THE UNIVERSITY OF ASTON IN BIRMINGHAM

ELECTRICAL ENGINEERING DEPARTMENT

AN EFFICIENCY ANALYSIS OF THE ASTON PLASMA TORCH.

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SUMMARY

Earlier work on the efficiency analysis of a recently developed mains frequency plasma torch indicated the need for two main fields to be investigated. Firstly, an overall efficiency balance had to be obtained in order to assess the suitability of the device for industrial applications. Previously, the efficiency was only considered relative to the torch itself, but an overall efficiency analysis will include the external auxiliary apparatus without which the torch cannot be operated. Secondly, it became apparent that the validity of results obtainable from certain electrical measuring instruments in estimating the non-sinusoidal power input to the arc was questionable. This, of course, affected the accuracy of the energy balance, and therefore the most suitable method for obtaining these measurements had to be estimated. An electronic multiplier was found to be most suitable, especially if used in conjunction with an integrator to average the results over a reasonable time. The thermal wattmeter was found to be nearly as accurate, and would be easier to handle in less favourable environments than the laboratory.

In accounting for the power converted into heating the gas, investigations showed the need for calorimetric methods to be used.

Final results proved the torch to be competitive economically, since an efficiency figure exceeding 60% was obtainable. The overall efficiency analysis indicated a total output/input conversion capability of more than 30%. These figures were well above the reported efficiencies of other a.c. plasma torches.

ACKNOWLEDGEMENT

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Mr. J. Partlow, of the technical staff, is specially thanked for the maintenance of the Plasma Torch throughout the period of this work.

CONTENTS

CHAPTER 1.

INTRODUCTION.

A Plasma Torch is a device for converting electrical energy to thermal energy and is used in special industrial operations. Its name does not really mean the production of plasma as the accepted terminology might suggest (i.e. the energy level of the gases imply a state of ionisation and dissociation). An Electric arc gas heater is an alternative and somehow more appropriate name, and is commonly used at this University. Actual plasma states do exist at those regions of the gas that are adjacent to the electric arc itself, however, the main technological interest lies in the thermodynamic properties of the gas leaving the torch, and therefore an "arc gas heater" appears more adequate a description for such a device.

The main current applications of plasma torches are in coating and spraying, spheroidising, chemical synthesis, and propulsion and position control of spacecraft.

The low contamination level in the output product and the extremely short time taken in reaching operating temperatures, in addition to the production of high temperatures and enthalpies, give the plasma torch certain advantages over other possible heat sources.

As the use of plasma torches was mainly for special "high quality product" applications, no great concern was given to operating efficiency levels. Typical values were 50 to 60 per cent for d.c. operations.

While d.c. operated plasma torches have been in existence since the turn of the century, a.c. torches have been developed only recently, and are mainly used for wind-tunnel applications. Although having the advantage of eliminating the need for rectification equipment, they are reported to be very inefficient compared with d.c. operated plasma torches. Typical operating efficiencies are in the range 20 to 30 per cent and values as low as 7 to 10 per cent have been quoted.[1]

If the plasma torch, whether d. c. or a. c., is to succeed in the field of industrial heating processes, higher efficiency levels are clearly essential. As a result, an attempt has been made at this University, to build an a. c. mains frequency plasma torch (thus reducing capital costs by that amount needed for rectification equipment) with an operating efficiency at least comparable to some of the highest obtained for d. c. operations, in order to justify its use in industrial processes.

The efficiency analysis and energy balance of a. c. plasma torches are not as straight forward as for their d. c. counterparts. The complications are mainly due to inadequate estimation of the electrical power input. The a. c. waveforms across the arc are not only non-sinusoidal, but are characterised by sharp peaks of fast rise and decay times. Furthermore, for cold cathode materials the arc will extinguish every half cycle unless a reignition system is used. This, in turn, will add to the fluctuations already present, in the arc parameters. Non-uniformity of arc current and voltage waveforms and complete arc extinction every few cycles will add further non-linearities to the electrical input characteristics.

The principal object of previous workers[2] in this field was to design a useful mains frequency plasma torch, and efficiency was only considered relative to the torch itself (i. e. useful heat in gas/electrical power input to arc) rather than the overall efficiency of the plasma torch system. Industry, however is interested in the overall efficiency of a device and therefore an attempt was made to look into this aspect. Improvement in the electrical power calibrations and a more accurate energy balance in addition to evaluating the overall efficiency were generally the main objectives of this work.

The structure of the thesis is shown in Fig. 1. 1. Chapter 2 gives a brief review of arc processes relevant to this work and gives a general description of the Aston Torch.

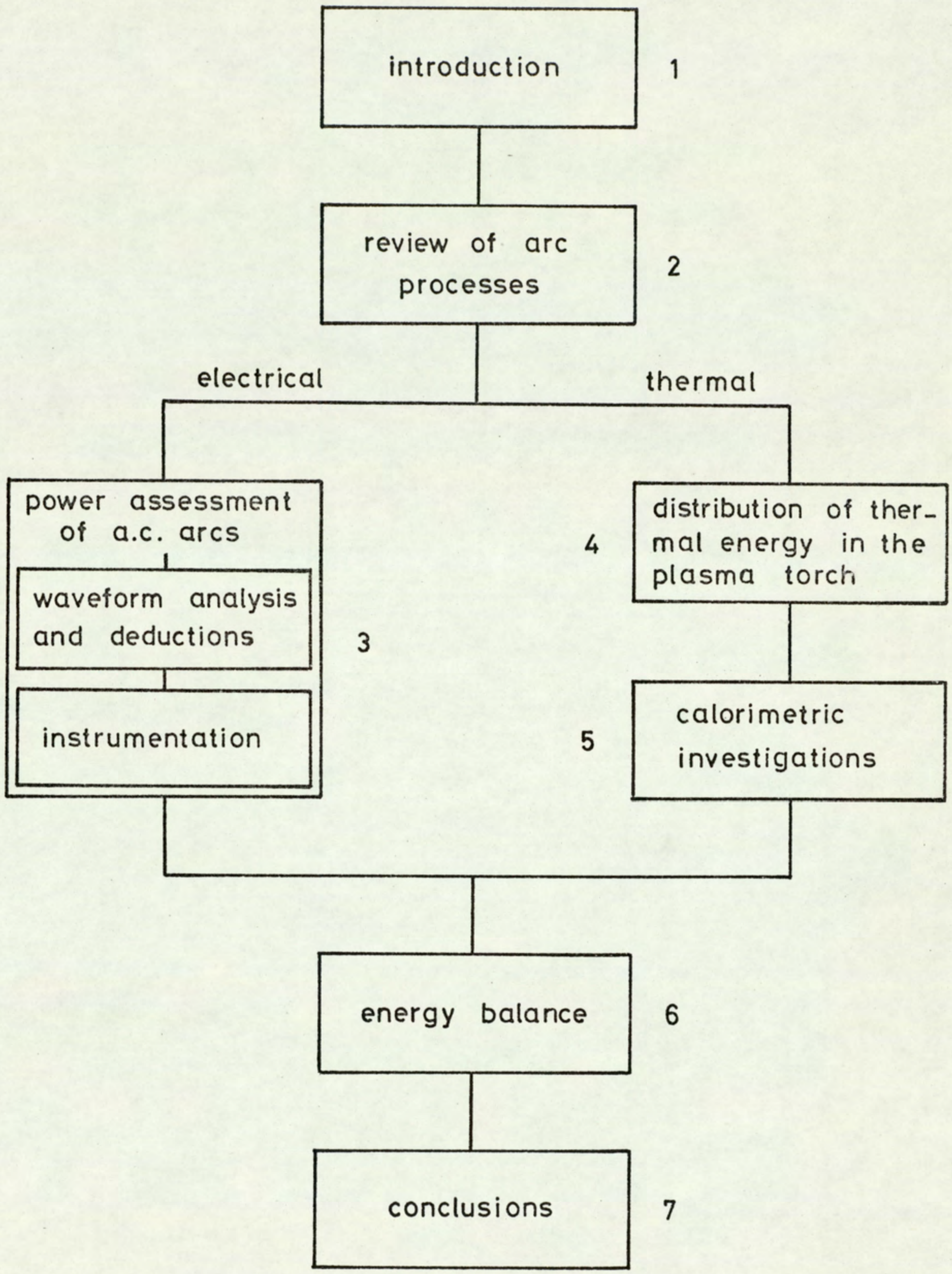


FIGURE 1.1. Structure of the thesis

Chapters 3 and 4 describe the electrical and thermal systems respectively. An alternative method to the use of conventional electrical measuring devices has been suggested in Chapter 3, while Chapter 4 is completely used for considerations of useful heat outputs and different heat losses within the system.

The necessity of using a calorimeter in an energy balance required a special investigation and was included in a separate Chapter (Chapter 5).

Using the three previous Chapters as the starting point, actual energy balance considerations are made in Chapter 6. These include electro-thermal and overall efficiency evaluations. Other electrical and thermal properties of the arc and gas are also examined.

In Chapter 7 concluding remarks and important results are summarised, and also fields for further research and developments are suggested.

CHAPTER 2.

REVIEW OF ARC PROCESSES.

2.1. The Electric Arc

2.1.1. Electrical Discharges

Electrical breakdown of a gas due to the application of an electric field results in a current discharge through the gas in association with transfers of heat. An electric arc is one form of various possible modes of discharge that can be ontained by increasing current values as seen in Fig. 2.1.

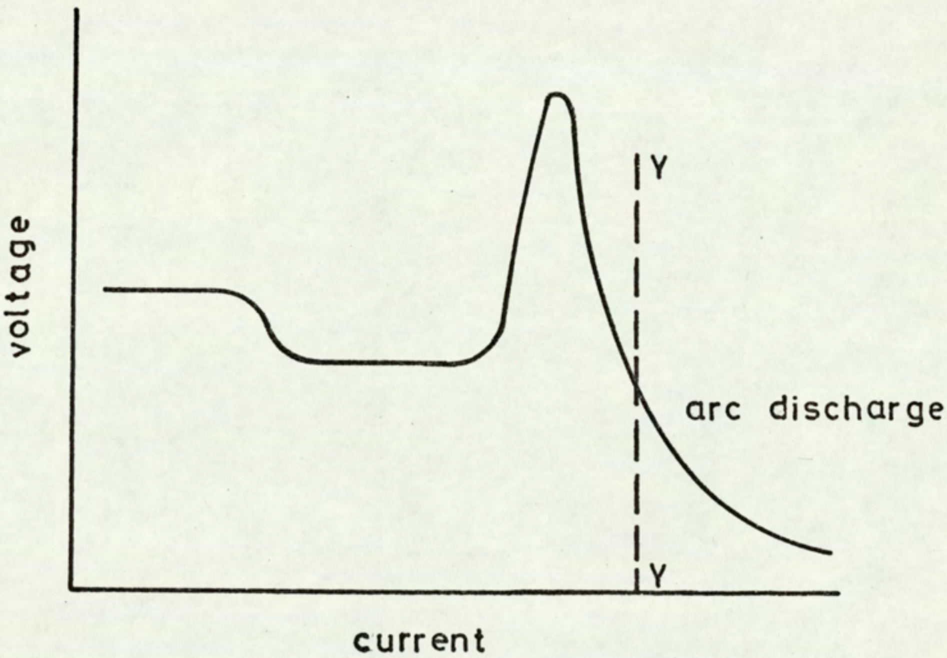


FIGURE 2.1. Voltage-current characteristics of an electric discharge.

The arc discharge occupies the region to the right of axis YY, and is often referred to as a stable discharge. In comparison to other forms of discharges, the arc is characterised by high current densities and temperatures.

In a plasma torch, an arc is used to heat up the gas passing through it, and the arc body temperature can assume values up to approximately 50,000^{o}K.[3]

2.1.2. Arc Characteristics

a) Voltage gradient across the arc gap

The voltage distribution across the gap has three distinct parts. Starting from the cathode it is apparent from Fig. 2.2. that the voltage rises sharply adjacent to the cathode surface; it then continues to rise but with a voltage gradient, $\frac{dv}{dx}$, much less than

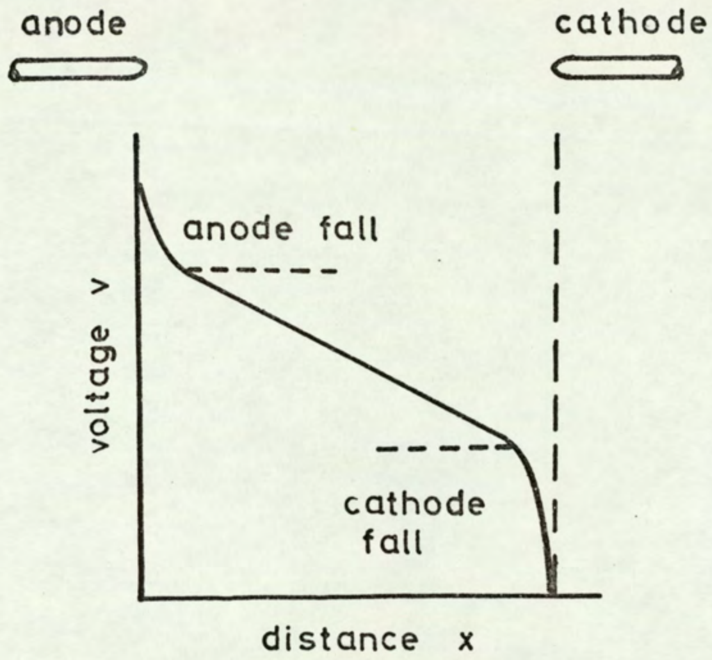


FIGURE 2.2. Voltage-distance characteristics across an arc.

before for most of the distance between the electrodes; the voltage gradient then increases again for the remaining distance adjacent to the anode surface. It can therefore be seen that the voltage gradient across the gap is not uniform and has sharp rises (or drops if going from anode to cathode) close to the electrode surfaces. These anode and cathode voltage drops are often referred to as the anode and cathode fall voltages, and are thought to be due to the space charge accumulations across the electrode-gas interfaces (junctions). Distances over which the fall voltages occur are estimated to be about 10^{-2}cm for cathode fall, and 10^{-3}cm for anode fall.

b) Regions of the arc

Figure 2.3. illustrates the existence of the three main regions in an arc. The arc column (or body) is jointed to each arc root by a transition region. Although the electrical and thermal properties of the column are reasonably well known, the properties of the transition regions joining the column to the electrodes are more complex, where the electrical and thermal properties may be discontinuous.

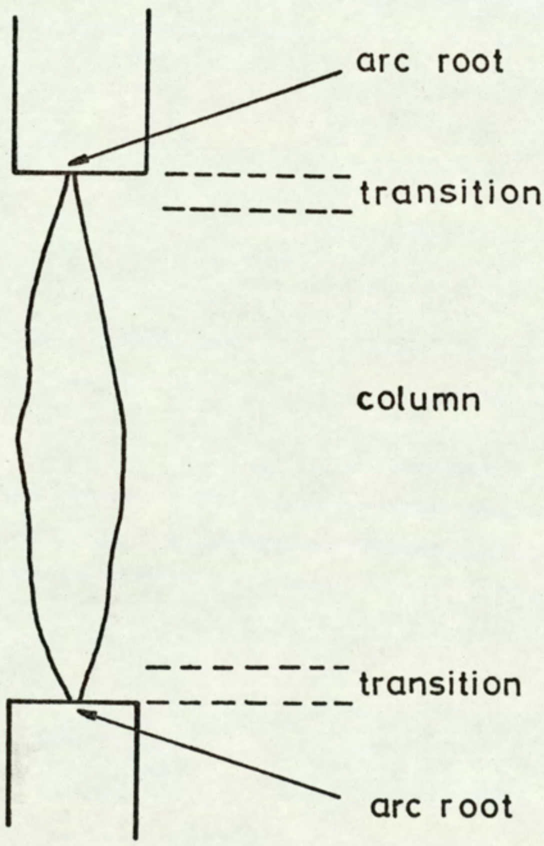


FIGURE 2.3. Regions of an arc.

In the arc column, the electron and positive ion densities are approximately equal. However, the current is mainly carried by electrons due to their higher mobility, and the ratio of the current density of the electrons to that of the ions is therefore large.

At the transition regions, this ratio is reduced and the current may be carried predominantly by positive ions. The positive and negative current carriers are both required to be present in order that each kind can balance the high electro-static forces due to the other. It can also be shown[4] that to balance this force at the cathode, electron emission is necessary. This can be provided by several combined processes, such as thermionic emission and field emission. The current at the anode is carried mainly by electrons(where the ionic/electronic current ratio is about 0.01). The ions needed for this region are produced by the electrons of the current by two mechanisms[5], field ionisation and thermal ionisation. There is no flow of positive ions from the metal to the gas.

2.1.3. Electrode Materials

Electrode materials used in plasma torches are of two kinds, thermionic and cold cathode.

a) Thermionic

As the name indicates, the mechanism of producing electrons is mainly one of thermionic emission. Graphite is one example of such materials. A main feature of these materials is their high boiling temperature in relation to the temperature required for maintaining thermionic emission; thus there will be no necessity for cooling if used as electrodes in plasma torches. At atmospheric pressures, current densities up to 10^3 A/cm^2 are common.

b) Cold Cathode

Copper is the most popular cold-cathode material used in plasma torches. Cold-cathode materials are characterised by higher current densities than those for thermionic materials (values around 10^7 A/cm^2 have been obtained by Froome[6] in 1949), but on the other hand, their boiling temperatures are too low for the emission of electrons to be maintained by thermionic emission alone; thus other mechanism (e.g. field emission) are involved.

