humidifier. The controlling humidity sensor was located up-stream of the product at a horizontal distance of 200 mm (Figure 6.7). Figure 6.8 offers a detailed view of the humidification unit.

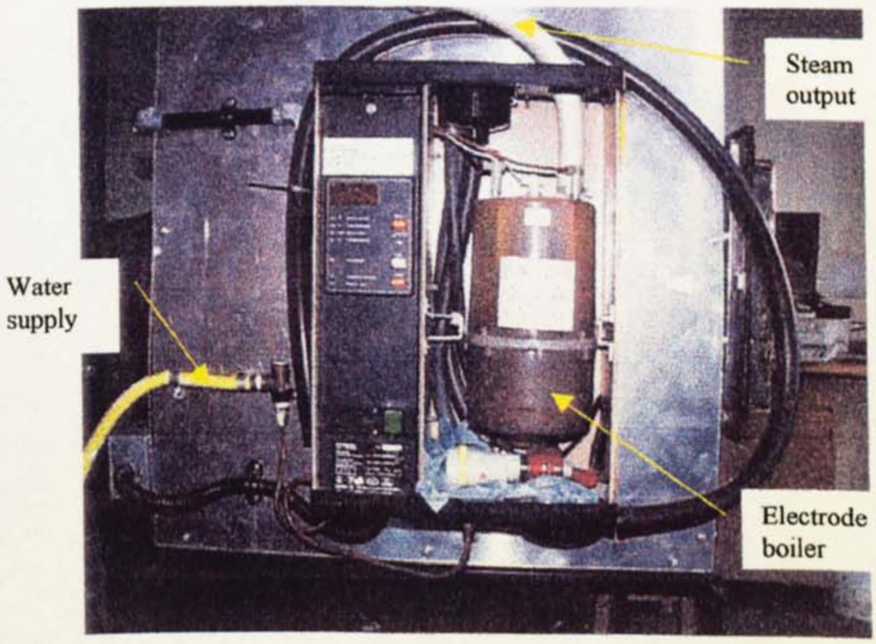


Figure 6.8 Direct steam injection humidifier (convective air dryer)

Moisture loss throughout the drying cycle was measured using an electronic load cell transducer. A shielded low-mass K-type thermocouple was used to register product core temperature during the drying cycle.

Product temperature and weight were recorded using a PicoLog PC data acquisition system. Extensive signal conditioning and filtering was used on sensor inputs to reduce the effects of airborne and electrical interference originating from the fan's variable frequency control unit.

Experimental Procedure

To achieve steady-state air flow, the re-circulation fan was run for 180 seconds prior to initiating heater and humidity control. The fan's inverter frequency was set at 50 Hz corresponding to an average air velocity of 1.5 ms^{-1} ± 33 % over the product. Air velocity was taken as the average of 6 velocity readings recorded 10 mm from the product surface. An AirFlow TA-2 hot-wire anemometer was used for all air velocity readings. After 180 seconds both heater and humidity controllers were initiated simultaneously.

Ambient air temperature and humidity were recorded prior to each drying trial and were found to show negligible variation over the period of testing. Scheduled calibration checks were made on the load cell and thermocouple after every 100 hours of drying duty.

Input data were sampled at 30 second intervals and the termination of drying was determined from on-line observation of product weight and sample core temperature.

Data Extraction: Drying Time and Drying Rate

Experimental data was loaded directly into the Matlab workspace where a series of filter programmes were used to minimise the effects of airborne high frequency electrical distortion on the data series. Drying times were determined using a simple gradient algorithm and verified by observation of graphical output data. Overall drying rates were calculated from drying time, moisture content and product surface area.

Results

Figure 6.9 illustrates the generalised drying and temperature profiles achieved from convective air drying trials.

Warm-up (I), constant rate (II) and falling rate drying (III) periods can be determined from the weight-loss graphs for all sets of results. Furthermore, the experimental plots of internal product temperature clearly demonstrate the transition from constant rate to falling rate. Figures 6.10 and 6.11 present empirical profiles for the drying of samples at 50 °C (40 % rh) and 90 °C (10 % rh). A full set of results is given in Appendix B.

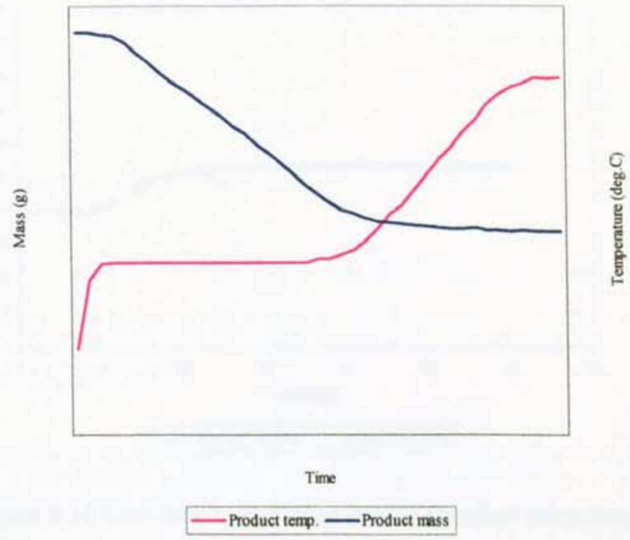


Figure 6.9 General drying schedule

Examination of figure 6.10 indicates that higher air temperatures result in increased drying intensity during the constant rate period. Moreover, at lower gas temperatures, the falling rate periods dominates overall drying time.

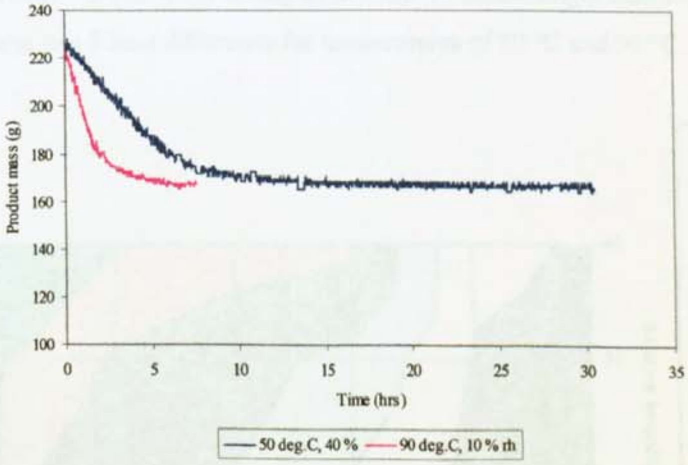


Figure 6.10 Convective air drying profile (product weight loss)

Figure 6.11 illustrates internal sample temperature profiles. A marked rise in temperature occurs at the critical moisture content, with the product reaching dry-bulb gas temperature on completion of drying. Close observation across all results indicates that the second falling rate period dominates the first falling rate period.

An assessment of moisture loss rates for all samples suggests that critical moisture content (CMC) remains relatively constant regardless of the drying regime followed. Average CMC was calculated to be 20 % ± 2 % dwb.

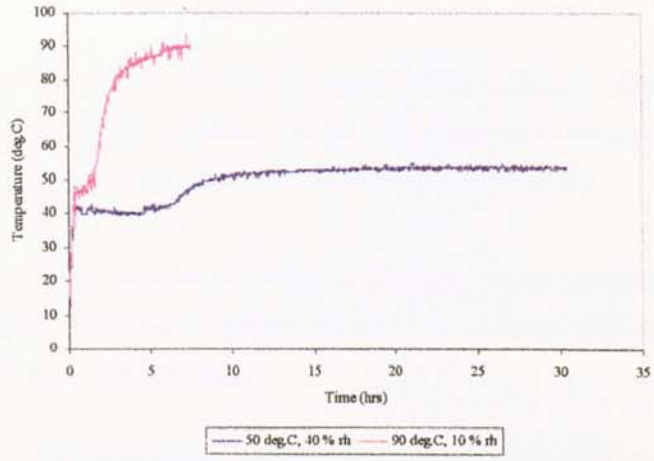


Figure 6.11 Convective air drying profile (product temperature)

Figure 6.12 presents averaged drying times in the form of a 'dying map' given in 5 hourly graduations. As expected, higher air temperatures at constant humidity yield faster drying times. Conversely, increased relative humidity at constant temperature extends the drying period.

Analysis of the 30 °C to 40 °C temperature range indicates a steep gradient in drying time, with samples processed at 30 °C (40 % rh) taking an average 15 hours longer than those dried at 40 °C (40 % rh). This compares to a 5 hour difference for temperatures of 80 °C and 90 °C.

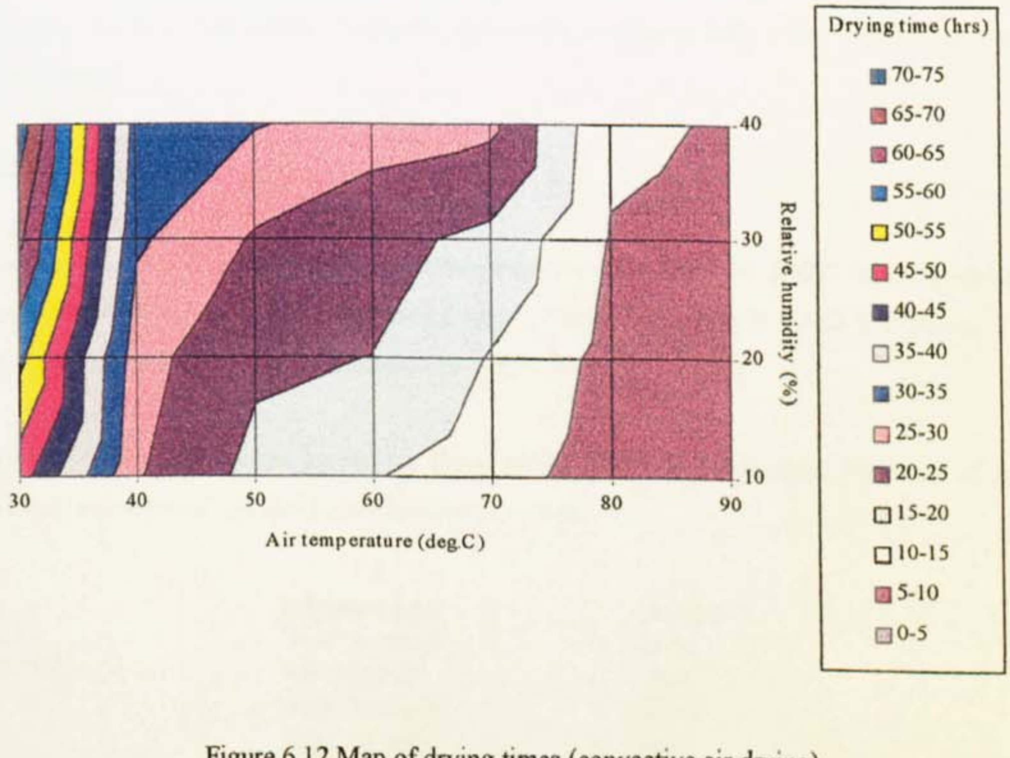


Figure 6.12 Map of drying times (convective air drying)

Drying rates were calculated from the drying times underlying figure 6.12.

Fuzzy Drying Model: Convective Air Drying

The use of adaptive neuro fuzzy inference systems (ANFIS) within the Matlab Fuzzy Logic Toolbox is restricted to first order sugeno regimes or lower. The dual input structure considered for convective drying is a first order sugeno system and thus satisfies this requirement.

Experimental data was divided into three parts: humidity input, temperature input and drying rate output data. Each fuzzy input was assigned 3 membership functions (MF) [115]. Table 6.1 presents the meta-data for input and output domains.

	Fuzzy temperature	Fuzzy humidity	Fuzzy drying rate
No. of MFs	3	3	9
MF type	generalised bell curve	generalised bell curve	linear
Input range	30 - 90	4 – 40	n/a
Output range	n/a	n/a	0.021 – 0.1437

Table 6.1 FIS input-output data (air drying)

Generalised bell curves (gbellmf) were used for the input domain. Ranges were chosen to reflect the scope of empirical data. All fuzzy modelling was conducted using Matlab's Fuzzy Logic Toolbox.

ANFIS mapping of input space to output space was achieved using 9 rules and 9 output MFs. Interestingly, the software package limits the maximum number of MFs which can be assigned to any input/output to 9.

Formulation of Rules

Data was loaded into a purpose written Matlab programme in which all ANFIS training and fitting of membership functions was undertaken. Rules were generated using an IF-AND-THEN logic structure. Figure 6.13 demonstrates the rule structures in symbolic form.

A sugeno system was chosen as the de facto method of fuzzy inference. Methods of operation, implication, aggregation and defuzzification were as follows,

Inference type	:	sugeno
'And' method	:	prod
'Or' method	:	max
'Imp' method	:	prod
'Agg' method	:	max
Defuzzification method	:	wtaver

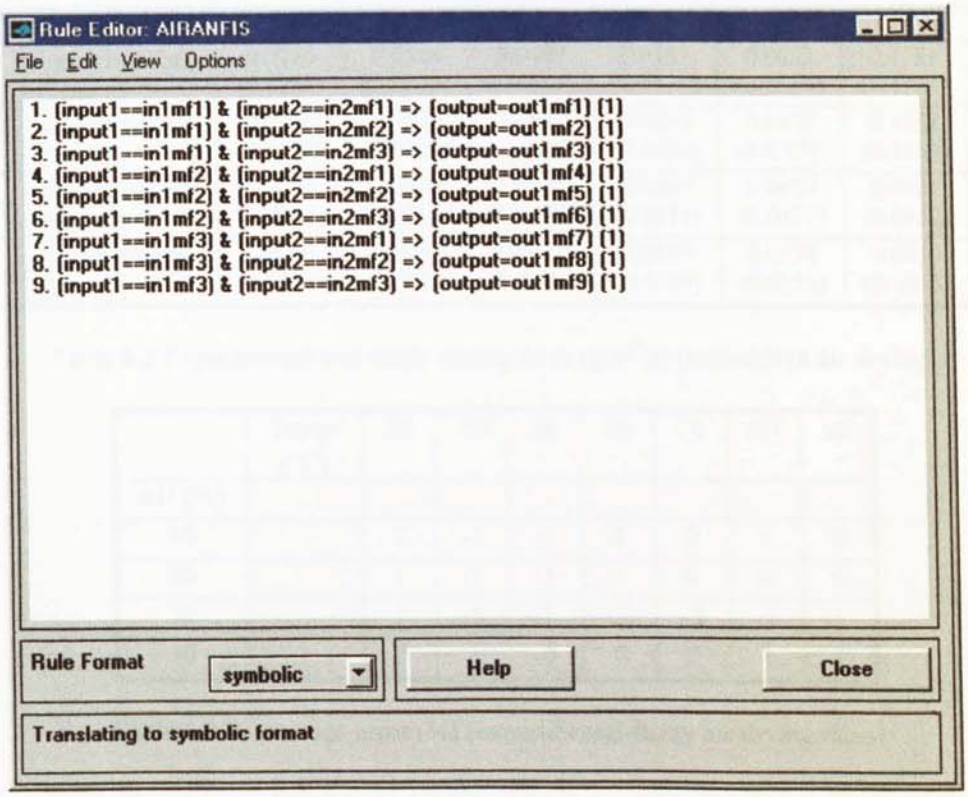


Figure 6.13 Fuzzy rules (convective air drying)

Figure 6.16 illustrates the reduction in root mean square error (RMSE) between experimental data and model values as training epochs increase. The reduction in modelling step size indicated in figure 6.17 suggests that 153 epochs were sufficient to obtain a minimal training RMSE equal to 0.000643.

Figure 6.18 illustrates the adapted input MFs after training, and figure 6.19 demonstrates the ANFIS modelling output data.

The full fuzzy inference diagram is given in figure 6.20. Inputs for temperature and humidity are presented on the left side with the output drying rate indicated on the lower right hand side.

The output surface space of the fuzzy model is presented in figure 6.21. Using this surface model, any input combination of drying temperature and rh which lie within the experimental range will derive an estimated fuzzy drying rate at the output.

Model Verification

Tables 6.2 and 6.3 demonstrate the accuracy of the fuzzy model in comparison to experimental drying rates.

	Temp. (°C)	30	40	50	60	70	80	90
RH (%)								
10	Experimental (Fuzzy)	0.0260 (0.0266)	0.0348 (0.0339)	0.0449 (0.0445)	0.0567 (0.0576)	0.0862 (0.0859)	0.1283 (0.1283)	0.1437 (0.1437)
20	Experimental (Fuzzy)	0.0240 (0.0243)	0.0332 (0.0329)	0.0343 (0..0340)	0.0454 (0.0457)	0.0575 (0.0.574)	0.1052 (0.1053)	0.1347 (0.1346)
30	Experimental (Fuzzy)	0.0220 (0.0223)	0.0308 (0.0294)	0.0341 (0.0355)	0.0407 (0.0411)	0.0479 (0.0471)	0.0937 (0.0932)	0.1026 (0.1032)
40	Experimental (Fuzzy)	0.0210 (0.0211)	0.0269 (0.0278)	0.0332 (0..0317)	0.0359 (0.0359)	0.0370 (0.0376)	0.0810 (0.0815)	0.0900 (0.0895)

Table 6.2 Experimental and fuzzy drying rates ($g/m^2/s$) (convective air drying)

	Temp. (°C)	30	40	50	60	70	80	90
RH (%)								
10		2	-3	-1	2	0	0	0
20		1	-1	-1	1	0	0	0
30		1	-5	4	1	-2	-1	1
40		0	3	-5	0	2	1	1

Table 6.3 Percentage error (%) (experimental-fuzzy air drying rates)

Table 6.3 clearly demonstrates that typical errors between experimental drying rates and fuzzy drying rates rarely exceed ± 3 %. The averaged percentage error across all experimental trials is negligible.

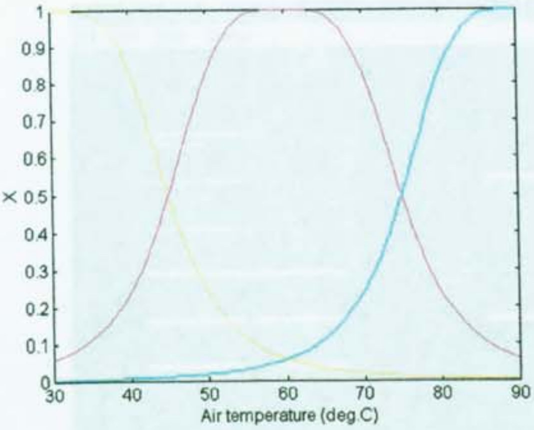


Figure 6.14 Initial MFs (air drying)

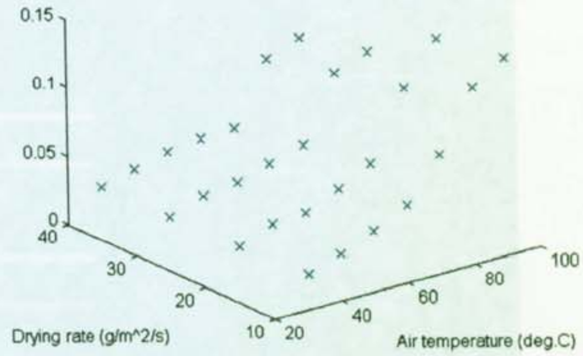


Figure 6.15 Training data (air drying)

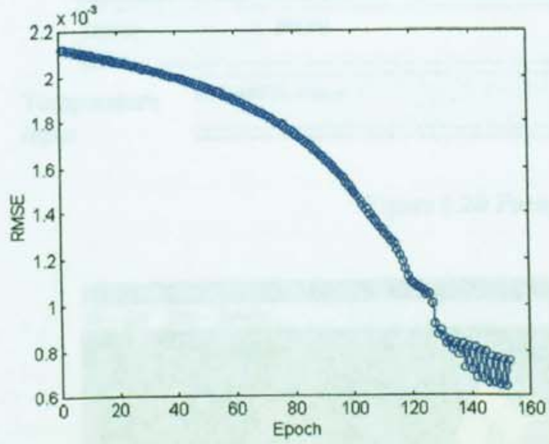


Figure 6.16 Training RMSE (air drying)

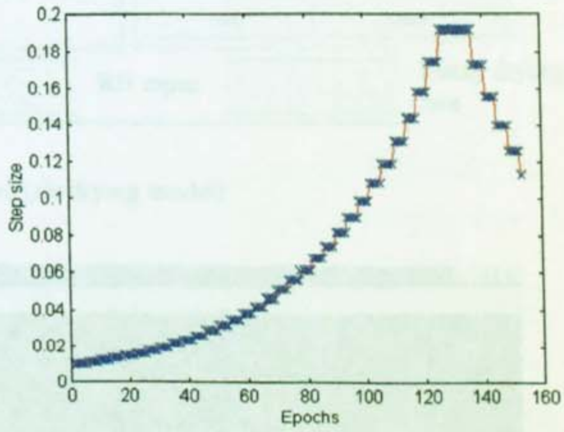


Figure 6.17 Step size reduction (air drying)

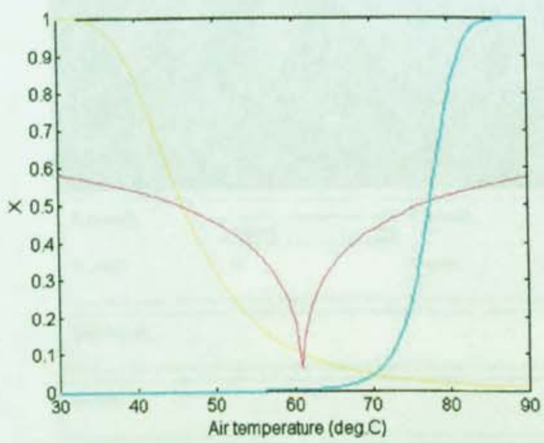


Figure 6.18 Adapted MFs (air drying)

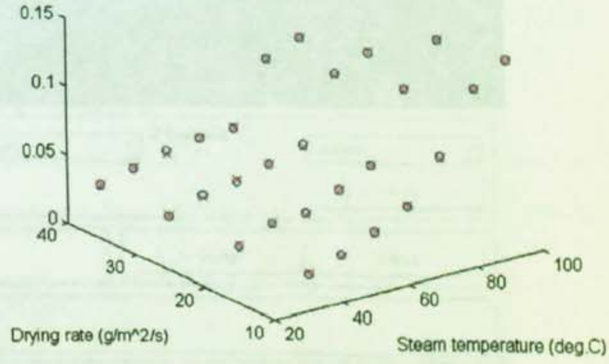


Figure 6.19 Model output (air drying)

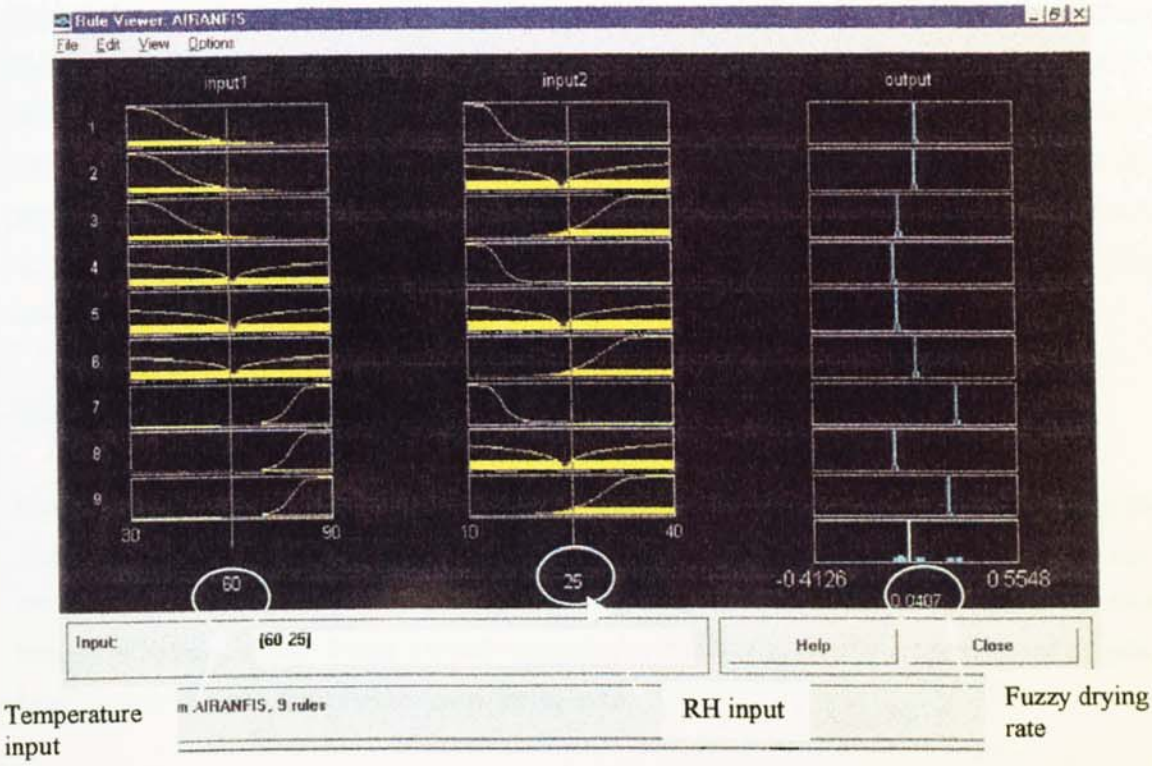


Figure 6.20 Fuzzy rules (air drying model)

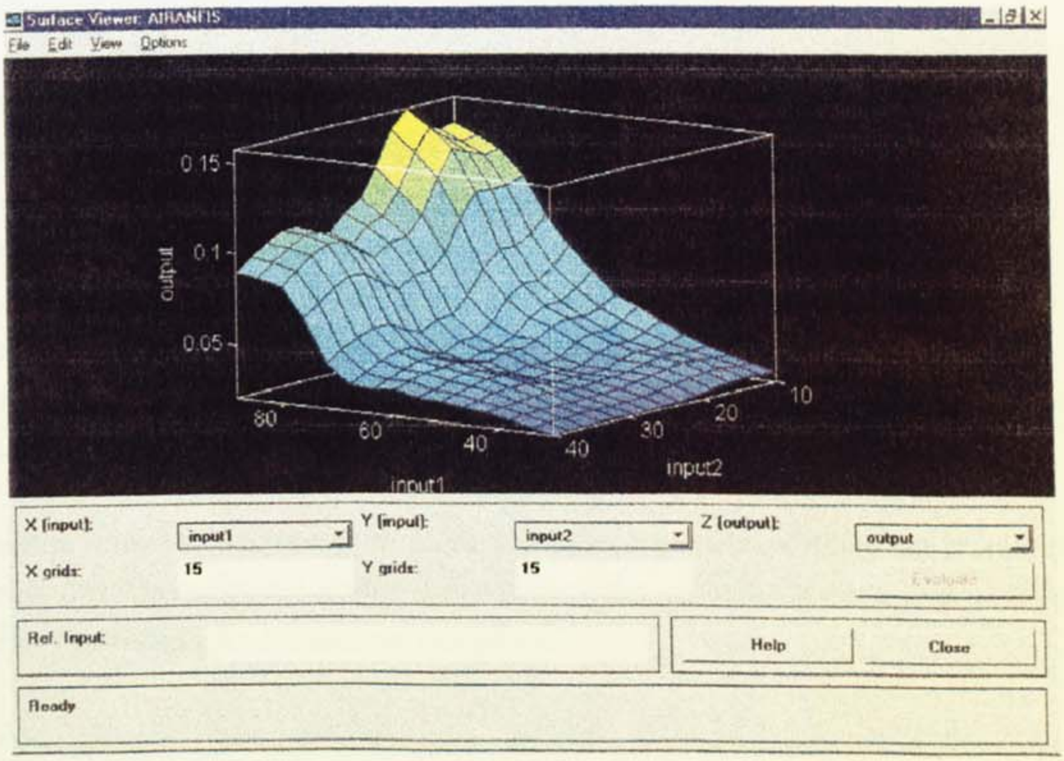


Figure 6.21 Output surface (air drying model)

Airless Drying of Electrical Ceramic

Limited literature has been found which describes the use of airless drying in the ceramics industry. Analysis of published work suggests that atmospheric steam temperatures between 120 °C and 130 °C offer the best compromise between rapid drying rates and acceptable product quality [138] [180] [50]. For the experimental work in this thesis, it was subsequently decided to conduct drying trials using steam temperatures between 120 °C to 150 °C graduated in steps of 10 °C. Temperatures between 100 °C and 120 °C were avoided due to the risk of excessive condensation and subsequent protracted and unrepresentative drying times.

Choice of Dryer Configuration

Theory suggests that industrial scale airless dryers operate by generating sufficient drying steam from product moisture loss. Clearly the drying of relatively small sample masses precludes the use of industrial dryer configurations as a method of empirical data collection. Furthermore, the limited number of airless ceramics dryers currently operating in the UK eliminates the possibility of adopting a working unit for small scale experimental drying trials.

It was therefore decided to construct a custom airless drying unit capable of simulating industrial superheated steam drying conditions. A literature survey highlighted a number of possible airless dryer configurations; two of which were deemed viable as experimental units.

Schwartze et al. used a ducting arrangement for the through-drying of woven wool fibre mats with superheated steam at atmospheric pressure [117]. Operational temperatures ranged between 130 °C and 150 °C, with superficial steam velocities between 1.0 ms^{-1} and 1.5 ms^{-1}. Product weight was registered using an electronic balance inserted vertically through the dryer wall and steam egress was prevented by its lower density compared with that of air. Nonetheless, comments were made which suggest ingress of air as a result of such an arrangement. In comparison with the drying of clay ceramics, the drying times for wool mats were significantly shorter: typically 290 seconds compared to 540 seconds for simple tableware pieces [117] [177].

Chu et al. devised an experimental rig for the continuous evaporation of liquids into their superheated vapours [20]. The system used a boiler to raise steam, which was passed of over a superheating element and the liquid sample to a condenser on the exhaust.

For the experimental work in this thesis, it was decided to fabricate a custom hybrid airless dryer based on the work of both Schwartze et al. and Chu et al [117] [20].

Experimental Set-up

Figure 6.22 provides a block schematic of the experimental equipment, comprising of a steam boiler, a bank of infra-red superheaters, a drying chamber and a condensing system. Steam enters the dryer and is raised to a pre-determined level of superheat, from where it is passed into the drying chamber and over the ceramic sample. The exhaust is then directed into a re-circulating water bath to be condensed.

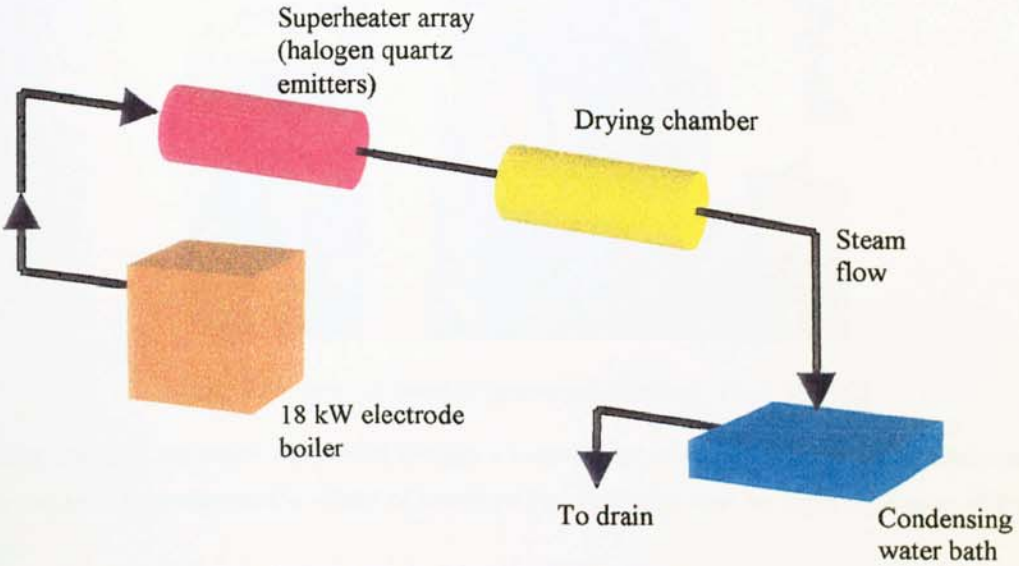


Figure 6.22 Experimental airless dryer

Steam was generated using a 18 kW 3 phase Parkinson-Cowen 710 Steamlode electrode boiler. The boiler's output was maintained under pressure control at 0.39 MPa. Prior to entering the dryer, steam output was throttled from its boiler exit pressure down to 0.1 MPa for use in the dryer. A monitoring thermocouple was used to log steam temperature at the dryer's inlet, allowing the steam flow to be maintained at a constant 100 °C ± 5 %. Figure 6.23 demonstrates the inlet plate and thermocouple arrangement.