2.2. Plasma Torches

(A brief consideration only is given, as the Astón Torch and its associate systems are discussed in Section 2.3.).

It is usual to divide plasma devices into two types, non-transferred arc and transferred arc. The reference is made to the configuration used for the electrodes and arc, as will be seen below.

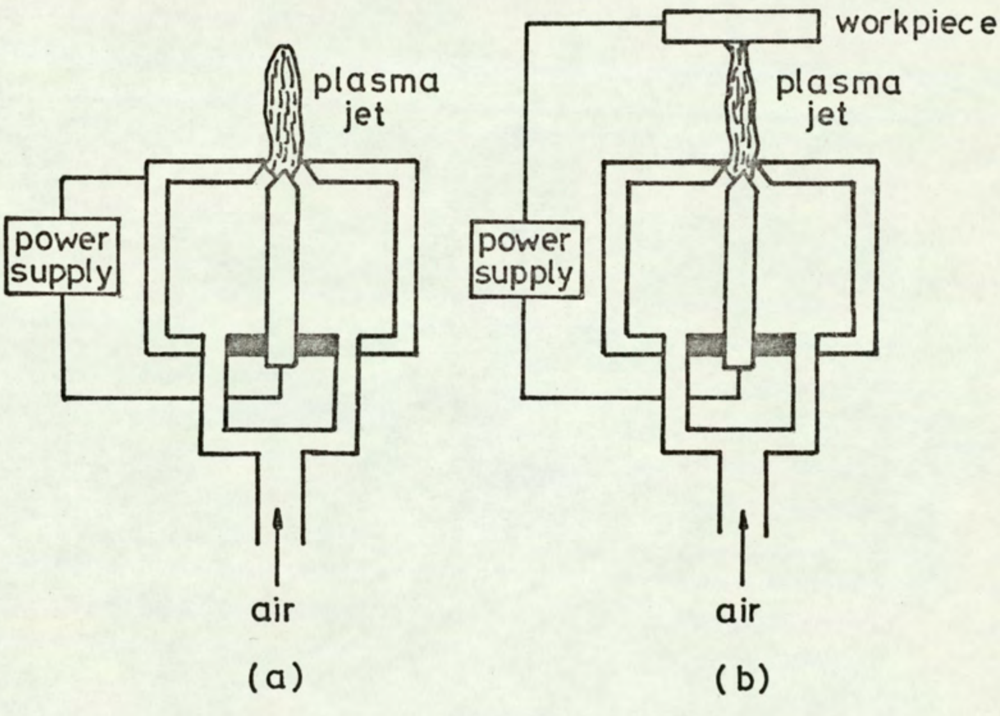


FIGURE 2.4. Plasma torches, (a) Non-transferred.
(b) Transferred.

Fig. 2.4a. shows a schematic diagram of a non-transferred plasma torch in which the arc is struct between two electrodes and forced out through the nozzle as a jet by an axial flow of gas. The output of this type will therefore consist of hot gas to be used in a way most suitable for any particular application. In contrast, Fig. 2.4b. represents a transferred arc plasma torch, where one of the electrodes becomes the workpiece in a similar way to arc welding.

The electrical input to plasma torches can be either a. c. or d. c. The d. c. input power is the most widely used owing to the inferior efficiency and enthalpy figures reported for a. c. torches. An inherent advantage in the use of a. c. plasma torches, however, is the lower cost of power and capital equipment. The Aston Torch, described in Section 2. 3. is an example of an a. c. mains frequency, single-phase device. Three-phase versions have also been used elsewhere; the general arrangement is shown in Fig. 2. 5.

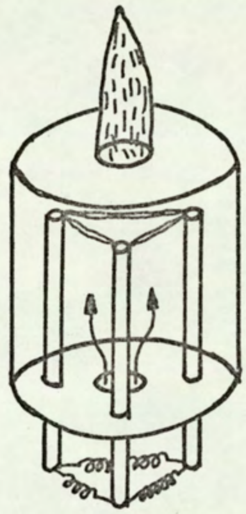


FIGURE 2. 5. Three-phase plasma torch.

High frequency plasma torches have also been developed; a typical frequency range is 10-1000 MHz. Practical difficulties in power transmission at these high frequencies and the effect of interference with communication systems will limit the use of these types.

2. 3. The Aston Torch

The existing a. c. mains frequency plasma torch was produced as a result of extensive development and design stages most of which were completed before the start of this project. This work is therefore not concerned with reviewing these stages as this was adequately carried out elsewhere[7]. It will, however, be reasonable to give an outline of the torch's most important features.

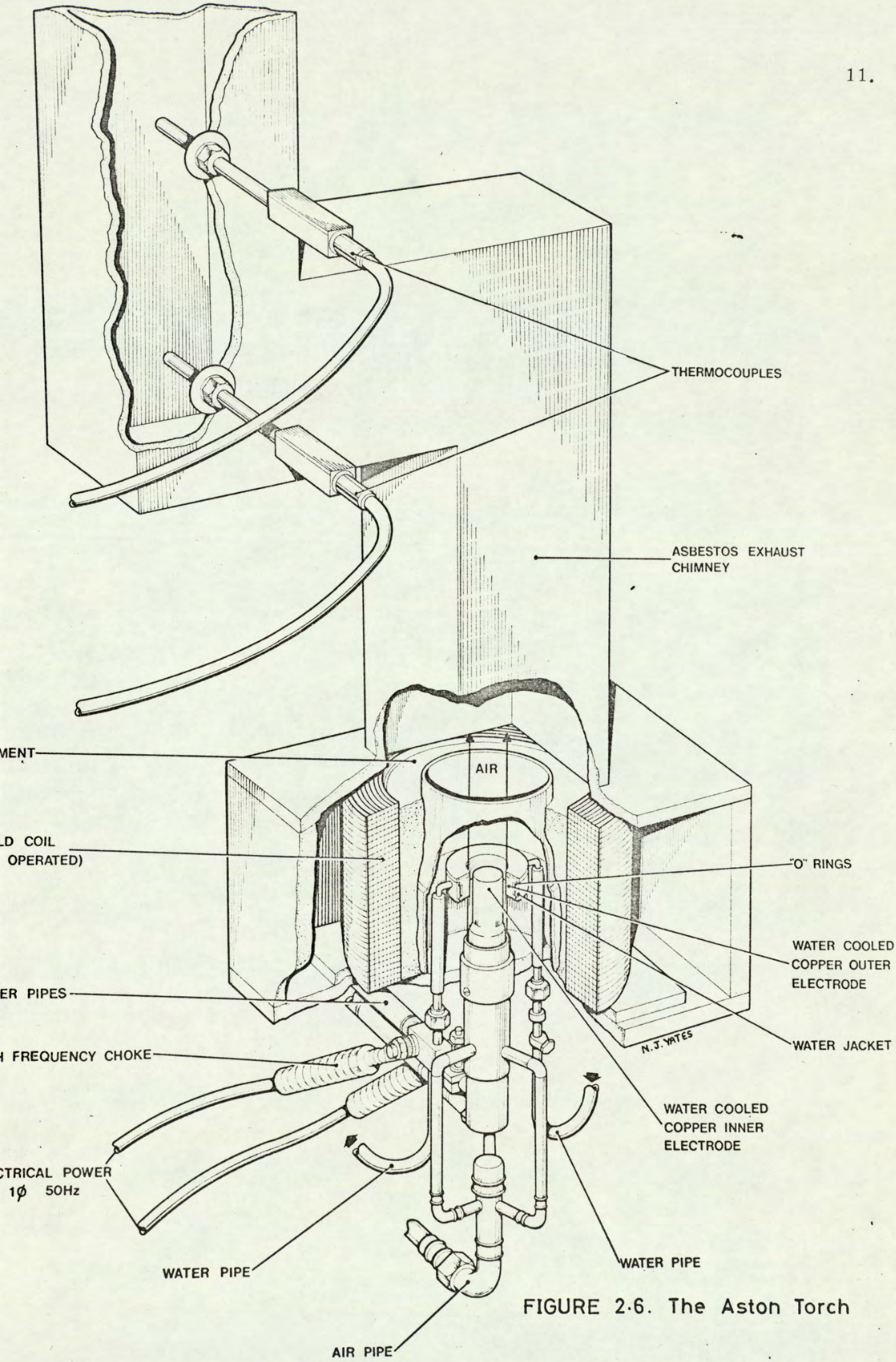


FIGURE 2.6. The Aston Torch

2.3.1. General Description

Fig. 2.6. is a sectional view of the present Aston Torch. The whole assembly rests on a block of asbestos and is fixed by cement. Both electrodes are easily removable for replacement in cases of fracture (which could be frequent), and are water cooled.

The air pipe branches into three parts in order evenly to distribute the air round the inner electrode. The air then passes through the air gap between the electrodes and, after being heated by the arc, emerges to atmosphere via an asbestos exhaust chimney. This exhaust arrangement need not be permanent, but can be substituted by other forms depending upon the particular use (as an example, see Figs. 5.7. and 5.8.

The external circuit arrangement is shown in Fig. 2.7.

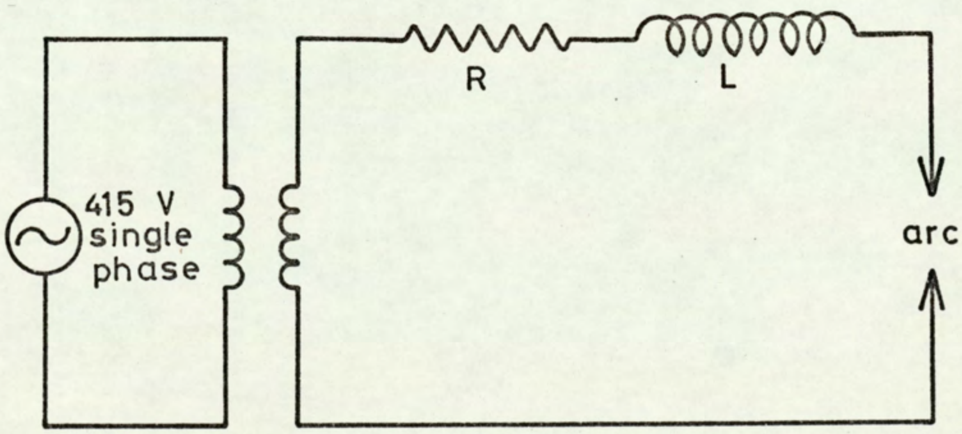


FIGURE 2.7. A typical a.c. arc circuit.

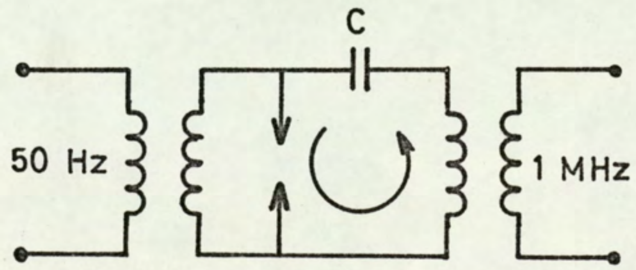
L and R are the series inductance and resistance respectively. They are mainly used for stability of arc and current control. L, had a value of 2.8 mH and R could take several values within the range 0 to 0.5 Ω. The coil L also had a resistance of 0.02 Ω. This circuit was coupled to the supply via an isolating transformer, the primary of which was connected across two lines of the three-phase mains supply to give a 415 V, single-phase, 50 Hz condition.

2.3.2. The Ignition System

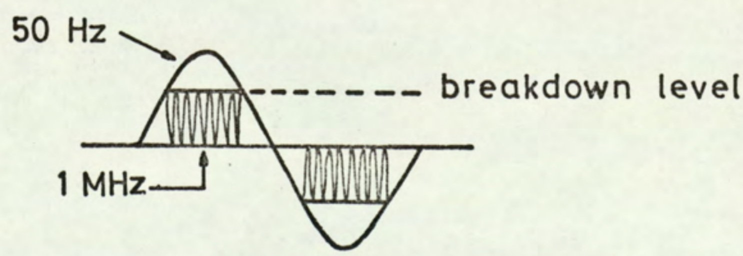
One of the main difficulties facing the proper operation of an a.c. plasma torch is the extinction of the arc twice every cycle.

Although thermionic electrodes can be used to maintain an a.c. arc, their use is not practical due to rapid deformation and material disintegration as well as giving lower current densities compared with cold-cathode electrodes. If the latter type is used the arc cannot be maintained and a separate re-ignition system becomes a necessity.

The method used for generating high frequency ignition voltages is illustrated in Fig. 2.8.(a) and (b).



(a)



(b)

FIGURE 2.8. Principle of the re-ignition system.

In (a) a 50 Hz voltage is applied to a circuit consisting of a capacitance, an inductance (in the form of the primary of a transformer) and an adjustable spark gap.

Originally, the applied voltage charges the capacitance until the voltage across the spark gap is sufficient to break it down. Once this condition is reached, the capacitor discharges through the gap (as the direction of the arrow indicates) and charging and discharging continues until the applied voltage is no longer sufficient to break down the gap. Fig. 2. 8. b. illustrates this action. The value of C together with the primary inductance of the output transformer were chosen to resonate at 1 MHz.

As this train of high frequency voltages was required to re-ignite the arc at its current zero region, a phase adjuster was used to improve the high frequency pulses mainly during this time as seen in Fig. 2. 9. These high frequency pulses had voltage values across the main gap of nearly 30 kV.

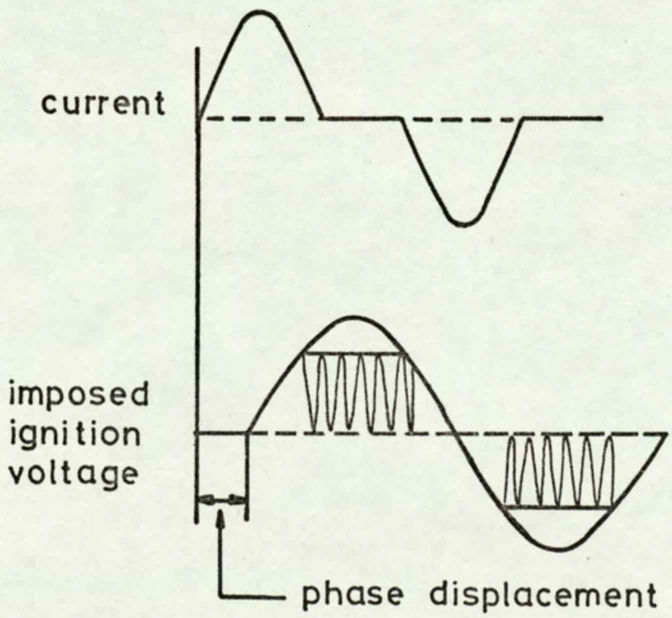


FIGURE 2. 9. Phase adjustment of ignition voltage.

The complete circuit in relation to that of the main arc is shown in Fig. 2.10.

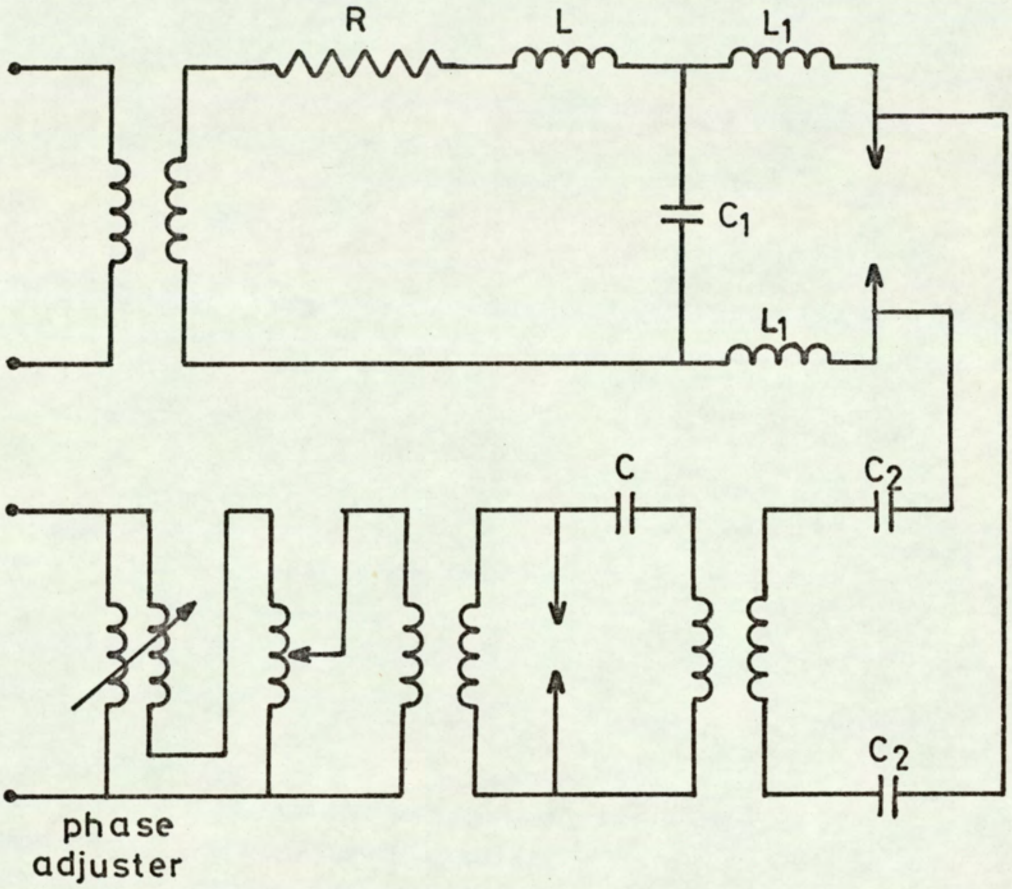


FIGURE 2.10. Combined ignition, and arc circuit diagram.