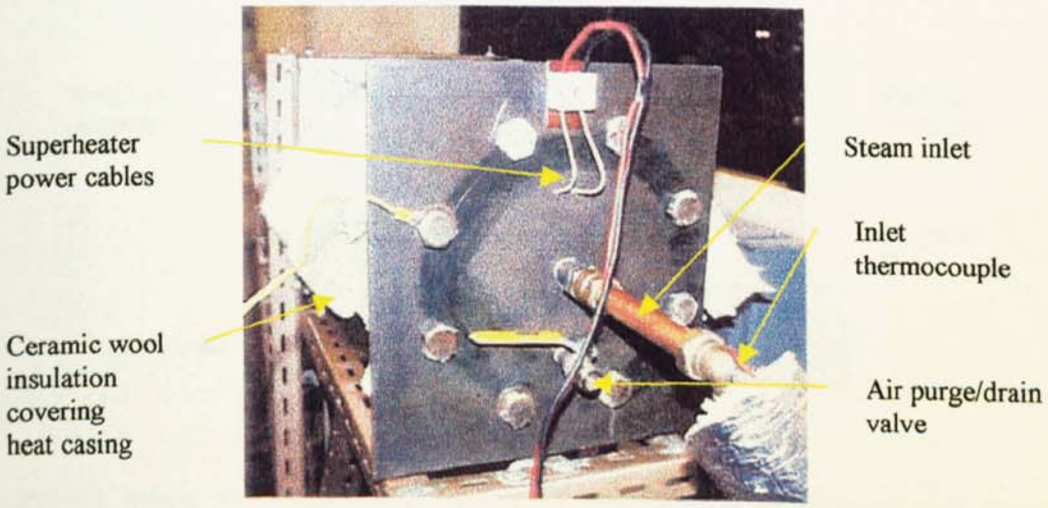


Figure 6.23 Inlet plate and thermocouple arrangement (airless dryer)

Superheating of the steam stream was facilitated by a PID Kanthal unit controlling a bank of 6 infra-red halogen quartz emitters rated at 0.5 kW each. The emitters were aligned longitudinally with the direction of steam flow and the internal surface of the heaters' stainless steel housing was polished to maximise boundary reflections. Figure 6.24 illustrates operation of the superheaters during a drying cycle.

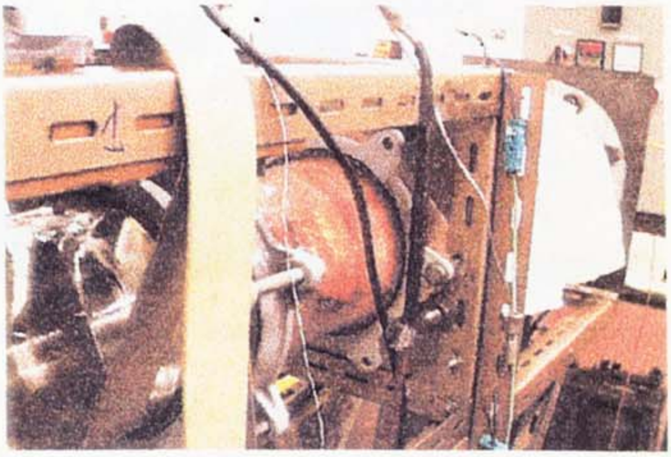


Figure 6.24 Infra red halogen quartz superheaters (T_{shs} = 150 °C)

Once superheated, the steam was passed through a 1 mm gauge mesh and into the drying chamber. The mesh was used to ameliorate the effects of turbulent flow resulting from the rapid expansion of the inlet steam.

The drying chamber was constructed from 6 inch diameter QVF glass tubing. An inverted QVF T-piece was included in the chamber to allow for the insertion of a weight pan into the steam path. To prevent steam egress from the dryer, and air ingress to the dryer, the T-piece was closed off using an insulation plate. In addition to the limiting of steam discharge, the plate reduced the effects of thermal bridging from the drying gas to the load cell. Figure 6.25 illustrates the isothermally insulated load cell arrangement.

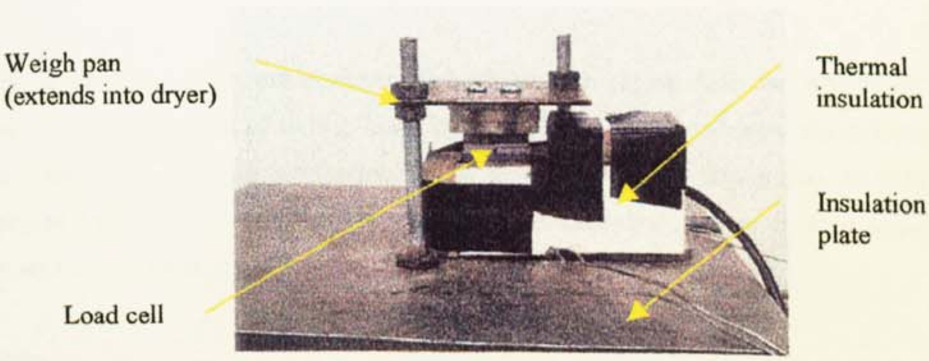


Figure 6.25 Load cell arrangement

Product weight was logged using PicoLog PC software and temperatures were recorded using Windmill data acquisition software. Following the work of Schwartze et al., steam velocity was measured using a vane anemometer and was found to average 1.4 ms^{-1} ± 20 % for all drying tests [117]. Figure 6.26 illustrates the data logging apparatus and control panel.

Figure 6.26 Control instrumentation and data logging equipment

Experimental procedure

Initial drying trials highlighted sample deformation and cracking as a significant problem during the first 30 minutes of drying. To eliminate sample damage, it was decided to pre-heat the sample using the infra-red emitters only. Experimental trial and error suggested that a core product temperature of 40 °C was sufficient to ameliorate the rapid heating and drying effects resulting from the use of superheat steam.

After sample pre-heating, the superheaters were re-set to the desired level of superheat and the steam was introduced into the chamber. Initial steam flow was restricted to prevent priming of the boiler and 'blow out' of condensation onto the product. The boiler's output throttling valve was opened incrementally until inlet steam temperature stabilised at 100 °C ± 5 %.

Three samples were dried at each temperature set-point, resulting in the total drying of 12 samples over a period of 74 hours.

Ambient air temperature was recorded throughout each drying trial and was found to show little variation over the period of testing. Data was sampled at 15 second intervals and calibration checks were made on the load cell and thermocouples after every second drying trial. As with the convective air drying trials, the termination of drying was determined from on-line analysis of product mass and core product temperature.

Results

Overall drying times and rates were calculated using identical methods to those followed for air drying data.

As expected, airless drying produces generalised profiles similar to those derived from air drying (figure 6.9). Figure 6.27 illustrates the drying profile for a steam temperature of 150 °C.

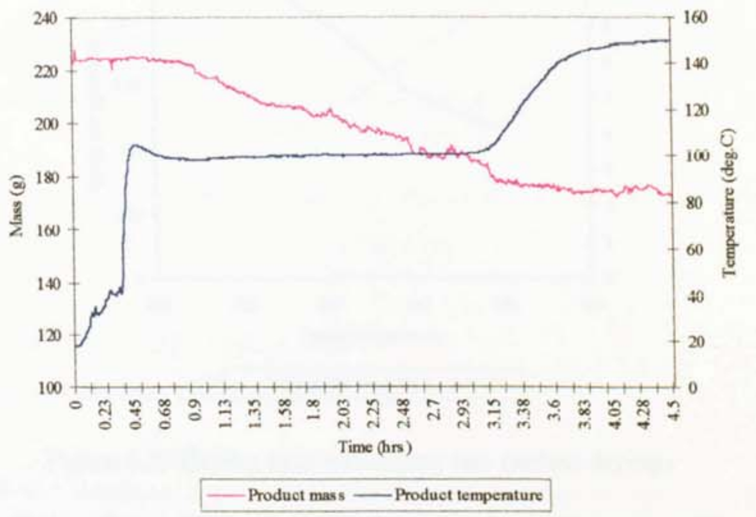


Figure 6.27 Airless drying profile: temperature and product mass (T_{shs} = 150 °C)

In accordance with superheated steam drying theory, all samples dried at the saturation temperature during the constant rate period. A marked rise in product temperature occurs at the critical moisture content and the product attains the temperature of the drying gas once drying has terminated. Drying profiles for the remaining steam temperatures are given in Appendix B.

Figure 6.28 demonstrates boiler and heater temperature profiles over the drying cycle. Off-boiler temperature is maintained at a constant 98 °C. With the exception of overshoot, the superheaters remain at a constant temperature of 150 °C throughout the drying cycle.

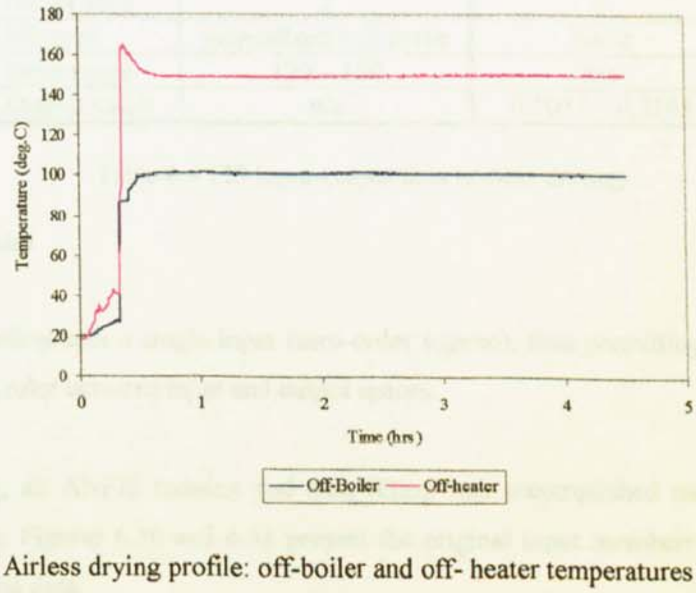


Figure 6.28 Airless drying profile: off-boiler and off- heater temperatures (T_{shs} = 150 °C)

Overall drying times and drying rates are given in figure 6.29.

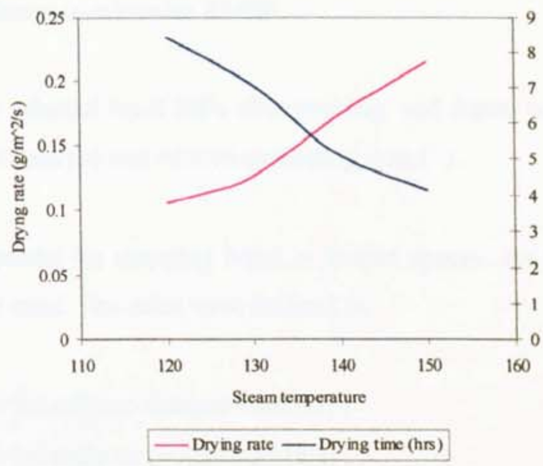


Figure 6.29 Drying time and drying rate (airless drying)

Ostensibly, airless drying demonstrates a linear increase in drying rate with respect to steam temperature. As with air drying, the constant rate period becomes less pronounced with increased drying intensities.

Fuzzy Drying Model: Airless Drying

Experimental data was divided into input and output domains: steam temperatures and experimental drying rates respectively. Steam temperature was assigned 2 generalised bell curve MFs. Input/output ranges are given in table 6.4.

	Fuzzy steam temperature	Fuzzy drying rate
No. of MFs	2	2
MF type	generalised bell curve	linear
Input range	120 – 150	n/a
Output range	n/a	0.1057 – 0.2145

Table 6.4 FIS input-output data (airless drying)

Formulation of Rules

Fuzzy airless modelling uses a single input (zero-order sugeno), thus permitting the use of ANFIS to define the mapping rules between input and output spaces.

As with air drying, all ANFIS training and data fitting was accomplished using a purpose written Matlab programme. Figures 6.30 and 6.31 present the original input membership functions and raw experimental training data.

Reduction of root mean square error (RMSE) between experimental data and model values is given in figure 6.32. The eventual reduction in modelling step size indicated in figure 6.33 suggests that 95 training epochs were sufficient to minimise RMSE.

Figure 6.34 illustrates the adapted input MFs after training, and figure 6.35 demonstrates the close fit between raw experimental data (o) and ANFIS modelling data (–).

Two fuzzy rules were derived for mapping input to output spaces. As with air drying, an IF-AND-THEN logic structure was used. The rules were defined as,

1. (input1==in1mf1) ⇒ (output=out1mf1)
2. (input2==in1mf2) ⇒ (output=out1mf1)

The inference type and methods of operation, implication, aggregation and defuzzification were as follows,

Inference type	:	sugeno
'And' method	:	prod
'Or' method	:	max
'Imp' method	:	prod
'Agg' method	:	max
Defuzzification method	:	wtaver

The full fuzzy inference diagram for airless drying is given in figure 6.36. Steam temperature is highlighted on the left side with output drying rated on the lower right side. The output space is presented in figure 6.37.

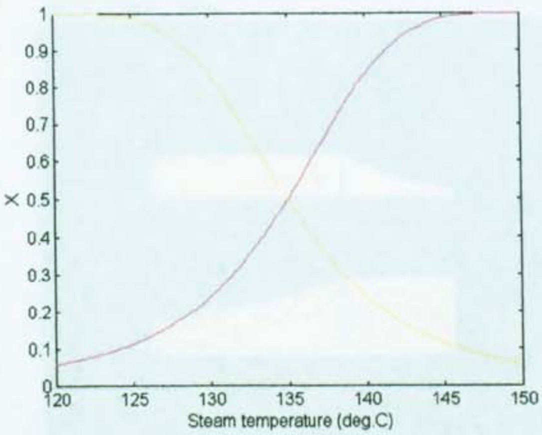


Figure 6.30 Initial MFs

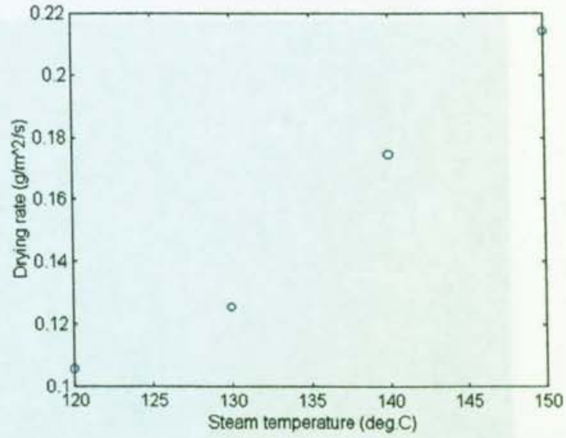


Figure 6.31 Training data

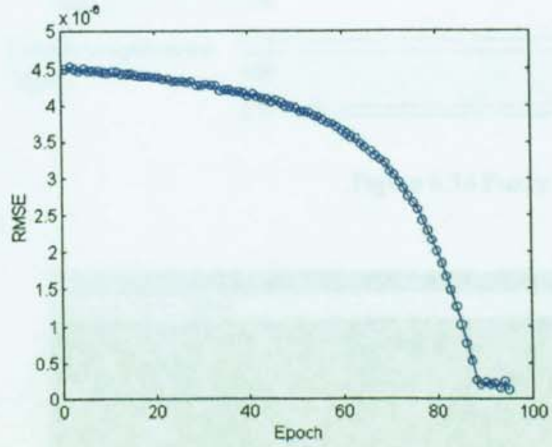


Figure 6.32 Training RMSE

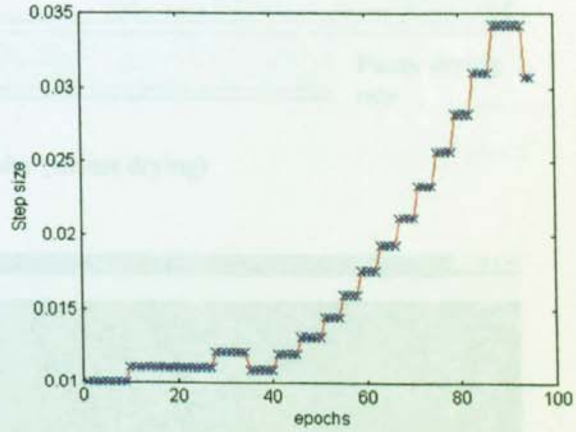


Figure 6.33 Step size reduction

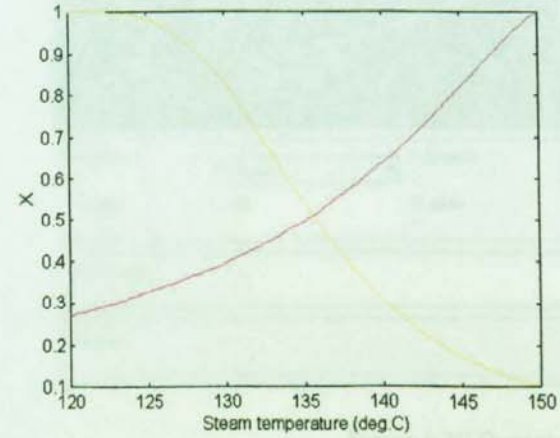


Figure 6.34 Adapted MFs

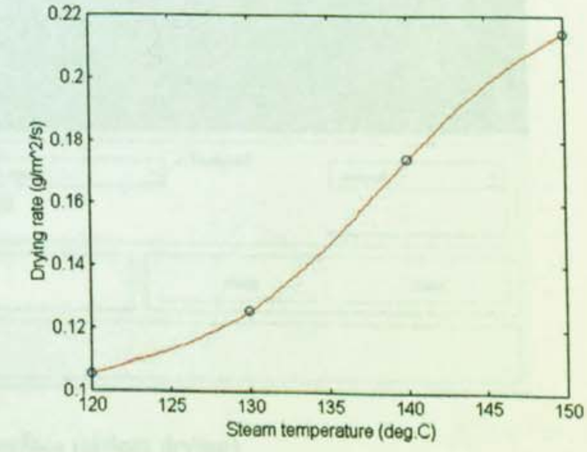


Figure 6.35 Training data and model output

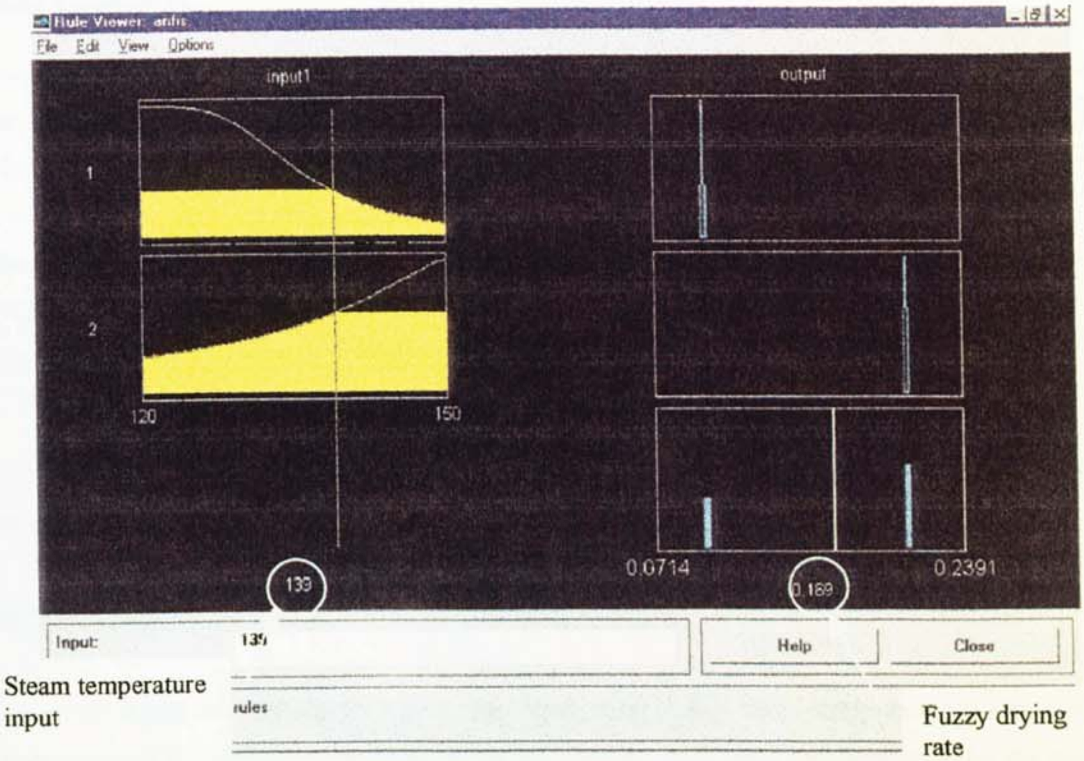


Figure 6.36 Fuzzy rules (airless drying)

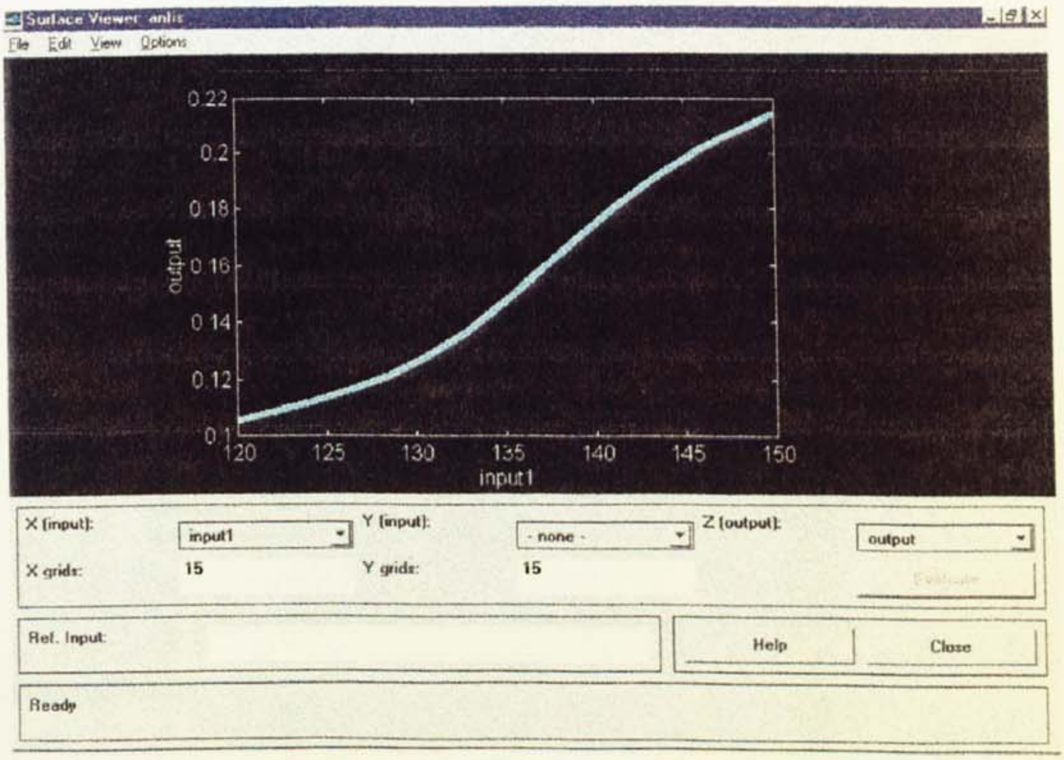


Figure 6.37 Output surface (airless drying)

Model Verification

Temp. (°C)	Experimental rate (g/m²/s)	Fuzzy rate (g/m²/s)	Error (%)
120	0.106	0.106	0
130	0.126	0.126	0
140	0.174	0.174	0
150	0.214	0.214	0

Table 6.5 Experimental and fuzzy drying rates, incl. percentage error (airless drying)

As demonstrated by figure 6.32 and table 6.5, no measurable error exists between empirically derived data and fuzzy drying rates.

Heat Pump Dehumidification Drying of Electrical Ceramic

Heat pump drying was limited to 1 trial. The small sample size and correspondingly low moisture content resulted in significant oversizing of the compressor, evaporator and condenser for the required drying duty. In an attempt to increase evaporation rate a 'dummy load' of wet clay was introduced into the dryer.

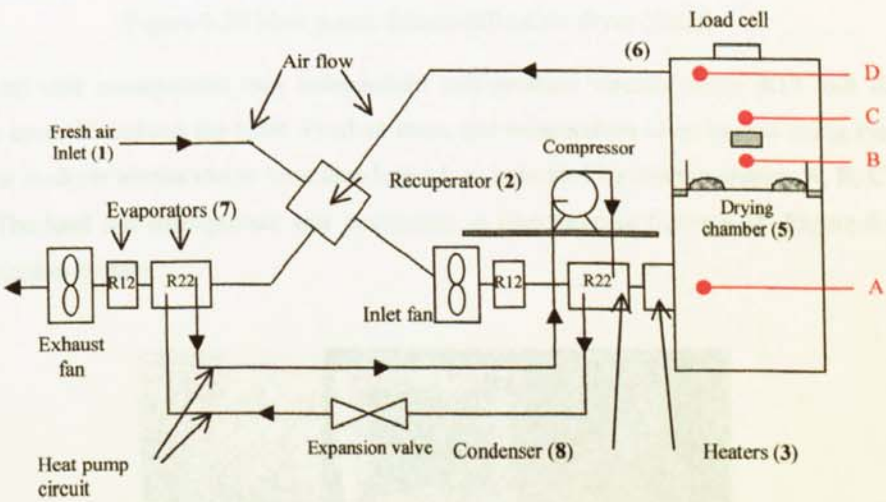


Figure 6.38 Schematic of heat pump dehumidification dryer

Experimental Set-up

Drying was conducted using a modified heat pump, originally used by Marshall and Metaxas as a novel radio frequency assisted unit [90]. Figure 6.38 illustrates the dryer configuration in schematic form. The drying rig represents a 200th scale model of an industrial malt kiln.

Ambient air is drawn into the dryer at point 1 and passed through a recuperator (2) and heater units (3) into the drying chamber (5). The hot dry air undergoes heat/mass transfer with the product and is exhausted at point 6. From exhaust, the warm wet air is passed back through the opposite side of the recuperator and over the evaporators (7). The evaporated refrigerant is compressed and condensed in the path of the incoming air (8).

On reaching steady-state, sufficient energy for drying is obtained from the condenser and recuperator. The heaters are subsequently switched off for the remainder of drying. Figure 6.39 illustrates the drying chamber and control panel.

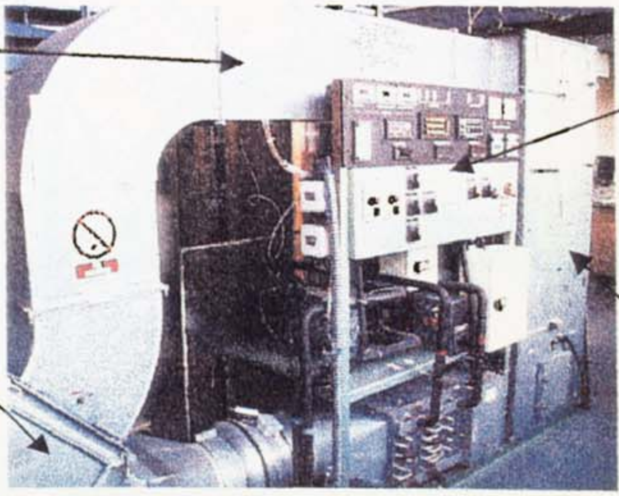


Figure 6.39 Heat pump dehumidification dryer (front)

The heat pump unit incorporates two independent refrigeration circuits using R12 and R22. Both systems were used throughout the trials. Product mass and temperature were logged using PicoLog PC software. Four in-dryer temperatures were also logged, as indicated by thermocouples A, B, C and D in figure 6.38. The load cell arrangement was positioned as illustrated in figure 6.38. Figure 6.40 shows the data acquisition system.

Figure 6.40 Data logging (heat pump dryer)

Experimental procedure

Ten kilograms of dry crushed pewt brick were thoroughly mixed with 7.5 kg of water. The resulting wet mixture was evenly distributed around the periphery of the dryer's internal tray. Sufficient area was left clear for exposure of the product to the air flow. The sample was suspended from a load cell located above the drying chamber. Figure 6.41 demonstrates the product arrangement and figure 6.42 illustrates the internal tray and sample support.

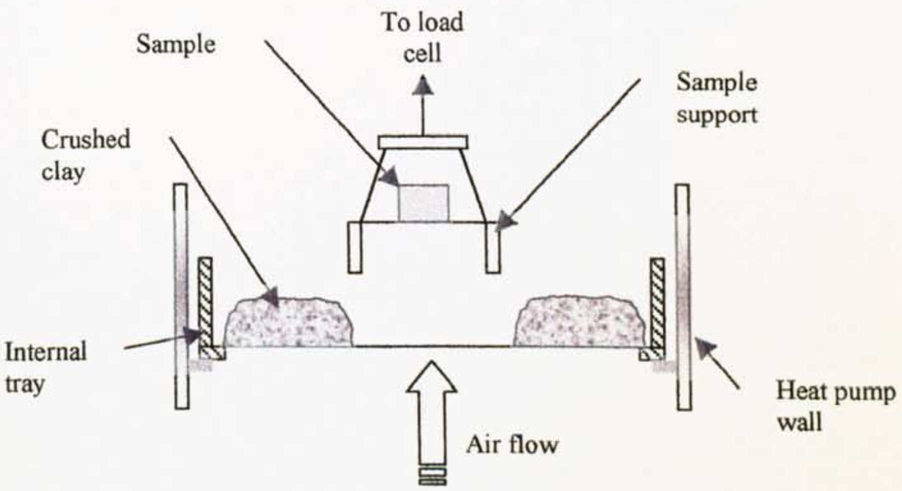


Figure 6.41 Cross section of heat pump dryer rig

Recirculation fans were set to level 8, corresponding to an average air velocity of 1.5 ms^{-1} ± 33 %. Air velocity was calculated from flow grid readings and verified using an AirFlow TA-2 hot-wire anemometer.

Air flow was allowed to attain steady state conditions over a period of 5 minutes, after which time the heaters were initiated. Once off-heater temperature reached 40 °C, the heaters were turned off and the compressors were switched on.

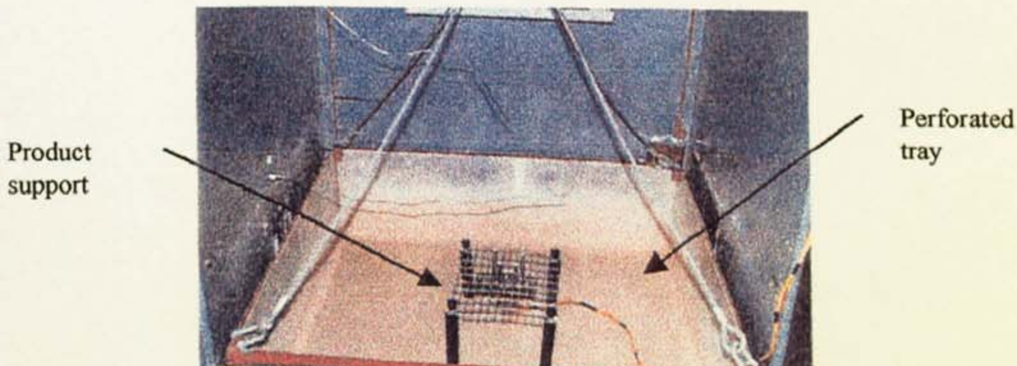


Figure 6.42 Heat pump tray and sample support

As with previous trials, drying data was extracted from results using a Matlab regression algorithm. Drying times and rates were verified by simple mathematical and graphical checks using load cell and product thermocouple readings.

Results

The laboratory unit was not capable of accurately controlling the range of air temperature and humidity entering the dryer. Subsequently, only 3 identical drying trials were performed. Figure 6.43 presents the results for one data series. As with air and steam drying, heat pump drying clearly demonstrates the existence of constant and falling rate periods.

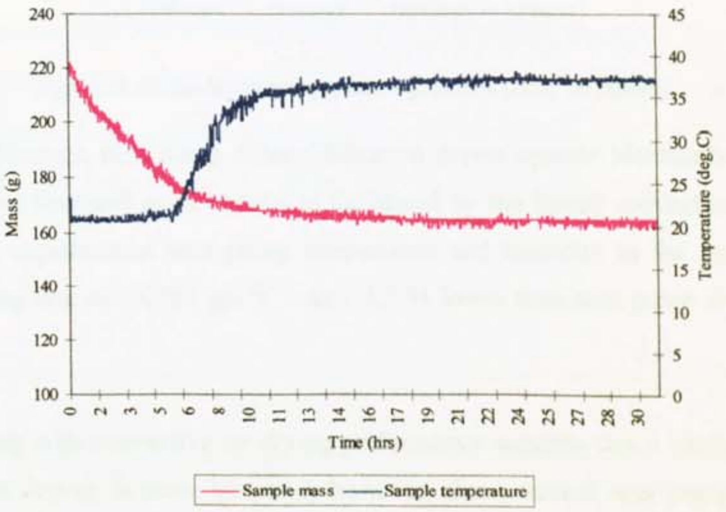


Figure 6.43 Heat pump drying profile

Average total drying time was calculated to be 31.2 hours, corresponding to an evaporation rate of 0.029 $gm^{-2}s^{-1}$. Analysis of figure 6.43 suggests that drying occurred at 37 °C with a gas relative humidity of 25 %.

Figure 6.44 shows recorded air temperatures within the drying unit, namely off-heater, pre-product, off-product and exhaust temperatures. A temperature gradient clearly exists across all 4 points. Off-heater and exhaust temperature were maintained at a constant 41 °C and 33 °C respectively, whilst off-sample temperature showed negligible difference to that of the exhaust air.

Of greatest concern to the author is the difference between off-heater and pre-product temperature. It is difficult to determine whether such a difference arises from energy losses through the dryer's boundary, air ingress or the effects of evaporation from the 'dummy' thermal load. Furthermore, it remains unclear whether differences between pre- and off-sample temperature derive from sample evaporation or the 'dummy' thermal load.

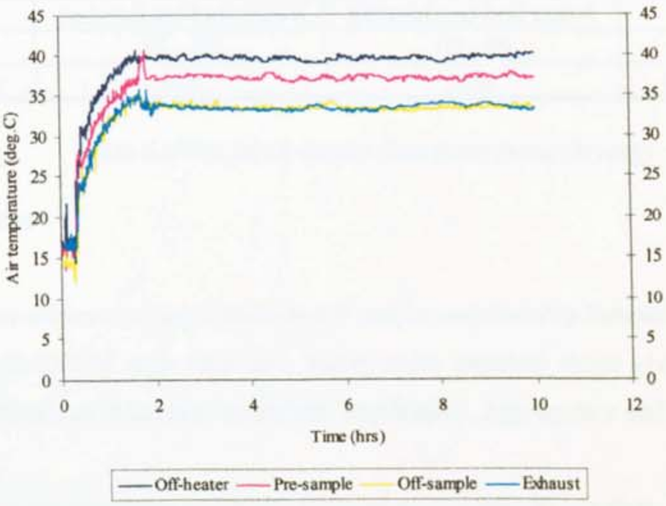


Figure 6.44 In-dryer temperature profiles (first 10 hours)

In terms of drying kinetics, heat pump dehumidification dryers operate identically to convective air dryers. For both cases heat and mass transfer is facilitated by the forced convection of hot air over a wet product. Using experimental heat pump temperature and humidity in the fuzzy convective air model yields a drying rate of 0.0283 $gm^{-2}s^{-1}$: only 2.5 % lower than heat pump drying at similar air velocity.

The close relationship with convective air drying performance suggests that a similar FIS can be used for dehumidification drying. It must be noted, however, that practical heat pumps are restricted to operating temperatures imposed by the refrigerant used.

For the reasons given above, the fuzzy modelling of heat pump drying rates will continue based on results gained from standard convective chamber drying.

Fuzzy Drying Model: Heat Pump Drying

A survey of literature suggests that air temperatures between 25 °C and 50 °C, and humidities from 22 % to 60 % rh are typical for the heat pump drying of ceramics [176] [186]. It is important to note that these values refer to off-product conditions, and are not dryer inlet conditions. Literature indicates that modern heat pump dryers will process ware at temperatures of 70 °C or less.

Fuzzy model data for heat pump drying are given in table 6.6. As with air drying, 3 generalised bell curves were assigned to each input, with input/output ranges chosen to reflect the scope of empirical data.

	Fuzzy temperature	Fuzzy humidity	Fuzzy drying rate
No. of MFs	3	3	9
MF type	generalised bell curve	generalised bell curve	Linear
Input range	30 – 70	10 - 40	n/a
Output range	n/a	n/a	0.021 – 0.0862

Table 6.6 FIS input-output data (heat pump drying)

Formulation of Rules

ANFIS mapping was achieved using 9 rules and 9 output membership functions. As before, rules were generated in IF-AND-THEN logic structure. Fuzzy rules matched those given for air drying (figure 6.13); as did the methods of inference, operation, implication, aggregation and defuzzification

Figure 6.47 indicates the reduction in RMSE with increasing epochs number. Figure 6.48 suggests that 110 epochs were sufficient to minimise RMSE to 1×10^{-6}. Adapted air temperature MFs are given in figure 6.49, and figure 6.50 demonstrates the ANFIS output modelling data. The full inference diagram is given in figure 6.51 and the output fuzzy surface is presented in figure 6.52.

Model Validation

Tables 6.7 and 6.8 indicate that averaged percentage error across all results equals 0 %.

	Temp. (°C)	30	40	50	60	70
RH (%)						
10	Experimental (Fuzzy)	0.0260 (0.0260)	0.0348 (0.0348)	0.0449 (0.0449)	0.0567 (0.0567)	0.0862 (0.0862)
20	Experimental (Fuzzy)	0.0240 (0.0240)	0.0332 (0.0332)	0.0343 (0..0343)	0.0454 (0.0454)	0.0575 (0.0.575)
30	Experimental (Fuzzy)	0.0220 (0.0220)	0.0308 (0.0308)	0.0341 (0.0341)	0.0407 (0.0407)	0.0479 (0.0479)
40	Experimental (Fuzzy)	0.0210 (0.0210)	0.0269 (0.0269)	0.0332 (0..0332)	0.0359 (0.0359)	0.0370 (0.0370)

Table 6.7 Experimental and fuzzy drying rates ($g/m^2/s$) (heat pump drying)

	Temp. (°C)	30	40	50	60	70
RH (%)						
10		0	0	0	0	0
20		0	0	0	0	0
30		0	0	0	0	0
40		0	0	0	0	0

Table 6.8 Percentage error (%) (experimental-fuzzy heat pump drying rates)

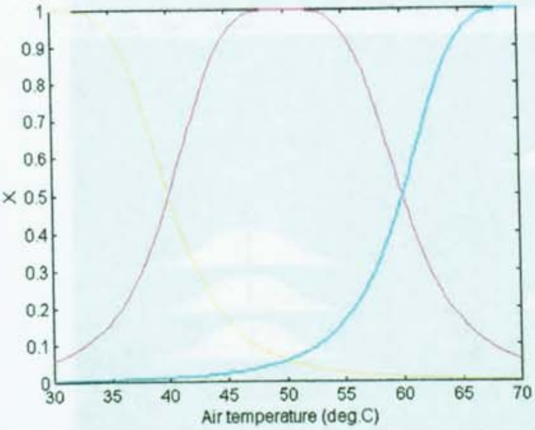


Figure 6.45 Initial MFs (heat pump)

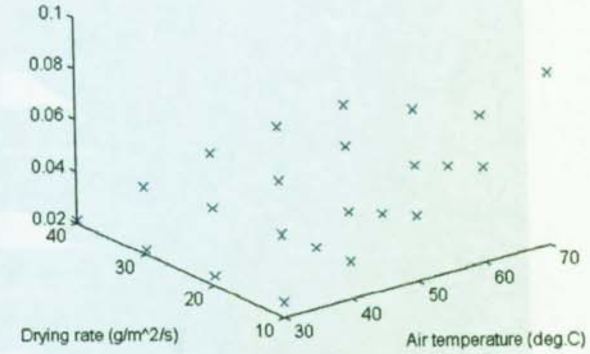


Figure 6.46 Training data (heat pump)

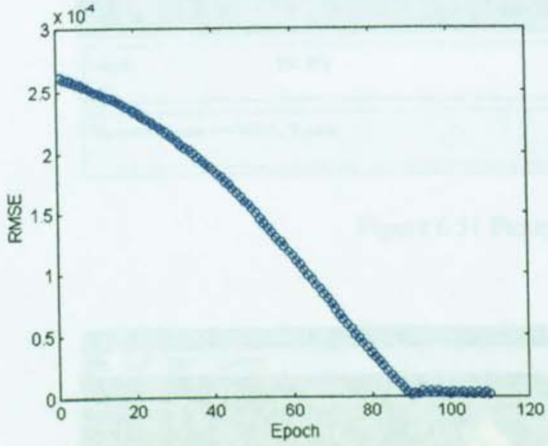


Figure 6.47 Training RMSE (heat pump)

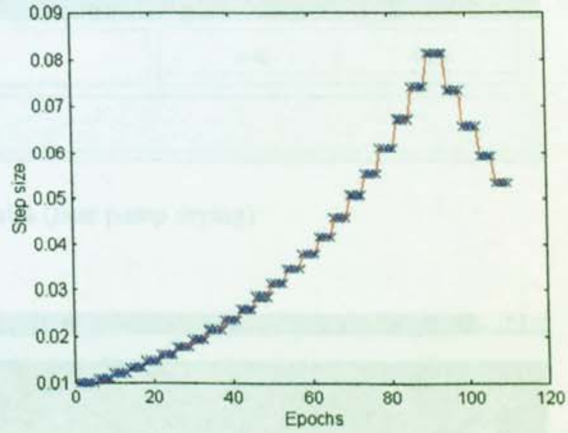


Figure 6.48 Step size reduction (heat pump)

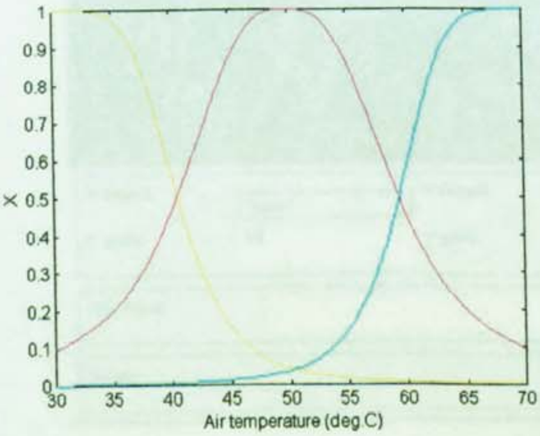


Figure 6.49 Adapted MFs (heat pump)

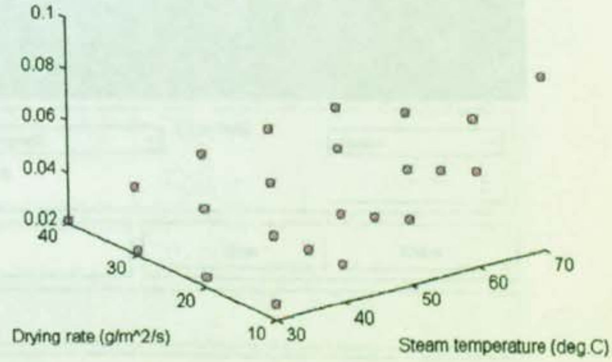


Figure 6.50 Model output (heat pump)

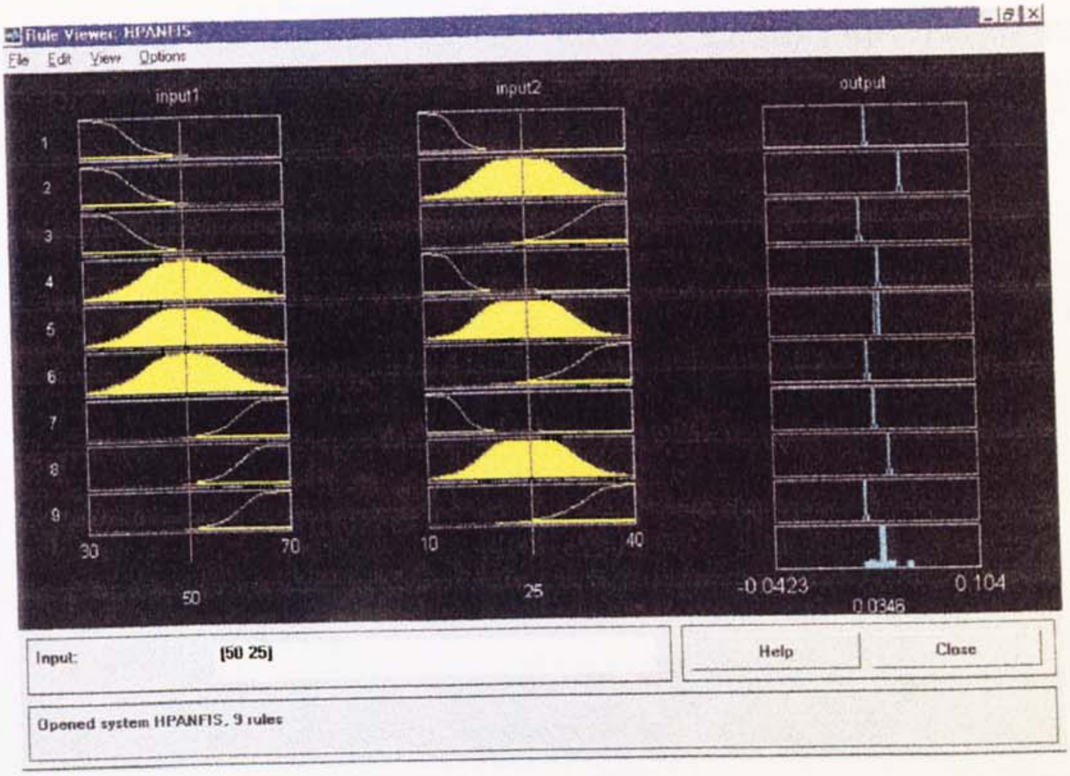


Figure 6.51 Fuzzy rules (heat pump drying)

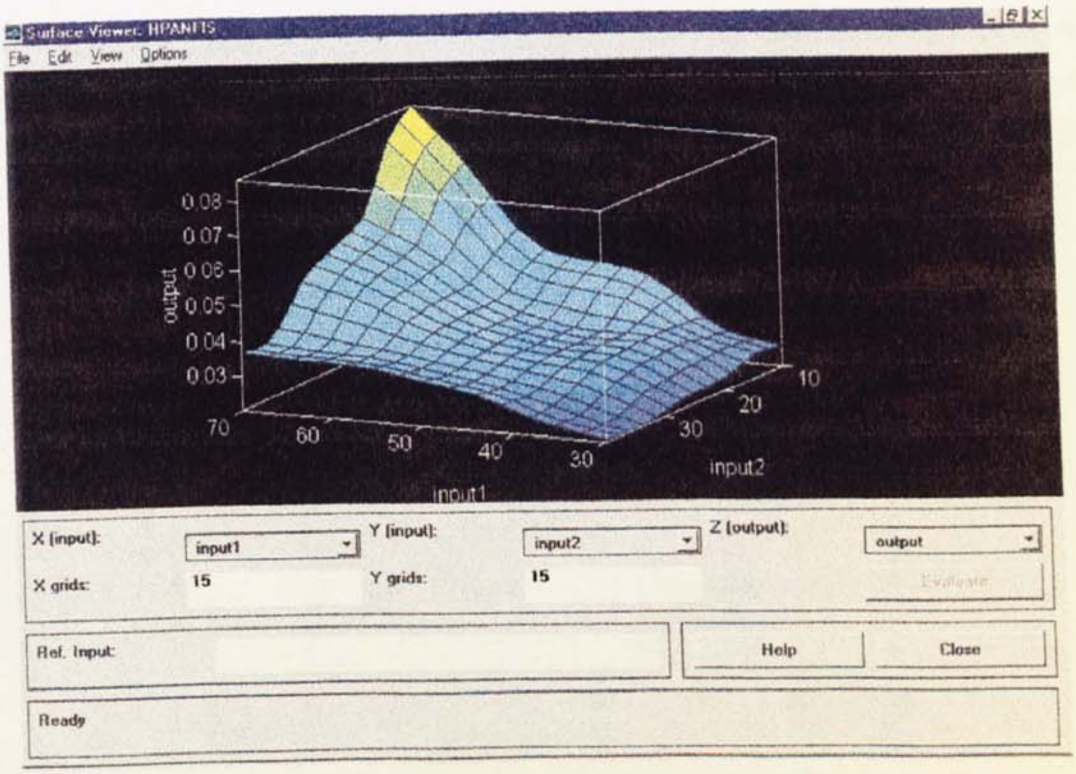


Figure 6.52 Output surface (heat pump drying)

Comparison of Drying Rates: The Inversion Temperature

A direct comparison between drying rates provides a useful tool for the assessment of relative drying time. Figure 6.53 illustrates air and superheated steam drying rates as a function of gas temperature. Air drying is assumed to operate with no humidity control.

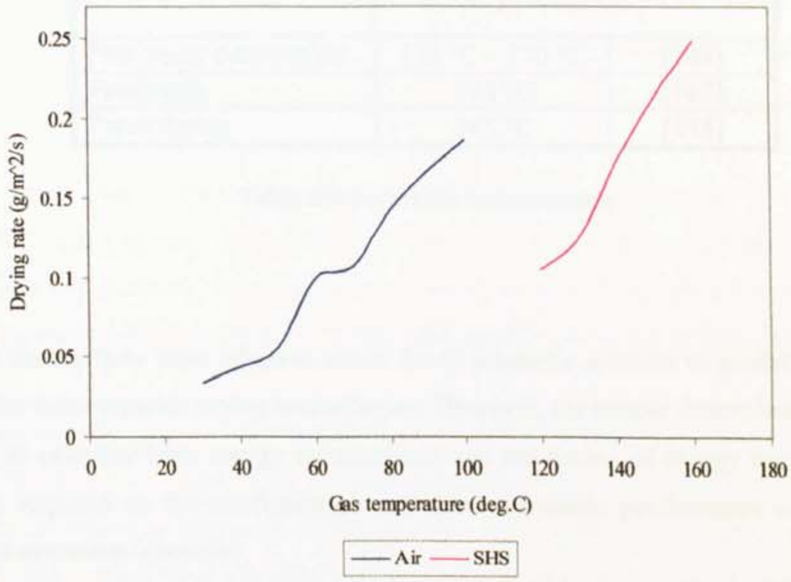


Figure 6.53 Drying rate comparison: air drying vs. airless drying

At the temperatures tested, airless drying only begins to demonstrate superior drying rates at steam temperatures above 140 °C. Assuming that both drying disciplines show an ostensibly linear increase in drying rate, the data series can be extended to find the inversion temperature. Figure 6.54 illustrates the extrapolation of data for higher gas temperatures.

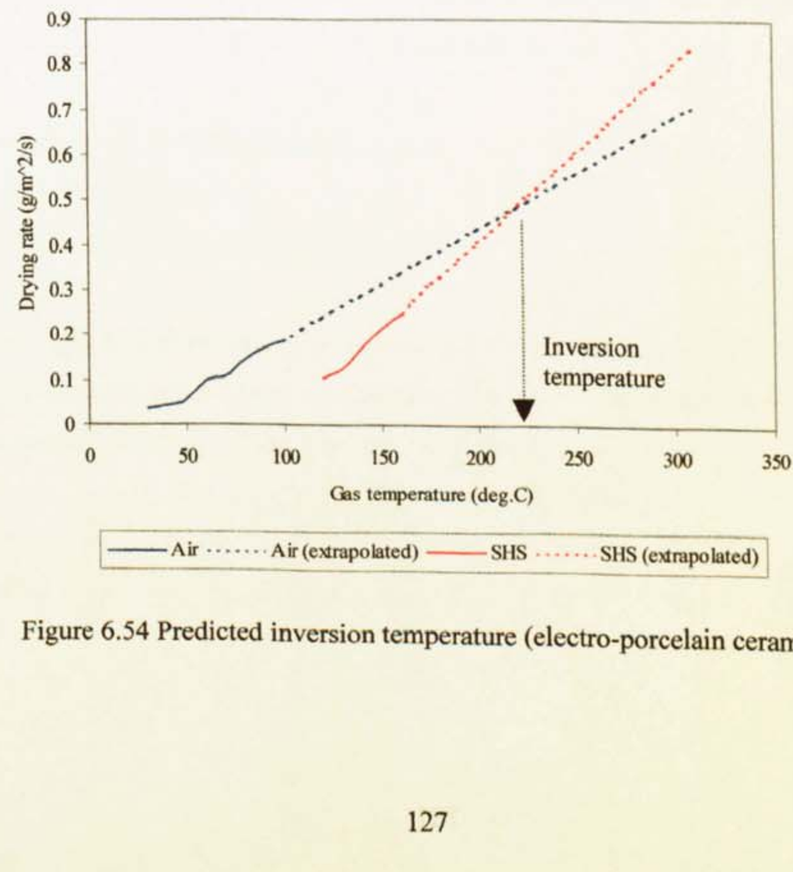


Figure 6.54 Predicted inversion temperature (electro-porcelain ceramic)

Equating the trendlines, it can be suggested that the inversion temperature approximates to 220 °C. As far as the author is aware, this is the first published work to estimate the inversion temperature of electro-porcelain clay. Table 6.9 summarises previous estimates of inversion temperature found in literature.

Study	Inversion Temperature	Reference
Free water evaporation	150 °C – 170 °C	[104]
Foodstuffs	175 °C	[167]
Paper drying	245 °C	[148]

Table 6.9 Inversion temperatures

Summary

Chapter 6 has successfully used adaptive neuro fuzzy inference systems to model the drying rates of clay material for three separate drying technologies. However, the simple determination of 'drying rate' is insufficient to calculate both energy consumption and the timing of energy use for drying. Further information is required on the configuration and thermodynamic performance of dryers, factors of production and operation schedules.

To this end, chapter 7 takes the fuzzy models developed within this chapter and incorporates them into an energy services tool for the prediction of energy demand for drying.

CHAPTER 7

FUZZY LOGIC TOOL FOR ENERGY SERVICES

Introduction

Chapter 6 presented a novel fuzzy logic model for the prediction of drying rates. This unique fuzzy approach allows for rapid and frequent up-dating of the model, without the need for the expert knowledge frequently required by more specialised mathematical and neural network approaches.

Previous chapters have highlighted a need for an automated system capable of aiding the Public Energy Supplier (PES) and customer determine the benefits of energy efficient drying methods; particularly as an integral part of a market-led energy services approach to DSM. The author believes that an energy services model can be successfully integrated with the fuzzy prediction system discussed in the previous chapter.

This chapter uses the MATLAB computing environment to derive a set of simplified energy services models for air, airless and heat pump dehumidification drying. The purpose of these models is to illustrate the potential for automated analyses of dryer energy use. To the best of the author's knowledge, this work is unique in being the first to describe a computerised simulation model of energy use for drying in the context of DSM. Moreover, the author believes this to be the first energy services simulation to incorporate FISs.

Model Development

Although the scope of energy services is wide and varied, the primary objective is reduced energy consumption at the point of use. Secondary aims include improved production factors and reduced atmospheric emissions. The model outputs can be suggested as,

- Energy use and energy costs
- Overall drying time
- Cumulative carbon dioxide emissions.

Input data must be in a form which can be both easily interpreted and readily available to the PES and/or customer. To this end, input data was sub-divided into the three groups: material characteristics, energy and drying system characteristics, as presented in table 7.0.

Material characteristics	Drying system characteristics	Drying rate	Energy data
• Starting and final moisture contents	• No. of fans	• Drying rate ($g/m^2/s$)	• Gas cost (p/kWh)
• Starting 'wet weight'	• Fan rating		• Electricity cost (p/kWh)
• No. of pieces	• Dryer size		• Burner efficiencies
• Average product surface area			• Thermal efficiencies

Table 7.0 Model input requirements

Figure 7.0 provides a basic high level overview of the model in graphical form.

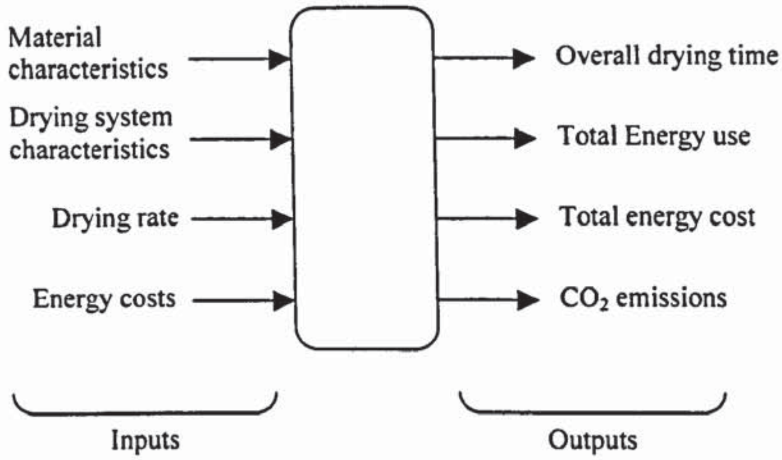


Figure 7.0 Basic model overview

All three energy models display a significant degree of commonality, in particular the calculation of drying time, energy cost and carbon dioxide emissions. Figure 7.1 presents the generic model structure in which the common sections are highlighted in green. Energy calculation modules remain dependent upon the specific drying discipline modelled. Data input and outputs for figure 7.1 are signified by blue and red arrows respectively.

The use of common modules demonstrates significant benefits, including

- reduced programming effort
- a manageable and simple to follow model structure
- easy maintenance of modules
- easy refinement of individual modules.

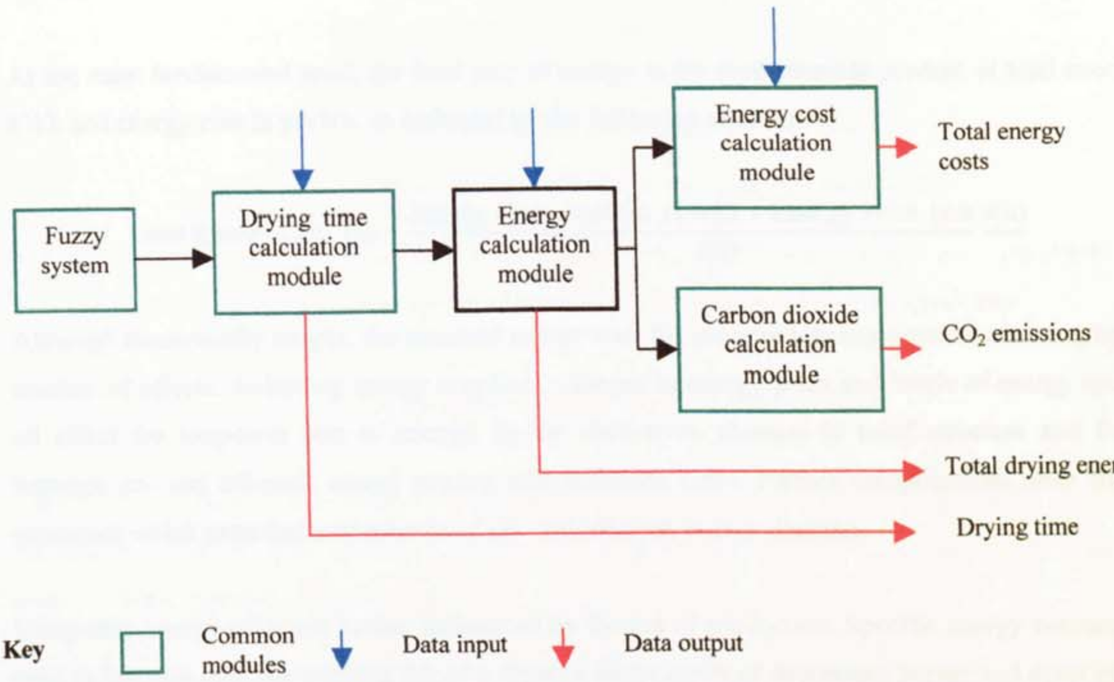


Figure 7.1 Generic model structure

The following sections provide a brief explanation and discussion of the common calculation modules. All modelling was undertaken using Matlab in conjunction with Fuzzy Logic and Simulink Toolboxes.

Drying Time Module

It has been shown previously that drying rates are a function of a multifarious range of variables: drying temperature, relative humidity and air velocity dominating during the constant rate period, with material characteristics dictating during the falling rate. Once a fuzzy system has been established to determine the drying rate it is relatively easy to calculate overall drying time using the following equation.

$$\text{Overall Drying Time (hrs)} = \frac{3600 \times (\text{Start MC} - \text{Final MC})(g)}{\text{Drying Rate } (g/m^2/s) \times \text{Product Surface Area } (m^2)}$$

In this particular instance, 'overall drying time' is simply the estimated minimum required drying time based on empirically derived data. Practical industrial drying cycles often incorporate a factor of safety (FoS) into the drying schedule, thus ensuring all product are fully dried. Furthermore, in mixed batches the drying cycle is usually dictated by the piece which takes longest to dry. The result is significant over-drying of smaller products, or products with lower moisture contents.

For the purposes of an ES model, it has been assumed that products are of equal starting moisture content, surface area and experience similar drying conditions at all points within the dryer. A linear sliding gain has been incorporated to accommodate the use of FoSs in the drying schedule.

Energy Cost Module

At the most fundamental level, the total cost of energy is the mathematical product of total energy use in kWh and energy cost in p/kWh, as indicated by the following equation.

$$\text{Total Energy Cost (£)} = \frac{\text{Energy Consumption (kWh)} \times \text{Energy Price (p/kWh)}}{100}$$

Although theoretically simple, the practical energy cost for industrial drying processes is complicated by a number of effects. Switching energy suppliers, changes in energy price and levels of energy taxation will all effect the long-term cost of energy. In the short-term, changes in tariff structure and fluctuations between on- and off-peak energy pricing will influence costs. Further complications arise from drying processes which extended across times of on- and off-peak energy demand.

Long-term energy costs are further influenced by factors of production. Specific energy consumption will tend to increase over the working life of a dryer; a direct result of decreasing burner and dryer efficiencies. Changes in working practices such as schedule length and dryer maintenance also impact on patterns of energy use.

For the purpose of easy solution, a constant energy cost has been taken throughout the simulation. At the time of writing (August 1999), analysis of industrial ceramics manufacture indicates a typical energy price of 4.2 p/kWh electricity and 1 p/kWh gas [123] [27] [180].

Carbon Dioxide Emission Module

Combustion of natural gas is the main energy source for modern industrial drying operations [24]. Natural gas is a mixture of methane, smaller amounts of higher order hydrocarbons and other gases. However, for the purpose of combustion calculations, natural gas can be treated as pure methane (CH_4) [19].

Assuming complete combustion in air, the stoichiometric equation for the burning of natural gas is given by,

$$CH_4 + 2(O_2 + 3.76N_2) \rightarrow CO_2 + 2H_2O + 7.52N_2$$

As a molecular proportion, carbon dioxide accounts for only 10.7 per cent of total gas production from methane combustion, as indicated by table 7.1.

	Mol/mol fuel	Mol %
Nitrogen	7.52	88.3
Carbon dioxide	1.00	10.7
Sum total	8.52	100.0

Table 7.1 Products from water-free methane combustion [73]

Assuming that the enthalpy of combustion for methane, h_{cb}, is –890,360 kJ/kmol at a temperature of 25 °C (0.1 MPa), and the heating value of methane is equal to its absolute value of h_{cb}, such that

$$\text{Heating value} = |h_{cb}| \qquad \text{(kJ/kg fuel)},$$

it is possible to form a basic relationship between energy consumption and carbon dioxide production. For the purposes of all three ES models, it is therefore assumed that 0.178 kg of carbon dioxide is liberated for every 1 kWh of natural gas consumed.

It is important to note that under industrial conditions, levels of carbon dioxide emission are complicated by incomplete combustion and changes in burner efficiency between service schedules and over the lifetime of the dryer. To account for such inherent inefficiencies, an overall burner efficiency of 80 per cent has been assumed to operate for all models.

Electricity consumption is an indirect source of carbon dioxide, producing CO_2 emissions at the point of generation rather that at its end point of use. Assuming a generation and distribution efficiency of 30 per cent within the UK [57], it can calculated that each kWh of electricity consumed corresponds to an equivalent emission of 0.5 kg CO_2 [53] [192]. Again, this equivalence has been incorporated within all three drying models.

Convective Air Drying Model

The Simulink model for convective air drying is given in figure 7.2. Blocks highlighted in red are openly available for user-defined input, allowing the user to experiment with the following variables,

- Drying gas temperature and relative humidity
- Product mass and moisture content
- Product surface area
- Number of pieces per drying unit
- Gas and electricity prices
- Dryer's fan loading.