During the main arc current extinction, L, will offer high impedance to the ignition voltages, thus isolating the ignition circuit from the arc circuit and allowing discharge only across the main arc gap. When the arc current flows, the inductance L, will become saturated and acts as a short circuit, thus the ignition voltages will discharge through C_1. Capacitors C_2 were used to isolate the main arc circuit from the ignition circuit.

2.3.3. The magnetic field system

As was shown in Fig. 2.6., the magnetic field coil surrounds the electrodes, thus in effect maintaining a transverse magnetic field B (Wb/m^2) in the way shown in Fig. 2.11.

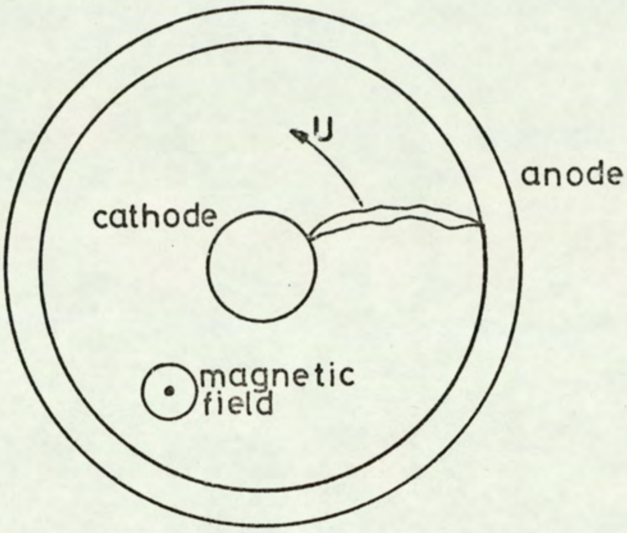


FIGURE 2.11. Rotation of an arc in a magnetic field.

From basic electromagnetism, the arc can be treated as a current-carrying conductor and therefore the force acting on the arc is B I l , where I is the arc current in ampers and l, the arc length in meters (this treatment is not entirely correct as the phenomena of rotating an arc in a magnetic field is more complicated[8]. It is, however, beyond the scope of this work to go into this in detail since for the operation of the Aston Torch it is sufficient to assume that the speed of arc rotation is proportional to the magnetic field).

This force has a direction given by the left hand rule, thus rotating the arc as shown. As the arc rotates, it will rapidly reach a condition where the electromagnetic force will be balanced by aerodynamic drag. The velocity of rotation, U, can be expressed[9-10] in the form $U = A.B^m.I^n.$, A, m, n being constants depending mainly upon the geometry of the electrode system.

It is desired to use a magnetic field in plasma torches for the following main reasons :

1 - Improved stability (Section 2.4.)

2 - To prevent puncture of the electrodes and to minimise electrode erosion. This consequently reduces gas contamination level.

3 - "even heating" in the gas stream.

The effect of the magnetic field on electrode erosion was studied by Harry[11]. It was found that although it was true to suggest less erosion rates with increasing magnetic field, only small reduction in erosion was experienced above about 0.2 Wb/m^2 and no apparent advantage was obtained above 0.4 Wb/m^2. Certainly, if there were any advantage to be gained by increasing the magnetic field above a certain level, it would be offset by the cost of supplying extra power to the field system. This can be seen from the energy balance of Chapter 6.

The shape and relative position of the field coil was shown in Fig. 2.6. As the coil was a multi-layer type, some error would have been incurred in calculating the value of the magnetic field on the basis of the Biot-Savant law. The magnetic field was therefore calibrated using a Hall-effect probe at the position occupied by the nozzle to within $\pm$ 2%[12-13].

The maximum value of possible flux density obtained was 0.5 Wb/m^2. Intermediate values were determined by varying the circuit current, which was supplied from a separate d.c. source. This involved the use of rectification equipment. The alternative would have been to supply the field system from a separate a.c. supply but difficulties in synchronising the field power load with the main arc current would have arisen.

An interesting method of supplying the field current is to connect the field coil in series with the arc a.c. supply, giving maximum speed of arc rotation when the current is maximum and zero field when the current is zero. This could lead to considerable economics in the size of the field coil; furthermore its inductance produces extra stabilisation to the arc. With such a series connection however, it will no longer be possible to treat the magnetic field as an independent parameter since the remainder circuit parameters will change whenever the field is charged.

A disadvantage in the present coil design is overheating, not only due to the usual resistance heating, but also to heat transfer from the plasma torch. The latter is minimised by insulating the inside of the coil with cement and asbestos. Both types of heating can be overcome by adequate water cooling. This was not thought essential at this stage since the temperature-rise specification for the coil was not exceeded by a 30 minute test, provided an adequate cooling-off period was allowed before re-use. It is, however, essential to eventually use a water-cooled coil as the plasma torch must prove its suitability for industrial use in which semi-continuous operation is essential.

2.4. Stability Considerations

The stability of an electric arc, is a subject that has not received adequate attention in spite of its importance in nearly all aspects of arc devices and technology. There also appears to be no definite accepted quantitative approach hitherto in treating this concept.

There are, however, some signs that this trend is on the verge of being halted, as shown by a publication by Harry[14], in which it was attempted to suggest a definition for instability.

2.4.1. Features of Arc Instability

The limiting operating conditions of an electric arc are simply either a "constant arc parameters" condition or "complete cut out". In the former, it is meant that an arc will have a constant voltage and current (r.m.s. values in a.c. case) and a constant arc column length, position and diameter.

These two limits may be described as the most stable and the most unstable arc conditions respectively.

Arc behaviour within these limits has been discussed in terms of arc lifetime[15], arc fluctuations[16], impedance stability criterion[17], the maintenance of a continuous flame[18] and simply stability[14].

Arc instability has been observed and examined photographically[19-16]. An unstable arc can be even sensed by an observer, arc noise disturbance and discontinuity of illumination being rough indications.

2.4.2. Causes of Instability

Instability can ultimately (directly or indirectly) be related to changes occurring in the arc column, such as lengthening and short circuiting and arc root movements along the electrode surfaces[16].

Reasons for column changes are due to several causes, and the cumulative effect being to give the arc its randomness of movement. Some important factors are:

1. Arc lengthening due to gas flow. This continues until the voltage across the column becomes high enough to short circuit the arc elsewhere within the nozzle. This process is then repeated, thus producing continued fluctuations.
2. The cathode spot mechanism on cold cathode materials, where rapid variations occur in the decay and reformation of the cathode spots.
3. Variation of arc column due to convection which might result in shunting effects.

Column changes will therefore influence the electrical characteristics of the arc, since voltage and power are proportional to arc length and will also affect the thermal distribution of the emergent gas in a plasma torch and consequently affect the efficiency of the device.

2.4.3. Methods of Suppressing Instability

Although the parameters of an electric arc are related (directly or indirectly) to each other, it is useful to adopt some classification to methods of arc stabilisation. Generally, improvement of arc stability can be achieved by,

1 - Electrical means,

and 2 - Arc column constriction and forced movement.

1 - Electrical Stability Considerations

It has been found that fluctuations and changes that occur in an arc causing instability (that could appreciably affect the loading of the circuit) have equilibrium times of about 1 ms[20-21]. Assuming this, it is reasonable to suggest that the external electric circuit must be such that it can respond within 1 ms to these variations.

The external electric circuit usually employs a series resistance for adjusting and limiting current values and a series reactance for isolation purposes, therefore for a stable arc condition, the time constant of the circuit must be less than 1 ms i.e. $\frac{L}{R} \leqslant 1$ ms, where L is the total series inductance and R being the total series resistance, including the arc resistance, of the circuit.

A further condition which must be satisfied for maintaining the arc is what is usually referred to as the Kaufman criterion. This requires the sum of the load resistance and that of the arc at the point of operation to be positive.

i.e. $R + R_{arc} > o$

If, therefore, (x) & (y) are two possible operating conditions for a particular load line (Fig. 2.12) we find that :

$R_{(x)} + R_{arc(x)} < o$

and $R_{(y)} + R_{arc(y)} > o$

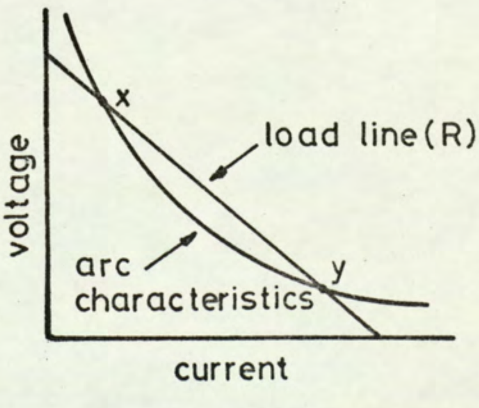


FIGURE 2.12. Kaufman's criterion.

Therefore (y) will be the actual operating point for the stable arc condition. For total electrical stability, the ($\frac{L}{R}$) time constant and Kaufman's conditions must both be satisfied.

2 - Arc Constriction and Forced Movement

Here, stability is achieved by constriction, compression, and rotation of the arc column by some means outside the arc itself. As a result, the arc is confined and therefore the current density increases. This is done by cooling the outside of the arc column by gases or liquids used as stabilisers, thus decreasing the conductivity of the outer regions. Higher conductivity in the inner regions allows more current to concentrate there, resulting in column constriction.[3]

In vortex stabilisation, a rotational as well as constricting effect is obtained by introducing the stabiliser tangentially. Normally, however, a transverse magnetic field can be used to rotate the arc, thus reducing the randomness of arc movement and minimising shunting effect at the arc roots. (This has already been discussed in Section 2.3.3.).

Axial magnetic fields have also been used to stabilise the arc[22], but some contradictory observations were also reported.[19]

2.4.4. A Quantitative Approach to Arc Stability

As mentioned earlier, Harry proposed an actual mathematical definition for instability. Instability was chosen since it is reasonable to express it as a function tending to zero as stability tends to infinity. Instability was therefore defined by the expression $\int \Delta\phi \, dt / \int \phi \, dt$, where $\int \phi \, dt$ is the area of the optimum arc waveform and $\int \Delta\phi \, dt$, the area of the total deviation from the reference waveform. As this definition does not attempt to describe what is meant by the optimum or reference waveforms, it will not be possible to use it in practical analysis unless some definite starting point is assumed. It is, therefore, intended to suggest below some definitions and characteristics of possible reference waveforms.

Definitions

Instability : Let the instability of an electric arc be, the deviation of its waveform from that of the most desirable waveform possible depending on the particular operating conditions.

By "deviation", it is meant, either the deviation in area as suggested by Harry, or any other type of deviation which an observer feels fit to use. An example of another possible measure of deviation could be the difference in the harmonic content of the waveforms.

By "desirable", it is meant, that the most stable case must be defined each time an instability evaluation is required, and this could be varied in accordance with any particular operation.

As a step to clarify this discussion it is intended to state the most desired stable arc conditions as related to the aims of this work.

D. C. Arcs.

The most stable arc can be considered to have a constant voltage and current, and also consumes constant power. The reference waveforms can obviously be represented by straight lines, and deviations easily calculated.

A. C. Arcs.

For reasons that are apparent in Chapter 3, the most stable a. c. arc waveforms can be taken as rectangular for voltage and sinusoidal for current. These are shown below (Fig. 2. 13.) with the stable power waveform resulting by multiplying V and I.

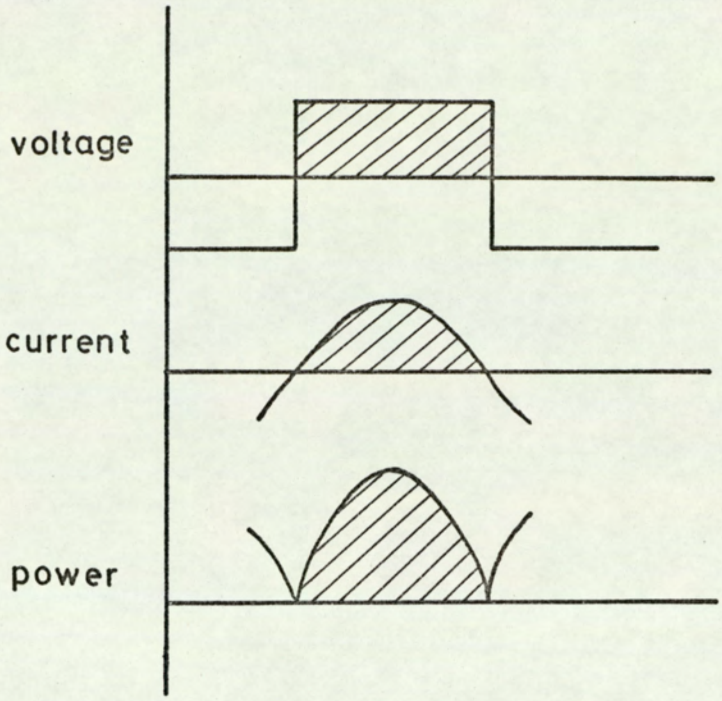
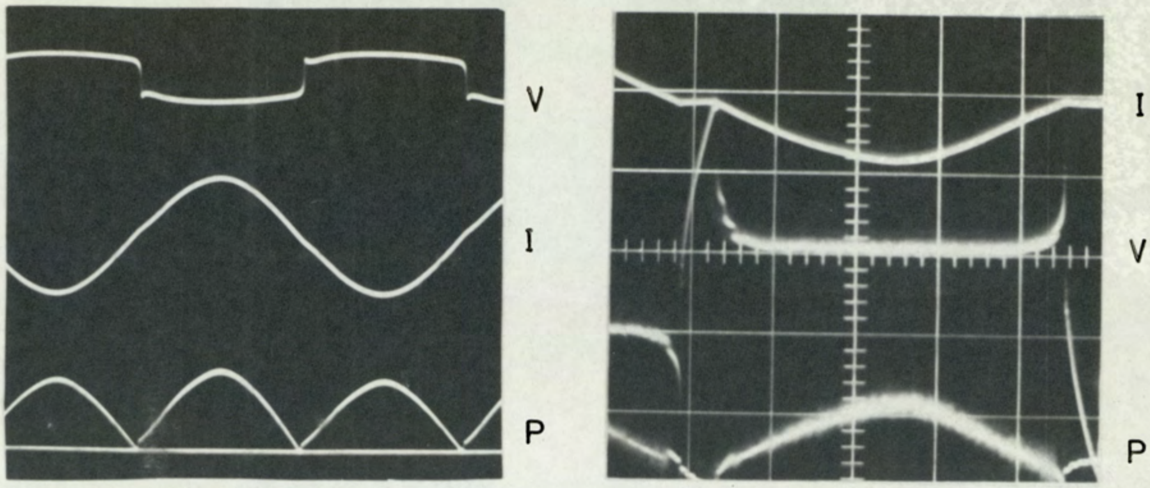


FIGURE 2.13. Stable a.c. arc waveforms

Evaluation

In accordance with the criterion set above, the two conditions shown in Fig. 2.14. can now be examined.
(a) Shows a nearly perfectly stable arc while (b) is a case of an arc with a noticable degree of instability. As it was convenient to use the voltage waveform of (b) this was reproduced in Fig. 2.15. and the defined square waveform reference also drawn. Calculations showed that the instability was 15%.



(a) stable (b) unstable

(V=voltage , I = current , P= power)

FIGURE 2·14 . Stable and unstable a.c. arc waveforms

(a)

V(=50 V/cm)
I(=30 A/cm)
P(=400 W/cm)
Time base = 5 ms/cm

(b)

I(=30 A/cm)
V(=25 V/cm)
P(=400 W/cm)
Time base = 2 ms/cm

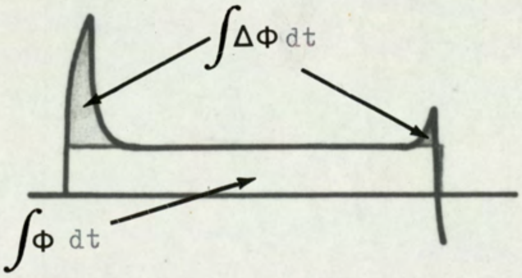


FIGURE 2·15. Instability calculations

CHAPTER 3.

POWER ASSESSMENT OF A. C. ARCS.

3.1. Electrical Properties of a.c. Arcs.

The voltage-current characteristics of an electric arc are shown in Fig. 3.1. It can be seen that the arc has a negative dynamic impedance. With no current flowing (no arc), the open circuit voltage across the arc gap will rise to the supply voltage. If this voltage is such that it can break down the gap, an electric

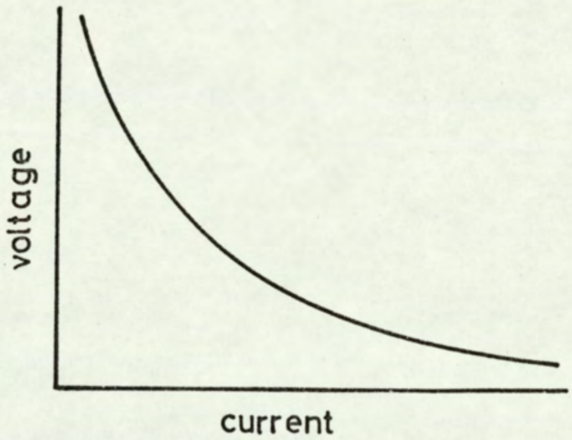


FIGURE 3.1. The V/I Characteristics of an Electric Arc.

discharge is initiated and a current flows. The current will increase the conductivity of the air-gap and less voltage is required to maintain it. The situation can be seen as going down the V/I curve until the point of zero slope is reached. If an a.c. supply is used, the sequence will be as follows:- The voltage across the arc gap starts increasing until the gap breaks down (Fig. 3.2.) and the current begins to flow. The voltage will fall, very sharply, to what is called "Plateau" level, xy, as this voltage level is sufficient to maintain the arc. As the main's a.c. voltage (shown dotted) decays so will the current until it is finally cut off at y. The half-cycle then repeats itself in the negative sense.

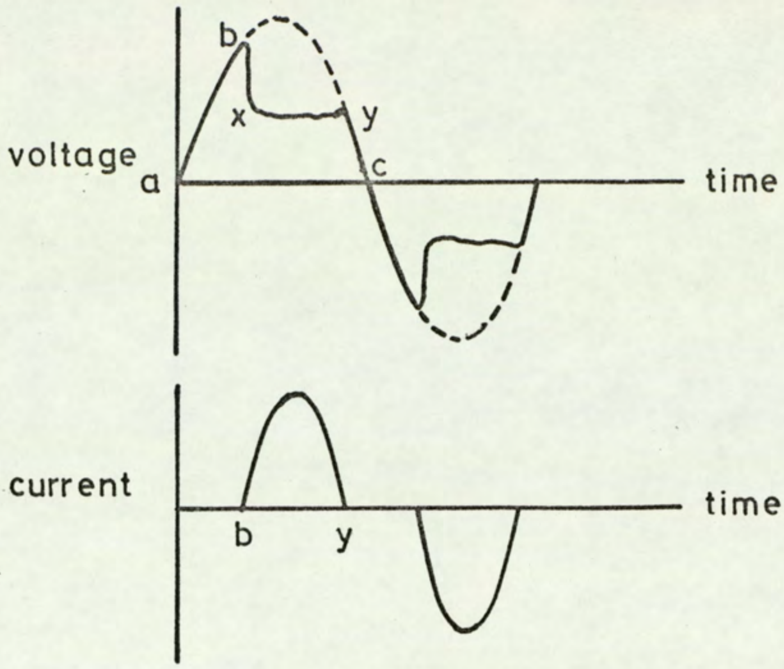
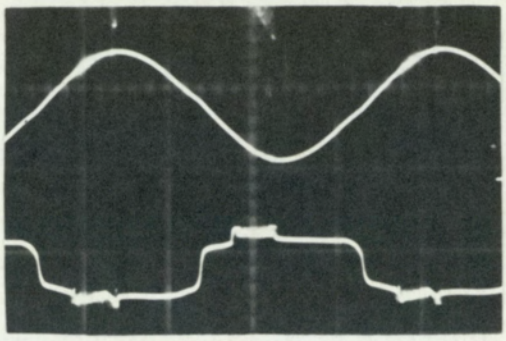


FIGURE 3.2. A.C. Voltage and Current Waveforms of an Electric Arc.

Apart from the main transients present in the voltage waveform (i.e. a to b and b to x), there could be others depending on the stability of the arc; material used as electrodes, air gap dimensions and the possible need for reigniting the arc. If, for example, graphite is used (thermionic), the a.c. arc can be maintained without the need for a reignition system, but it can contain fluctuations at the Plateau level as shown in Fig. 3.3.

If copper is used, the arc will not reignite after the current passes through zero and a separate ignition system is needed. This will introduce severe fluctuations at the Plateau level as seen in Fig. 3.4. which in fact represents typical a.c. Plasma torch waveforms using copper electrodes and a separate ignition system.

The electric arc of a plasma torch will have to be rotated to avoid electrode puncture and severe erosion, and to evenly heat the gas passing through the nozzle. As the arc is rotated (by using a magnetic field), its length varies and there is a possibility of multiple roots causing further transient effects and less repeatability.



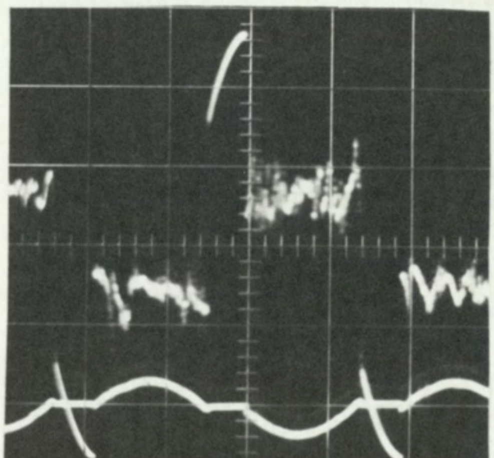
I (=30 A/cm)

V (=25 V/cm)

(V = voltage , I = current)

Time base = 5 ms/cm

FIGURE 3·3. "Graphite electrodes" a.c. arc waveforms without ignition system



V (=200 V/cm)

I (=400 A/cm)

(V = voltage , I = current)

Time base = 5 ms/cm

FIGURE 3·4. "Copper electrodes" a.c. arc waveforms using an ignition system

3.2. Waveform Analysis and Deductions.

Typical a.c. electric arc voltage and current waveforms, found in available literature[23] are shown below Fig. 3.5. It should be stated that although these are possible types of arc waveforms, there could be other equally possible cases such as those of Fig. 3.3. Workers in this field[23] tend to conclude that the errors experienced during measurements of such parameters are mainly due to the failure of conventional measuring instruments to respond to such non-sinusoidal waveforms. In particular, there is a tendency to show that the region a-b-x of the voltage waveform is such that it is not normally followed by available conventional instruments due to the sharp rises and decays.

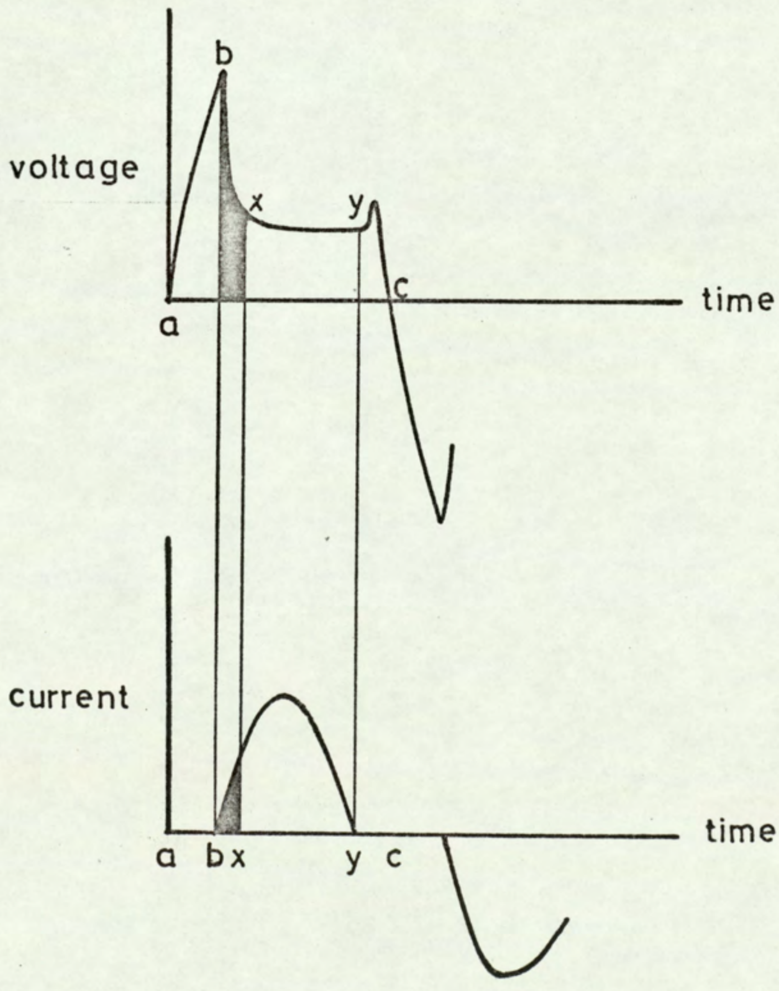


FIGURE 3.5. Typical voltage and current waveforms.

A critical study of various waveforms indicate that this approach, in general, could be misleading and indirect for the following main reasons:

1. As the line of interest lies in manipulating the power input, the voltage and current waveforms should be examined together rather than individually as is usually done.

2. Before examining and testing instrumental deficiencies in detail, it is necessary to investigate just how significant is the power content of the region (a-b-x).

3. The use of sketches (e.g. Fig. 3. 5.) could be very misleading as they may exaggerate the power content of the region (a-b-x); this is shown below.

3.3. The Power Content of the Transient Region.

3.3.1. With Particular Reference to Plasma Torch Waveforms.

Examining Fig. 3. 5. again, it can be seen that since the region a-b of the voltage coincides with zero current then there can be no power contribution. Similarly, the region y-c is accompanied by zero current and the power content of this half-cycle will be represented by the range b-x-y.

An approximate estimation of the ratio of the power content of range b-x (i.e. transient range) to the total power content of the half cycle (i.e. range bxy) can be achieved as follows:-

The equation of the voltage in the range b-x is approximately,

$$v_t = V \left[3 - \frac{2t}{t_{bx}} \right].$$

where v_t = the voltage at any instant, t,

V = the value of the Plateau level voltage

and t_{bx} = the time interval of region b-x.

Also the current through this range

$$i_t = \frac{10}{19} \hat{I} \times \frac{t}{t_{bx}}$$

where i_t = the current at any instant, t,

and $\hat{I}$ = the peak value of the current.

$$\text{Therefore, Energy}_{bx} = \frac{10}{19} \hat{I}V \int_o^{t_{bx}} \frac{t}{t_{bx}}\left(3 - \frac{2t}{t_{bx}}\right) dt.$$

$$= \frac{10}{19} \hat{I}V \int_o^{t_{bx}} \left[\frac{3\,t}{t_{bx}} - \frac{2t^2}{t_{bx}^2}\right] dt$$

$$= \frac{10}{19} \hat{I}V \left[\frac{3\,t^2}{2\,t_{bx}} - \frac{2\,t^3}{3\,t_{bx}^2}\right]_o^{t_{bx}} = \frac{10}{19} \hat{I}V \left[\frac{3}{2}t_{bx} - \frac{2}{3}\,t_{bx}\right]$$

$$= \frac{50}{114} \hat{I}V\,t_{bx}.$$

Taking the total energy during the range bxy as

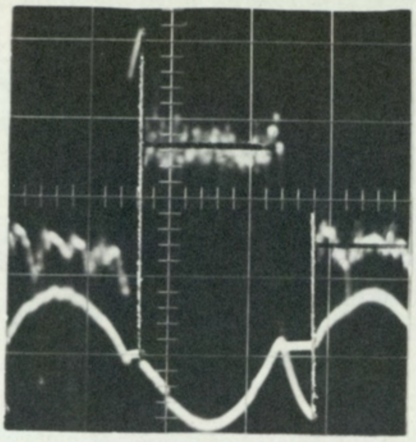
$$\text{Energy}_{bxy} = \frac{1}{\sqrt{2}} V\hat{I}\,t_{bxy}, \text{ then,}$$

$$\text{percentage error} \,\underline{\Omega}\, \frac{50/114\,\hat{I}V\,t_{bx}}{1/\sqrt{2}\,\hat{I}V\,t_{bxy}} = \frac{50/114}{1/\sqrt{2}} \times \frac{1}{4}$$

$$\left(\text{since } \frac{t_{bx}}{t_{bxy}} = \frac{1}{4}\right)$$

$\therefore$ error = 15.5%

If this power is not properly accounted for by measuring devices, it appears that an error of anything up to this value is possible with energy balance and efficiency analysis. To verify the validity of such a prediction, the waveform of Fig. 3.6. can now be examined.



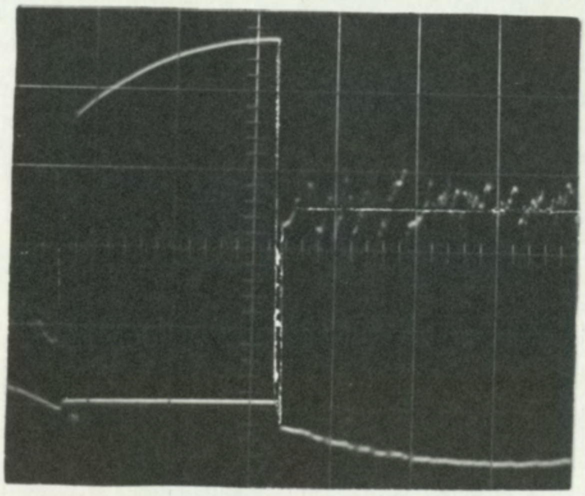
V (=200 V/cm)

I (=200 A/cm)

Time base = 5 ms/cm

(V = voltage , I = current)

FIGURE 3.6. Typical plasma torch waveforms



V (=200 V/cm)

I (=200 A/cm)

Time base = I ms/cm

(V = voltage , I = current)

FIGURE 3.7. Analysis for transient region in a plasma torch waveforms

This waveform is taken from a Plasma torch discharge and it shows that the current wave adequately resembles its counterpart in Fig. 3. 5. However, the voltage wave appears to be different. (The fluctuations of the Plateau level will introduce little error as they could be averaged by measuring instruments). The striking feature of the voltage is the very short decay time compared with the time taken throughout the effective power range.

An attempt to analyse such a waveform was performed on Fig. 3. 7. in the same manner as before, thus the voltage and current equations can be written as :

$$v_t = V\left[5 - \frac{4t}{1 \times 10^{-4}}\right]$$

and $$i_t = \frac{2}{7}\hat{I} \cdot \frac{t}{1 \times 10^{-4}}$$

where 1×10^{-4} is the time in seconds of the transient range bx.

Since, Energy = $\int_0^T iv\,dt$, then

$$\text{Energy}_{bx} = \int_0^{1\times10^{-4}} \frac{2}{7}\hat{I}V \frac{t}{1\times10^{-4}}\left[5 - 4\frac{t}{1\times10^{-4}}\right] dt.$$

$$= 0.34 \times 10^{-4}\,\hat{I}V.$$

The total Energy of this half cycle is $\frac{\hat{I}}{\sqrt{2}} \cdot V \cdot 7{\cdot}25 \times 10^{-3}$

Where 7.25×10^{-3} is the time in seconds of the effective power range.

Therefore, $$\frac{\text{Energy}_{(transient)}}{\text{Energy}_{(total)}} = \frac{0.34 \times 10^{-4}}{\frac{7.25 \times 10^{-3}}{\sqrt{2}}}$$

$$= \frac{0.34 \times \sqrt{2}}{72.5} = \underline{\underline{0.66\%}}$$

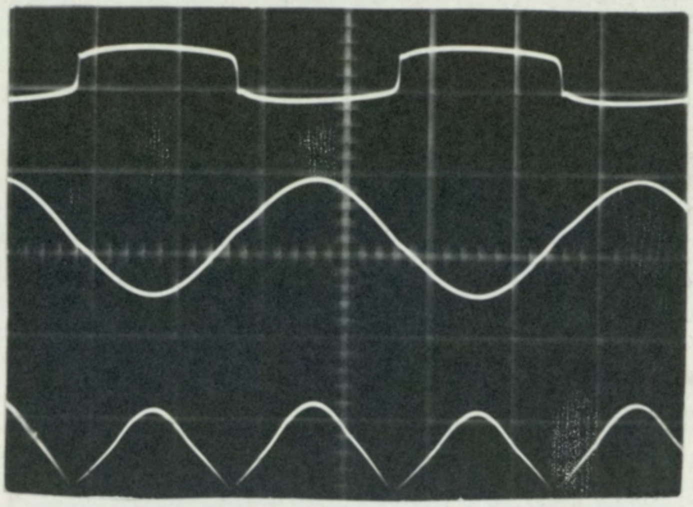
The previous analysis was based upon waveforms from an a.c. mains frequency Plasma torch and it can be seen that the power contribution of the transient b-x-y is very small and that this lies within the accuracy of the most accurate power measuring devices. Certainly, even if this power is not accounted for and neglected by any instrument it will be very much less than the 15.5% estimated from Fig. 3.5.

3.3.2. Calculations for Other Possible Waveforms.

The waveforms previously examined apply to an a.c. Plasma torch. Various other types of a.c. arc parameters are shown below. These were determined by the method described in Section 3.4.1.

Fig. 3.8. shows a reasonably smooth and steady a.c. arc, where the voltage is nearly a square wave and the current very nearly sinusoidal. The two waves were multiplied together using a multiplier (Section 3.4.2.). The electrodes in this case were of the thermionic type, thus eliminating the need for a reignition system. By varying the arc length and voltage, fluctuations and instability were introduced into the arc waveforms (Figs. 3.9. (a) and (b)) in order to study the arc input power under other possible operating conditions. The waveforms of Fig. 3.9.b. will not represent, in general, an unstable arc as the voltage is still nearly a square wave and the current nearly sinusoidal. If the waveforms appear as in Fig. 3.10. where the transient time has been extended, then an attempt can be made to find a worst case condition for arc transients and to extend the findings of Section 3.3.1. The transient region of Fig. 3.10. has been extended and is about five times as long as that for the plasma torch. Fig. 3.11. represents similar waveforms and is used for the next examination.