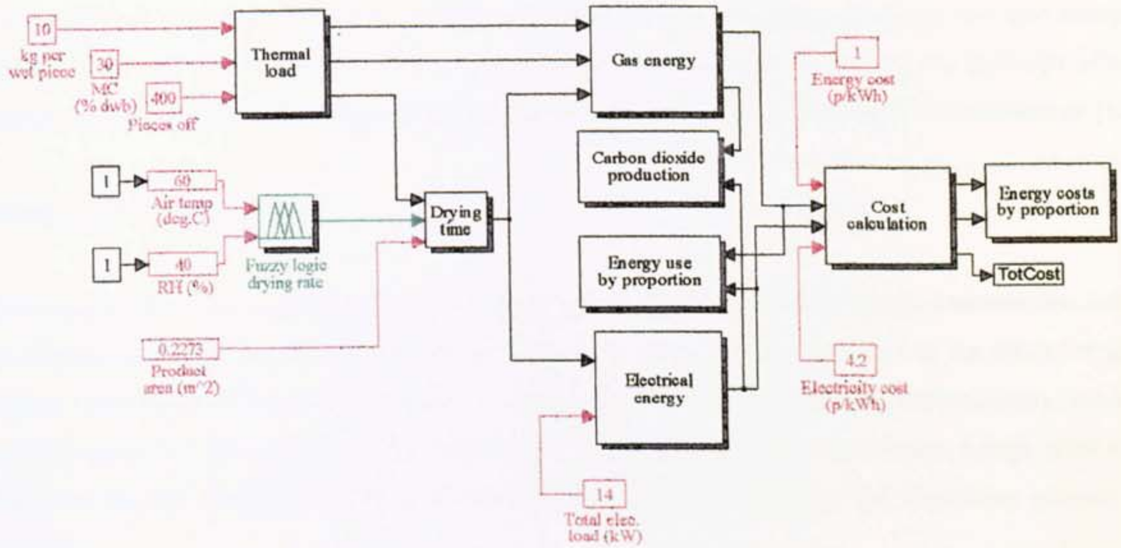
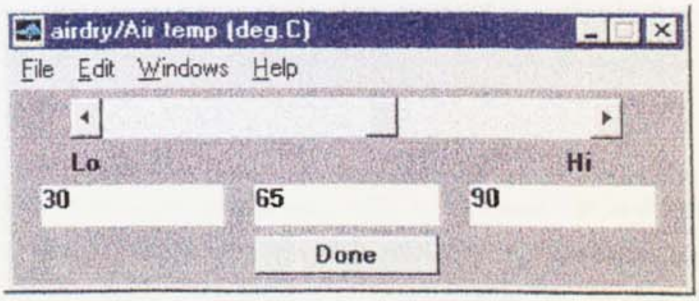
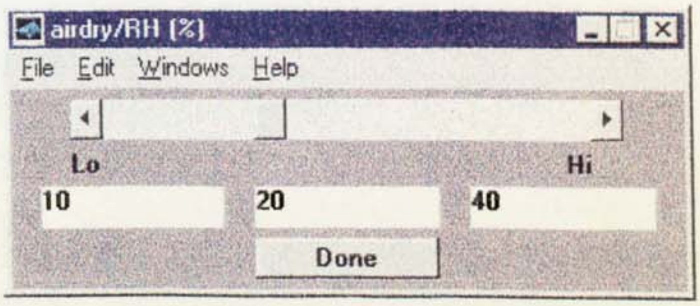


Figure 7.2 Simulink model (convective air drying)

The embedded fuzzy system is highlighted in green. To ease operation, temperature and humidity inputs to the fuzzy system are facilitated using sliding gains as illustrated in figure 7.3.



Sliding temperature input (current setting: 65 °C)



Sliding humidity input (current setting: 20 % rh)

Figure 7.3 Fuzzy model input controllers (convective air drying)

Once established, the fuzzy drying rate is routed into the drying time module together with information on product surface area and moisture content. The thermal load is calculated from material characteristics and then directed, along with 'drying time', into the energy calculation modules from where total energy consumption is determined. Once levels of energy use have been established, energy costs and carbon dioxide emissions can be calculated.

Two additional modules have been included to assimilate the proportion of energy use and energy cost allocated to each energy source. This information proves useful for modelling the potential effects on energy supply systems, particularly the interconnected networks supporting electricity distribution [123].

Energy Calculation Modules

The engineer faces a dichotomy when attempting to investigate the general energy consumption behaviour of drying systems. Initial decisions must be made as to the scope and accuracy of the results required: a high level of detail will yield a more accurate energy model and vice versa [85]. Unfortunately, most dryers are bespoke units built specifically for individual companies, processes or products. A high level of detail therefore has the detrimental effect of lowering the model's capability for describing general drying systems.

It has been suggested that for most comparative analyses it is convenient to consider the case of a simplified ideal dryer [73]. In an ideal convective air dryer, the energy derived from fuel combustion is restricted to two functions,

1. provision of sufficient latent heat to evaporate the moisture
2. provision of sensible heat used in raising the inlet air temperature to the required level for drying.

As such, only the enthalpy of process streams need to be considered under commercial drying conditions [73]. Research indicates that the most rapid method for finding the energy consumption is to undertake a thermal balance across the dryer [57] [15]. The energy balance for an ideal dryer can be performed using three temperature measurements, namely

1. Ambient air temperature
2. Temperature of air entering the dryer
3. Exhaust air temperature.

At best, the results of a simple audit will only be "rough and approximate in character", and not necessarily a good indication of true energy consumption [85]. To gain a more accurate model, the engineer requires a knowledge of both temperature and moisture of air entering and leaving the dryer, in addition to the work done by fans, heat loss through dryer walls and the energy lost in heating the dryer's furniture and structure. Unfortunately, the collection of such detailed thermodynamic data often requires lengthy and costly measurement of process stream enthalpies and logging of burner efficiency.

To maintain a balance between accuracy and generality, the decision was made to base the energy consumption of all models on specific energy consumption (SEC) values obtained from up-to-date literature and industry sources.

The use of pre-determined SEC values based on thermal efficiency has three prime benefits,

1. facilitates the direct calculation of total energy use
2. encompasses dryer losses, hence providing a reasonable indication of thermal efficiency
3. avoids the need for expensive and lengthy energy surveys.

Research suggests that modern ceramics air dryers are now capable of operating between 50 per cent and 58 per cent thermal efficiency, corresponding to SEC values between 3,965 kJ/kg and 4,600 kJ/kg [63] [24]. A detailed study of the UK ceramics industry indicates that SECs ranging from 4,600 kJ/kg to 7,667 kJ/kg are common [121]. The ES model given in this chapter allows the user to define a SEC value between 3,965 and 7,667 kJ/kg.

The calculation of energy consumption for air drying has been divide between the two prime energy sources: natural gas and electrical energy. Input and output data from the energy calculation modules is given in figure 7.4.

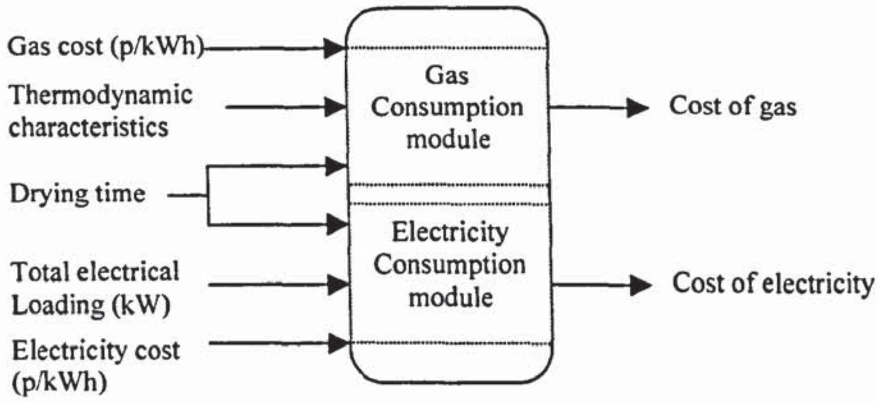


Figure 7.4 Energy calculation by fuel type

Electricity Consumption

Traditionally, fan work has been viewed as a 'small item' in comparison to fossil fuel consumption [73]. However, more recent studies demonstrate that the constant running of fans over lengthy drying cycles, and the inherently higher associated cost of electricity, highlights electrical energy consumption is an important area of study [123].

A good approximation of electricity consumption can be made from simply assessing a dryer's total electrical load, the main source of which derives from motors driving re-circulation, burner and exhaust fans. Assuming that motors run at rated capacity throughout the warm-up, drying and cooling stages, total electrical energy consumption is equal to the mathematical product of electrical load in kW and total drying time in hours.

For the purposes of model simplification it is assumed that no steam or water vapour injection is used during the drying cycle. Although steam injection has been found to account for significant instantaneous electrical demand on convective air batch dryers [123] [47], the exact contribution to overall energy consumption cannot be predicted accurately without detailed and lengthy on-line logging of demand.

Airless Drying Model

The Simulink model for airless drying is given in figure 7.5.

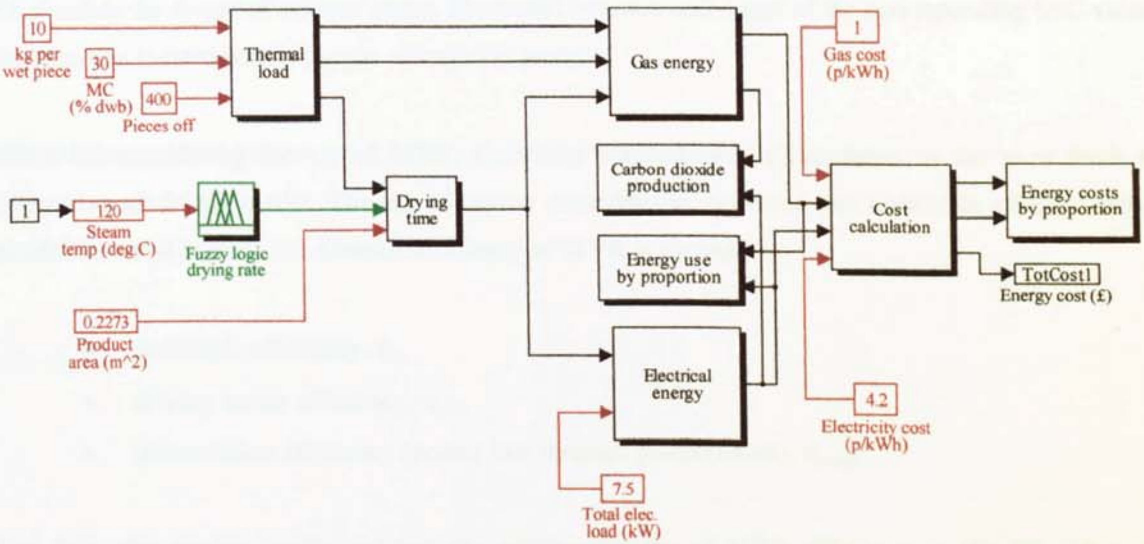


Figure 7.5 Simulink model (airless drying)

Operation of the airless drying model closely follows that of the convective air drying model described previously. Again, user-defined inputs are given in red type and the embedded fuzzy prediction system in green type.

The fundamental differences between the air and airless drying models are two-fold. For airless modelling,

- the fuzzy system is restricted to a single input
- the SEC values can be defined externally to the gas energy calculation module.

Energy Calculation Module

The energy savings which accrue from superheated steam drying are directly related to the use of the dryer's exhaust stream. For an explanation of airless dryer operation and its energy saving potential, the reader is directed to the detailed discussion provided in Chapter 3.

A variety of scenarios have been included into the ES model to account for the alternative uses of exhaust steam, as summarised in table 7.2.

Application of exhaust steam re-use	SEC (kJ/kg water)	Thermal efficiency, η_{th} (%)
No re-use of exhaust	3,583	65
Water heating	3,066	75
Multi-stage drying	3,066	75
Mechanical Vapour Re-compression (MVR)	2,875 – 2,556	80 - 90

Table 7.2 Alternative uses of the airless dryer exhaust

To simulate the re-use of exhaust steam, the model requires user-input of the corresponding SEC value into the data-box located within the gas calculation module.

When not considering the use of MVR, electricity consumption is calculated on the same basis as the convective air drying model. The use of vapour compression, however, has a variable effect of efficiency as demonstrated in table 7.2. Overall efficiency of MVR is dictated by

- isentropic efficiency, η_{is}
- driving motor efficiency, η_{mot}
- transmission efficiency (power loss through gearbox/belt), η_{trans}.

The following section briefly outlines the implementation of MVR efficiency in the ES airless drying model.

MVR Efficiency

Figure 7.6 provides a schematic of a compressor and its energy parameters [208].

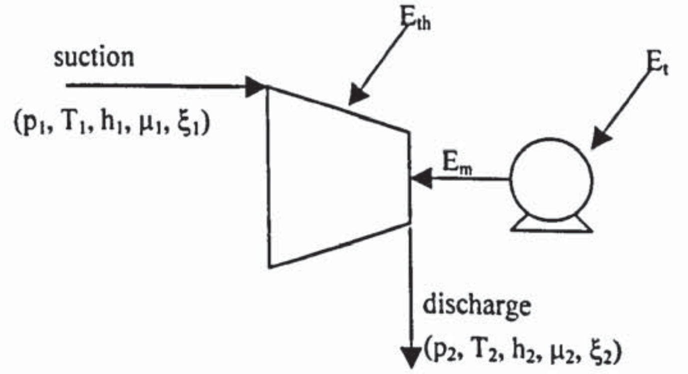


Figure 7.6 Compressor energy analysis [208]

Vapour enters the compressor at state 1 and exits at state 2. The Bernoulli equation governing energy transfer is given by

$$E_{th} + E_m = (h_2 - h_1) + \frac{(u_2^2 - u_1^2)}{2} - g.(\xi_2 - \xi_1) \qquad (kJ/kg)$$

E_{th}	Supplied thermal energy [kJ/kg]	u	Fluid velocity [m/s^2]
E_m	Supplied mechanical shaft energy [kJ/kg]	ξ	Elevation from inlet to exit [m]
h	Fluid mass enthalpy [kJ/kg K]		

Assuming that the compressor is perfectly insulated, and that differences in kinetic and potential energy are negligible, the energy equation reduces to,

$$E_m = h_2 - h_1$$

Assimilating compression to polytropic behaviour, the mechanical energy supplied to the compressor can be given as,

$$E_{m_{pol}} = \frac{E_{m_{is}}}{\eta_{is}}$$

where,

$$E_{m_{is}} = C_p.T_1.\left[\left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}} - 1\right]$$

C_p	Specific heat [kJ/kg K]	p_2	Vapour outlet pressure [bar]
T_1	Vapour inlet temperature [K]	k	Isentropic compression coefficient
p_1	Vapour inlet pressure [bar]		

To calculate electricity demand, mechanical shaft energy is treated as follows,

$$E_t = \frac{E_{m_{pol}}}{\eta_{mot} \cdot \eta_{trans}}$$

Table 7.3 indicates model inputs and their default values taken from literature. The open architecture of the ES airless model allows the user to define inputs as required.

Input	Default value	Units
η_{is}	0.80	n/a
$\eta_{mot} \times \eta_{trans}$	0.85	n/a
C_p	2.03	kJ/kg
k	1.30	n/a
T_1	378	K
p_1	1	bar
p_2	1.4	bar

Data sources: [208] [19]

Table 7.3 Default compressor data (airless drying)

Heat Pump Dehumidification Dryer

The Simulink model for heat pump dehumidification drying is given in figure 7.7.

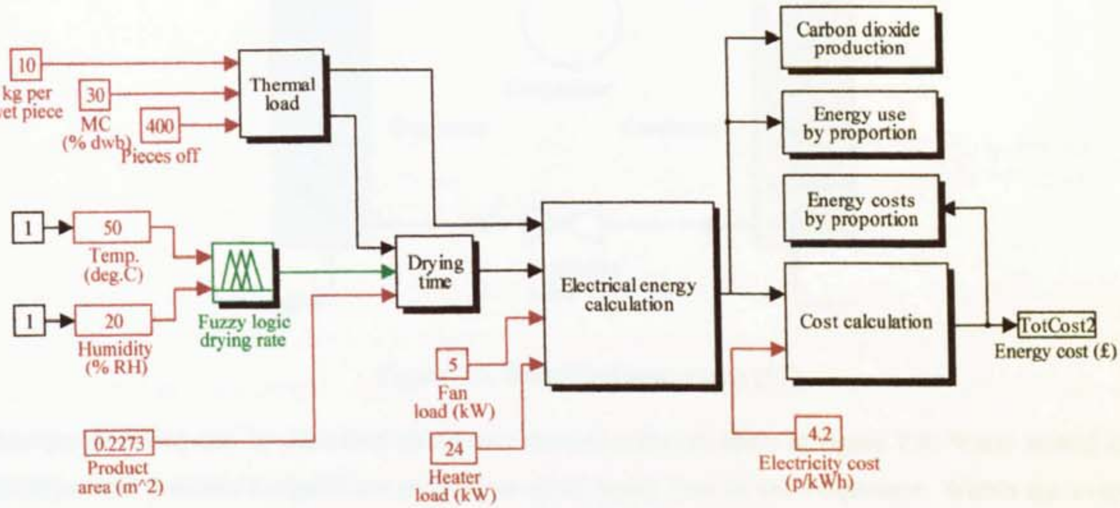


Figure 7.7 Simulink model (heat pump dehumidification drying)

As with air and steam drying, the heat pump model is constructed around common core modules. The fundamental difference for dehumidification drying is the exclusion of the gas consumption module. Whilst convective air dryers use direct or indirect fossil fuel combustion as the main energy source, dehumidifiers use electrical energy to upgrade the heating potential of a refrigerant within a closed heat pump cycle.

Prior to discussing implementation of the energy calculation module, the author deems it necessary to provide a brief description of heat pump theory and operation.

Heat Pump Theory

In its simplest form a heat pump dryer is a thermodynamic machine using four simple mechanical devices: a compressor, condenser, expansion valve and an evaporator. Figure 7.8 illustrates a simplified heat pump system which operates on a reverse Rankine cycle.

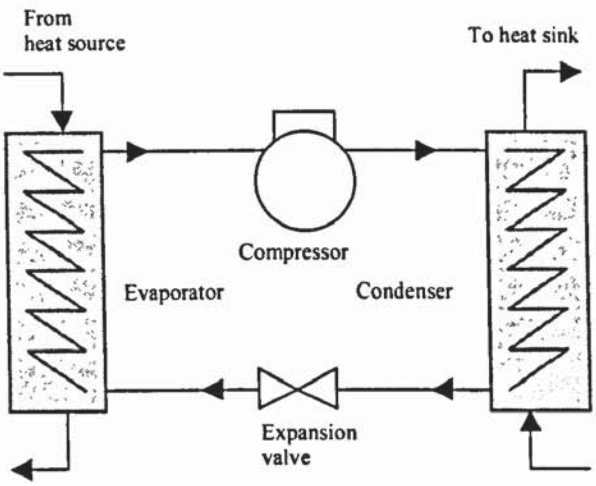


Figure 7.8 Simplified heat pump [57]

Heat pump drying can be described using the pressure-enthalpy chart in figure 7.9. Warm humid air exits the dryer and transfers a significant proportion of its latent heat to the evaporator. Within the evaporator, liquid refrigerant is boiled off at low temperature and pressure, P_e (point 4 to 1).

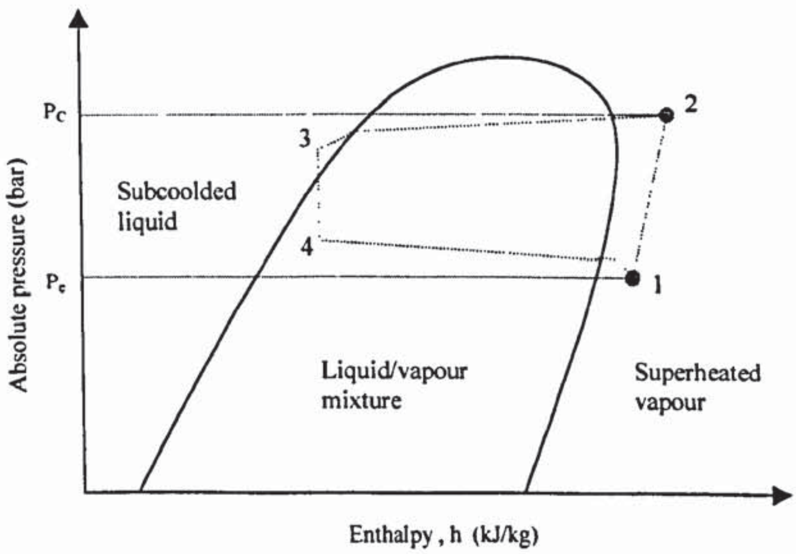


Figure 7.9 P-h diagram (heat pump refrigerant)

The refrigerant vapours are compressed to the condensation pressure, P_c (point 1 to 2), and then condensed in the condenser (point 2 to 3). Upon condensing the refrigerant's latent heat is rejected to the heat sink, namely the dry air entering the drying chamber.

Heat pump performance

Heat pump performance is measured using a coefficient of performance (COP) and is given as the ratio of useful heat output to input work.

$$COP = \frac{\text{Useful heat output}}{\text{Work input}}$$

For practical purposes the overall COP can be calculated as,

$$COP_{overall} = \frac{Q_c}{E} = \frac{m(h_2 - h_3)}{E}$$

Q_c Condenser heat output (W)
E Electrical consumption (W)
m Liquid refrigerant mass flow rate ($kg/m^2/s$)
h_2 Off-compressor enthalpy (kJ/kg)
h_3 Off-condenser enthalpy (kJ/kg)

Assessment of heat pump dehumidification dryers is measured using specific moisture extraction rate (SMER) rather than COP. SMER is defined as the mass of water evaporated per unit of energy input ($kg_{wat.}$ kWh^{-1}). Practical heat pumps operate using SMER values between 1 and 4 kg kWh^{-1}, with average performance between 2.0 and 2.5 kg kWh^{-1} [57]. In general SMER is found to increase with increased temperature and humidity [1] [72] [124] [57].

Energy Calculation Module

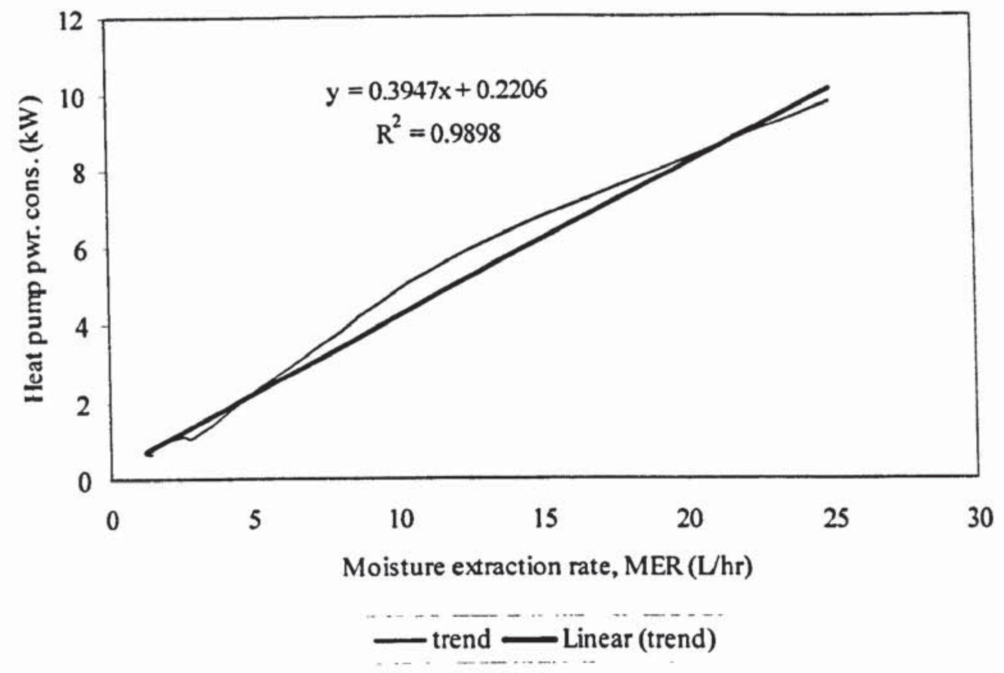
The use of first-principles thermodynamic relationships to calculate performance was deemed too specific for generalised modelling. Calculation of energy use was subsequently based on performance data sourced from heat pump manufacturers. Use of manufacturers' data has two distinct benefits,

1. data is representative of 'real world' performance
2. quoted SMER/MER values incorporate motive fan power within the heat pump unit.

A literature survey indicated that heat pumps used for ceramics drying operate at conditions which ensure products are not susceptible to excessive drying rates, typically 50 °C [72] [186] [176]. To this end, data was collected from manufacturers detailing the performance of heat pumps operating over the temperature range 20 °C and 50 °C. Figure 7.10 indicates total heat pump power consumption as a function of humidity averaged moisture extraction rate (MER).

Fitting a linear trendline to data in figure 7.10 allows the heat pump model to derive an approximate electricity load from a time-averaged evaporation rate. Total energy use can then be calculated over the full drying cycle. Trendline accuracy gives an R^2 value of 0.99.

Although energy use within a pre-packaged heat pump unit is primarily a function of compressor load, additional electrical load is required inside the drying chamber. Heaters are used for initial warm-up duties and baffle-mounted fans provide air recirculation within the dryer. Research suggests that a typical heat pump dryer used for ceramics drying will use 5 re-circulation fans of 1 kW rating each, and two electric heaters rated at 12 kW each [186]. Air re-circulation operates throughout the drying cycle, whilst heating occurs typically for the first 30 minutes only.



Source: Manufacturers information sheets [176] [186]

Figure 7.10 Heat pump compressor load vs. humidity averaged MER (50 °C)

Data Comparison

A separate 'comparator' module was configured to run in the Matlab workspace. This program provides a structured comparison between drying times, energy use, energy costs and carbon dioxide emissions for all 3 drying models.

Model Validation

Validation of the energy services models described in this chapter is difficult. Discussion with production engineers in the UK sanitaryware industry indicates that monitoring of energy use and energy costs for drying is infrequent or non-existent. Information detailing energy use was found to be available on an overall site basis only, with no sub-division by process or individual production unit. On visiting sanitaryware manufacturing sites, it became apparent that no sub-metering of electricity supply existed other than for large kilning operations [123].

The following section provides a case study for the drying of electro-porcelain. The case study has been chosen to demonstrate the energy services modelling systems described within this chapter.

Case Study: Drying of Electro-Porcelain

Porcelain clays are hygroscopic in structure. Such materials possess a dispersion of predominantly fine pore spaces which act to retain substantial amounts of bound water. The reduced vapour pressure exhibited by bound water over that of 'free' liquid water serves to lengthen drying residence times and/or serves to increase applied driving forces. Shrinkage during early drying is common [15] [85]. Furthermore, the thickness of electrical insulators differs significantly in cross-section, resulting in the preferential drying of the thinner ribs over the main body.

To minimise the risk of product distortion, it becomes necessary to administer "mild conditions" during the first and most critical stage of convective air drying [15]. As such, products are initially subject to low temperatures and high relative humidities. Higher temperatures are reserved for the final stages of drying when products have gained sufficient dry strength to withstand higher drying rates.

Current Drying Regime

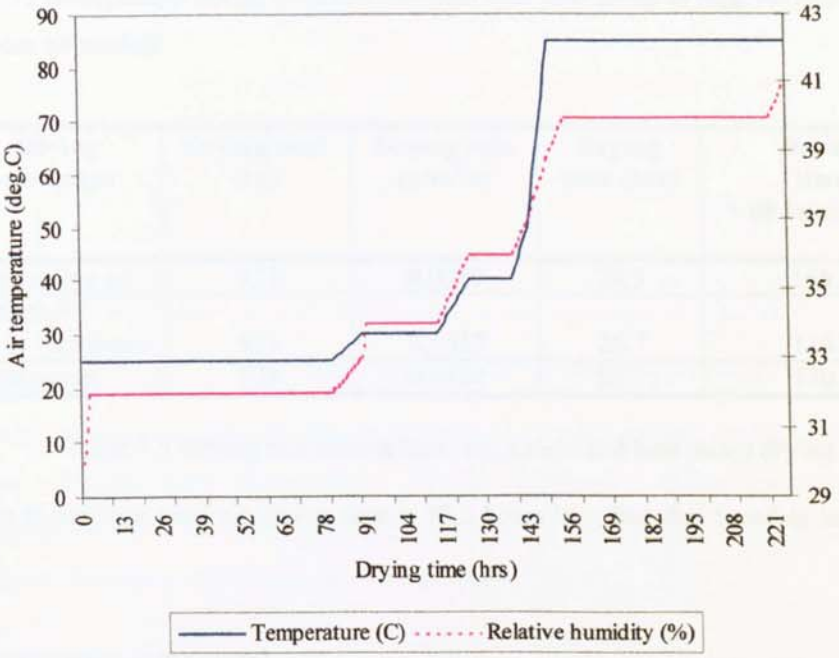
After shaping, insulators are set on wooden batts for a period of 2 days. This process, commonly termed 'ageing', allows moisture to distribute evenly whilst enabling the relaxation of residual stresses within the product. At the end of this period the shapes are carefully transported into a heat pump dehumidification chamber where a gentle drying schedule is administered over a period of 2 days. Heat pump drying allows for gradual first-stage drying of the product free from the cracks and sub-surface defects which result from rapid drying.

The operational temperature and humidity of the heat pump cycle is maintained at a constant 40 °C and 20 % rh. Products exit the heat pump dryer with a typical moisture content of 26 % dwb [23].

Once a desired level of moisture has been reached using heat pump dryers, direct convective air drying is used for the final drying stage. Chamber drying typically lasts for 225 hours (9.4 days) and follows the schedule given in figure 7.11.

The chamber is maintained at a constant factory temperature of 25 °C for the first 82 hours of drying. During this period relative humidity is increased to 19 % in order to suppress evaporation. Essentially, this lengthy pre-drying period allows for relaxation of stresses introduced at the heat pump drying stage. Drying proper commences from 88 hours onwards.

The main priority for electro-porcelain manufacturers is to reduce bottleneck drying times, thus decreasing production lead-time. In this instance, product quality is given a high priority and energy cost minimal priority.



Source: UK insulator manufacturer

Figure 7.11 Typical chamber air drying schedule for 6 inch diameter ceramic insulators

Example Problem

A manufacturer of electrical porcelain insulators runs 2 convective air dryers simultaneously for 42 weeks a year. Each dryer is of modern design and is capable of holding 400 pieces of 152 mm diameter and 380 mm height. All pieces have a wet weight of 10 kg and a moisture content of 30 per cent dwb. It is assumed that both dryers are modern designs operating at overall efficiencies of 50 %.

Assuming that the first 88 hours of processing are not used to dry ware, what are the potential benefits from using airless dryers for the remaining drying time ? Alternatively, what benefits can be realised form continuing the drying schedule using heat pump dehumidifiers ?

Equating the current drying schedule (figure 7.11) with the air drying simulation is complicated by the existence of dwell periods throughout the cycle. Nevertheless, for the purposes of this study air drying temperature and humidity can be approximated as the weighted average across the drying schedule. Table 7.4 gives the drying conditions assumed for each drying discipline.

	Air drying	Airless drying	Heat pump drying
Gas temperature	65 °C	120 °C	50 °C
Relative humidity	40 %	n/a	20 %

Table 7.4 Drying conditions (simple example)

Table 7.5 presents output data which suggests that airless drying exhibits a significantly higher drying rate compared to heat pump and convective air drying. Overall, airless operation is expected to reduce air drying time by 52 hours, whilst taking 55 hours less time than heat pump drying. As expected, thermal load is identical across all models.

Drying discipline	Drying load (kg)	Drying rate ($g/m^2/s$)	Drying time (hrs)	Drying time + 88 hours (hrs)
Convective air	923	0.0359	78.5	166.5
Airless				
No re-use	923	0.1057	26.7	114.7
Heat pump	923	0.0344	82.1	170.1

Table 7.5 Drying rate comparison: air, airless and heat pump drying

It is interesting to note that total air drying time is 58.5 hours less than that found in industry. This can be explained by,

- inaccuracies in the model
- errors in estimating equivalent drying rates to account for dwell periods
- the inclusion of FoS into the industrial drying schedule.

Discussion with an insulator manufacturer suggest that FoSs of 25 per cent are not unusual.

Table 7.6 gives estimated costing and carbon dioxide emission levels.

Drying discipline	Total cost (£)	Cost/piece (p)	CO_2 output (kg)
Convective air	£ 60.87	15.2	760
Airless			
No re-use	£ 19.90	5	264
Water heating	£ 18.24	4.6	240
Multi-effect	£ 18.24	4.6	240
MVR	£ 17.11	4.3	224
Heat pump	£ 33.80	8.5	402

Table 7.6 Costing and carbon dioxide emissions

Airless drying demonstrates substantial cost benefits over both air and heat pump drying. Neglecting the additional use of exhaust energy, steam drying provides an estimated cost saving of £ 41 per cycle over air drying, and £ 14 per cycle over heat pump drying. This relates savings of 10 p and 3.5 p per piece respectively. It is interesting to note that dehumidification drying shows substantial cost savings over air drying for approximately the same drying time.

Drying discipline	Gas energy/ Electrical energy	Percentage gas energy	Percentage elec. energy
Convective air	1.3	57 %	43 %
Airless			
No re-use	5.7	85 %	15 %
Water heating	4.9	83 %	17 %
Multi-effect	4.9	83 %	17 %
MVR	4.3	81 %	19 %
Heat pump	0.0	0 %	100 %

Table 7.7 Energy comparison: air, airless and heat pump drying

Tables 7.7 and 7.8 present data on proportional energy use. Airless drying demonstrates a lower dependence on electricity than air drying. It can be suggested that the higher thermal capacity of superheated steam results in the requirement for reduced fan size and power [86]. On a cost basis, all drying disciplines demonstrate significant use of electrical energy.

Drying discipline	Gas cost/ Electrical cost	Percentage gas cost	Percentage elec. cost
Convective air	0.32	24 %	76 %
Airless			
No re-use	1.37	58 %	42 %
Water heating	1.17	54 %	46 %
Multi-effect	1.17	54 %	46 %
MVR	1.04	51 %	49 %
Heat pump	0	0 %	100 %

Table 7.8 Cost comparison: air, airless and heat pump drying

Modelling a Wider Range of Processes

The above case study successfully illustrates the potential application of a fuzzy based energy services model at the single business unit (SBU) level. However, to demonstrate the relevance of a fuzzy drying model as part of a targeted DSM programme, the author believes it necessary to provide an relevant example of a wide-ranging application for the system. To this end, the chapter 8 presents a rigorous case study of drying processes in the UK sanitaryware industry. The purpose of the case study is to demonstrate the potential energy savings which can accrue from the replacement of a standard convective air drying with energy efficient airless or heat pump dryers for the processing of cast ceramic sanitaryware products.