The ratio of the power content under the transient to the total power of the half cycle was determined by calculating the corresponding areas of the multiplied waveform. The ratio was found to be 1.3%. This confirms the findings of the last section since a

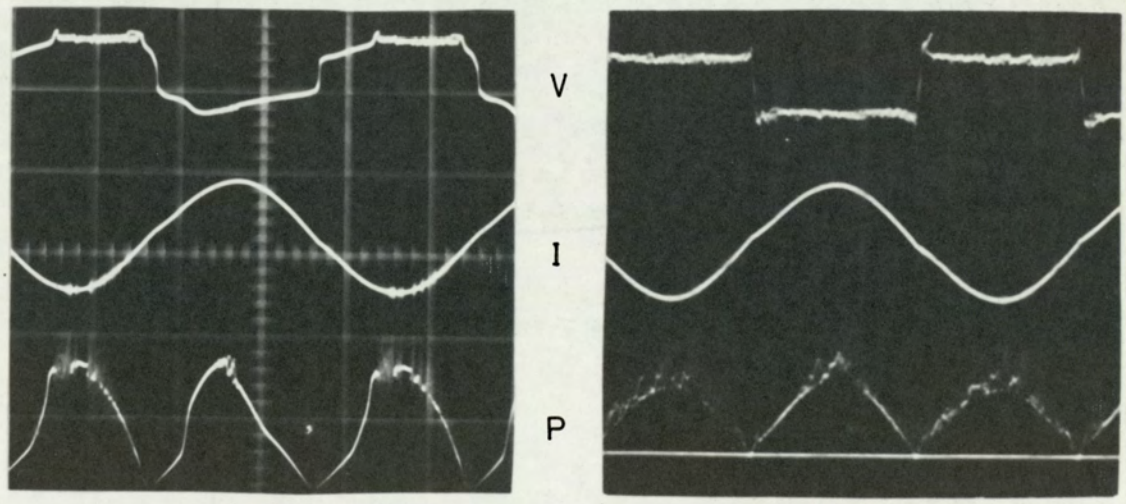


V (=50 V/cm)
I (=30 A/cm)
P(=400 W/cm)

(V =voltage , I =current ,P= power)

Time base = 5 ms/cm

FIGURE 3.8. Steady a.c. arc waveforms



(a) (b)

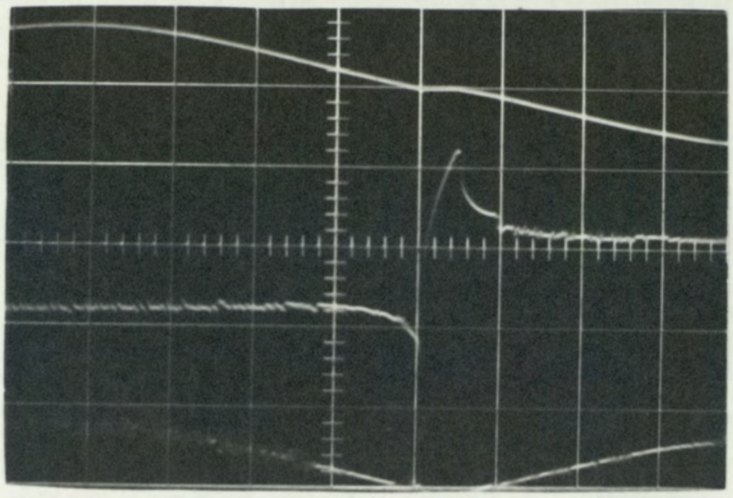
(V = voltage , I = current , P = power)

Time base = 5 ms/cm

FIGURE 3.9. The introduction of nonlinearities into arc waveforms

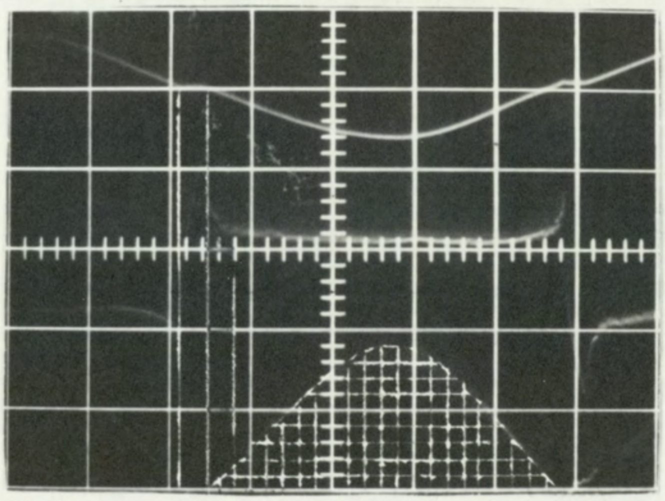
(a)
V(=50 V/cm)
I(=30 A/cm)
P(=350 W/cm)

(b)
V(=50 V/cm)
I(=30 A/cm)
P(=400 W/cm)



(V =voltage , I =current , P = power)
Time base = I ms/cm

FIGURE 3.10. A worst case condition for arc transients



(V =voltage , I =current , P = power)
Time base = 2 ms/cm

FIGURE 3.11. Calculations of percentage power distributions in arc waveforms

worst case condition of transient time will produce a maximum error which is well within the range of accuracy of standard measuring devices.

3.4. The Measurement of A.C. Arc Power

Although the results of Section 3.3. indicated that the proportion of the "transient regions" power to the total power was negligible, it is intended to give some consideration to the measurement of power by conventional measuring instruments. This, however, is preceded by describing the electrical system of which the arc is part.

3.4.1. The "Arc-Power Supply" System

An understanding of the arc-power supply system is important especially if a quantitative approach to arc behaviour is to be done. Describing the system performance in a manner that would account for the periodic variations and non-linearities of arc behaviour can be achieved by using an equivalent circuit. With the aid of such a circuit, Manz[24] developed a set of equations to describe the performance of a consumable-electrode welding system. Also, Harry[23] used an equivalent circuit in studying the performance of measuring instruments in determining the electrical parameters of an arc. A typical equivalent circuit is shown in Fig. 3.12., where v, R_s and L_s can be considered as included in the power supply, and

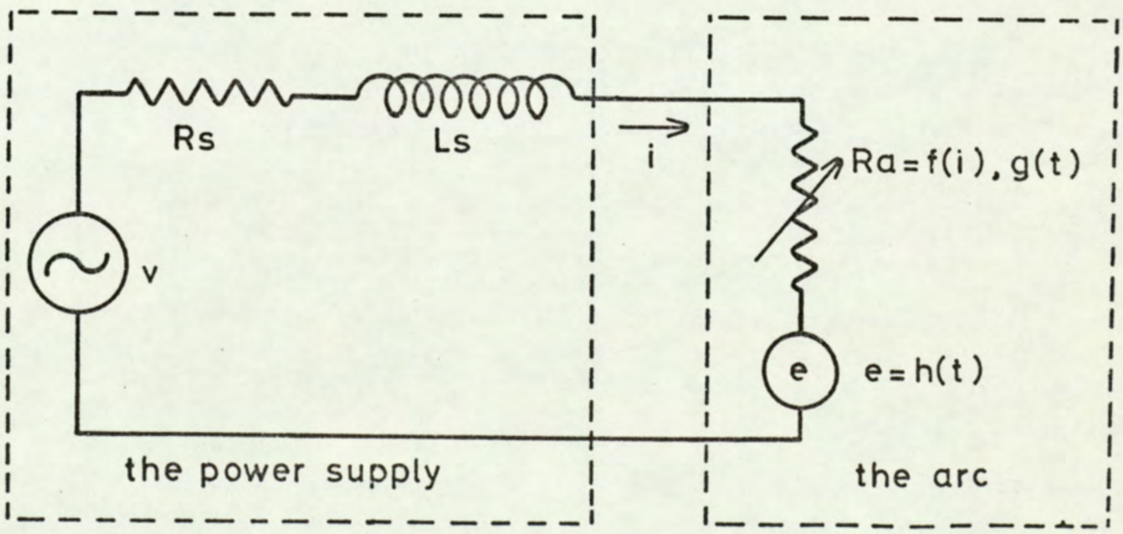


FIGURE 3.12. Typical arc equivalent circuit.

are independently-variable parameters. The arc can be represented by R_a, the equivalent non-linear arc resistance which is determined by two functions f(i) and g(t). f(i) accounts for the operating point on the arc "voltage-curve characteristics (Fig. 3.1.), and g(t) represents the equilibrium time for the arc to return to its initial operating conditions when subjected to a change (2.4.2. and 2.4.3.). The fluctuations resulting from column changes and arc root movement is accounted for by a voltage source e(=h(t)).

3.4.2. A.C. Arc Simulation Circuit

Arc parameters (e.g. column length, voltage, current) should be varied when examining different measuring techniques in order that the conditions are as general as possible, and cases of extreme instability and non-linearity may be simulated. It was not possible to use the plasma torch for this investigation due to its permanent-construction design. Therefore, a separate a.c. arc system had to be used to simulate arc waveforms similar to the ones already met.

This separate arrangement (Fig. 3.13.) included a variable output transformer, to give a range of 0-250 volts on open

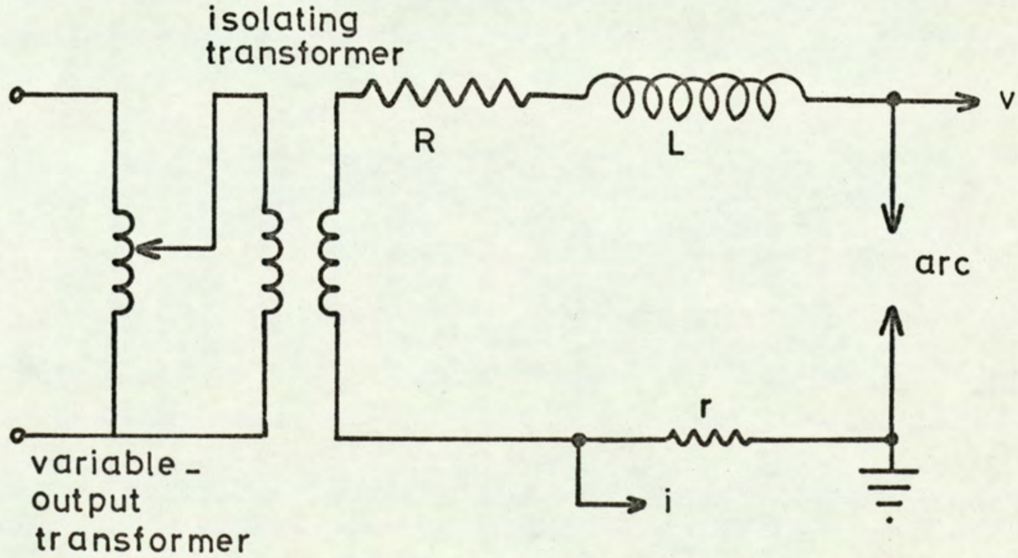


FIGURE 3.13. An a.c. arc simulation circuit.

circuit. A transformer was used to isolate the circuit from the supply, thus the "earthing" needed for reference was accomplished as shown. Current limiting and stabilisation was achieved by variable resistors and inductors. The need for an ignition system was eliminated by using thermionic electrodes. The electrodes were mounted horizontally on specially designed copper holders that enabled the arc gap to be adjusted to any desired value. Voltage was measured directly across the arc, and a current shunt in series with the arc circuit was calibrated to indicate the current.

3.4.3. Preliminary Investigations

The experiments that were done using the above circuit were limited by two factors.

1 - Only measurements that are (directly or indirectly) related to power assessment were of real interest to this work.

2 - The instruments to be considered were conventional, bench-type, measuring devices. Examples are, moving coil, dynamometer type, and thermal type of measuring instruments, with the exception of the electronic multiplier which will be used as the basis for comparison.

As the voltage and current waveforms of an arc are in-phase, the power could be measured indirectly by separately measuring the current and voltage and then multiplying. The measurement of arc voltage by an indicating instrument is, however, liable to errors as will be seen below.

The torque of an indicating moving coil instrument, is

$$T = K . I = C . \theta . \qquad 3.4.1.$$

where K = Meter Constant.

I = r.m.s. current.

C = Control Constant.

and θ = Angular deflection in radians.

Also, the deflection of the meter at time t, is given by

$$J \frac{d^2\theta}{dt^2} + D \frac{d\theta}{dt} + C\theta = Gi \qquad 3.4.2.$$

where J = Moment of inertia.

D = Damping factor.

G = Displacement constant

and i = instantaneous current due to the applied voltage.

As the applied voltage waveform can be considered[23] to have a d.c. component and a polynomial that accounts for the fluctuations just before and just after the plateau level, the instantaneous deflection current i (due to this voltage) can be expressed as :

$$i \propto (a + bt + ct^2 + dt^3 + \ldots) \qquad 3.4.3.$$

where a, b, c, d, ... are constants.

Equation 3.4.2. will therefore have a solution of the form,

$$\theta = JP^2 + DP + C + l + mt + nt^2 + \ldots \qquad 3.4.4.$$

$$\text{where } P = \frac{-D + \sqrt{D^2 - 4CJ}}{2J}$$

and l, m, n ... are constants.

The non-linear nature of 3.4.4. implies that if i is neither constant nor periodic, then from equation 3.4.1.

$$\frac{K}{t} \int_0^t i \, dt \neq \frac{C}{t} \int_0^t \theta \, dt.$$

For a dynamometer wattmeter, the steady-state power indication is given by,[25]

$$P_W = P_L + I^2 R_c + \left[\frac{L_p + M}{R_p}\right] \omega V I \sin \phi \qquad 3.4.5.$$

where P_L = the actual power in the load.

R_c = the resistance of the current coil.

L_p & R_p = the inductance and resistance of the voltage coil circuit.

M = the mutual inductance between voltage and current coils.

V = the voltage.

I = the load current.

and ϕ = the load phase angle.

The change in inductance due to the relative positions of the coils will introduce errors at frequencies higher than the supply frequency.

A more significant source of error is due to the high frequency harmonic content of the arc waveforms, since the error is also proportional to ω.

For the thermal wattmeter, it can be shown[26] that the torque T is given by

$$T = K\,(A\,vi + B\,i^2) \qquad 3.4.6.$$

K, A and B being constants and v and i the instantaneous voltage and current respectively.

If the internal circuit elements for the meter are properly chosen, $B\,i^2$ can be neglected and

$$T \simeq (\text{constant}) \times (vi) \qquad 3.4.7.$$

This makes the thermal wattmeter response directly proportional to power, and for this reason is quite suitable for measuring non-sinusoidal waveforms as those of an a.c. electric arc.

The system which is capable of producing the best results is shown in Fig. 3.14.

Using a suitable potential divider, the voltage across the arc, Vv, is introduced to one input of a (quarter-square) electronic multiplier. A voltage indication of the current, V_i, was taken from a current shunt to the other input. The output from the multiplier

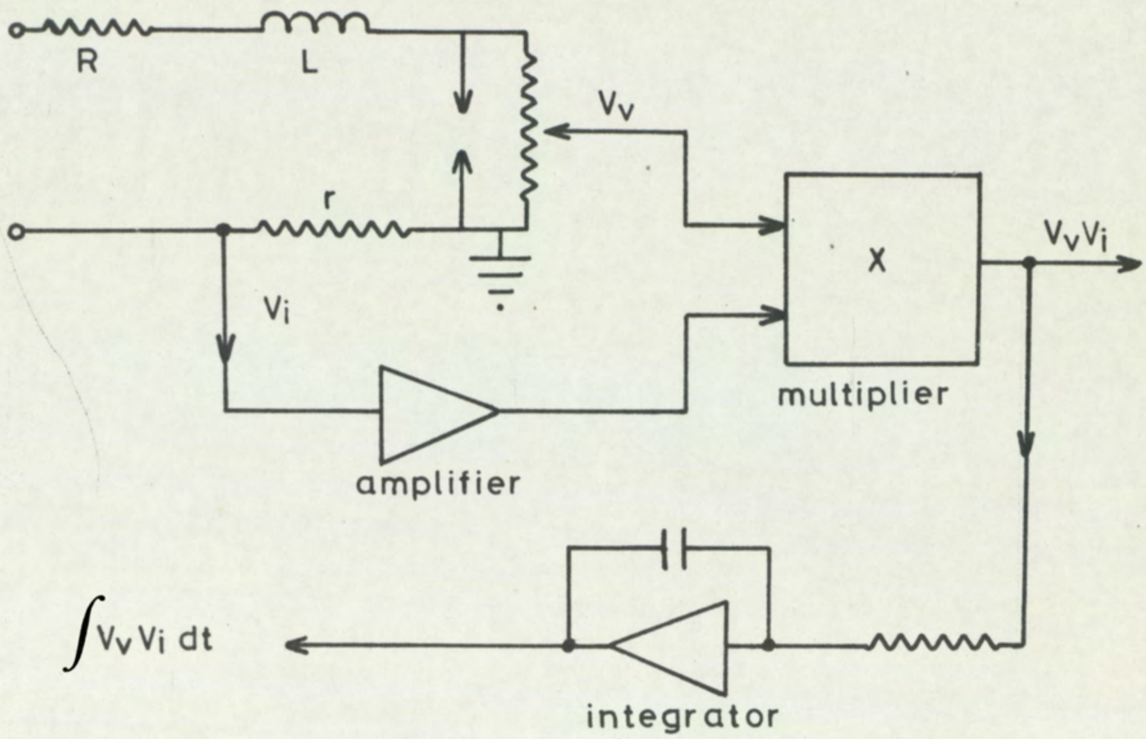


FIGURE 3.14. The electrical system for arc power measurement

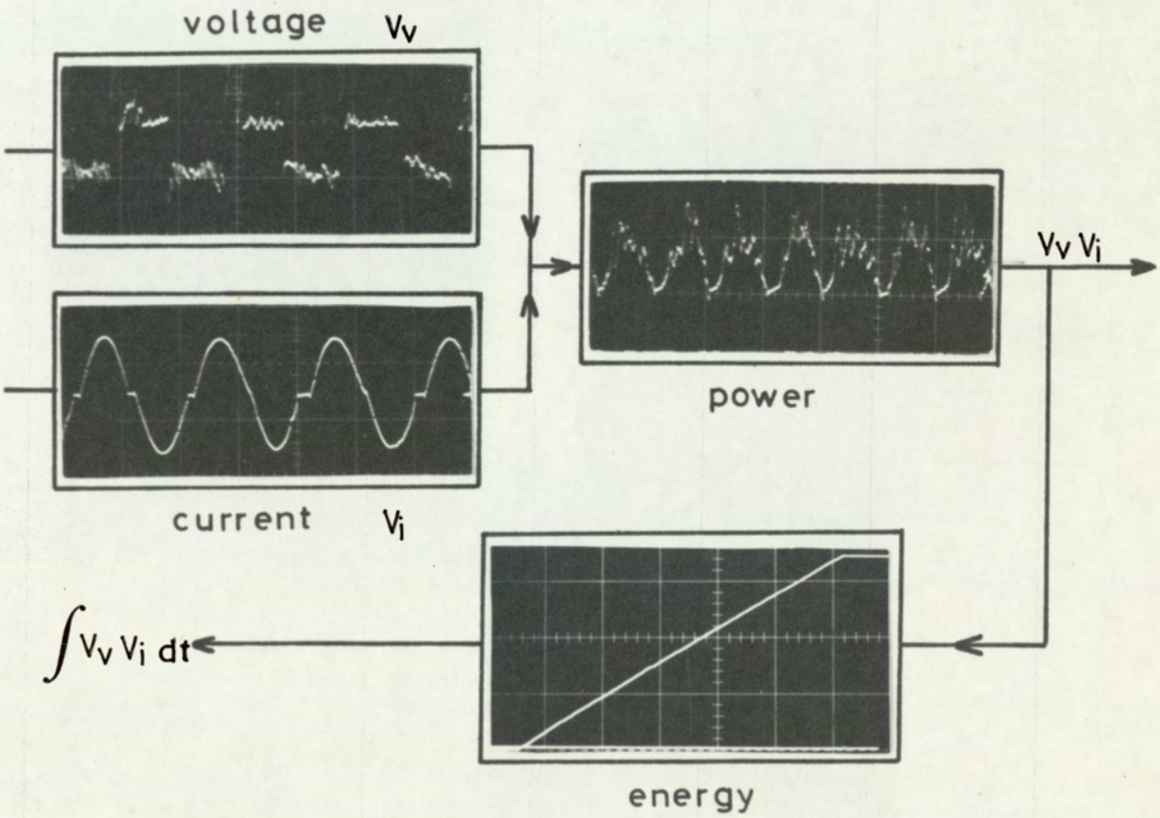


FIGURE 3.15. Typical waveforms at different parts of the system

was passed through an integrator to give the energy taken over a known period of time. An oscilloscope view of this sequence is shown in Fig. 3.15.

3.4.4. A comparative study of instrumental results

The electronic multiplier and its associated system can be considered as the basis for arc power measurements for the following reasons :

1 - The frequency response (250 kHz) is better than that for conventional measuring instruments.

2 - By its multiplying action the power measurement will be less liable to errors since the transient regions of arc voltage will be largely diminished by the regions of zero current.

3 - When used in conjunction with an integrator, the errors will be further limited due to the averaging effect.

It was therefore decided to treat the deviation in the reading of any instrument from that of the above standard system as error. Figs. 3.16. and 3.17. represented the behaviour of a dynamometer wattmeter and a thermal wattmeter in comparison with the electronic system. The difference in indications of the first two, to those of the third was expressed as a percentage error. This was obtained for several increasing and decreasing power values. At the time of the measurements, it was made sure that the arc waveforms contained as much non-linearity as possible in order to get a worst case of arc power.

In both graphs, the randomness of the errors is apparent. It can also be seen that the general trend shows the errors to be decreasing with increasing power. The dynamometer wattmeter, rather expectedly, was less consistent compared with the thermal wattmeter, in that its errors were generally of twice the order of the latter. The manufacturer's estimate for the accuracy of the thermal wattmeter of 4% was verified, as seen from Fig. 3.17.

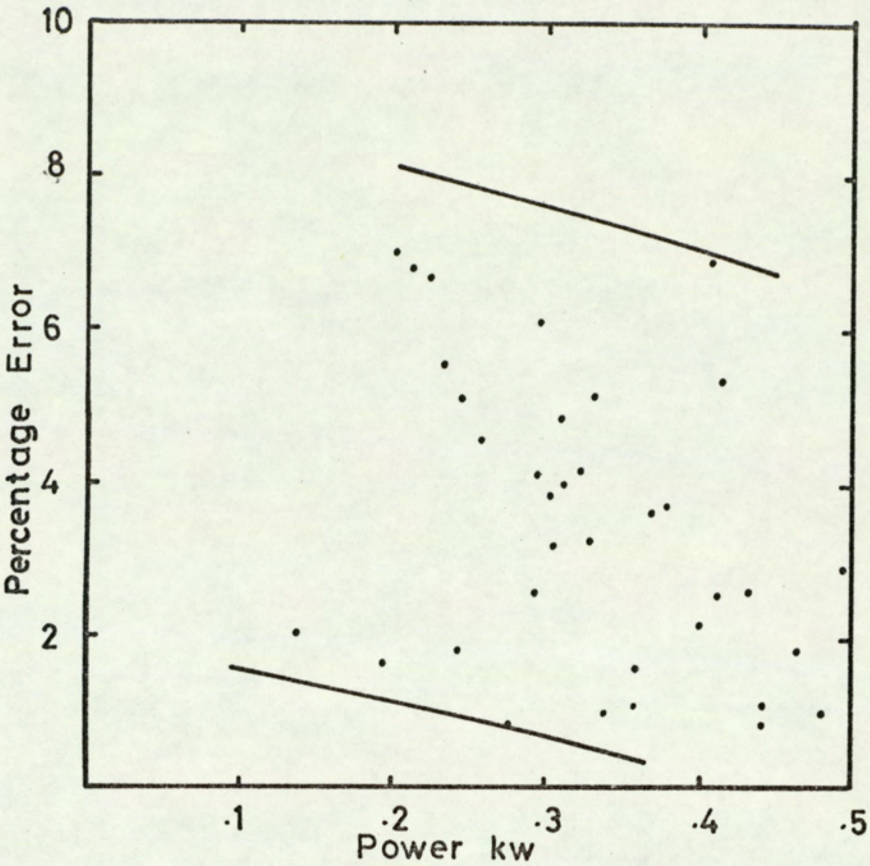


FIGURE 3·16 Dynamometer Wattmeter

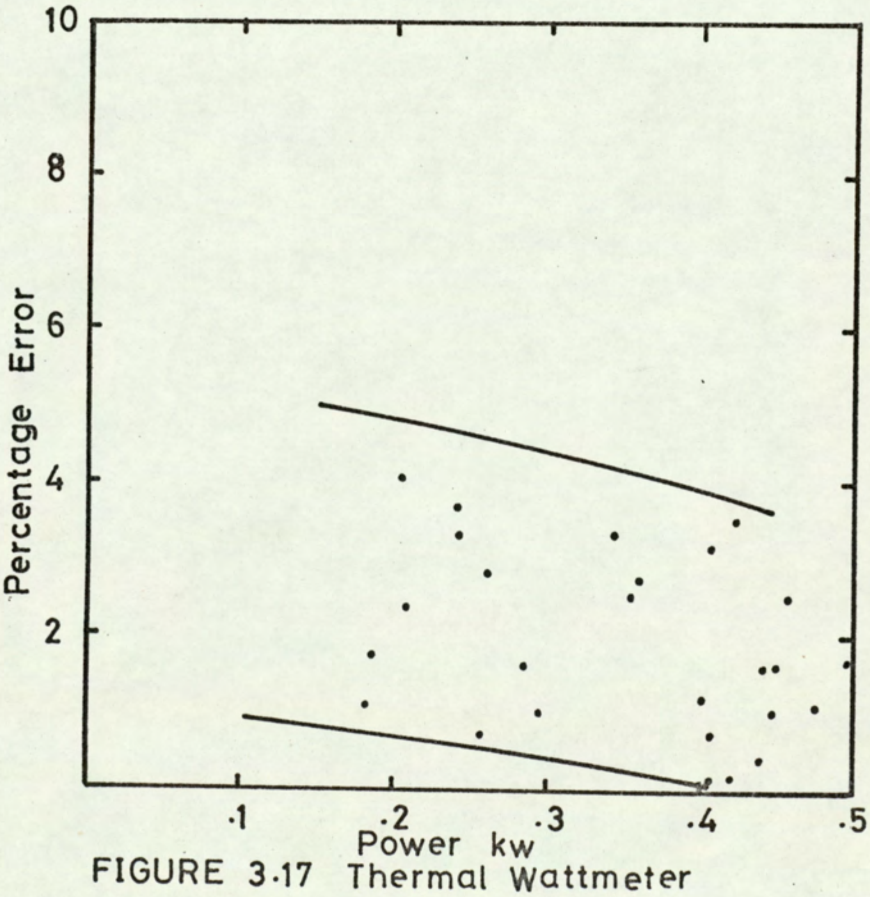


FIGURE 3·17 Thermal Wattmeter

The "dynamometer wattmeter" indications presented a bigger problem by responding too rapidly to arc fluctuations. To ascribe an average value to any particular reading was therefore in itself a formidable task. The indications on the thermal wattmeter were usually much steadier, and readings could be taken with greater ease.

Other types of wattmeters (standard dynamometer, and other thermal types) were also examined, but their response was very similar to those already studied.

It was seen that the thermal wattmeter was very suitable in assessing a. c. power of arcs. Practical handling and use in less favourable places than the laboratory gives it certain advantages over the electronic system.

CHAPTER 4.

DISTRIBUTION OF THERMAL ENERGY IN THE PLASMA TORCH.

The conversion of other energy forms to heat is a very common and natural process. Heat energy, however, is easily lost by heat transfers and, in effect, the advance of plasma generation technology into the high temperature range may ultimately be limited by numerous heat transfer problems. A study of thermal energy distribution in a plasma torch will account for the heat content of each part and will therefore be an integral part of the energy balance.

4.1. An Account of Energy Conversion

The electrical energy supplied to a plasma torch is partially converted to heating the gas and partially dissipated as losses to different parts of the torch internal system. In Fig. 4.1., a general account of energy distributions is shown. It is reasonable

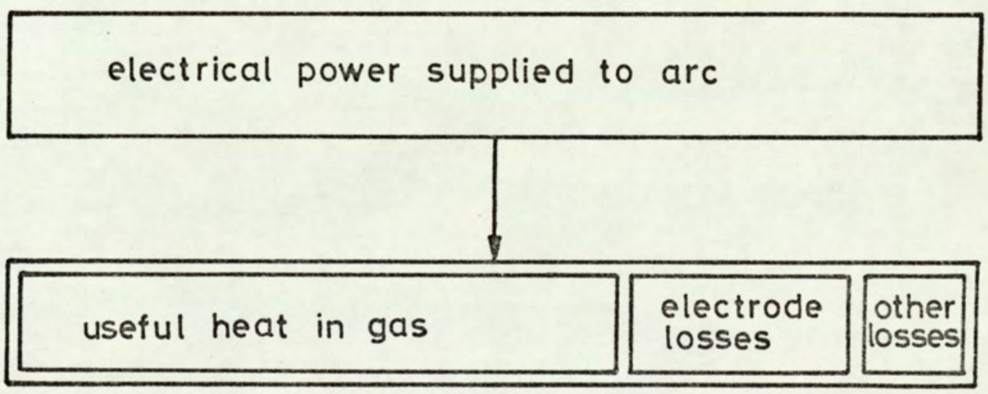


FIGURE 4.1. Energy distribution in the torch.

to consider the useful heat in the gas to be more than half the total power originally supplied to the arc. Electrode losses account for most of the remainder. Other forms of energy dissipation include radiation and convection losses.

Fig. 4. 2. is a more detailed view of the stages that lead to the final analysis of input energy. The electronic and ionic properties at different regions of the arc will give rise to three distinct voltage drops. As a result, power dissipations exist at the cathode and anode falls and within the column. Due to the different cathode and anode mechanisms, more power is lost at the anode than at the cathode. However, since the power is a. c., each electrode becomes anode and cathode alternately. The sum of the two fall losses is referred to as "electrode losses". At the electrodes, 10 to 30% of the total power is normally dissipated.

The column power is the power available for useful conversion since the column occupies most of the distance between the electrodes, and therefore is in contact with most of the gas flow. Also, it is normal to water-cool the electrodes, thus the heat due to fall voltages is quickly taken away by the coolant.

4. 2. Electrode Losses

The existence of the electrode fall regions is due to space change accumulations associated with the conditions required for the passage of a current across the junction of a metallic and gaseous conductor[4]. It is not intended to review the theories that explain this; rather, the emphasis is focussed upon evaluating the power dissipated at the electrodes. Due to their different "transport" mechanisms, the fall voltages, current densities and heat dissipation are not normally the same for the cathode and anode even if they were of the same material. Fig. 4. 3. shows a typical energy balance at the cathode[27].

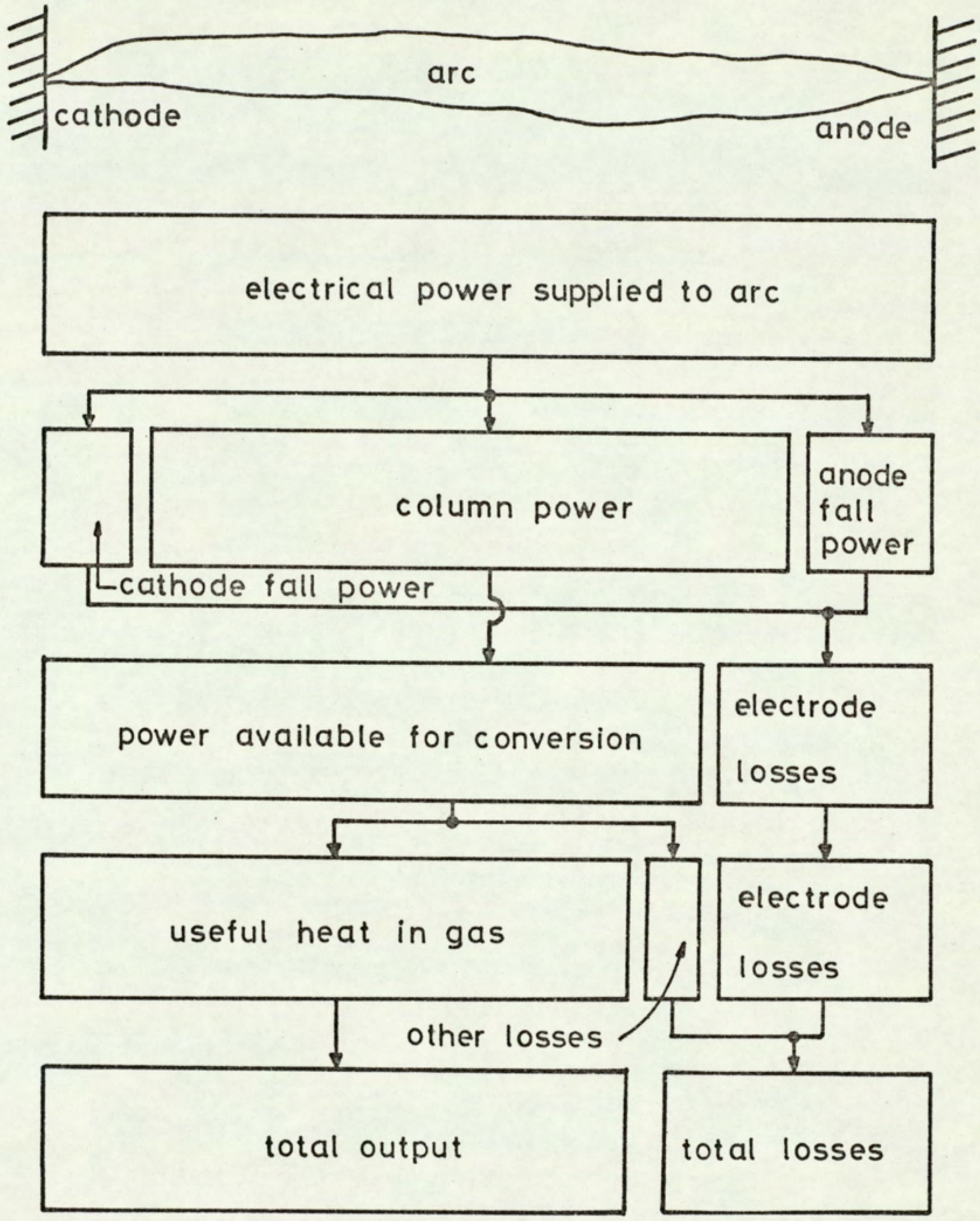


FIGURE 4.2. Stages of electro-thermal energy analysis

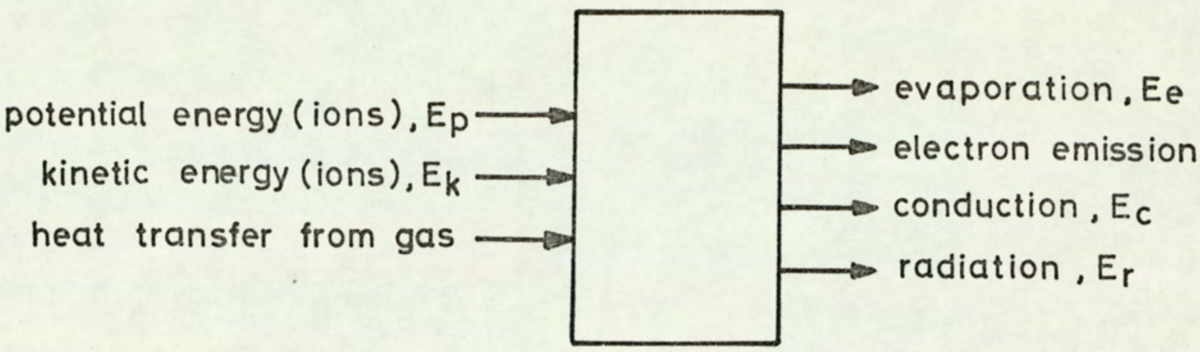


FIGURE 4. 3. Energy balance at the cathode.