CHAPTER 8

CASE STUDY: ENERGY USE FOR DRYING IN THE UK SANITARYWARE INDUSTRY

Introduction

Sanitaryware production forms a subsector of the United Kingdom ceramics industry. Other subsectors include the Tableware, Tile, Electrical and Engineering ceramics industries. Brick production is sufficiently large to be considered an altogether separate industry [63].

Sanitaryware products include,

- Basins and sinks
- Baths
- Bidets
- Cisterns
- Channels
- Pedestals
- WCs and urinals
- Bathroom fitments.

Generally, sanitaryware pieces are larger and more complex in shape than their tile and tableware counterparts [63].

UK ceramics manufacturing is regionally concentrated in the Potteries, an area covering Stoke-on-Trent, Staffordshire. It has been estimated that the UK ceramics industry employs over 20,000 people in 1,500 companies, 90 per cent of which are located in the Stoke region [199].

The present economic climate and proposed changes in environmental regulations are increasing the commercial pressures on UK sanitaryware manufacture. Cost competition from cheap overseas imports and a mature low-growth European market are gradually leading to the consolidation of what was a traditionally small family owned industry. Above all, there is an increasing need in UK sanitaryware production to reduce manufacturing costs in what remains an essentially labour- and energy-intensive industry [209].

Previous surveys of energy use in the UK ceramics sector have been infrequent and limited in scope. This chapter presents the results of a unique industry-wide survey covering energy use for drying processes within the sanitaryware industry. The results presented are believed to be the first from a full industry-wide survey to be completed anywhere in the UK. In addition to energy estimations, this study summarises and discusses the different types and configurations of drying system presently used within the industry.

The Purpose of the Study

A detailed assessment of drying technology, and the energy used for drying, in the UK sanitaryware industry has been completed for three reasons. The assessment provides

- an accurate and comprehensive audit of energy use for drying throughout an industrial sector to a level of detail previously unrecorded. This audit essentially provides a reference against which past studies of energy use for drying can be compared and validated.

- a unique model of energy use for drying in the sanitaryware industry. This model can be used in 'what-if ?' scenario planning for energy, cost and carbon dioxide emission saving schemes aimed at benefiting the industry.

- an insight into the timing and nature of electrical energy demand and gas use for drying. Ultimately, this information will prove useful to energy supply companies targeting energy services and Demand Side Management (DSM) measures.

A Reference Study

Previous industry-wide assessments have followed a 'top-down' approach to surveying, using national, EC and OECD data to provide an adequate estimate of energy use for industrial drying on a national scale. [207] [25] [198]. Chapter 4 successfully re-evaluated the consumption of UK industrial energy for drying processes using a method devised by Hodgett [57]. However, as with all previous wide-ranging industrial energy surveys [163] [165] [63] [7], limitations and deficiencies can be readily highlighted. These limitations are not shortcomings in the survey method, but rather restrictions due to the enormity of the surveying task and the need to use summarised and approximated data.

Large-scale energy surveys sacrifice detailed information for breadth of coverage, whereas energy audits of individual manufacturing sites offer accurate 'bottom-up' assessments of energy use within specific industrial sectors [123]. The new survey presented in this chapter uses energy data collected directly from the shop floor to provide an accurate model of energy use for drying processes in the sanitaryware industry. This approach enables a reference to be set; a standard against which large-scale industrial energy audits can be compared and validated. Moreover, an accurate assessment of energy use provides a base against which the potential cost and energy saving benefits of energy efficient technologies can be accurately quantified.

Reduced Energy Costs and Carbon Dioxide Emissions

Chapter 2 discussed the comprehensive European Community (EC) strategy for reducing carbon dioxide (CO_2) emissions [200]. The strategy proposed by the EC builds upon reduced energy consumption, increased energy efficiency and fuel-switching as the most effective methods of reducing CO_2 emissions from industry [197]. Consequently, the need to limit industrial CO_2 emissions from the burning of fossil fuels highlights the efficient use of energy as an important requirement for the future assessment of legal plant operating requirements [209].

UK sanitaryware manufacturing needs to remain competitive in the face of cheap imports and new atmospheric emission standards. Reducing energy consumption for drying processes will lower emissions from the on-site burning of fossil fuels, whilst also lowering energy costs and helping protect the manufacturer from fluctuations in energy prices. The results of this unique survey enable an accurate assessment of the potential effects on CO_2 emissions and energy costs that energy efficient technologies will bring.

Energy Services and the Sanitaryware Industry

Regional Electricity Companies (RECs) are interested in Energy Services as a method of building effective long-term relationships with customers, helping the customer to reduce energy costs whilst affording the RECs an opportunity to implement Demand Side Management (DSM) measures for the optimisation of network assets.

The sanitaryware industry has been selected as a potential application of Energy Services for a variety of reasons. As discussed previously, sanitaryware drying is an energy-intensive process with the potential for reduced energy consumption. Sanitaryware manufacturing plants have also grown organically with little previous thought given to energy management. Therefore, an opportunity exists to provide expert advice on end-use technologies for energy saving drying schemes.

The regional concentration of the Potteries provides further interest for Midland Electricity. With the majority of UK ceramics manufacturers operating from the northern section of MEB's distribution network, a potential exists to control the significant cumulative electrical loading in the Stoke area. Theoretically, the transfer and application of similar energy saving technologies throughout the industry can be used as a DSM measure to influence the timing and loading of industrial electrical demand.

Large-scale energy assessments provide insufficient detail when assessing the potential for energy services at the sectorial and process levels. More specifically, attempting to model energy consumption within an industrial sector requires exacting information on the timing and nature of energy use over a production process. This survey provides sufficient detail for use in preliminary planning of Energy Services.

The Sanitaryware Industry

The world's sanitaryware industry is currently undergoing major changes in its operation and structure. Small European sanitaryware suppliers are dependent on a mature market, whilst multinational manufacturers have started to import product lines from low cost plants in emerging countries. Evidence suggests that mergers and alliances between the European producers will be necessary if the threat of cheap imports is to be reduced [52]. The resultant European market will eventually comprise of a few companies operating as large global concerns.

Cheap labour and low production costs are viewed as the driving forces of change within the $7bn sanitaryware industry [52]. American Standard's £259m acquisition of the UK's Armitage Shanks gave the US firm an estimated 18 per cent share of the European market; a market which still remains the world's largest. Large-scale manufacturers, such as American Standard, can now switch production between international sites to take advantage of reduced manufacturing costs. This forces smaller manufacturers into mergers and acquisitions to maintain competitiveness.

	Country	**Capacity (million pieces)**	**Overseas Operations (prod. plants)**
American Standard *(of which Europe)* (Armitage Shanks)	US UK	**24.0** 9.0 4.2	**21**
Keramik Laufen	Switzerland	**14.6**	**9**
Sanitec-Laufen	Finland	**8.0**	**10**
Roca	Spain	**6.5**	**4**
Villeroy & Boch	Germany	**4.0**	**3**
Sphinx-Gustavsberg	Netherlands	**4.0**	**5**

Table 8.0 Leading global sanitaryware manufacturers [52]

European sanitaryware production is clustered around a relatively small number of internationally operating companies [199]. Table 8.0 lists the world's six largest sanitaryware manufacturers by capacity. With the exception of American Standard's non-European operations, European manufacturers currently hold a strong position in the world's sanitaryware market. However, the fastest growing markets are currently situated in the Far East, Africa and South America. European manufacturers now face the threat of losing market position to manufacturers already operating within these countries.

The UK has 7 sanitaryware manufacturers operating a total of 13 production sites. Concentration of the industry has occurred over the past decade, a result of increased international competition, global recession and a downturn in the construction industry and its associated replacements market [63].

It has been estimated that 7 million pieces of sanitaryware were produced in the UK in 1995, the majority of which were exported to the United States and the Europe [121]. The results from this new survey suggest that the UK produced 9.9 million pieces in 1998.

The financial performance of the UK sanitaryware production is closely linked to that of the building industry, with new and refurbished buildings, including domestic, commercial and public structures, forming the largest market for sanitaryware in the UK [123]. By way of example, the housing market boom in the late 1980s resulted in peak sanitaryware sales of £182m (1996 prices), whereas the house market collapse in 1991 forced reduced sales of £158m (1996 prices) [63] [25].

The Sanitaryware Production Process

Ceramic ware is formed using one, or more, of the following techniques,

- Slip casting
- Isostatic pressing of ceramic granules
- Extrusion of plastic ceramic body
- Pressure casting.

Sanitaryware is formed using traditional slip casting and newly adopted pressure casting techniques.

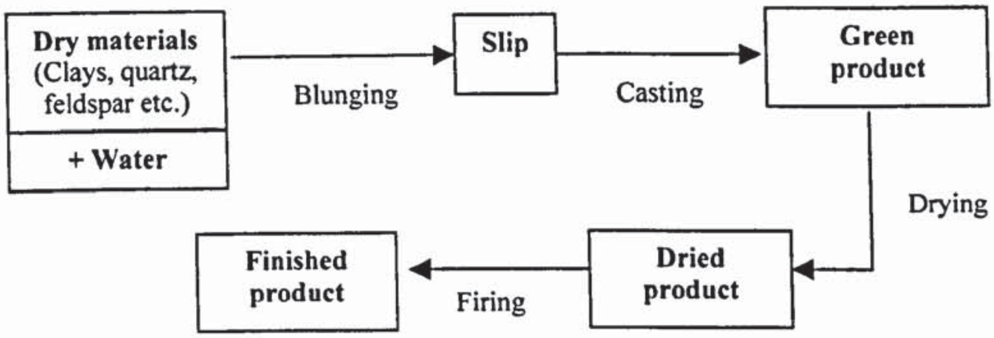


Figure 8.0 Sanitaryware production process

After forming, the ware is dried, glazed and fired. Figure 8.0 describes the sanitaryware manufacturing process from materials preparation to finished product [199].

Slip Preparation

The composition of slip used in vitreous sanitaryware varies between manufacturers and manufacturing sites. Essentially, slip is a water based suspension of china clay and ball clay; both of which are aluminosilicates. Manufacturers then add varying amounts of quartz, feldspar, fillers and binder flux as required. The final slip mixture is typically 25 % china clay, 25 % ball clay, 30 % quartz and 20 % feldspar, with a moisture content of 30 % [199].

High volume sanitaryware manufacturers often prepare slip on-site using the basic raw materials. Small-to-medium sized operations frequently out-source their slip.

Casting

Sanitaryware is formed by slip casting, although some manufacturers now use pressure casting for smaller, more simply shaped pieces. Pressure casting is also proving popular for bulk-line production of lower priced, high volume products. The majority of manufacturers use slip casting for premium quality products, primarily 'specials' and more expensive ware.

Drying of Sanitaryware and Moulds

Convective drying is an important process in the ceramics industry [33] [44] [196]. Indeed, it can be argued that drying is the most important stage in sanitaryware manufacture, with unsatisfactory drying practices culminating in glazing defects and structural failure of the ware during kilning [21]. In the worst example, pockets of moisture within the ware flash to steam during firing causing explosions within the kiln and subsequent kiln shut-downs. The result is a costly reduction in production capacity.

All UK sanitaryware manufacturers use open shop drying to a greater or lesser extent. In its simplest form, open shop drying is the storage of ware within the casting shop. The shop is maintained at constant temperature and humidity throughout the working day. After the last casting shift, the shop doors are closed and the internal environment is raised to, typically, 40 °C and 50 per cent relative humidity. Essentially, the casting shop becomes an over-sized drying chamber [123]. The alternative chamber drying method uses batch dryers designed specifically for repeatable and accurate control of optimised drying schedules. Subsequently, batch drying offers higher drying rates than traditional open shop drying.

Drying is often the most time consuming stage in sanitaryware manufacture. The need to eliminate residual moisture within the ware often results in extended drying times; typically 18 hours to 24 hours for shop and semi-dedicated ware dryers, down to 10 hours in purpose built dryers. Recent surveys suggest that drying forms the production bottleneck operation in sanitaryware production [63].[123], preventing upstream and downstream processes from operating at optimal capacity.

Drying in the sanitaryware industry is complicated further by the need to dry casting moulds prior to re-use. Casting moulds are made from porous gypsum plaster, an attribute which allows them to absorb an average 10 % moisture content (dwb) from the slip during casting. Drying removes this moisture, allowing the moulds to be recycled approximately 110 to 130 times before replacement [178]. Mould drying must take place at temperatures as low as 60 °C to prevent structural damage of the gypsum plaster. This results in extended in-dryer residence times, typically 60 hours or more.

Glazing and Firing

After drying, the ware is glaze sprayed and fired in a kiln. The application of glaze and the subsequent firing imparts structural strength to the ware, whilst preventing permeation of moisture into the piece during use.

Energy Use in the Ceramics Industry

The Energy Technology Support Unit (ETSU) published a report in 1992 which calculates that European ceramics manufacturing consumes 120 PJ of energy annually, 75 per cent (90 PJ) of which is consumed by the tile industry, with the tableware and sanitaryware industries consuming a combined 25 per cent, or 30 PJ [199]. ETSU go further by identifying key features of energy use in the ceramics industry, and by providing a typical SEC for European sanitaryware manufacture of 30 GJ per tonne [199].

Energy use in the UK ceramics industry is rarely monitored and no trends can be readily highlighted between those reports that do exist. A paper by Hodgett [57] calculated that UK ceramics production used 73 PJ in 1972, although this figure is noted as a 'very approximate guess'.

Work by Baker and Reay [7] reveals the results of an energy audit covering six broad industrial sectors in 1979. Ceramics and building materials consumed 127 PJ of energy. However, as with the work of Hodgett, no energy consumption figures for the sanitaryware industry are provided.

Energy Use in the Sanitaryware Industry

Recent surveys by Steer [123] [47], Smith [121] and Jay [63] are more explicit and detailed in their assessments of energy use in the sanitaryware industry. Jay [63] calculated the proportion of total energy consumed within the UK ceramics industry in 1995. The results are presented in figure 8.1.

To date, the most detailed treatise on energy use in sanitaryware manufacturing is provided by Steer [123] [47]. Steer collected data concurrently with the work presented in this chapter. However, rather than concentrating wholly on the drying stage, Steer approached the energy audit in terms of end-use technology application and Energy Service opportunities at all process stages, namely materials preparation, casting, drying, glazing and kilning.

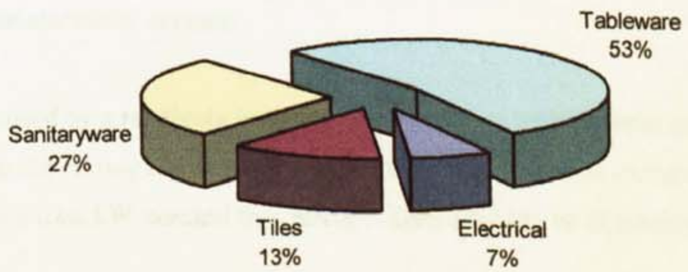


Figure 8.1 Proportion of total energy consumed in 1995 [63]

Table 8.1 summarises Steer's findings for a medium sized sanitaryware manufacturer producing between 10,000 and 12,000 pieces per week [123]. Figures for drying processes have been derived from work presented in this chapter.

Process Stage	MWh/yr Consumed	Electricity Cost (£k/yr)*	Sector Range Energy Usage (%)
Material Preparation	973	39	10–20
Casting	224	9	1–5
Drying	384	16	5-20
Glazing	37	1.5	0.5-1.0
Firing	1382	58.5	15–25
Site Services	3638	146.3	3-30
Total	**6638**	**270.2**	

* Based on constant 4.0 pence/kWh

Table 8.1 Average electricity consumption in the sanitaryware sector by process area [123]

After site services, firing consumes the greatest proportion of energy, typically 3 to 30 per cent of sectorial energy use. The open-flame tunnel kilns which dominate the industry use natural gas as their prime energy source, with electrical power utilisation accounting for between 18 % and 33 % of instantaneous site electricity demand.

Correct firing temperatures and maximum production capacity are maintained by operating tunnel kilns twenty four hours a day. The constant heating of kilns results in a continuous gas and electricity demand, giving in an average total SEC value of 14.0 GJ/tonne. Electricity is used primarily for burner, exhaust, cooling and recirculation fans, all of which account for a SEC of 0.7 GJ/tonne.

Steer indicates that materials preparation is dominated by induction motors driving grinding, mixing, and pumping devices within the blunging and storage stages. Although electricity demand for materials preparation is relatively high, it presents a predictable, relatively constant base load between 7 % and 22 % of instantaneous site electricity demand.

Casting is characterised by a relatively low energy requirement with demand suggesting an average SEC of 0.0324 GJ/t for manual casting and 0.324 GJ/t for pressure casting. The instantaneous demand between 1.0 to 2.0 per cent of site total kW demand for casting is considered to be of minimal consequence [123].

Site services is a general term covering compressor, ventilation and lighting loads. Among other uses, compressors are utilised for pressure casting giving an average sector SEC for compressors of 0.378 GJ/t and between four and seven per cent of site annual kWh consumption. Generally, lighting loads are unrelated to production variables [123].

Prior to the work of Steer, the most comprehensive record of energy use in sanitaryware production was published by Smith [121]. Smith completed a postal survey of 8 manufacturers, representing 65 per cent of the UK sanitaryware industry. Energy-use data for the full UK sanitaryware industry was calculated by extrapolating from the survey results, providing a total SEC value of 38.1 GJ per tonne of dry raw material.

A literature search indicates that previous assessments of energy use for the processing of ceramics have concentrated upon the kilning process, a major consumer of natural gas. For tableware and sanitaryware, ETSU suggest that 50 % to 80 % of total energy is consumed by kilning and between 15 % and 40 % is consumed by drying processes, with the remaining processes taking between 5 % to 40 % [199]. Smith calculates that energy consumption for sanitaryware production is split 54 %, 17 % and 29 % for kilning, drying and 'other' processes respectively [121]. Understandably, it is the significant gas consumption and electrical energy use for firing that contributes most to high annual energy costs and has, consequently, focused past research on the design, operation and efficient control of kilns rather than drying processes. Nevertheless, drying still consumes a significant proportion of total energy and offers the most potential for the application of energy saving technologies.

Energy Use for Sanitaryware Drying

Limited specific data exists on the use of energy for sanitaryware drying, a legacy of the infrequent energy monitoring that exists within the industry. Jay [63] has derived both individual SEC values and thermal efficiencies for the shop drying, chamber drying and heat pump dehumidification drying of sanitaryware. The data, given in table 8.2, is sourced from one manufacture only and as such cannot be taken as representative of energy use across the industry.

According to Jay, shop drying operates at a higher thermal efficiency than dedicated chamber drying. To account for this result, Jay concedes that efficiencies for space heating do not account for mould warming, mould drying or daytime heating. Compensating for equipment age and operating conditions increases the chamber drying SEC to a value of 2.25 GJ/tonne, a thermal efficiency of 12.5 %.

Dryer Type	Drying SEC (GJ/tonne dry product)	Thermal Efficiency (%)
Space heating	1.45	13.5
Chamber	0.79	10.7
Heat pump	0.12	n/a

Table 8.2 SEC for sanitaryware drying (after Jay [199])

ETSU calculated a typical drying SEC for European sanitaryware production in 1978 and 1990 [198] [199]. The results highlight a fall in total SEC from 15.07 GJ/tonne to 6.00 GJ/tonne over the twelve year period.

The infrequent surveying of energy use for sanitaryware drying is exacerbated further by the limited disclosure of the methodologies used for deriving SEC and energy efficiency values. This is not to say that previous assessments of energy consumption for sanitaryware drying are erroneous, rather that existing energy values lose integrity when under direct comparison. The works of Jay [63] and Smith [121] provide comprehensive accounts of energy use in the sanitaryware industry using data collected from postal surveys or direct from manufacturers. However, no account is given for the method of calculating SEC or efficiency values. Moreover, the extensive Europe-wide energy survey commissioned by ETSU [199] notes that a common, structured methodology for data collection was used, yet no examples of data analysis are provided. Results of this new audit are based on an accurate and detailed on-site 'bottom-up' audit of energy use for drying, forming a reference study against which the work of Jay, Smith and ETSU can be assessed.

Energy Use for Sanitaryware Drying : A New Audit

The use of energy for ceramics drying has received little attention. Drying of ware and moulds consumes the second largest volume of gas in the production of ceramics, yet drying is traditionally viewed as an energy wasteful 'nuisance' process rather than an essential, value-adding process [33] [34] [63] [123] [62]. Although advances in the efficiency of spray drying and dry-forming techniques have enabled reduced energy consumption in the tile industry [199] [63], little of this technology has been transferred to the sanitaryware industry which still relies on traditional, relatively inefficient, drying techniques.

Drying must be performed on an economic basis, producing the highest quality product at the lowest possible cost [40]. Indeed, the majority of UK ceramic manufacturers operate with product quality, not cost, as a prime concern. To ensure economic drying, UK industry has always shown a preference for convective drying wherever possible [174]. Reasons for this preference include,

- Product temperature can be accurately controlled
- Maximum product temperature never exceeds that of the hot air
- Capital cost of dryers tends to be lower than alternatives.

'Product quality versus cost' is not the only compromise that must be made when drying sanitaryware. Conversations with shop floor managers in the sanitaryware industry highlights a further trade-off: The speed of drying is usually of greater importance than the attainment of highest thermal efficiency [40]. The objectives of sanitaryware drying can now be hierarchied in order of importance to manufacturers; product quality first, drying time second and finally thermal efficiency, or energy costs. This list supports the findings of the author, namely that energy monitoring for the drying of sanitaryware industry is rarely undertaken because it is a low priority to manufacturers.

Use of Dryers in the Sanitaryware Industry

Engelbach noted that every pottery industry has developed its own methods of drying, with the same types of air circulation dryers used throughout the individual industries [40]. This assertion certainly holds true in the UK sanitaryware industry where chamber drying and open shop drying predominate as the methods of moisture removal [47] [48].

Jay [63] identified the following dryer configurations operating in the UK sanitaryware sector,

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

The only historical audit of dryer types used in the UK sanitaryware was a report covering 65 % of the industry in 1997 [121]. The results of the survey, given in table 8.3, provide a correlation between dryer type and the primary source of energy.

Table 8.3 demonstrates the popularity of chamber, hood and open shop drying within the sanitaryware industry. The majority of dryers use natural gas as the prime energy source with only one electrically driven unit in existence; a single heat pump dehumidification dryer. However, it is only through studying the results of the new survey, given in tables 8.4 and 8.5, that the heavy reliance on open-shop and chamber drying becomes apparent.

Type of Dryer	Natural Gas	Waste Heat (+ gas)	Electricity	Steam	Total
Chamber	53	2	-	4	59
Hood	28	-	-	-	28
Tunnel	1	-	-	-	1
Open Shop	10	3	-	1	14
De-humidifier	-	-	1	-	1
Total	92	4	1	5	103

Table 8.3 Dryer configurations in UK sanitaryware sector (1997) (after Smith [121])

Results from table 8.4 indicate that 135 separate drying units operate across the UK's thirteen manufacturing sites, some 31 per cent more than previously thought. Again, chamber dryers, hood dryers and open-shop dryers are the most common drying technologies, with every manufacturing site using shop and chamber drying systems to some extent. Five tunnel dryers and ten casting mould dryers were registered. One manufacturing site used dehumidification dryers and one other used microwave dryers. Interestingly, only one manufacturer was currently experimenting with an airless drying unit.

Dryer Type	Natural Gas	Waste Heat (+ gas)	Electricity	Steam	Total
Chamber (ware)	49	2	-	7	58
Chamber (mould)	10	-	-	-	10
Open Shop	24	6	-	1	30
Tunnel	4	-	1	-	5
Hood	28	-	-	-	28
Dehumidifier	-	-	2	-	2
Microwave	-	-	1	-	1
Airless	1	-	-	-	1
Total	116	8	3	8	135

Table 8.4 Dryer configurations in UK sanitaryware sector (1998)

Table 8.5 assigns an average production throughput value to each dryer type. Ostensibly, open shop drying accounts for between 50 % and 75 % of all UK sanitaryware production capacity, with chamber drying accounting for 20 % to 45 % of total throughput. Tunnel drying is used across 30 per cent of manufacturing sites, processing an average 6,000 pieces per week per dryer.

The 28 hood dryers surveyed in this report operate on one manufacturing site only and subsequently account for an insignificant proportion of total national production. The combined output from hood dryers, heat pump dehumidification dryers and microwave dryers is estimated to be in the order of 22,000 pieces per week, or 10 per cent of UK weekly production. Weekly production volumes from airless drying are unknown.

<table>
<tr><th>Dryer Type</th><th>% Sites Using Technique</th><th>Number of Units</th><th>Total Throughput (pieces/wk)</th><th>Average Throughput (pieces/wk /dryer)</th><th>Average Capacity per Dryer (pieces)</th></tr>
<tr><td>Chamber dryer (ware)</td><td>100 %</td><td>58</td><td>62,000</td><td>1,589</td><td>317</td></tr>
<tr><td>Open shop</td><td>100 %</td><td>30</td><td>102,000</td><td>6,000</td><td>1,200</td></tr>
<tr><td>Tunnel</td><td>30 %</td><td>5</td><td>30,000</td><td>6,000</td><td>400</td></tr>
<tr><td>Hood</td><td>8 %</td><td>28</td><td rowspan="3">22,000*</td><td>n/a</td><td>n/a</td></tr>
<tr><td>Heat pump</td><td>8 %</td><td>2</td><td>n/a</td><td>400</td></tr>
<tr><td>Microwave</td><td>8 %</td><td>1</td><td>n/a</td><td>n/a</td></tr>
<tr><td>Airless</td><td>0 %</td><td>1</td><td>n/a</td><td>n/a</td><td>n/a</td></tr>
</table>

* combined total across industry

Table 8.5 Drying systems in the UK sanitaryware sector (1998)

With very few exceptions, open shop drying systems were found to have significantly larger drying capacities than their chamber drying counterparts. The average capacity for chamber dryers was between 300 and 400 pieces, although two larger capacity dryers were found, each one capable of holding 1000 pieces. By contrast, open shop dryers varied from small casting shop systems holding 300 pieces to bulk-line casting shops with the potential to hold 6500 pieces or more.

Operation of Dryers

Drying schedules vary between production sites and between manufacturers. Typically, shop drying is carried out at temperatures between 40 °C and 45 °C, with chamber drying proceeding between 80 °C and 90 °C. The higher drying temperatures used in dedicated batch and tunnel dryers result in lower drying times, nominally 12 to 14 hours cold-to-cold, compared with 48 hours for open shop drying.

Real-time monitoring of drying conditions is common on both chamber dryers and shop drying systems. Figure 8.2 presents a section of a condition monitoring chart taken from the main casting shop of a medium size sanitaryware manufacturer producing 10,000 to 13,000 pieces per week.

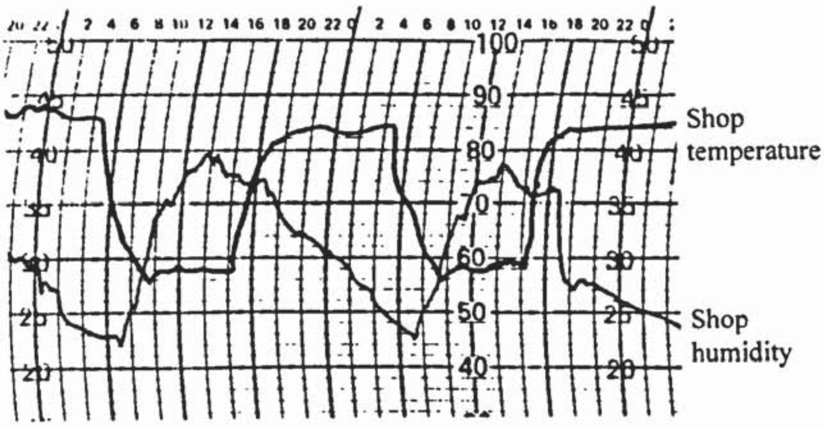


Figure 8.2 Typical shop drying profile

Shop drying commences after the last casting shift, normally from 15:30 or 16:00 hours onwards. The shop is cleared of personnel and sealed after which the internal atmosphere is heated to 40 °C. Humidity drops during the night from a day-time level of 80 % rh to 45 % rh at the end of drying. Burners are then switched off at 05:00 hours, allowing the shop to reach a comfortable working temperature for the beginning of a new casting shift. Ware will often remain in-shop for a period of 48 hours, allowing a drying cycle to span two night-time heating periods.

For a chamber system, the length of a drying cycle depends upon several factors including the age of the dryer, the product type, the air-flow regime and the control system used. In practice, production scheduling precludes the use of chamber dryers dedicated solely to the processing of single product lines. For this reason, dryer loads are commonly mixed, comprising of different products with different physical dimensions. Consequently, the length of the drying cycle becomes dictated by the drying time of the largest piece, irrespective of other ware.

The most modern dedicated dryers were found to operate on cycles between 10 and 13 hours, almost at the theoretical lower cycle limit for air drying of sanitaryware. Chamber dryers above ten years of age were found to operate over significantly longer cycles, usually between 14 and 16 hours. Although no clear reasons for these extended drying times were found, it is suggested that worn door seals and damaged insulation were the prime causes.

Figure 8.3 illustrates a typical temperature and humidity trace from a modern dedicated chamber dryer. Again, data has been provided by a medium-size sanitaryware manufacturer.

Compared to shop drying, chamber dryers allow for much greater control over temperature and humidity during the drying cycle. Figure 8.3 illustrates the use of pre-programmed heating 'ramps' to control drying rates during the heating cycle. The ware is first heated from ambient shop temperature to 60 °C at a rate of + 15 °C per hour (section I). Heating then proceeds at a lower rate of approximately + 5 °C per hour until a temperature of 80 °C is reached (section II). A 4.5 hour period of temperature dwell at 80 °C is further allowed (section III), followed by a rapid cooling period .

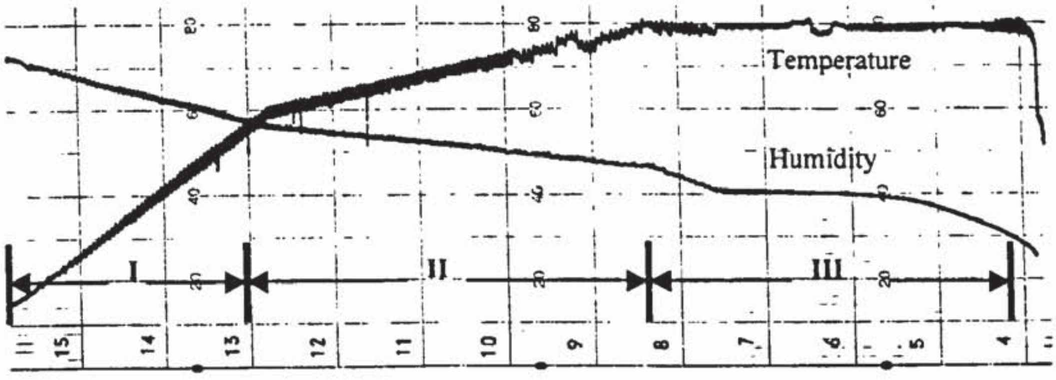


Figure 8.3 Typical sanitaryware drying profile (chamber drying)

Control of humidity within the sanitaryware drying cycle is of crucial importance. Sharp reductions in humidity, particularly at the start of the cycle, result in over-rapid drying leading to surface shrinkage and stress fractures in the ware [54] [15]. The end result is a low quality, non-saleable product. This survey reveals that all convective air chamber drying units in the sanitaryware industry offer humidity control, either by humidification techniques or direct steam injection. These two methods can be described as,

- **Humidification** - the injection of atomised water into the drying chamber using compressed air.
- **Steam injection** - the direct supply of pre-heated water vapour into the chamber.

The majority of modern chamber dryers are equipped with steam injection units, although it was noted that some manufacturers had abandoned steam injection in favour of humidification; their justification being that of similar drying performance without the energy costs incurred from raising steam.

It was found that the control of shop drying systems was minimal. All manufacturers operate temperature control to regulate burner output and maximum temperature, yet only 50 % of casting shops used humidity control. The humidity control systems that were audited used feedback to control in-shop ceiling fans and/or ventilation fans. One manufacturer used an advanced CPU system to control zoned areas of ventilation within the casting shop.

This survey suggests that a high proportion of all UK manufactured sanitaryware is over-dried, or dried twice; an occurrence unrecorded in previous audits of the sanitaryware industry. It has already been alluded to that sanitaryware manufacturers dry a mixed product load in order to maintain operational efficiency. In addition to this, production managers will only operate chamber dryers with full loads, thereby maintaining a correct, repeatable air-flow regime throughout the dryer. To ensure a full load, mixed part-dried ware is often taken from the casting shop and used in the chamber dryers. This ware is quickly dried in the chamber dryer, resulting in energy waste through reduced dryer efficiency.

In the most extreme instance of over-drying, ware is shop dried overnight, followed by chamber drying the next day. No subsequent alterations are made to the drying schedule to account for the already depleted moisture content of the ware. The results of this survey indicate that between 50 and 70 per cent of UK sanitaryware is over-dried to some degree.