As the fall voltages are so near the surface of the electrodes, the highest temperature occurs in the vicinity of the electrode-gas junction, resulting in heating of the electrode material. Direct heat transfer from the hot gas, in addition to the effect of the Kinetic energy of impinging ions, will add to the total energy transfer to the electrode. For balance, energy is lost by evaporation (due to local boiling), thermionic emission, radiation and heat dissipation by conduction. These factors can be related as

$$n \ (E_p + E_k - \phi) + E_g = E_c + (1-n)\,\phi + E_e + E_r \qquad 4.2.1.$$

where n = number of ions striking the cathode.

$1-n$ = number of electrons emitted.

and ϕ = work function.

At the anode, the energy balance is slightly less complicated, as seen from equation 4. 2. 2.

$$E_p + E_k + \phi + E_g = E_e + E_r + E_c \qquad 4.2.2.$$

Holm[28] suggested that the cooling effect of electron emission was negligible at high currents, and if radiation losses are ignored,

$$VI = W_c + W_e \qquad 4.2.3.$$

Where V, is the electrode fall voltage and I the arc current. W_c and W_e being the power dissipated by conduction and evaporation respectively.

Using this approximation, the electro-thermal efficiency of a plasma torch can be readily estimated as follows : If V_a and V_c are the anode and cathode fall voltages and I, the arc current, then if V is the total voltage across the arc,

the efficiency, $$\eta = \frac{VI - (V_a + V_c)}{V} \qquad 4.2.4.$$

Typical fall voltages for copper at 1 Atm[29] are 15 volts for cathode and 10 volts for anode. If the total voltage across the arc is 100 volts, the efficiency will be 75%.

In addition to the basic "transfer" mechanisms at the electrode-gas interface of an anode, several secondary transfer processes occur which tend to increase its thermal loading. As a result, substantial amounts of heat may be carried away by the anode coolant. Due to this, several workers[30-31] have examined gas transpiration cooling of a porous anode. Efficiencies as high as 90% have been reported for this method.

An essential requirement in the performance of a plasma torch, is the low contamination level of the output product. Since the contamination level is proportional to material evaporation at the electrode, the latter can be minimised by efficient electrode cooling; then equation 4.2.3. can be reduced to

$$VI = W_c \qquad 4.2.5.$$

This is a very important result, since the power dissipated can now be obtained by simply measuring the heat transfer to the coolant. Fig. 4.3. can therefore be reduced to that of Fig. 4.4.

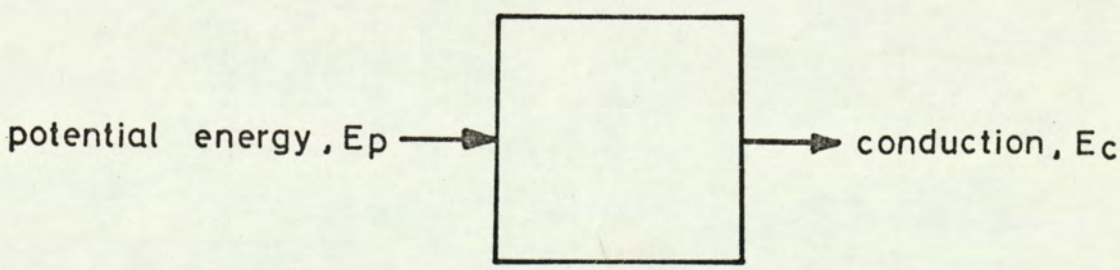


FIGURE 4.4. Final reduced energy balance at electrode.

4.3. Electro-Thermal Energy Conversion at the Column.

In Sections 4.1. and 4.2., it was shown that the arc column is the region responsible for the useful electro-thermal energy conversion, since it occupies most of the distance between the electrodes. The flow channel of the column, ideally, has a constant current density and a constant potential gradient. The channel must also be electrically quasi-neutral, i.e. it contains equal numbers of positive and negative charge densities. If this were not true, huge electrostatic forces would destroy the arc[4]. These forces, if not balanced, could be as high as 1700 tons/cm^3.

In a normal gas, electrical and thermal equilibrium prevails. The atoms and molecules are electrically neutral and are in a process of random motions and continuous collisions. During these collisions, energy is transferred from one atom to another and a thermal balance is maintained.

For an atom to travel and collide with another it must have a certain minimum velocity. Due to the directional randomness of this velocity, the gas as a whole appears positionally static, since the resultant velocity of all the elements in any direction is zero. The mean distance travelled between collisions is of importance, and is referred to as the mean free path. Due to its electrical neutrality, the gas remains impartial to an applied electric field unless the field is strong enough to cause a breakdown, in which case non-neutral elements are injected into the gas (or possible ionisation within the gas occurs). The channel of the electrical discharge will therefore contain neutral atoms (and molecules), as well as ions and electrons.

Due to their charges, electrons and ions will react to the electric field by gaining a drift velocity, giving rise to the electrical current. The much heavier mass of an ion compared to that of an electron makes its drift velocity negligible in relation to that of the electron. Therefore the current is predominantly electronic. As well as originating the drift velocity, the electric field also increases the random velocities, thus increasing the collision rates.

The elements taking part in the energy conversion are shown in Fig. 4. 5.

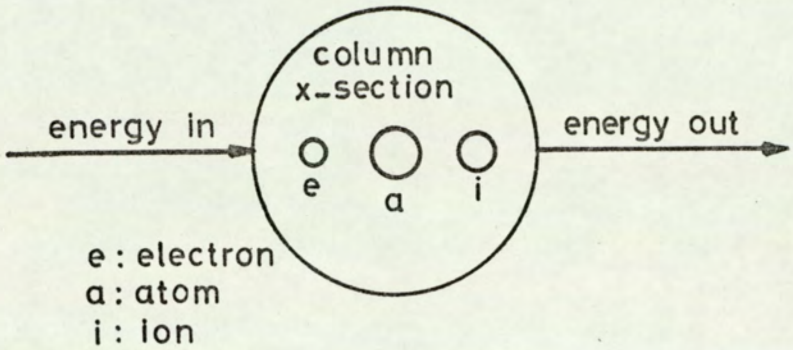


FIGURE 4. 5. Energy conversion at column.

As the charged particles drift under the influence of the electric field, their energy received from the field is partially dissipated every time there is a collision with a gas atom (or molecule). Due to the higher electronic drift velocity, the electrons receive this energy at a higher rate than the ions. Therefore, the transfer of the electrical energy to the gas atoms can be considered to have been done by electrons only. As temperature can be considered to be a measure of energy, the electron energy is often indicated by an electronic temperature, Te. The fraction of the electronic energy transferred to a gas atom can be shown[32] to be

$$= \frac{2m}{M} \left[1 - \frac{T_g}{T_e} \right] \qquad 4.3.1.$$

Where m and M are the electronic and atomic masses respectively, and T_g is the gas temperature. Although the electron temperature must be higher than the gas temperature in order that energy transfer can occur, it is often only slightly higher, and the fraction of energy transfer approaches $\frac{2m}{M}$. These type of collisions (with subsequent Kinetic energy transfer) are called elastic collisions. Inelastic collisions result in energy transfer either as ionisation or excitation energy. Fig. 4.6. illustrates the above description schematically.

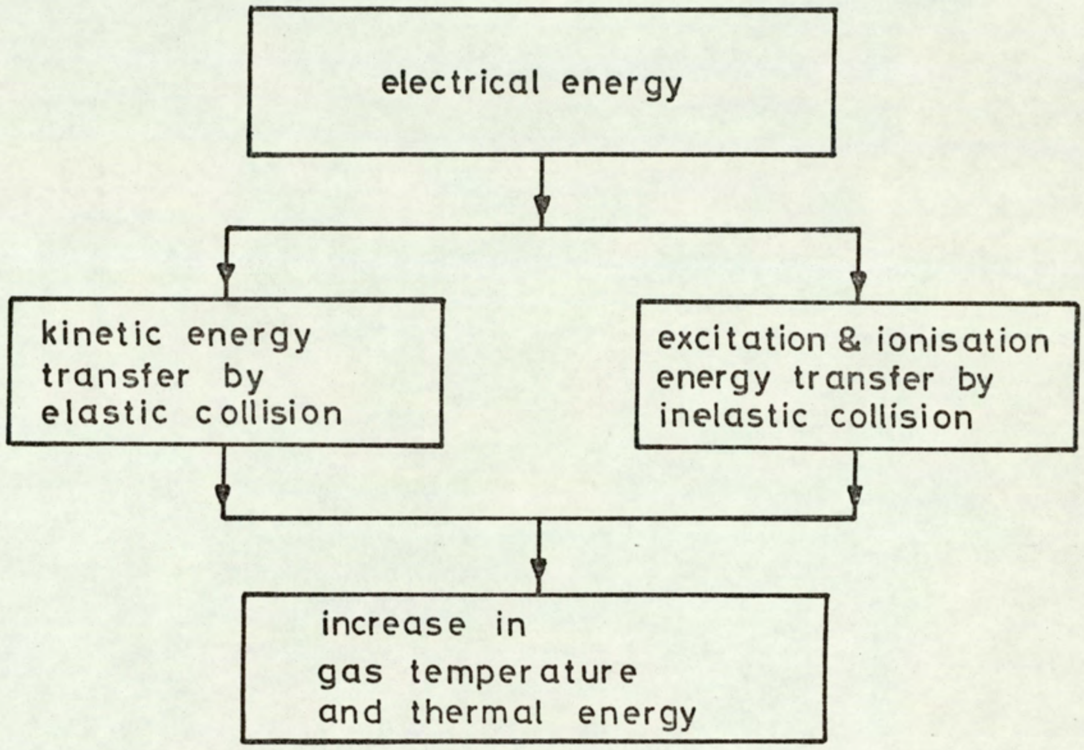


FIGURE 4.6. The sequence of energy change.

In a normal arc discharge, the heat in the channel is lost to the rest of the gas and to the container walls by convection, radiation and conduction. This flow of heat energy can only have a radial direction in relation to the column cross-section.

4.4. Thermal Measurements.

The thermal system under examination may be divided into three parts :

1 - Electrode losses.

2 - Heat content of the emerging gas.

and 3 - "Other losses" (e.g. radiation).

For an energy balance, it is essential to evaluate and account for the heat energy in all these parts. Furthermore, other thermodynamic properties like temperature and specific enthalpy need also to be determined due to their importance in assessing the plasma torch performance . Each part of the thermal system will be considered separately in the following sections.

4.4.1. Electrode losses.

Causes for heat dissipation at the electrodes have already been discussed in Section 4.2., and it was shown that nearly all this energy is gained by the coolant. The electrodes were water-cooled, as seen in Fig. 4.7. Their actual dimensions were largely influenced by the amount of water flow required.

For heat assessment, the inlet and outlet temperatures and rates of water flow for both electrodes had to be determined. Water flow rates were adjusted such that the water temperature seldom increased by more than about 10^{o} above room temperature. Platinum resistance thermometers were used for the temperature measurements at a rated accuracy of $\pm$ 0.5%. The water flow rates were determined by measuring the time taken to fill a calibrated 5 litre flask. The value taken was the average of several readings.

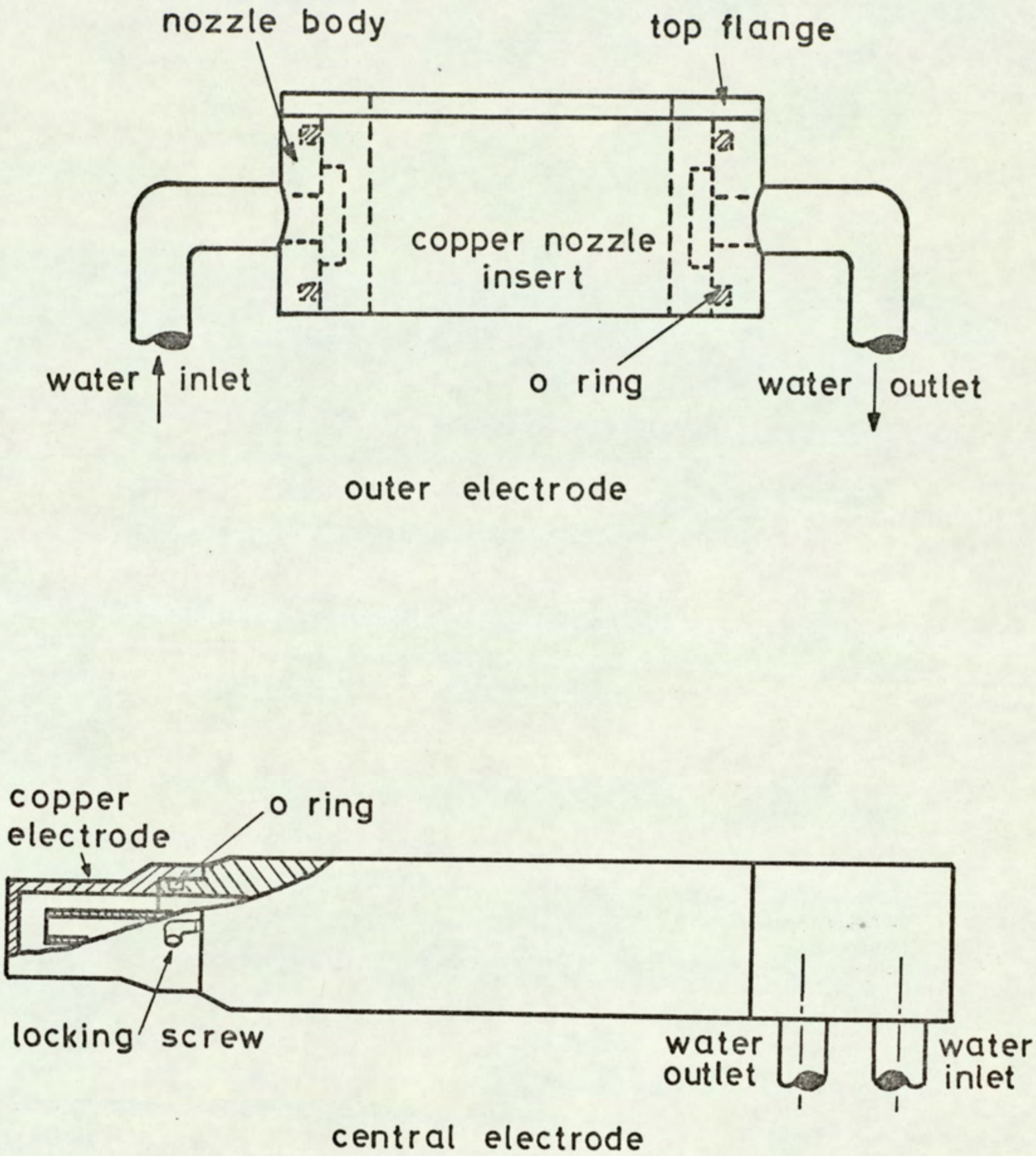


FIGURE 4.7. Electrode cooling.

4.4.2. Thermal properties of the gas

In a plasma torch, the thermal properties of the output gas that are of general importance to this work are, pressure, temperature and specific enthalpy. During the operation of the Aston Torch, the pressure is maintained constant and approximately atmospheric. The temperature of special interest is the mean gas temperature. Other relevant parameters include the electronic temperature and the isothermal temperature distributions in the plasma jet, but these are beyond the scope of the present work.

If the gas flow rate is known, specific enthalpy and mean temperature are interrelated. If one is known, therefore, the other can be determined. For an electro-thermal energy balance it is necessary to account for the heat content of the gas. An apparently simple method of achieving this is to use a thermodynamic relationship , thus ,

$$\text{Power in gas} = \dot{m}\ c_p\,(T_2 - T_1) \qquad 4.4.1.$$

where $\dot{m}$ = the mass flow rate of gas,$(= \frac{dm}{dt})$

c_p = the specific heat at constant pressure

and, T_2 and T_1 = final and initial temperatures respectively.