Energy Use

Sanitaryware drying is a time consuming process which presents a high load to the drying system [123] [48] [47] [121] [63]. Slip casting produces green ware with a typical moisture content of 18 % to 20 % dwb, an equivalent of 2 to 3 kgs of water per sanitaryware piece. The resultant energy load on a dryer is therefore significant. For example, a chamber dryer with capacity for 300 pieces has to supply enough energy to remove between 600 kg and 900 kg of water over its drying cycle.

This survey reveals that sanitaryware manufacturers are conscious of total factory-wide energy requirements, yet remain generally unaware of exact data on energy use and its timing at the process level. Moreover, it is suggested that the monitoring of energy use for sanitaryware manufacture is made more difficult by the disaggregated nature of process operations. Although one modern 'green field' site was found to exist, sanitaryware potteries have generally grown organically, evolving over many decades. Changes in production demand have been met by the incremental expansion of existing buildings, rather than the re-planning of factory layouts or the use of green field sites. The result is a production plant with similar processes located at different points across the site. It is this organic growth of sanitaryware manufacturing sites, and the lack of sub-metering for electricity supplies, that makes for the difficult up-dating and monitoring of energy use.

A literature search indicates that the modelling of energy use for ceramics drying is limited. A paper by Engelbach [40] concentrates on the air circulation drying of porous materials, with separate sections devoted to the drying of clay products and the types of dryer used in the pottery industry. A basic analysis of dryer performance is given, demonstrating the calculations and assumptions required for the practical design of dryers. Energy use for drying is derived from heating duties whilst also giving initial consideration to moisture removal rates, air humidity and the specific air consumption (SAC) required by the drying process. It is assumed within this work that drying is essentially adiabatic evaporation of moisture at the surface of the material.

Denissen and Velthuis [34] have derived a computer model (DRYSIM©) which simulates the changes in air temperature and absolute humidity for chamber drying, whilst simultaneously predicting product temperature and moisture content throughout the drying cycle. A simplified drying model is used to highlight the energy inefficiencies of drying, suggesting that 3,856 kJ/kg_w is the theoretical minimum SEC for chamber drying. Denissen and Velthuis go further, indicating that High Humidity Drying (HHD) in a chamber can reduce energy requirements to 2,863 kJ per kg of moisture removed.

To illustrate the HHD DRYSIM© model, Denissen and Velthuis give a practical demonstration for the drying of 44,352 Dutch bricks. The assessment follows the simplified thermodynamic model represented in figure 8.4

Results of the new audit are based on a simple thermodynamic model, designed to assess the energy use and thermal efficiencies of shop and batch drying within the sanitaryware industry. Initial data collection was made by on-site visits to all UK sanitaryware manufacturing plants. Follow-up data was collected using questionnaires, interviews, site re-visits and logging of energy consumption using real-time data acquisition.

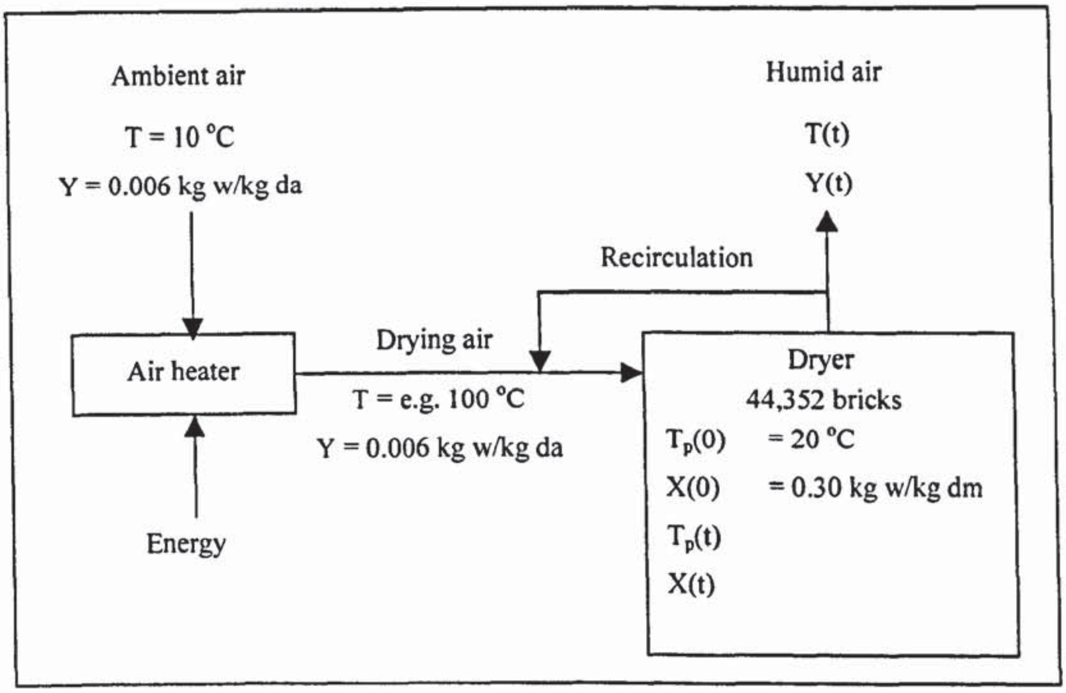


Figure 8.4 Schematic representation of an industrial dryer (after [34])

Energy calculations for each drying unit are made on an individual basis, using typical drying cycle times, thermal loads, and psychrometric conditions for intake and exhaust air. The effects of energy loss through system boundaries are also considered. Motive devices and specific burner capacities are based on face-plate ratings within each factory.

Assumptions have been made to account for missing or unobtainable data. For example, it has been assumed that dryer furniture and ware supports do not retain heat energy. Each drying unit is assumed to operate with a homogeneous boundary condition, using similar building materials for walls with no heat loss through door seals and windows. Gas burners are assumed to operate at a uniform 80 % thermal efficiency. The model assumes adiabatic evapouration from the product surface.

It is axiomatically accepted that sanitaryware drying processes consume 15 % to 17 % of total energy for production [123] [63]. The survey findings agree with these values, suggesting a slightly higher figure of approximately 19 per cent. Table 8.6 presents the estimated total sectorial energy use, divided into electrical power and gas consumption for drying and firing.

	Natural Gas (TJ)	Electricity (TJ)	Total (TJ)	Percentage of Total (%)
Firing	1874	145	2019	76.0
Drying	387.8	109	496.8	18.7
Total*	2354	303	2657	100

* Figures from Steer [123]

Table 8.6 Fuel usage by application in UK sanitaryware sector

As expected, kilning consumes the highest proportion of gas in the sanitaryware industry, with drying consuming a relatively low proportion of total gas use, typically only 14.6 %. Table 8.7 provides a further, more detailed, breakdown of proportional energy use by dryer type.

Table 8.7 reveals shop drying and chamber drying of ware as the prime consumers of energy, particularly natural gas. The drying of moulds is the third largest energy consumer, with the limited number of heat pumps, microwave and airless dryers representing insignificant energy use. Energy use by hood dryers and tunnel dryers was not available.

Dryer Type	No.	Gas (%)	Electricity (%)	Total Energy Use (TJ)
Chamber (ware)	58	92.3	7.7	155
Chamber (mould)	10	92.3	7.7	23.8
Open shop	30	66.0	34.0	313
Tunnel	5	n/a	n/a	5
Hood	28	n/a	n/a	
Dehumidifier	2	0	100.0	n/a
Microwave	1	0	100.0	n/a
Airless	1	96.1*	3.9*	n/a
Total	135			496.8

* Estimate based on thermodynamic calculations

Table 8.7 Gas and electricity use for UK sanitaryware drying

Analysis of total energy use indicates open shop drying as the majority energy consumer, accounting for more than 60 % of the total energy demand for UK sanitaryware drying; an average 8 % of total gas use. However, of greater importance for the application of DSM measures, drying takes 36 % of total site electricity load. On a more detailed level, 78 per cent of energy use for UK sanitaryware drying is derived from the burning of natural-gas and 22 per cent from electricity; a sectorial energy use of 388 TJ and 109 TJ respectively. This compares to previous assessments which have traditionally under-estimated electricity use at 15 per cent of total energy demand [121] [63].

The majority of the electrical load for drying is due to motive devices, predominantly burner, re-circulation and exhaust fans. Humidification systems account for the remaining electricity use. Table 8.8 provides specific details of electric motor use by application, giving both typical kW loads and duty cycles.

It becomes apparent from the survey results that shop drying is the key contributor to the relatively high electricity consumption attributable to drying systems. Shop exhaust and distribution fans operate continuously, providing recirculation and extraction of warm humid air. Whether operating under humidity control or fixed damper load, shop ventilation forms a significant and constant electrical base load. Large shops capable of holding 6000 pieces of ware were found to operate up to 9 exhaust fans, each motor rated between 7 and 22 kW.

	Application	Motor size (kW)	Duty cycle	Comments
Shop Dryers	Exhaust fans	5 – 15	Continuous	• No. and size dependent on drying system. • Either multiple 5 kW motors or single 25 kW Units
	Burner fans	5 – 25	Continuous	
	Recirculation fans	5 – 25	Continuous	
	Bunker fans	0.06	Continuous	• Very low kW rating, but often more than 1,500 units per site
Chamber Dryers	Burner fans	2 – 25	During drying cycle only	• No. is function of dryer design • Multiple low kW fans, or one single large kW burner fan
	Recirculation fans	1 – 25		

Table 8.8 Electrical fan operation in the UK sanitaryware industry

Circulation of air within the casting shops is facilitated using AC induction motors and arrays of DC 'bunker' fans. Although bunker fan ratings were found to be low, nominally 60 W each, the high number of units and their continuous operation results in continuous electrical loads up to 90 kW. In-shop burner fans are used to draw fresh air across, or through, the burner's combustion chamber, aiding in the efficient burning of gas whilst encouraging circulation of heated air into the drying environment. Air circulation, facilitated by burner, circulation and bunker fans, is often the highest electrical load within a shop drying system.

Dedicated chamber dryers use specialised fans to provide optimised and controlled atmospheres for the rapid drying of sanitaryware. The most common fan configuration is the dryflex unit which uses a vertical rotating cone to sweep heated air across the wares' surface. Dryflex fans are available as stand-alone portable devices, or are incorporated into the dryer's structure. In either configuration, motor sizes were found to be larger than their open shop counterparts, usually between 2 and 4 kW. Where dryflex fans were not used, linear arrays of smaller 1 kW recirculation fans were placed along the length of the dryer to provide a uniform air flow across the ware. In a few cases, only single large burner fans are found to operate. These fans, rated between 10 and 25 kW, provide sufficient draught to act as a combined burner and air recirculation fan. All chamber dryer fans operate continuously over the drying cycle.

Specific Energy Consumption (SEC)

In combination with the work of Steer [123], it has been established that a SEC of 43.3 MJ can be apportioned to each finished sanitaryware piece. Scaling of this value suggests a SEC of 2.95 GJ/tonne, translating to a SEC of 560 MJ/tonne for drying processes. Table 8.9 gives a summary of SECs for individual drying processes.

Although SEC values are useful for comparing energy use between processes, it must be noted that manufacturing defect rates have an effect on overall SEC values. Although data was readily provided on weekly production volumes, little information was proffered on scrap rates within each manufacturing site. Specific energy consumption prior to drying is relatively low, typically 0.454 MJ/piece to 4.54 MJ/piece [123] [47]. After drying and kilning, SEC increases to an average 16.13 MJ/piece and 43.3 MJ/piece respectively. Subsequently, it becomes apparent that products failing after drying or firing have already incurred substantial energy costs. Moreover, scrap occurs most frequently after the physically demanding firing process, the point at which SEC is largest and material cannot be re-cast. The effect of scrap rates on total SEC can be illustrated by way of example: a weekly scrap rate of 10 per cent taken over the whole UK sanitaryware industry will reduce calculated SEC from 43.3 MJ to 39.4 MJ per saleable piece. This corresponds to an estimated annual energy cost of £153,000 for the processing of defective ware across the UK sanitaryware industry.

Dryer type	Average SEC (MJ/piece)	Total UK drying footprint Area (m^2)
Chamber (dedicated ware)	15.68	8404
Chamber (ware)		
Chamber (mould)	n/a	2249
Tunnel (ware)	n/a	2451
Open-shop	49.32	83339

Table 8.9 Summary of dryer efficiencies in UK sanitaryware sector.

Energy Profiles

The prime objective of DSM is to optimise loading on electricity distribution networks. Modelling of energy profiles requires an in-depth knowledge of electrical demand and its variance of over time. Results of the new survey have been used to plot kW demand profiles for the drying of sanitaryware in shop, chamber and heat pump drying systems. Figure 8.5 demonstrates the electrical load profile for three arbitrarily chosen shop dryers.

All shop drying systems are scheduled to operate throughout the night, as indicated on figure 8.5 by an increase in electrical loading from 16:30 hours to 04:30 hours. Small casting shops, typified by shop A, often cease to operate as dryers during casting, whilst larger manufacturers use burners to provide constant low-level daytime heating of the casting shop. Shops which provide constant heating, illustrated by shops

B and C, have a higher electrical consumption as a result of an increased reliance on air circulation and extraction fans during the day.

Figure 8.5 Electrical demand for shop drying

Operating times for chamber dryers depend on production scheduling and manufacturing policy. The shorter processing times associated with batch dryers allow for flexibility in production, although it was found that most chamber dryers are loaded at the end of casting, enabling drying to occur concurrently with night time shop drying. The ware is then ready for glazing and firing at the start of the following work shift. If the cycle time is sufficiently short, manufacturers will operate chamber units for two drying runs per 24 hours.

Figure 8.6 A comparison between shop, chamber and heat pump drying profiles

A comparison between electrical energy profiles for shop drying, chamber drying and heat pump dehumidification drying is given in figure 8.6. The profiles presented in figure 8.6 represent electrical loads for the drying of a similar mass of sanitaryware product. As such, it becomes immediately apparent that shop drying consumes significantly more electrical energy than chamber and dehumidification drying, reflecting open shop drying's operation as an over-sized and inefficient drying enclosure. The performance of shop drying is lowered further when considering that ware may have to undergo further in-shop drying for another 24 hours.

Heat pump drying shows a low electrical energy requirement. Furthermore, with all the heat for evaporation derived from electrical compressor loads, heat pump operation consumes little or no gas during the drying cycle. A disadvantage of dehumidification over chamber drying is the substantially longer drying times needed.

SEC values and energy profiles provide a useful insight into the effectiveness of energy use on a process level. However, for the purposes of Energy Services and DSM it is also imperative that the relative efficiencies of the different drying technologies are discussed. Analysis of dryer efficiency allows the engineer or energy manager to assess the main causes of energy inefficiency, thereby highlighting issues of energy use which can be targeted by energy service measures.

Dryer Efficiency

Traditionally, the operating performance of sanitaryware drying systems was left to the experience of the plant operator. Control of the dryer atmosphere was achieved by the manual setting of burners and air inlet/outlet dampers. A report published in 1963 suggests that drying of sanitaryware requires days to reach acceptable quality [40], thus suggesting that shop drying was the sole drying method in use before the 1970s. Today the automated control of the drying process has significantly reduced drying times whilst achieving higher efficiency and increased cost savings by providing optimised and repeatable drying cycles.

Drying is an inherently inefficient process. The convective air drying of sanitaryware uses a high proportion of energy to heat incoming air to a temperature needed for drying [34]. The majority of heat is then carried away by the exhaust gas resulting in a maximum theoretical operating efficiency of around 60% for a convective air batch dryer, a resultant SEC of 3,800 kJ/kg_w [46] [174].

Past studies base dryer performance on thermal efficiency, as opposed to operational efficiency which takes into account the additional energy use from motive devices such as fans and humidification systems. The steady-state thermal efficiency of a convective air batch dryer is given as,

$$\eta_{therm} = \frac{T_2 - T_3}{(T_2 - T_3) + (1 - W)(T_3 - T_1)} \quad \text{Equation 8.0 [57]}$$

T_1	Ambient air temperature [K]	T_3	Exhaust air temperature [K]
T_2	Air entering dryer [K]	W	Ratio of recirculated air to total airflow

However, it remains difficult to asses dryer efficiency using equation 8.0, particularly when assessing shop drying with its multiple burners and multiple exhaust outlets. Moreover, dryer efficiency is dynamic, changing over the length of the drying cycle. A more accurate calculation for thermal efficiency across the drying cycle can be defined as,

$$\eta_{therm.} = \frac{\Delta H_v . W_{wat.}}{q_T} \qquad \text{Equation 8.1 [163]}$$

ΔH_v	Latent heat of water at ambient temperature [kJ/kg]	q_T	Energy used for drying each kg product [kJ]
$W_{wat.}$	Water removed per kg product [kg]		

The inclusion of energy consumption for motive work can be included in q_T to give an overall operational efficiency.

Inefficiencies in both shop and chamber drying were made obvious during the auditing of UK sanitaryware dryers. Key sources of energy loss include,

- Minimal servicing of motors and burners
- Worn door seals
- Accuracy of humidity and temperature sensors
- Damaged dryer insulation
- Open/broken doors and windows in casting shops
- Little insulation on recirculation ducts
- Open sky-lights.

Table 8.10 provides a summary of key findings for the assessment of dryer efficiencies. It is apparent that open shop drying exhibits poor performance, with typical thermal efficiencies between 6 % and 22 %. Batch ware dryers operate with efficiencies in the order of 22 % to 54 %. In general, those batch dryers which are dedicated to the role of ware drying operate at average efficiencies of 49 %. Figure 8.7 is a histogram of estimated operational efficiency for all 58 chamber drying units in the UK sanitaryware industry. The majority of batch ware dryers operate at efficiencies of 49 % or below. The three dryers found to operate at efficiencies of 56 % and 57 % were specialised sanitaryware dryers of 6 months of age or less.

Dryer Type	Range of Efficiency (%)	Average Efficiency* (%)
Chamber (dedicated ware)	46 – 57	49
Chamber (ware)	22 – 26	23
Chamber (mould)	27 – 46	36
Tunnel (ware)	20 – 23	22
Open shop	6 – 22	14

* Weighted and averaged over full UK sanitaryware production

Table 8.10 Average efficiencies for UK sanitaryware drying

Batch dryers which comprise of drying rooms or heated storage areas operate at an average thermal efficiency of 23 %. As expected, the 'open-to-atmosphere' configuration of tunnel dryers result in operating efficiencies below those of hermetically sealed ware or mould dryers.

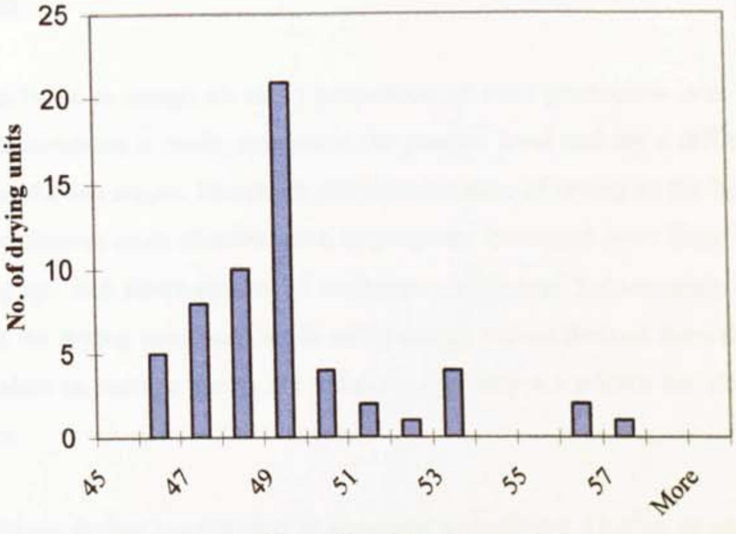


Figure 8.7 Operational efficiency for sanitaryware chamber drying

Sanitaryware moulds are over-dried, usually at temperatures between 40 °C and 60 °C thereby ensuring a dry product with no degradation in mould quality. It is suggested that the thorough and extensive drying cycle is a prime contributing factor to the lower efficiencies exhibited by mould dryers. However, discussion with shop floor operatives suggests that energy efficiency is not a concern for mould drying: the need to ensure a defect-free mould is of prime concern, rather than overall energy costs.

Form of energy loss	Percentage energy consumption (Chamber drying)	Percentage energy consumption (Open shop drying)
Moisture removal	49 %	23 %
Heating of air	41 %	37 %
Boundary heat loss	10 %	40 %
Total energy supplied	**100 %**	**100 %**

Table 8.11 Breakdown of energy consumption for sanitaryware drying

Table 8.11 apportions percentage energy use to the sources of energy loss. The largest inefficiency in chamber drying is the heating of air for drying purposes. Modern chamber dryers dissipate only 10 per cent of energy through boundary losses, due in part to the use of thermal insulating materials for dryer construction.

Compared to chamber dryers, open shop dryers lose a significant proportion of energy though boundaries, typically 40 % of the energy supplied for drying. Although the size and construction of casting shops varies between manufacturing sites, most shops were found to be of brick construction with little or no cavity insulation. The majority of ceiling and roof structures were comprised of corrugated metal with numerous open sky-lights and ventilation fans running continuously under free-load. It is estimated that 37 per cent of energy for shop drying is lost to atmosphere through extraction of warm humid air, a similar proportion to that estimated for chamber drying.

Energy Costs

It is often difficult to assign an exact proportion of total production cost to a drying process. Gas and electricity consumption is rarely metered at the process level making it difficult to attribute energy costs to individual production stages. Moreover, the identification of drying as the bottleneck process highlights the additional production costs of extra work in progress, increased dryer floor space and the under-utilisation of processes up- and down-stream of sanitaryware drying. Subsequently, the following estimations of current costs for drying have been made using energy values derived from the new survey. Energy charges have been taken as average across the industry, typically 4.5 p/kWh for electricity and 1.0 p/kWh for gas consumption.

UK sanitaryware drying is estimated to consume a combined £3.47m of energy per annum, or an average 32 p per sanitaryware piece. The substantially higher price of electricity results in a total cost of £1.39m for gas and £2.08m for electricity. Table 8.12 and 8.13 provide a breakdown of energy costs in four UK sanitaryware drying units. Shop A and Chamber A are representative of a small sanitaryware manufacturer producing 6,000 pieces per week. Shop B and Chamber B illustrate the use of energy for drying in a large site producing over 35,000 pieces per week.

	Shop A 1500 pieces/week			**Shop B** 6680 pieces/week		
Application	**Cumulative load (kW)**	**Annual Energy Use (MWh/yr)**	**Annual Energy Cost (£/yr)**	**Cumulative load (kW)**	**Annual Energy Use (MWh/yr)**	**Annual Energy Cost (£/yr)**
Bunker fans	7.124	22.4	1.008	60	189	8,505
Distribution fans	30	94.5	4,253	28	88.2	3,969
Extraction fans	15	47.25	2,126	108	340	15,300
Burner fans	6	18.9	851	8	25.2	1,134
Sub-total	**58.124**	**183.05**	**8,238**	**204**	**642.4**	**28,908**
Gas use	586	1,846	18,460	1,758	5,539	55,390
Total	**98.124**	**783.05**	**26,698**	**1,962**	**6,181.4**	**84,298**

Table 8.12 Energy use for shop drying of sanitaryware

Shop A and B consume an average £26,698 and £84,298 of energy respectively. Although total energy costs for shop B are over three times that for shop A, analysis on a piecewise basis results in much closer energy costs of 42 p and 30 p per piece.

Analysis of electrical power utilisation reveals that both shops use a similar proportion of energy costs for electricity, 29 % for shop A and 34 % for shop B. It is also interesting to note that the majority of electrical load for shop drying derives from the use of distribution and extraction fans, highlighting the importance of a suitable air-flow regime throughout the casting shop.

	ChamberA	1500 pieces/week		**Chamber B**	4000 pieces/week	
Application	**Cumulative load (kW)**	**Annual Energy Use (MWh/yr)**	**Annual Energy Cost (£/yr)**	**Cumulative load (kW)**	**Annual Energy Use (MWh/yr)**	**Annual Energy Cost (£/yr)**
Burner fans	0.15	0.5	23	12	40.3	1,814
Distribution fans	4	13.4	603	24	80.6	3,628
Extraction fans	4	13.4	603	12	40.3	1,814
Sub-total	**8.15**	**27.3**	**1,229**	**48**	**161.2**	**7,256**
Gas use	293	984.5	9,845	879	2,953.4	29,534
Total	**301.15**	**1,011.8**	**11,074**	**927**	**3,114.6**	**36,790**

Table 8.13 Energy use for batch drying of sanitaryware

In terms of energy use, chamber drying is more cost effective than shop drying. Chamber A and B consume £11,074 and £36,790 of energy for similar product throughput rates to those used in shop A and B respectively. These energy costs give an associated piecemeal cost of 18 p for chamber A and 22 p for chamber B; between 2.3 and 1.3 times less than the corresponding shop systems. Overall, tables 8.12 and 8.13 demonstrate the dominance of gas as the main energy source for chamber drying.

In contrast to shop drying, chamber dryers were found to differ significantly in their proportional electricity load. Chamber A derives 11 per cent of its energy costs from electricity, with chamber B taking 20 per cent. Again, the majority of electrical power utilisation for chamber drying is due to air distribution and extraction.

It can be estimated that the UK drying of sanitaryware produces an equivalent 59,000 tonnes of CO_2 per annum [48]. Therefore, the potential exists within the sanitaryware industry to reduce energy consumption and CO_2 emissions, in combination with a reduction in production costs.

Energy Saving for Drying Processes

Many UK sanitaryware manufacturers do not hold sufficient resources to commission regular energy surveys or employ full-time Energy Managers. The existence of resource constraints and limited company size is as a major barrier to innovation in areas of achieving energy efficient operation within the ceramics industry [62]. Interviews with production engineers highlighted a willingness to embrace proven energy efficient drying technologies, yet a lack of financial backing to undertake the projects.

ETSU provide a list of 'major technologies' with potential to achieve energy savings and market penetration in the sanitaryware industry [199]. Suggestions include,

- Use of waste heat from kilns
- Replacement of steam heating with direct heating
- Controlled humidification
- Fast drying (specifically infrared and microwave).

The use of heat recovery within the UK sanitaryware industry is low. Results of the survey indicate that only 15 % of manufacturing sites use heat recovery from kilns for drying and space heating. Discussion with site engineers suggests that the widespread re-use of kiln exhaust is restricted due to,

1. The complex layout of manufacturing sites
2. Poor reliability of heat exchangers.

Kiln exhaust is inherently dusty, carrying with it ceramic fines and glaze particulates which result in the rapid failure of heat exchangers. Fouling and corrosion of heat exchanger plates has been cited as a fundamental reason why the adoption of kiln re-claim is limited. Furthermore, the capital expense of providing the necessary duct work, insulation and control systems is seen as a financial deterrent.

Although indirect steam heating is slowly being supplanted by direct gas-fired batch dryers, heat pump drying has made little penetration into the sanitaryware industry (table 8.3). The superior energy efficiency of dehumidification dryers over gas-fired chamber dryers is outweighed by the longer drying times required. In terms of technology replacement, heat pump dryers only offer real production benefits over the inefficient and lengthy shop drying process. With the widespread use of shop drying and the low priority currently given to energy efficiency in the UK sanitaryware sector, it is viable that heat pump drying will not penetrate much further.

Further reductions in energy consumption for drying can be achieved using a variety of methods including,

- accurate control of the drying process
- general housekeeping measures
- effective design of process plant
- studies and modelling of material behaviour during drying
- the use of replacement drying technologies.

The author suggests that new rapid drying technologies offer the most significant opportunity to reduce energy consumption and increase cost savings in the sanitaryware industry.

The new breed of fast drying technologies can be divided into two categories: Those technologies which already exist but have previously been confined to a limited number of industrial applications, or those drying technologies which are novel and innovative. Table 8.14 provides examples of both categories.

Drying Technologies Already in Existence	Innovative Drying Systems
• Microwave • Infra-red • Radio Frequency • HT Heat Pumps	• Airless Drying • Dual Fuel Drying

Table 8.14 Rapid drying technologies

To date, Radio Frequency (RF) and Infra-red (IR) drying have not undergone trials in the sanitaryware industry. It has been suggested that the application of RF and IR would be inappropriate for the drying of complex sanitaryware shapes, with the rapid surface heating effects resulting in differential stresses and cracking within the piece [123].

Microwave drying is used by one sanitaryware manufacture for the drying of large Belfast sinks and shower trays. In this particular configuration, microwave energy is used to assist drying within a traditional convective air tunnel dryer. The volumetric heating effect provided by microwave power results in significantly faster drying times, yet the rapid volumetric heating effect of microwaves is deemed too hostile for use as the sole source of heat energy.

At the time of writing (April 1999), Dual Fuel drying is still in its testing stage. Essentially, dual fuel drying is the combination of electroheat drying technologies with traditional air drying in a chamber environment. To date, trial work has been conducted with microwave and RF energy in combination with forced air convection. As such, no literature is yet available regarding energy use, energy efficiency and the performance of dual fuel systems.

Heat pump dehumidification drying and airless drying are the only drying technologies which are currently viable as direct replacements for batch and shop drying system. Table 8.15 provides analysis of the theoretical energy savings that airless drying can realise over convective shop drying.

Sanitaryware drying in the UK offers significant scope for the application of energy saving measures. The significant energy consumption of sanitaryware dryers is generally overlooked by manufacturers, whose prime concern is product quality, production lead times and energy use for kilning. Moreover, the marginal cost of energy for drying has historically prevented an allocation of resources for energy efficient drying projects. Subsequently, an opportunity exists for RECs to undertake Energy Services in the sanitaryware industry, helping customers' reduce energy costs whilst optimising electricity networks and securing long-term contracts for the supply of energy.

	Air drying			Airless Drying		
Dryer type	Average Efficiency (%)	Average SEC (MJ/piece)	Total UK footprint area (m^2)	Average Efficiency (%)	SEC saving (MJ/piece)	Saving in UK drying footprint area* (m^2)
Chamber (dedicated ware)	54	15.68	8404	64 - 90	11.83 - 12.94	5379 - 6975
Chamber (ware)	23					
Chamber (mould)	36	n/a	2249	64 - 90	n/a	1439 - 1867
Open-shop	14	49.32	83339	64 - 90	45.47 to 46.58	0†

† Reduction in casting shop area is negligible.

* Assuming production capacity remains the same as for air drying.

Table 8.15 Potential benefits of airless drying for UK sanitaryware production

CHAPTER 9

DISCUSSION

Introduction

This thesis has presented a new and innovative tool for the study of drying system performance as part of an energy services approach to demand side management. The purpose of chapter 9 is to discuss this substantial and original work, highlighting both the benefits and criticisms of the approaches taken. In addition to the author's own work, relevant comment will be passed on the work of others currently studying in similar areas of interest.

Prior to a detailed discussion of original content, it is necessary to reconcile original thesis objectives with the completed work.

Meeting Objectives and Aims

The primary aims of this thesis were presented in chapter 1 and included,

- An examination of the driving forces behind the application of DSM and energy services to drying processes
- The investigation of airless drying as a potential process for the application of energy services.
- The modelling and comparison of potential energy and cost benefits from the use of airless drying.

The author believes that all objectives have been reached with a degree of success. Chapter 2 expounded on the driving forces behind DSM and energy services, namely structural changes in the electricity supply industry, environmental concerns and political and market considerations. Incentives to promote energy efficiency were discussed and drying processes were highlighted as offering significant potential for reduced energy consumption.

Chapter 3 introduced superheated steam drying technology and highlighted the associated potential energy and cost saving opportunities. Current thinking on airless drying theory was presented along with discussion of the suggested mechanisms that result in reduced energy use and faster drying times. Overall, it was suggested that airless drying offers considerable scope for use in an energy services approach to DSM.

Modelling of drying processes was introduced in chapter 5. The majority of models and simulations were found to focus on complicated non-linear equations. Solution of these equations often requires wide-ranging assumptions, thereby leading to over simplification of the model. It is suggested that the most accurate modelling of drying behaviour derives from experimentally observed data.

A survey of literature indicated the lack of research into the modelling of energy use for drying. Moreover, no work was found which described the modelling of energy use for airless drying. Examination of modelling techniques suggested that neural networks have gained in popularity, yet little work had been conducted using fuzzy logic and fuzzy inference. It was suggested by the author that fuzzy systems demonstrate a greater user appeal than similar AI prediction systems.

Chapter 6 used empirical data to model drying rates for three technologies: conventional air drying, airless drying and heat pump drying. A fuzzy prediction model was derived for each technology and data was mapped using adaptive neuro inference. Each fuzzy model was then incorporated into an energy services tool for the prediction of drying time, energy cost and carbon dioxide emission levels. The energy services tools have been documented in chapter 7.

A thorough survey of drying within the UK sanitaryware industry is presented in chapter 8, thus providing a comprehensive case study for the application of a fuzzy energy services tool.

New Work

Overall, this thesis presents several areas of new or updated work relating to the use of drying systems in UK industry. Four aspects of this work are considered unique by the author.

1. the first study to model drying processes as an approach to DSM
2. the first use of fuzzy inference systems for the modelling of drying rates and times
3. the first work to model the comparative benefits of airless operation
4. the first complete study of drying practices within a UK industrial sub-sector.

In addition to this original work, a re-estimation of UK energy use for industrial drying has been completed. This study is the first in 22 years to follow the 'moisture loss' assessment method in preference to specific energy consumption (SEC) approach.

The remainder of this chapter discusses salient points of interest arising from the original and up-dated work detailed within this thesis.

Energy Use for Drying in UK Industry

It is generally accepted that drying is a widely used industrial process which demands a substantial proportion of UK energy resources. To this end, chapter 4 attempted to re-estimate the nationwide use of energy for industrial drying processes. It was the author's belief that such a study would provide a suitable reference against which to gauge the effectiveness of targeted DSM strategies using replacement energy efficient drying technologies.

Literature suggests that 6 previous surveys of national energy use for drying have been attempted in the UK. Detailed examination of each survey revealed a variety of omissions and assumptions. Moreover, surveys were found to follow two distinct methods of energy calculation: the specific energy consumption (SEC) method and moisture loss method. The preferred method since 1977 was found to be SEC.

A new assessment given in chapter 4 indicates that 350 PJ of energy was used in 1994, approximating to 17.7 % of total industrial energy use. This assessment follows the work of Hodgett and is believed to be the first survey in 22 years to use the moisture loss method.

Despite attempts to re-estimate energy use, the author experienced similar problems to those of previous surveyors, namely

- the need to omit industrial sub-sectors,
- omission of product classes,
- assumed plant efficiencies,
- use of historical data,
- insufficient knowledge of primary data accuracy.

Overall assessment of industrial energy use for drying is an enormous task requiring communication with trade organisations and collection of data from a wide range of sources. Subsequently, it can be suggested that many of the problems associated with wide-scope energy surveys are unavoidable. Even a Government funded energy survey was found to limit its scope to those industrial sectors consuming less that 2 PJ pa [198].

It is the author's belief that the new survey provides a good approximation of sectorial and national energy use for drying. However, it fails to provide the accuracy required for a detailed framework against which to assess DSM measures.

Fuzzy Logic Modelling of Drying Processes

Drying involves complex simultaneous heat and mass transfer processes. Attempting to formalise these processes into rigid models results in complex, difficult-to-solve non-linear partial differential equations. Although modern CPUs and advances in numerical methods allow for rapid solution of drying equations, the most reliable source of drying data currently derives from experimental observation.

The advent of artificial intelligence (AI) techniques allows the modeller to rapidly and economically build relationships between empirical input and output data. Of all the AI approaches, neural networks have gained increasing popularity for the modelling of drying. Only 2 references were found pertaining to the use of fuzzy logic for drying systems: one for the expert selection of industrial dryers and the other within a domestic dryer control system [6] [77].

Chapter 6 used an adaptive neuro trained fuzzy inference system (ANFIS) to model drying rates for air, airless and heat pump drying using single and multiple inputs. To the best of the author's knowledge, this modelling work is unique.

Modelling objectives were given as follows,

- to derive accurate drying times and drying rates from empirical drying data
- to demonstrate fuzzy systems as a robust, reliable method of predicting drying rate
- to use the resulting fuzzy system as a key process in the development of an energy services tool.

Accuracy of drying times cannot be fully quantified and is open to error. Table 9.0 provides a non-exhaustive list of factors which the author believes maintained an influence on modelling accuracy throughout drying trials.

Drying system errors	**Data sampling and extraction errors**
• Dryer control system	• Sample rate
– temperature fluctuations	• Filtering software
– rh fluctuations	– step size
• Load cell	– resolution
– linearity	• Gradient software
– resolution	– step size
– gas flow buffeting	– final gradient limit
• Thermocouple	
– linearity	
– RF interference	

Table 9.0 List of drying errors and inaccuracies

Drying rates were calculated from total drying times and were subject the same inaccuracies as those given in table 9.0. Furthermore, the calculation of drying rate becomes dependent on accurate measurement of product surface area and total moisture content.

Model verification was achieved by comparison with original drying data. However, model validation for heat pump and airless drying was not attempted: the limited use of dehumidification and airless drying in the ceramics industry limiting the availability of 'real world' test data.

To limit the scope of experimental work, gas temperature and/or relative humidity were chosen as the key determinants of drying rate. The models described in chapters 6 and 7 are subsequently limited to single or dual inputs. Nonhebel and Moss suggest that up to 36 variables influence overall drying behaviour [103].

Scope clearly exists for expanding the range of input variables to provide a more exacting determination of drying rate. The author has identified the following variables as suitable for additional investigation.

- drying gas velocity
- material dimensions, specifically product thickness.

Benefits of Fuzzy Systems

Unlike artificial neural networks (ANN), fuzzy systems allow the user to view the model's output surface, thus providing engineers with an opportunity to visually examine model integrity for all input values. It can be argued that such a feature has additional benefits including intuitively simple operation. Other frequently quoted benefits to fuzzy modelling include,

- Cheap and fast construction
- Easy to understand
- Intuitively simple to operate
- Flexibility in up-dating
- Tolerates imprecise data
- Non-linear systems can be easily modelled.

Flexibility in updating is an important feature. New experimental data can be readily incorporated into the system, followed by rapid system re-training. Moreover, once established, model inputs can be altered without the need to re-run the inference system.

As a supplement to fuzzy modelling, air and steam drying rates were compared and extrapolated to estimate inversion temperature. Data suggests the inversion temperature of electro-porcelain approximates to 220 °C. No other literature was found to confirm or deny such a claim.

Fuzzy Logic Tool for Energy Services

Strumillio and Kudra state that cost and throughput information alone is inadequate to assess the performance and selection of a drying system [125]. It was suggested that a more suitable method would be to standardise performance assessment using moisture removal rates and energy requirements. To this end, chapter 7 incorporated fuzzy logic models from chapter 6 into an overall energy assessment model. To the best of the author's knowledge this is a unique example of an energy services model for assessing drying, and the first energy model to base drying rate prediction on fuzzy systems.

The reader was introduced to the dichotomy faced when attempting to assess a dryer's energy performance, namely derivation of an accurate model with limited applicability, or a general model with wide applicability. To maintain a balance over model performance, it was decided to base energy consumption on data obtained from industrial drying applications. The benefits of this approach are three-fold,

1. allows for direct calculation of energy use
2. incorporates inherent dryer losses
3. avoids the need for lengthy and expensive surveys.

In addition to the use of industrial SEC values, assumptions made within the models introduce errors in to the final calculated energy, cost and CO_2 values. Table 9.1 provides a summary of those assumptions which the author believes contribute to overall errors.

Input	Assumption
• Product characteristics – start/finish moisture content – surface area – mass	Assumed to be equal for all pieces
• Production characteristics – number of pieces	Assumed to be a homogeneous dryer load
• Drying time – drying gas temperature – gas relative humidity	Reliant on experimental errors
• Energy consumption – energy efficiency	Based on typical industrial SECs/SMERs
• Costing – electricity prices – gas prices	 4.2 p/kWh 1 p/kWh
• CO_2 emissions – burner efficiency	Assumed constant at 80 %

Table 9.1 Modelling assumptions – fuzzy energy services model

Case Study

A simple case study was presented at the end of chapter 7 to illustrate the use of energy service models for the drying of porcelain insulators. Results of the study highlight some interesting characteristics. Figure 9.0 illustrates energy consumption split between gas and electrical energy, and figure 9.1 gives overall drying time and carbon dioxide emission levels. Although airless drying consumes less gas than air drying, the majority of energy saving derives from the reduction in electricity consumption.

Carbon dioxide emissions show significant reductions resulting from the use of dehumidification or airless dryers over standard air drying. Furthermore, analysis suggests that airless drying and heat pump drying can achieved a 67 % and 44 % lower energy cost then air drying. It is interesting to note that dehumidification drying shows substantial cost savings over air drying for approximately the same drying time.

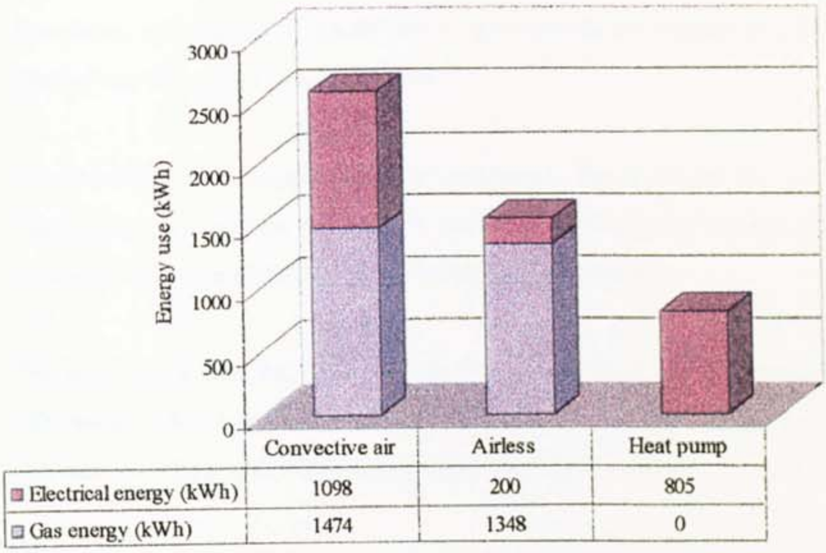


Figure 9.0 Drying time and carbon dioxide emissions

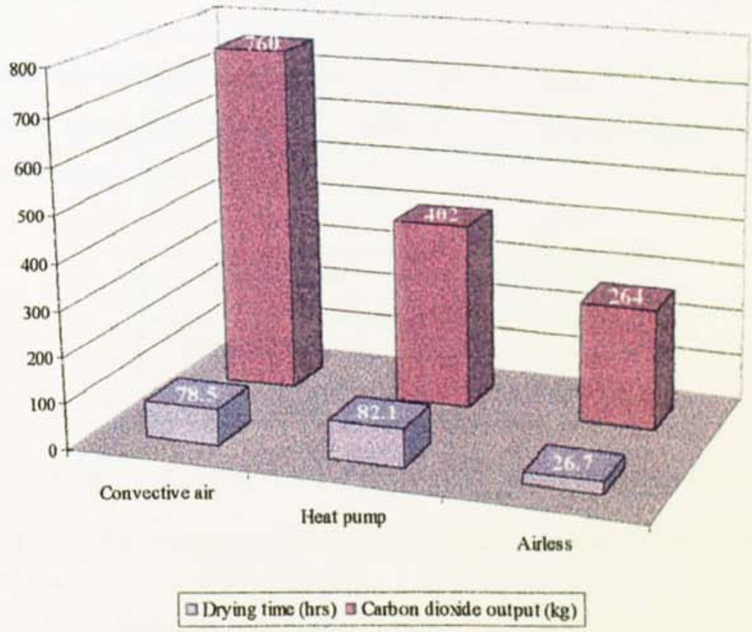


Figure 9.1 Drying time and CO_2 emissions

Energy Use for Sanitaryware Drying

A first order 'bottom-up' energy audit was completed at all 13 sanitaryware manufacturing sites throughout the United Kingdom. Energy data were collected direct from the shop floor to provide an accurate and comprehensive account of energy use for drying processes.

Details of the audit are presented in chapter 8. Survey objectives were given as,

- Provision of a reference against which past and future studies of energy use for sanitaryware drying can be compared and validated.

- Construction of a unique model of energy use for drying in the sanitaryware industry. This model can be used in 'what-if ?' scenario planning for energy, cost and carbon dioxide emission saving schemes aimed at benefiting the industry.

- To gain insight into the timing and nature of electrical energy demand and gas use for drying. Ultimately, this information will prove useful to energy supply companies targeting energy services and Demand Side Management (DSM) measures.

Survey results provide a interesting insight into the use of drying within the sanitaryware industry. Energy consumption for ceramics drying has received little attention in literature. Within industry, the lack of resources and prioritisation of product quality has meant that energy efficiency drives and monitoring are rare outside the larger organisations. The small manufacturers of expensive prestige ware were found to be least concerned with energy efficiency and energy prices.

The total number of drying units accounted for was 135, approximately 31 % more than surveyed by Smith in 1995 [121]. Of these units, 96 % were convective air dryers of the open shop or chamber variety. Other types of drying units found are given in table 9.2.

Dryer type	No. in industry
Airless dryers	1
Heat pump dryers	2
Microwave assisted`	2

Table 9.2 Alternative dryer types in UK sanitaryware industry

The following points were observations on operational procedure for the drying of sanitaryware.

- Drying was considered a bottleneck operation in most production sites.
- 75 per cent of estimated national production is shop dried, 25 per cent is processed in dedicated chamber dryers.
- Drying cycles for dedicated ware dryers operate from 10 hours upwards. Typically, shop drying cycles takes between 24 and 48 hours.
- Ware is commonly over-dried with a factor of safety, or even dried twice.

In terms of energy use, production staff were found to be conscious of factory-wide energy requirements yet remained unaware of process level energy use and its timing. Observations on energy use were as follows.

- The UK sanitaryware sector consumed an approximate total of 2357 TJ in 1996/1997

- Average specific energy consumption was estimated to be 0.56 GJ/tonne of dry product.
- Dryer efficiency varied across factories and between production sites. Efficiencies for shop drying were found to lie between 6 and 22 per cent, whilst dedicated ware dryers demonstrated higher efficiency, typically 20 to 57 per cent.
- Drying processes consume 19 per cent of total site energy load compared to the 15 to 17 per cent previously estimated.
- 25 per cent of total drying energy derives from electricity use compared to a previously estimated 15 per cent [63].

The calculation of energy use for drying was subject to a number of assumptions and, subsequently, results are open to error. Assumptions include,

- No heat energy retention in dryer furniture and structural fabric
- No heat loss through doors and windows
- Gas burner efficiency rated at a constant 80 %
- Evaporation is adiabatic
- All motive devices operate at face plate rating throughout the drying cycle.

It is impossible to quantify errors, but it is the author's belief that the assumptions made serve to enhance quoted efficiency above that found in industry.

CHAPTER 10

CONCLUSIONS AND PROPOSALS FOR FUTURE WORK

Introduction

The previous chapter discussed salient points of interest arising from the substantial and original work presented in this thesis. This chapter attempts to draw concluding remarks to the thesis and suggest areas of possible future work.

Chapter 10 has been divided into what the author believes are the 3 fundamental areas of future interest: DSM and energy use for industrial drying, modelling of airless drying and fuzzy modelling of drying processes.

DSM and Energy Use for Industrial Drying

The United Kingdom electricity supply industry is currently in a state of organisational and regulatory flux, a situation which has been on-going since privatisation in 1990. Changes within the ESI have been reflected by changes in the definition of demand side management. It can be suggested that DSM no longer exists in its traditional form, but has moved towards a customer focused energy services approach.

Driving forces behind DSM and energy services have also changed. The original need to manage customer demand as a method of optimising network load has been supplemented by the desire to help customers save energy and gain productivity. Public Energy Suppliers (PESs) hope to use customer relationships and energy services to secure long term supply contracts.

Two areas of potential interest are suggested for future work: DSM and its bearing on drying processes, and the general use of energy for industrial drying.

DSM and Industrial Drying

Drying processes offer significant opportunity for targeted energy services. Industrial dryers are energy-intensive, widely used and often inefficient in operation. The expert knowledge and resources held by the old RECs provide a valuable tool to help customers save energy.

Chapter 3 introduced an important objective for market-led DSM, namely the 'locking in' of customers. Understanding customers' needs, and then working in close partnership to reduce energy consumption can help build switching costs in to the customers' supply chain. Theoretically, the customer finds it financially and operationally disadvantageous to switch supplier on an energy cost basis alone. Unfortunately, little proof exists that customers are willing to undertake such relationships. Moreover, discussion with industry suggests that customers are more concerned with price and security of supply. An opportunity exists to approach a wide section of industry and canvas opinion on the use of energy services. Hopefully, results would highlight those sectors open to fostering advantageous relationships.

Home-grown expertise in energy efficient measures can benefit the UK. Opportunities exist to transfer energy saving technology outside the domestic market. Sixty per cent of all industrial electricity demand in the UK is for motive power such as fans, pumps and compressors. The demand for heating and drying is both significantly smaller and highly contested [44]. However, as part of the Convention on Climate Change Policy, OECD countries have an obligation to provide advice on energy efficiency measures to developing countries. An opportunity therefore exists to market energy services in less competitive foreign markets. Research is needed to identify possible implementations of energy saving techniques abroad on both a sectorial and process level.

Energy Use for Industrial Drying Processes

The successful application of energy efficiency measures requires a thorough understanding of customers' energy use. Such an understanding necessitates the supply of accurate information from the user, typically derived from surveys and questionnaires. Chapter 4 attempted to re-estimate the total national energy demand for industrial drying processes. The difficulties encountered from this survey highlight several areas current lacking understanding or background research.

Estimation of industrial energy use for drying is infrequent. Including this work, only 7 national surveys were found in literature. The author suggests that regular surveys are needed to provide a useful long term analysis of trends in dryer use. Moreover, an opportunity exists to set-up a standardised survey procedure to allow for accurate year-on-year comparison of results.

The 'moisture loss' calculation method followed in this thesis allows the user to model changes in dryer efficiency. Unfortunately, very few references were found which provided the necessary detail to cover a range of dryers. A clear opportunity exists to undertake a wide-ranging survey of dryer efficiency and operational practice. Information could then be compiled into a co-ordinated database for simple and rapid access. The benefactors of such a system could include,

- Public Energy Suppliers (PESs)
- Prime users of drying technologies e.g. Chemical and Pharmaceuticals industry
- Energy services companies
- Government funded energy organisations e.g. ETSU, BNCE.

Assessment of dryer efficiency requires intensive logging of enthalpy streams and electrical power consumption. Many industries cannot allocate the resources necessary for such activities. To solve this problem, work can be conducted using the expertise and survey equipment of energy suppliers or third party energy services companies.

Energy savings can be realised from the transfer of established energy efficient drying technologies between industrial sectors and sub-sectors. Furthermore, novel drying technologies are often pushed to market rather than pulled by demand for a new technology. A large opportunity therefore exists to gather information on current dryer use and emerging technologies. The information could be combined for easy cross-referencing of current and future dryer technology with potential target applications. It must be noted that the information requirements for such a task are significant.

Previous surveys have not fully discussed the economic or sociological effects of industrial energy use for drying. Little work can be found which accounts for total global CHG emissions, or discusses the relevant legal instruments on pollution control which effect industrial drying operations. The author believes that recent proposals for energy/carbon taxation will have major implications for the drive towards energy efficient drying.

A search of literature suggests that no work has been conducted to investigate the effects of replacement drying technologies on production schedules and profitability. Significant opportunities exist to study production factors and pollution, with the possible aim of incorporating them into an socio-economic model of national drying activities.

Development of Airless Drying

Several energy efficient drying technologies have come to the fore in the last 20 years, including the adaptation of traditional drying methods and the advent of entirely new drying systems such as airless drying.

The proponents of airless drying have championed it as an innovative, novel replacement for standard drying practices. Mujumdar describes steam drying as the 'most prevalent breakthrough in energy efficient drying' [98]. Nevertheless, it must be remembered that novelty per se is insufficient for wide-spread acceptance in industry. The technology must be proved safe, reliable, repeatable and economically viable when compared to current drying systems.

Chapter 3 provided an insight into the history and development of the airless drying technology. From this work, the author has identified several areas of airless operation which offer potential opportunity for future study. Table 10.0 provides a list of advantages and disadvantages for both airless and standard air drying. Areas warranting further work are highlighted in bold type.

Understandably, many of industry's doubts surrounding airless drying stem from a lack of operational experience. Airless drying case studies found in literature originate from either a single dryer manufacturer or ETSU's Best Practice Program. No report could be found from third party industrial users. The author proposes that a survey of all known industrial airless installations should be commissioned. Combined results would prove both a useful promotion tool for airless drying and an invaluable guide to current penetration and operation of airless dryers in the UK.

	Airless drying	Air drying
Advantages	• **Cost effective exhaust steam usage**	• Traditional systems are optimised
	• Lack of fire / explosive hazards	• Air ingress is possible but unlikely
	• Lack of oxidative damage	• Product never exceeds drying gas temp (50 ^{O}C)
	• **Improved product quality**	• More acceptable for sensitive products
	• **Increased drying rates**	• Final moisture content is more controllable
	• More compact dryers	• Drying may proceed during warm-up
	• **Less energy intensive**	
	• Simplifies solvent recovery	
	• **More simple control mechanisms**	
	•	
Disadvantages	• **Limited industrial experience and costing information**	• No use of exhaust air possible
	• Feed / discharge of materials • i.e. excessive air ingress	• Risk if product is particulate or combustible
	• Increased product temperatures i.e. 100 ^{O}C	• Oxidation damage
	• **Sensitive products ?**	• Standard, acceptable quality
	• **Harder to achieve a lower moisture content**	• Solvent recovery is expensive / impossible

Table 10.0 The potential of airless for DSM and energy services

Steam drying was originally promoted as an energy saving technology. However, communication with dryer manufacturers suggests that modern air dryers are now capable of thermal efficiencies similar to those of stand alone airless units. Subsequently, to gain an energy advantage, steam dryers need to re-claim latent heat energy within the exhaust [24] [99]. Re-claim methods have been discussed earlier and include MVR, space heating and steam raising for secondary processes. Very little information has been found to describe these operations and therefore an opportunity exists to examine the detailed benefits of exhaust re-claim.

Costing of airless drying technology is unclear and little information could be found in literature. Table 10.1 suggests some of the associated costs and cost savings from the use of airless drying.

A potential exists for the construction of an airless 'costing model' to compare the capital expenditure and running costs in table 10.1 against those of conventional drying systems. Such a model could analyse fixed and variable costs, and predict overall return on investment (ROI).

Costs	Cost savings
• Capital outlay (possibly larger than for air dyer)	• Increased production output
• MVR costs	• Energy savings
• Ancillary connection costs	• Increased drying capacity for future expansion
• Training and maintenance costs	• Removal of a key bottleneck areas
• Lost productivity due to initial unfamiliarity with dryer	• Reduction of Work in Progress (WIP)

Table 10.1 Costs and cost savings from airless drying

Improved product quality has been claimed from the use of airless drying, yet little work can be documented which broaches this subject. Future material investigations are necessary to define the types of improvement possible, if any. Product quality is an important aspect to many manufacturing processes. Any defined gains in quality will therefore enhance the promotion of airless drying.

Other proposals for future work on airless drying include,

- Modelling of energy use for continuous airless drying
- Detailed modelling of energy re-claim systems e.g. MVR, space and water heating
- Studying the effects of airless drying on up- and down-stream production processes
- Process integration.

<u>Fuzzy Modelling of Drying Processes</u>

Chapter 6 demonstrated the successful use of fuzzy systems to predict drying rates, whilst chapter 7 embedded the fuzzy systems within an energy services model. The ultimate aim for these systems is full implementation as a working industrial tool. However, the author recognises that a significant programme of development is required prior to implementation.

Three areas have been identified as requiring significant further development.

1. Refinement and expansion of fuzzy models
2. Refinement of energy calculation modules
3. Flexible costing modules.

Model Development: Fuzzy Systems

Continuous dryers form the vast majority of units within industry, yet the fuzzy systems constructed in chapter 6 are limited to three chamber drying technologies: air, airless and heat pump drying. Scope clearly exists to expand fuzzy modelling to cover continuous operation.

So far, fuzzy models have been based on laboratory drying data using singular or dual input variables. To provide a more accurate representation of industrial drying, it is suggested that models are re-trained using on-line data from factory-based dryers. Moreover, models should be expanded to accommodate a greater number of control variables, including gas flow characteristics.

Practical air drying cycles frequently incorporate important dwell periods. The purpose of these periods is to allow controlled, constant rate drying whilst the product is still vulnerable to physical damage. Work is needed to simulate the effects of dwell within the fuzzy systems.

Model Development: Energy Modules

Energy consumption and energy efficiency change throughout the drying cycle. Furthermore, thermal efficiency is a function of many variables including dryer construction, gas flow regime, dryer age and maintenance schedules. Although calculation of energy use for drying remains difficult, opportunities exist to improve the accuracy of the models presented in this thesis.

Energy use for both air and airless drying were based on historical SEC values extracted from literature and conversations with industry. The author believes that thorough energy auditing of industrial dryers will provide a more accurate estimation. A more comprehensive audit of drying conditions will also allow future work to treat each dryer type on an individual basis, rather than using averaged SEC values.

The study of electrical load on fossil fuel fired dryers is rare. However, considering the price differential between energy sources, electrical power consumption can often equal gas consumption on a cost basis. Electrical load within the energy services models is assumed to operate at face plate rating throughout the drying cycle. In reality motive devices are often oversized for their required duty. Areas for future investigation include,

- Modelling of total and instantaneous electrical load
- Modelling the efficiency and over sizing of fans
- The application of twin-speed distribution and exhaust fans
- Modelling of steam injection / humidification systems.

Model Development: Costing Modules

Costing modules currently assume constant energy prices over the drying schedule. In reality lengthy drying cycles span periods of on- and off-peak electricity demand. Incorporation of time-dependent energy tariffs would allow for the calculation of energy savings arising from re-scheduling of drying cycles.

CHAPTER 11

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APPENDIX A

SURVEY RESULTS

Survey results : Energy consumption for industrial drying in the UK, 1994.

Survey results : Energy consumption for industrial drying in the UK, 1994

Material	Annual production (tonnes × 10^6)	Average moisture content drop (%)	Water removed (tonnes × 10^6)	Efficiency (%)	Total Energy (PJ pa)
Paper and Board		200	18.62	50	91.83
Ceramics and Building Materials					
Bricks	6.614	15	0.9921	60	4.08
Vitrified clay pipes	0.564	15	0.0846	60	0.35
China Clay	4.49	20	0.838	60	3.44
Raw Clay	17.6	20	3.52	60	14.47
Dust making (tiles)	16	13	2.08	70	7.33
Shaped refractioners	0.45	16	0.072	60	0.30
Fuller's Earth	0.45	38	0.171	60	0.70
Electrical Porcelain	0.02	60	0.012	60	0.049
Tableware etc.	0.2	20	0.04	50	0.20
Tiles	16	8	1.28	70	4.51
Sanitaryware	0.13	18	0.0234	60	0.10
Plaster moulds	0.15	6	0.009	50	0.04
Glazed ceramics	1.6	1	0.016	60	0.07
Cement	12.14	35	4.249	79	13.26
Road Stone	60.7	4	2.428	82	7.30
Ball Clay	6	20	1.2	60	4.93
Silica Sand	9.79	35	3.4265	70	12.07
Limestone/Dolomite	18.5	4	0.74	82	2.23
Chalk	10.3	10	1.03	70	3.63
Food and Agriculture					
Sugar (incl. beet)	1.47	12	0.1764	70	0.62
Milk, Dried	0.24	900	2.16	70	7.61
Milk, Condensed	0.06	500	0.3	55	1.35
Milk, Skimmed powder	0.1	10	0.01	70	0.04
Coffee, instant	45	20	9	38	58.41
Vegetables	3.8	2	0.076	70	0.27
Whey	0.049	300	0.147	60	0.60
Tobacco	143.1	6.5	9.3015	50	45.87
Potatoes	6.5	0.1	0.0065	40	0.040
Instant Tea	0.005	20	0.001	40	0.01
Malt	1.2	42	0.504	70	1.78
Whiskey by-products	0.008	60	0.0048	60	0.02
Breakfast cereals	0.33	13	0.0429	60	0.18
Seed Cake	1.2	8	0.096	50	0.47
Meat and Bone meal	0.18	53	0.0954	70	0.34
Maize Starch	0.12	28	0.0336	70	0.12
Gluten	0.53	20	0.106	60	0.44
Fish meal	0.18	42	0.0756	70	0.27
Pasta	0.156	19	0.02964	50	0.15
Salt	5.2	25	1.3	70	4.58
Plaster and plasterboard					
Gypsum	2.99	20	0.598	60	2.46

Textiles					
Cotton	0.1	30	0.03	50	0.18
Wool	0.04	30	0.012	50	0.06
Leather	22.7	30	6.81	60	27.99
Linen	7.16	30	2.148	50	10.59
Timber					
Timber, softwoods &	4.03	32	1.2896	55	5.78
Timber, hardwoods					
Wood Pulp	0.602	140	0.8428	55	3.78
Chemicals					
Cellulosics	0.14	5	0.007	70	0.025
Fertiliser	0.8	3	0.024	55	0.11
Organics	3.9	4	0.156	70	0.55
Rubber	7.2	7	0.504	55	2.26
Potash	0.58	10	0.058	55	0.26
Fluorspar	0.06	10	0.006	55	0.027
Miscellaneous chemicals	0.3	4	0.012	70	0.04
Pharmaceuticals	0.2	3	0.006	70	0.02
Laundry					
Dry-cleaning	0.3	50	0.15	53	0.70
Other Industry	n/a	n/a	n/a	n/a	n/a
Iron and Steel	n/a	n/a	n/a	n/a	n/a
				TOTAL	348.8

APPENDIX B

EXPERIMENTAL RESULTS

Appendix B contains the following experimental results.

Section

B1 Convective air drying

B2 Airless drying

B3 Heat pump dehumidification drying

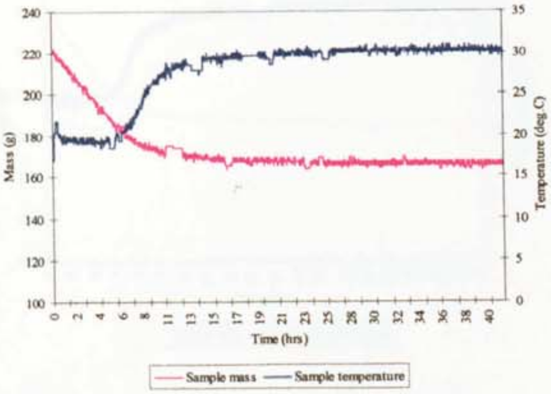

Figure B.0 Air drying of electro-porcelain
(T_a = 30 °C, no humidity control)

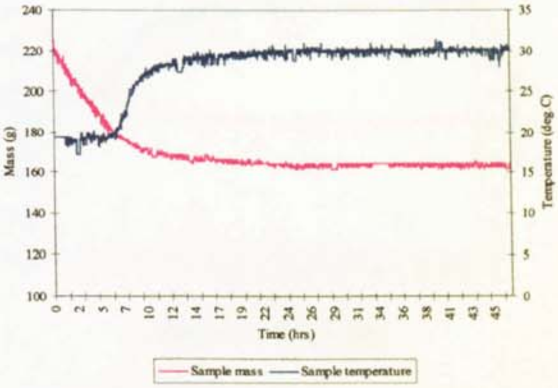

Figure B.1 Air drying of electro-porcelain
(T_a = 30 °C, 10 % rh)

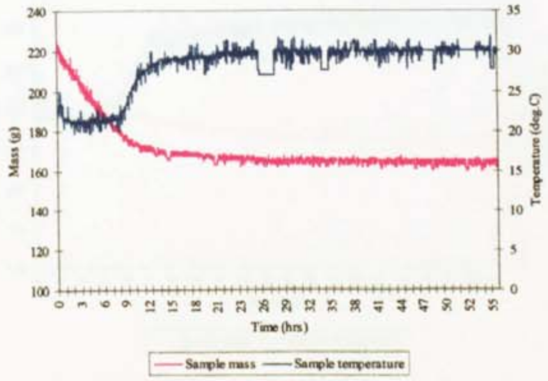

Figure B.2 Air drying of electro-porcelain
(T_a = 30 °C, 20 % rh)

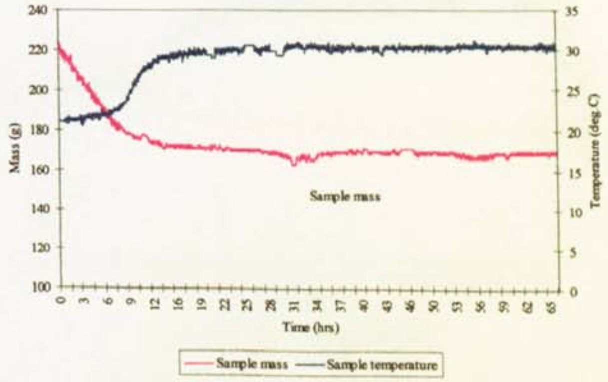

Figure B.3 Air drying of electro-porcelain
(T_a = 30 °C, 30 % rh)

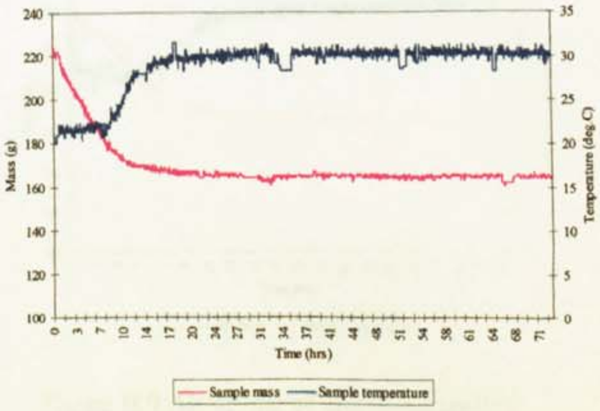

Figure B.4 Air drying of electro-porcelain
(T_a = 30 °C, 40 % rh)

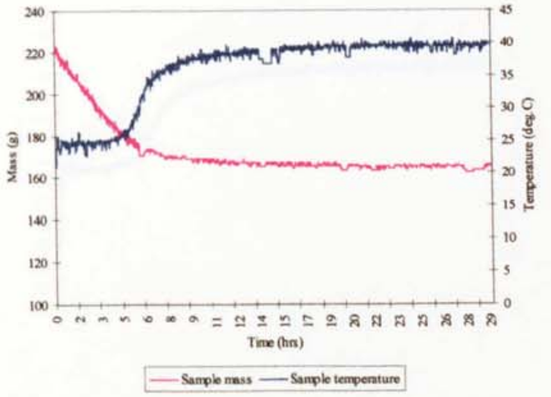

Figure B.5 Air drying of electro-porcelain
(T_a = 40 °C, no humidity control)

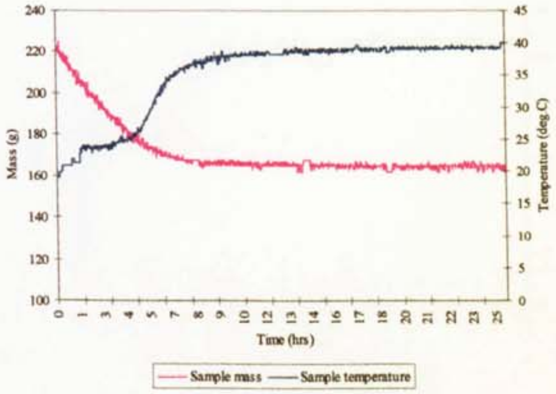

Figure B.6 Air drying of electro-porcelain
(T_a = 40 °C, 10 % rh)

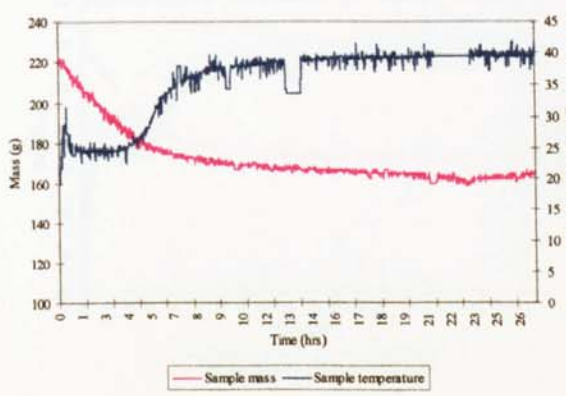

Figure B.7 Air drying of electro-porcelain
(T_a = 40 °C, 20 % rh)

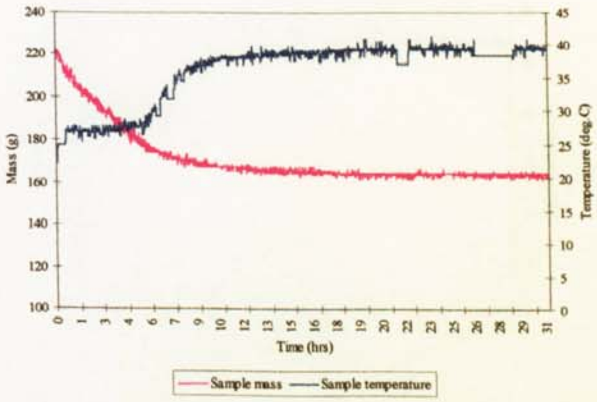

Figure B.8 Air drying of electro-porcelain
(T_a = 40 °C, 30 % rh)

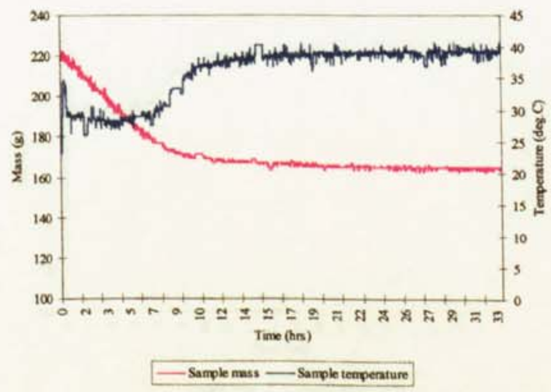

Figure B.9 Air drying of electro-porcelain
(T_a = 40 °C, 40 % rh)

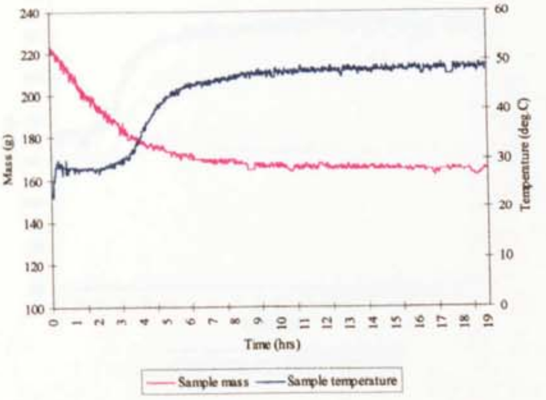

Figure B.10 Air drying of electro-porcelain
(T_a = 50 °C, no humidity control)

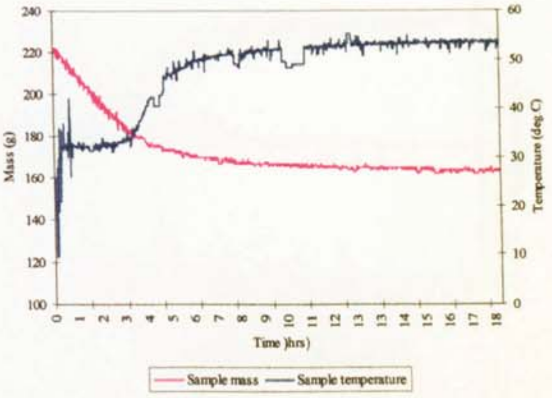

Figure B.11 Air drying of electro-porcelain
(T_a = 50 °C, 10 % rh)

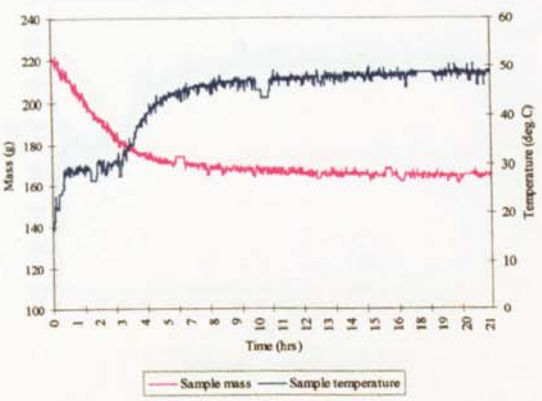

Figure B.12 Air drying of electro-porcelain
(T_a = 50 °C, 20 % rh)

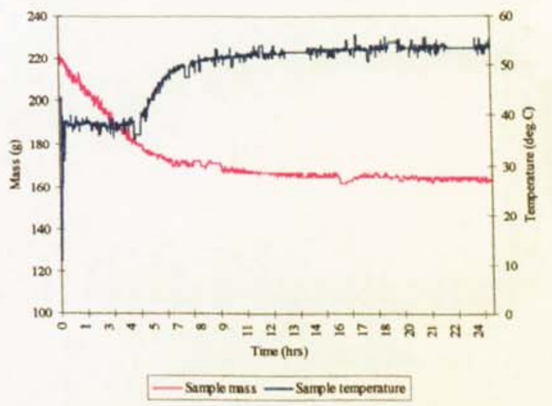

Figure B.13 Air drying of electro-porcelain
(T_a = 50 °C, 30 % rh)

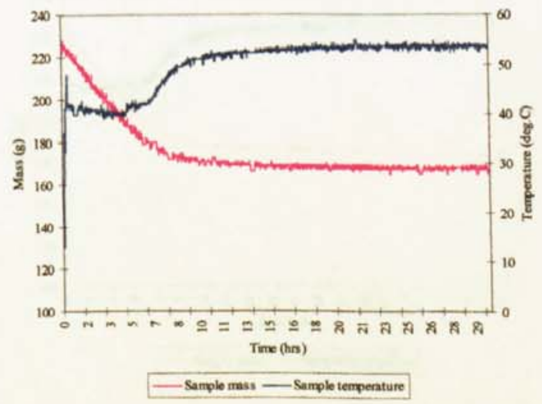

Figure B.14 Air drying of electro-porcelain
(T_a = 50 °C, 40 % rh)

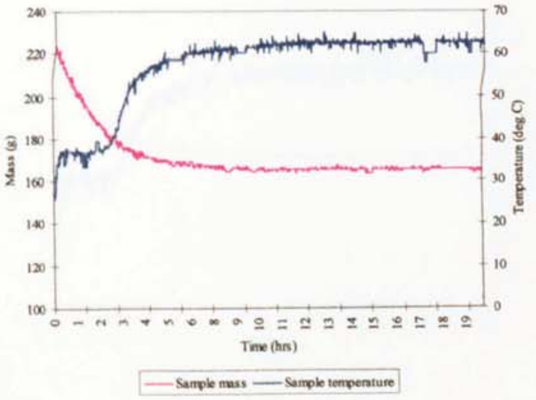

Figure B.15 Air drying of electro-porcelain (T_a = 60 °C, no humidity control)

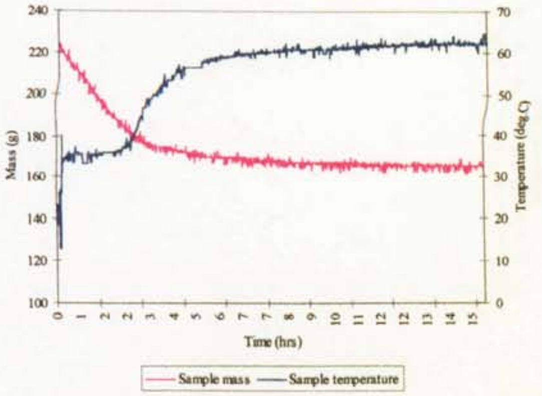

Figure B.16 Air drying of electro-porcelain (T_a = 60 °C, 10 % rh)

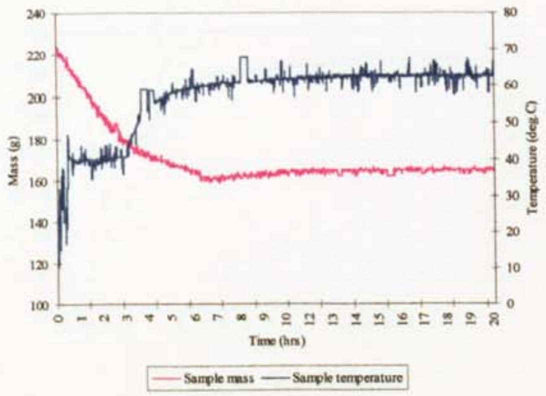

Figure B.17 Air drying of electro-porcelain (T_a = 60 °C, 20 % rh)

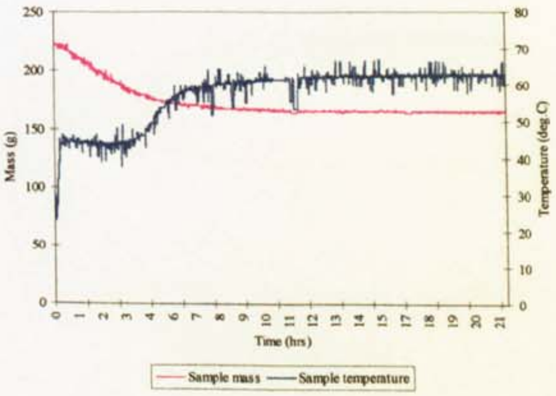

Figure B.18 Air drying of electro-porcelain (T_a = 60 °C, 30 % rh)

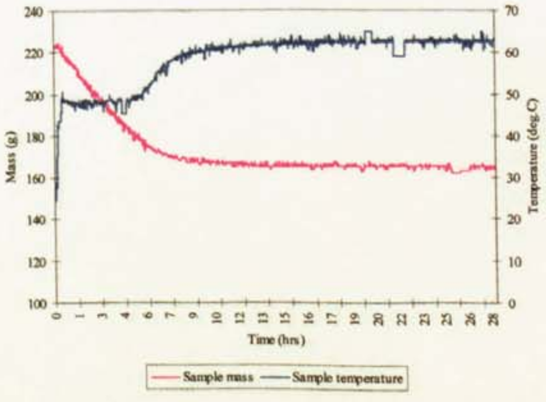

Figure B.19 Air drying of electro-porcelain (T_a = 60 °C, 40 % rh)

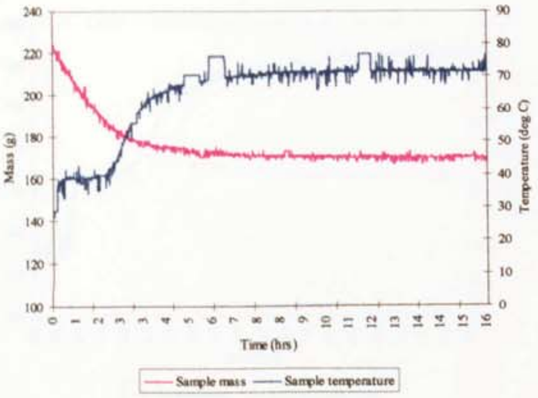

Figure B.20 Air drying of electro-porcelain
(T_a = 70 °C, no humidity control)

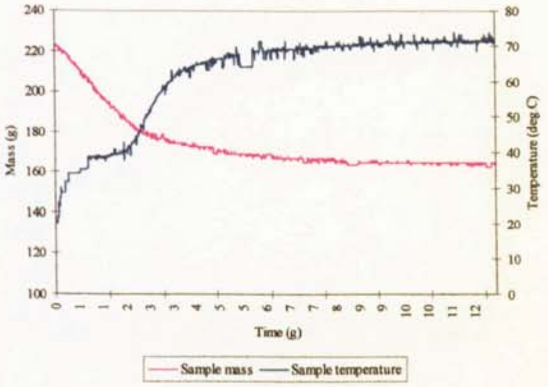

Figure B.21 Air drying of electro-porcelain
(T_a = 70 °C, 10 % rh)

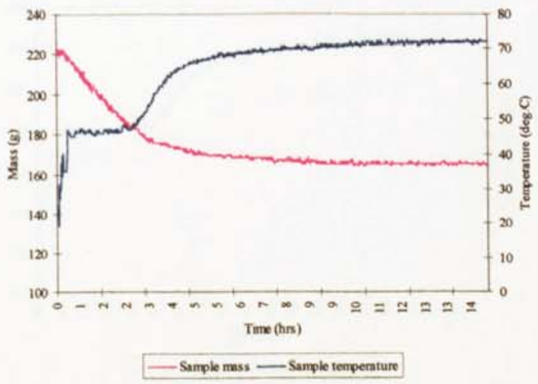

Figure B.22 Air drying of electro-porcelain
(T_a = 70 °C, 20 % rh)

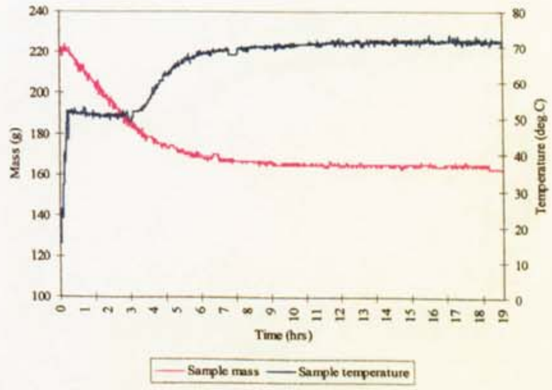

Figure B.23 Air drying of electro-porcelain
(T_a = 70 °C, 30 % rh)

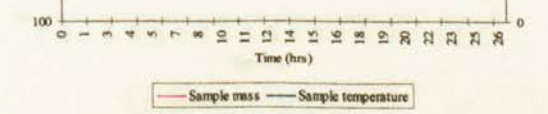

Figure B.24 Air drying of electro-porcelain
(T_a = 70 °C, 40 % rh)

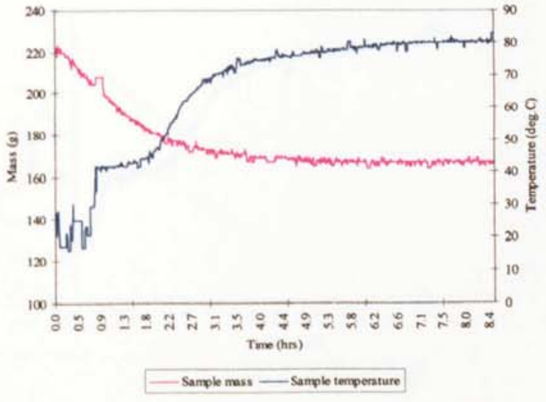

Figure B.25 Air drying of electro-porcelain
(T_a = 80 °C, no humidity control)

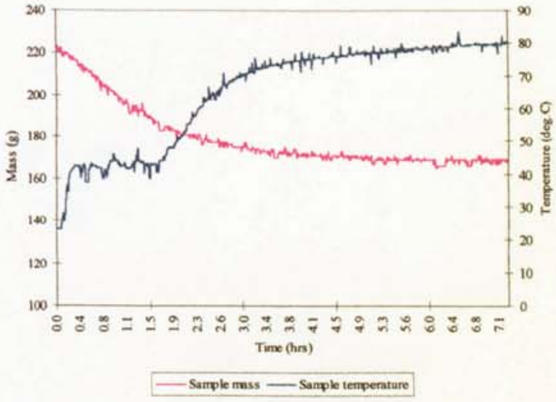

Figure B.26 Air drying of electro-porcelain
(T_a = 80 °C, 10 % rh)

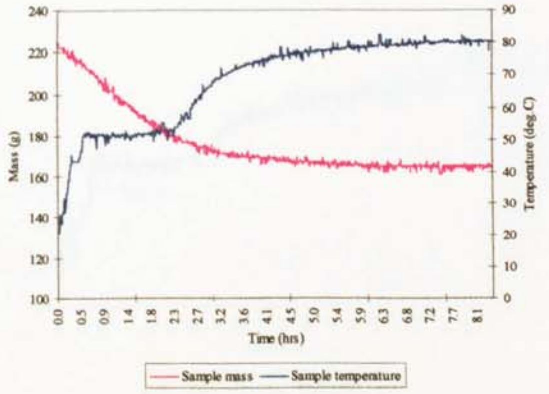

Figure B.27 Air drying of electro-porcelain
(T_a = 80 °C, 20 % rh)

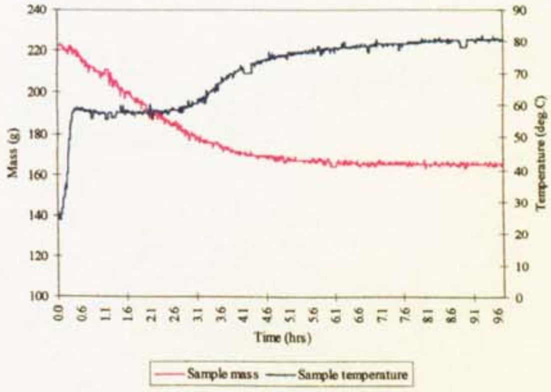

Figure B.28 Air drying of electro-porcelain
(T_a = 80 °C, 30 % rh)

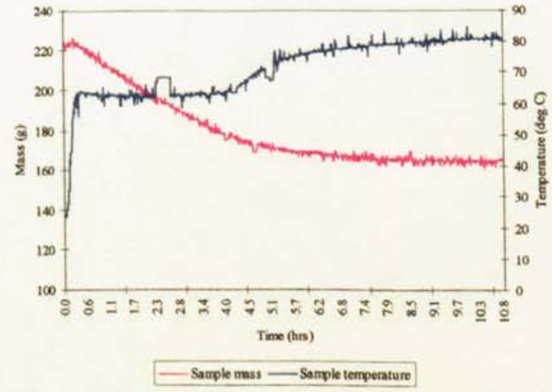

Figure B.29 Air drying of electro-porcelain
(T_a = 80 °C, 40 % rh)

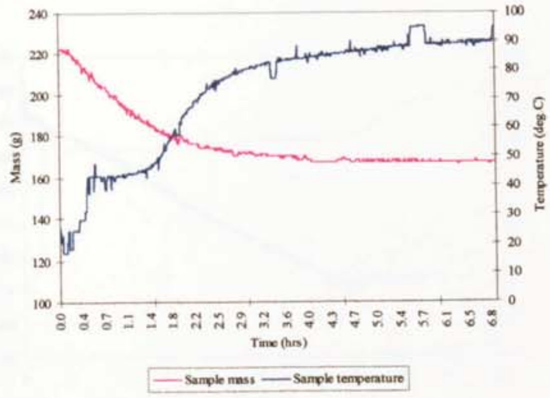

Figure B.30 Air drying of electro-porcelain (T_a = 90 °C, no humidity control)

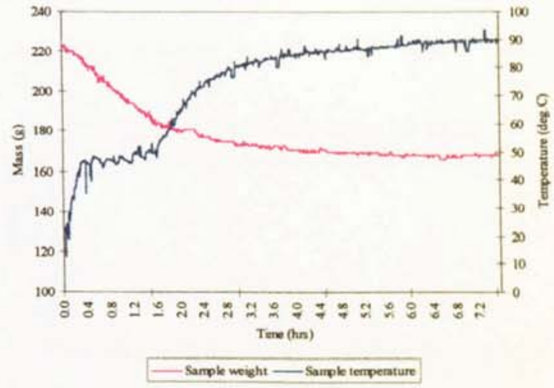

Figure B.31 Air drying of electro-porcelain (T_a = 90 °C, 10 % rh)

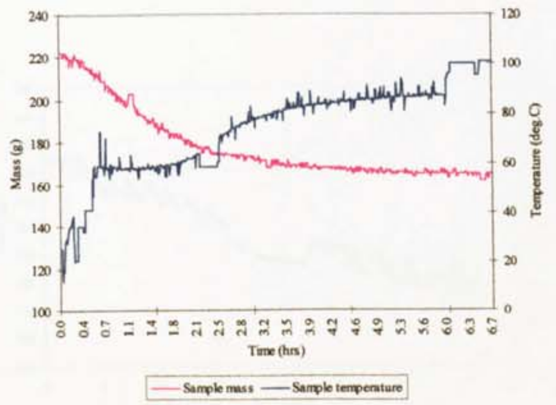

Figure B.32 Air drying of electro-porcelain (T_a = 90 °C, 20 % rh)

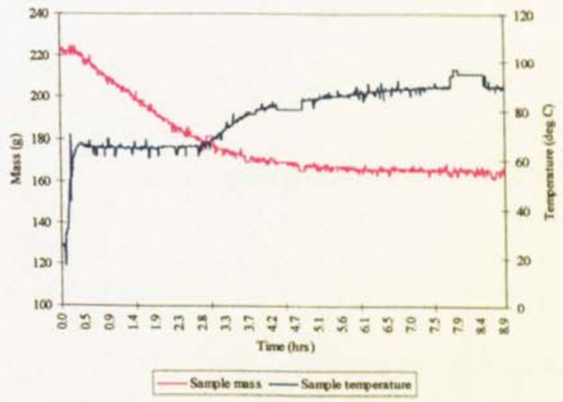

Figure B.33 Air drying of electro-porcelain (T_a = 90 °C, 30 % rh)

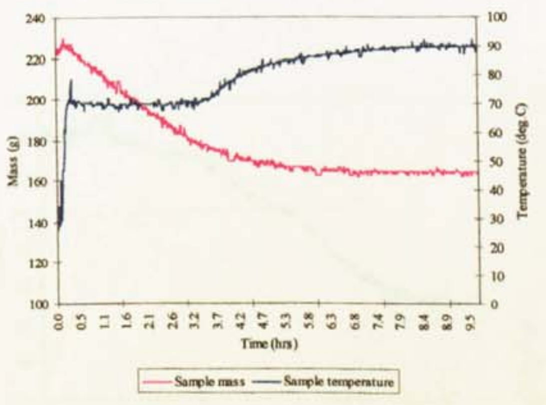

Figure B.34 Air drying of electro-porcelain (T_a = 90 °C, 40 % rh)

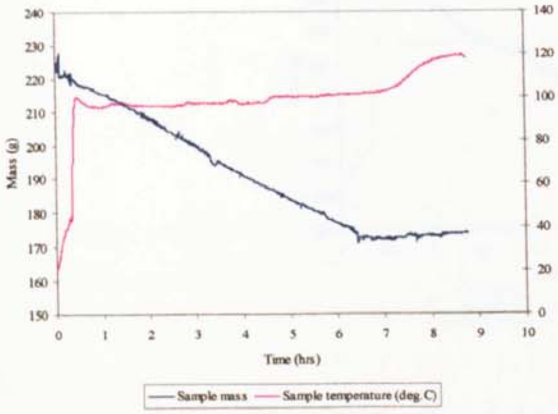

Figure B.35 Airless drying: sample temperature and mass profiles (T_{ss} = 120 °C)

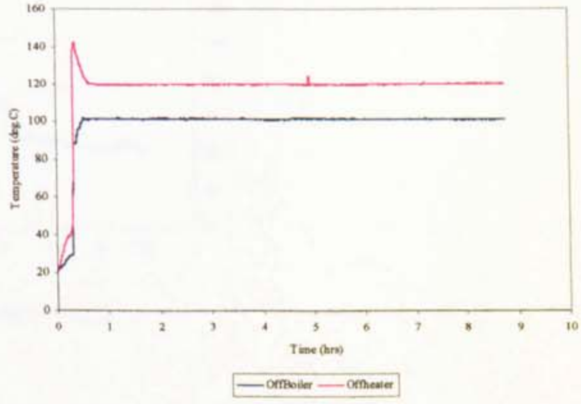

Figure B.36 Airless drying: boiler and off-heater temperature profiles (T_{ss} = 120 °C)

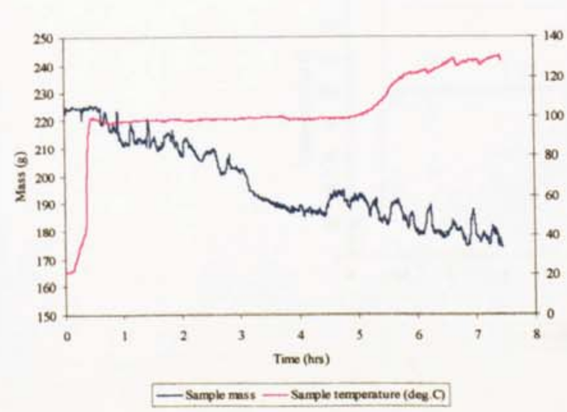

Figure B.37 Airless drying: sample temperature and mass profiles (T_{ss} = 130 °C)

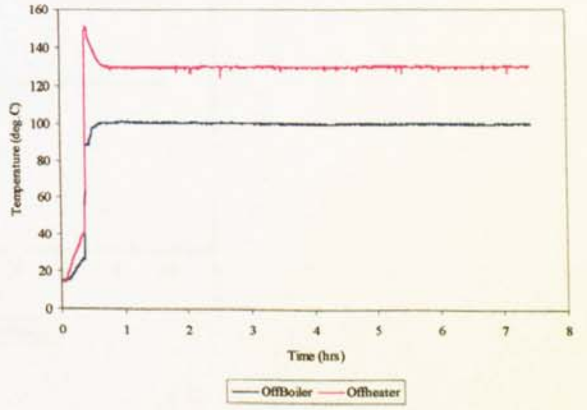

Figure B.38 Airless drying: boiler and off-heater temperature profiles (T_{ss} = 130 °C)

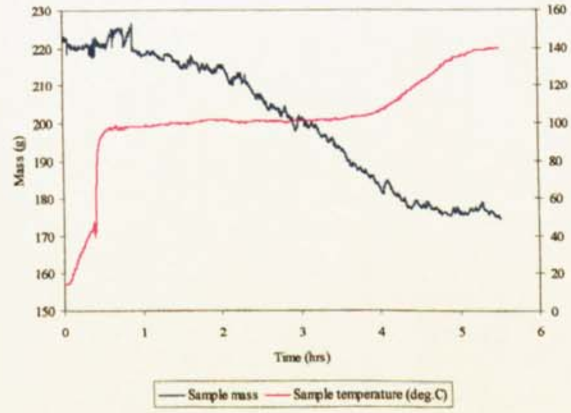

Figure B.39 Airless drying: sample temperature and mass profiles (T_{ss} = 140 °C)

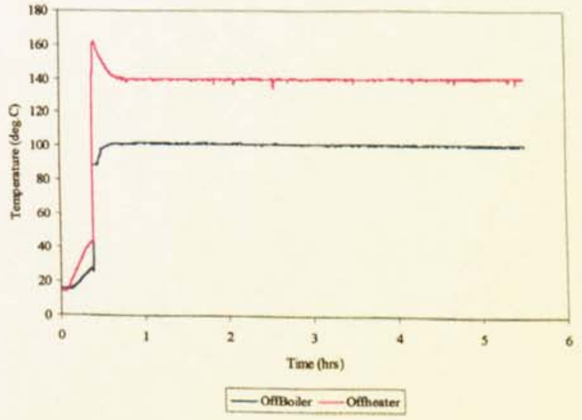

Figure B.40 Airless drying: boiler and off-heater temperature profiles (T_{ss} = 140 °C)

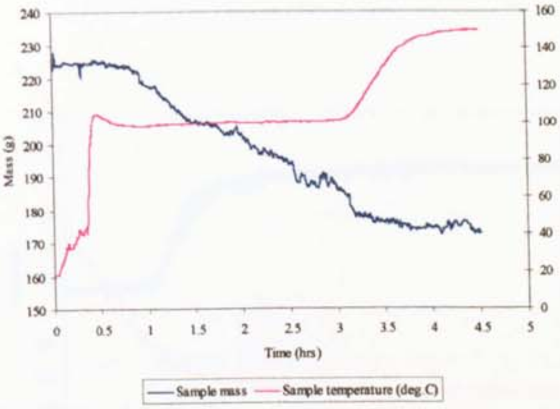

Figure B.41 Airless drying: sample temperature and mass profiles
(T_{ss} = 150 °C)

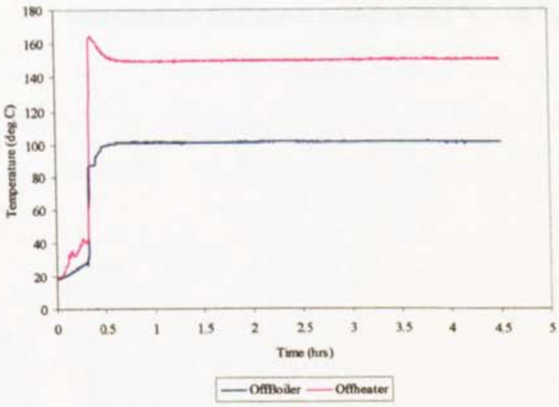

Figure B.42 Airless drying: boiler and off-heater temperature profiles
(T_{ss} = 150 °C)

APPENDIX B: Section 3. Experimental results for heat pump dehumidification drying trials.

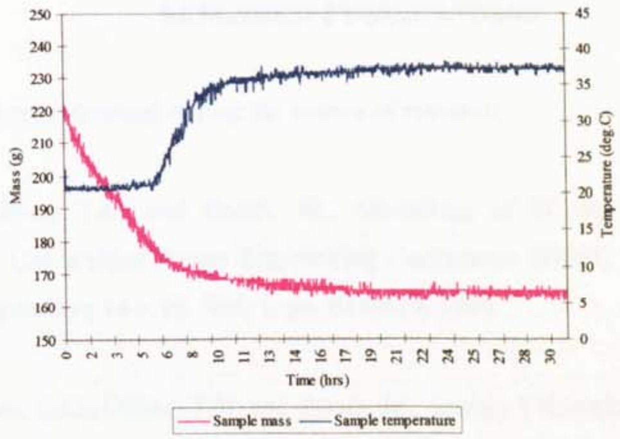

Figure B.43 Heat pump drying: sample temperature and mass profiles (40 °C, 18 % rh)

APPENDIX C

RESEARCH PUBLICATIONS

The following papers were published during the course of research.

- Gilmour, J.E., Oliver, T.N. and Booth, M., Modelling of Drying Processes for Demand-Side Management, 34th Universities Power Engineering Conference (UPEC '99), University of Leicester, Leicester, UK., September 14 – 16, Vol. 1, pp. 616-619, 1999.

- Gilmour, J.E., Steer, G.C., Oliver, T.N. and Booth, M., Energy Utilisation within the UK Sanitaryware Industry and the Potential for Energy Services, 33rd Universities Power Engineering Conference (UPEC '98), Napier University, Edinburgh, UK, September 8-10, Vol. 1, pp. 399-402, 1998.

- Gilmour, J.E., Oliver, T.N. and Booth, M., Energy Use for Drying Processes : The Potential Benefits of Airless Drying, Drying '98 – Proceedings of the 11th International Drying Symposium (IDS '98), Halkidiki, Greece, August 19-22, Vol. A, pp. 573-580, 1998.