For this power to be determined, it is clear that the gas flow rate and temperatures have to be measured.

(a) <u>The measurement of gas flow rate.</u>

In all tests, air (being the cheapest gas) was used as the working fluid. It was supplied from a compressor (Fig. 4.8.), and taken to the torch through a single pipeline. After passing through the arc the air discharges to atmosphere. The flow rate was determined

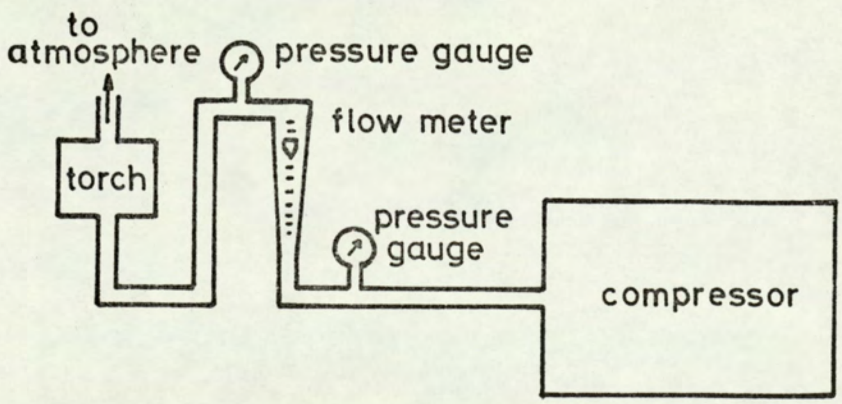


FIGURE 4.8. Air flow system.

using a rotameter which was mounted on the pipe as shown. The rotameter scale gave the flow in centimeters, but by means of a calibration chart it was possible to convert this into litres per minute. After correcting to S. T. P. conditions the readings were finally converted to grams per second of air flow. The float (made of Korannite) was liable to oscillations due to small pressure changes on the arc side. The origin of these fluctuations was the arc's random movement. The mean float position was taken as the flow meter indication.

(b) Temperature measurements.

Before discussing available measuring devices, it must be emphasised that the lowest acceptable gas temperature for a plasma torch is taken as 1000°C[33]. Below this, other low-contamination heat sources are available.

In general, the methods employed for temperature measurements[34] are classified as either of the "contact" or "non-contact" types. The first, imply that the measuring instrument is in contact with the hot body. In the second method, heat exchange between the sencing device and the hot body is normally by radiation.

Contact methods

Liquid-in-glass thermometers are usually employed for measuring temperatures not exceeding 200°C, but with suitable modifications, their use up to 600°C are possible[35]. A liquid-in-steel thermometer, if used to measure the temperature of a gas has a similar range of up to 600°C. Both these types, however, clearly fall below the required minimum of a plasma-torch.

Electrical resistance thermometers are normally used within the range, - 240 to 600°C. A platinum resistance thermometer, however, can have the gold point (1063°C) as its upper limit. In addition, some high temperature resistance thermometers that are able to measure temperatures as high as 1600°C (under special conditions) have also been reported[36]. These types were rejected for use in this work since they can only measure temperatures that are within the minimum requirements of the torch. The Aston Torch may produce gases at temperatures as high as 10,000^{o}C.

Thermocouples are quite suitable for measuring gas temperatures up to the temperature limits of the thermocouple wires. The maximum reported temperature for base-metal thermocouples is 1350^{o}C [36]. The more usual temperature range is, however, between -190 to +1100^{o}C. Refractory-metal thermocouples can be used up to the melting points of pure metals and their alloys, (the melting point of Tungsten is 3380^{o}C). Non-metallic thermocouples are also available. One form (graphite v boronated graphite) can be used up to 3100^{o}C [37].

When placed in a gas, thermocouple junctions normally exhibit three forms of heat transfer, namely convection from the gas, radiation to the surrounding walls and conduction along its supporting wires. In addition, in the case of arc heaters, the junction can pick up direct radiation from the arc. Radiation losses and pick up can be significant at temperatures higher than about 300^{o}C [36].

Minimisation of radiation errors include decreasing the diameter of the thermocouple wires and using radiation shields in the form of concentric, open-ended, polished metal cylinders enclosing the junction[34]. Other problems associated with using thermocouples for this work are the contamination of the junction due to gas flow and the disruption of local temperature distributions.

Non-contact (or radiation) methods

The radiation pyrometer is a reasonably accurate device for measuring temperatures in excess of about 1000^{o}C and with practically no upper limit[34]. Below this temperature, the intensity of visible light emitted by a hot body is too weak, and errors are introduced in the measurements. Generally, radiation pyrometers are only used for measuring the temperature of a solid surface since the radiation emitted from a solid is a continuous spectrum. In a gas, however, the radiation occurs only at certain wavelengths, and therefore the accuracy of the device is limited by the uniformity of the temperature of the gas stream and is affected by the temperature of the solid background.

Above about 8,000^{o}C, spectroscopic methods appear to be favourable, especially in determining the temperatures of plasma jets[31-38]. In nearly all the cases, however, this method was used in studying isothermal temperature profiles across the sectionof a plasma jet and therefore will not indicate the mean temperature of the gas stream.

The comparative study of this section indicated the limitations and difficulties associated with determining an actual mean gas temperature in a plasma torch. An alternative would be to calculate the heat energy of the gas from which a mean gas temperature can be estimated by using thermodynamic relationships. This method involves some calorimetric investigations which are done in Chapter 5.

4.4.3. Other Losses

By "other losses", it is mainly implied the radiative and convective losses from the arc column and hot gas stream. Both losses are proportional to pressure, enthalpy and temperature.

Radiation losses are seldom significant in Plasma generators at temperatures below about 7,000^{o}C.[46-8] As far as the Aston Torch is concerned, although such temperatures may be attained, operation has rarely been at temperatures higher than 2,000^{o}C.

John and Bade[8] have provided information describing the losses as functions of pressure and enthalpy. Both losses were only significant at enthalpies beyond the capabilities of the Aston Torch (Chapter 6). If the torch is operated at 1 atm., as is the case in the present work, the losses will even be less significant. It will be seen (Chapter 6), that the heat in the air plus the electrode losses accounted for more than 95% of the power input to the torch. Allowing for the inaccuracy of the balance, it is clear that the radiation and conduction losses can be neglected as far as this work is concerned.

CHAPTER 5.

CALORIMETRIC INVESTIGATIONS.

The need for a calorimetric assessment of thermal energy in the gas stream was emphasised in Section 4.4.2. The validity of this method will now be examined.

5.1. The Use of Calorimeters in Plasma Jet Technology.

In comparison with other thermal studies in the field of plasma jet technology, calorimetric methods have hitherto received inadequate attention. This was possibly due to the limitations imposed on the type of applications using the plasma generator. In general the fields of applications were of special nature that in effect made the determination of efficiency (by means of a proper energy balance) of secondary importance.

The main reason for employing a calorimeter was apparently to measure the "rate" of heat transfer from the plasma jet to its surroundings, as this was considered to be an important characteristic of the flow. One form of a calorimeter used for this purpose is shown in Fig. 5.1.

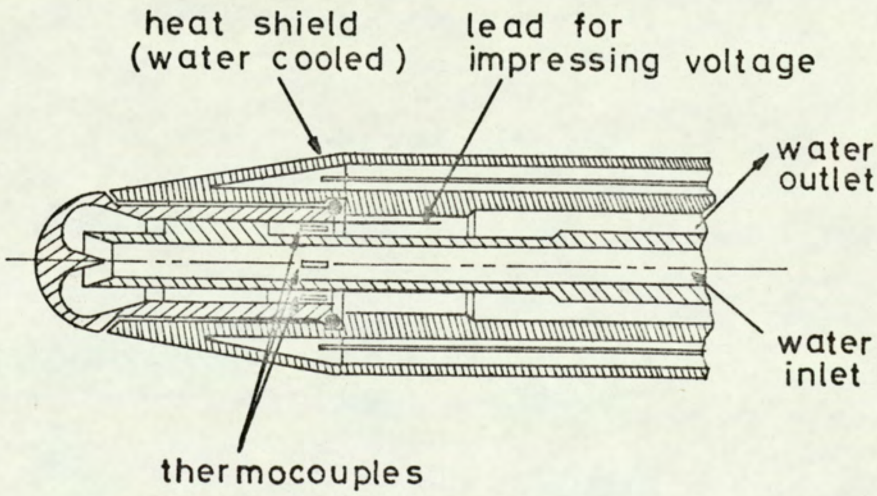


FIGURE 5.1. A Plasmadyne Corporation Calorimeter.

The heat transfer rate was obtained from a knowledge of the water flow rate and its temperature rise. Temperature measurements were usually made by thermo-couples.

Kelly and Scott[39], used the calorimeter shown schematically in Fig. 5.2. to determine the rate of heat transfer from a plasma jet

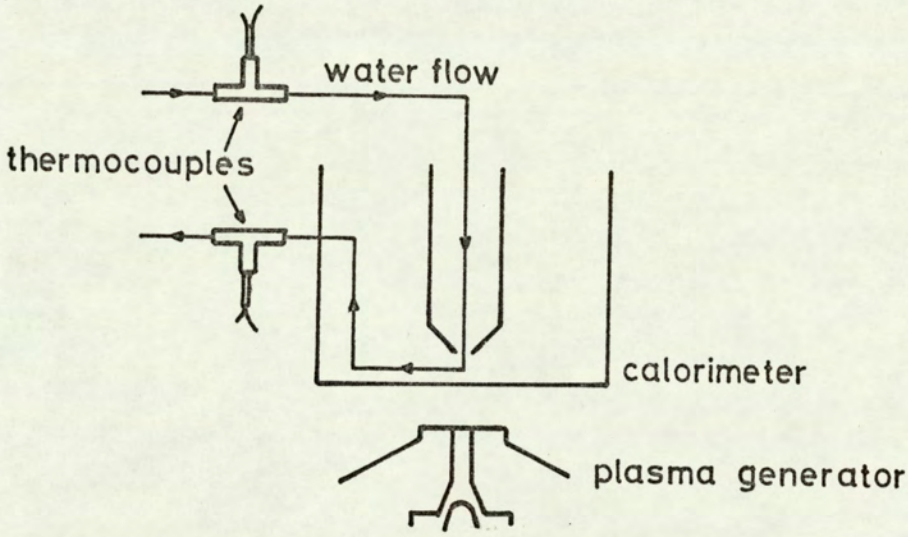


FIGURE 5.2. The Kelly and Scott calorimeter.

and also to obtain an energy balance.

Heat transfer rates in an argon plasma jet were investigated using a transient probe by Stokes et al[40]. A high-speed air piston was to thrust the probe into the jet periodically.

Heat transfer rates were also investigated under a variety of operating conditions. Raelson and Dickerman[41], for example, used a set of four calorimeters to obtain the rate of heat transfer of an arc-heated air flow, not only as a function of axial position, but also as a function of magnetic field strength. Examples exist where the energy content of the emerging gas stream had been accounted for by using specially designed calorimeters[42]. The interest (as in this work) was in measuring the efficiency of electrothermal conversion. This was evaluated as :

$$\eta = \frac{\text{calorimeter power}}{\text{arc input power}} \qquad 5.1.1.$$

showing that the calorimeter was used to dissipate all the thermal energy in the gas.

Methods of measuring the efficiency without the use of a calorimeter depend upon evaluating the electrode losses[3]. It is therefore assumed that most of the losses inside the plasma torch are dissipated at the electrodes, an assumption that, in the case of the Aston Torch, is not justified unless investigated and proved.

5.2. Important Calorimetric Characteristics

A calorimeter, that is to be used in conditions applicable to the Aston Torch must have the following special characteristics :

1 - The positioning of the calorimeter should not result in any electrical contact with either electrode. As the calorimeter is rested on the outer electrode (which is the case for the Aston design), it should be electrically insulated. Failure to do this could result in arcing between the central electrode and the calorimeter. This subsequently changes the operating conditions, and eventually results in puncturing the calorimeter.

1 - The calorimeter air-channel should be as near the arc as possible in order to minimise the heat losses during the time taken for the emergent gas to reach the channel.

3 - Most of the gas energy is required to be transferred to the calorimeter coolant. This helps in reducing possible inaccuracy in the temperature measurements at the outlet of the calorimeter. The most desirable condition would be to have the outlet gas at nearly room temperature. For this case, efficiency = $\frac{\text{calorimeter power}}{\text{input power}}$.

4 - The inside surface area, exposed to the gas flow should be large enough to permit adequate quantities of heat to be transferred from the hot gas to the coolant.

5 - As heat transfer is proportional to the temperature difference between the hot gas and the coolant, the water flow rate should be made as high as possible. This will also limit the temperature rise of the water, thus reducing heat losses to the surroundings.

6 - The outside surface area of the calorimeter should not be made too large, since the minimisation of the area exposed to the surroundings will reduce heat losses. Also, the outside surface should preferably be lagged and shielded.

7 - The gas flow through the calorimeter channel must be restricted to allow for adequate contact between the hot gas and the cold surface.

8 - Direct radiation from the arc must be prevented from affecting any temperature measuring instrument at the exit of the calorimeter as this may give rise to false readings. Radiation baffles can be used in this case.

The calorimeter used, had been designed to take into account the above requirements. However, due to the interdependent nature of these requirements, a compromise in design had to be made. The calorimeter, shown in Fig. 5.3., was of the self jacketed type with the water entering on the outside, and therefore surrounding and

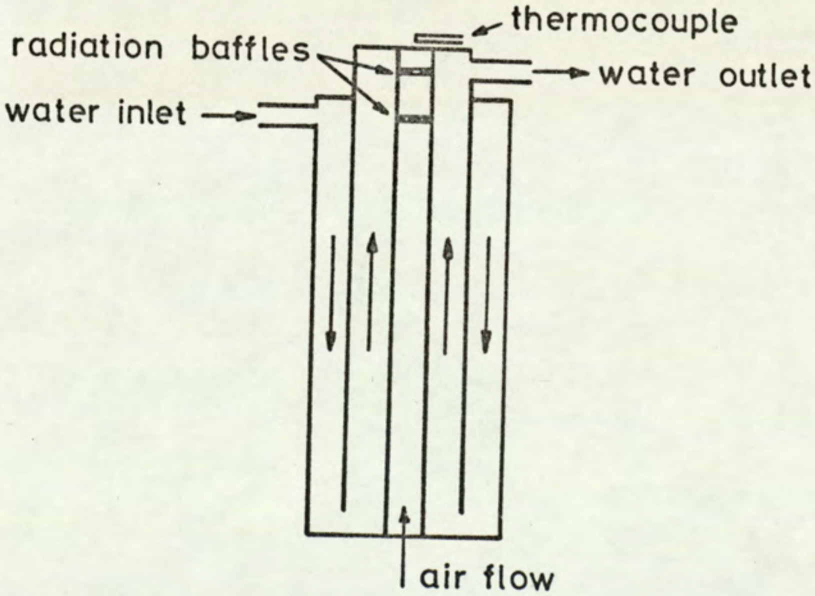


FIGURE 5.3. The Calorimeter

shielding the water flow next to the hot air channel. With this flow arrangement, the calorimeter was, in effect, a heat exchanger. A heat exchanger can operate on either parallel flow or counter flow (Fig. 5.4.). A counter flow heat exchanger is known to be more

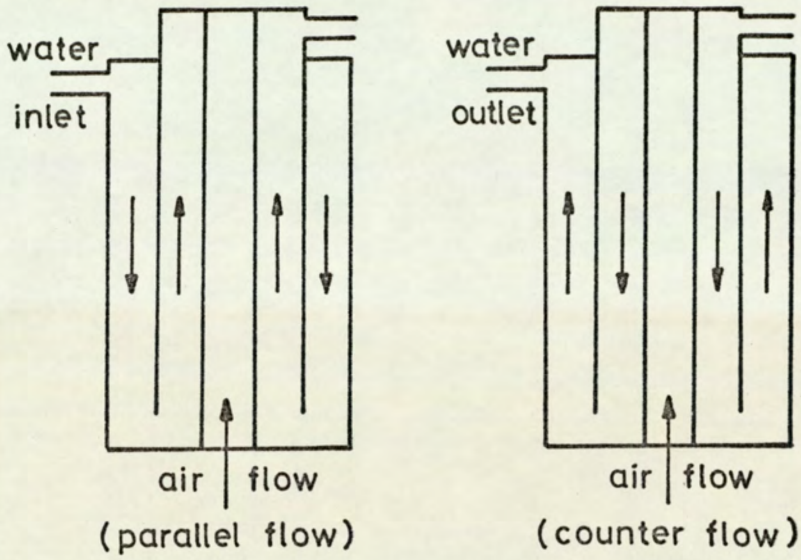


FIGURE 5.4. Possible directions of water flow.

efficient (for a given length) than its parallel flow counterpart[43]. For counter flow operation, the water inlet should be on the inside. This also produces a condition of higher temperature gradient that could result in better heat exchange. Final preference was, however, given to the parallel flow arrangement since, with the water entering on the outside, the outside surface of the calorimeter will be very nearly at room temperature; therefore, heat losses from this surface to the surroundings by convection and radiation are minimised. In addition, the advantages of having higher temperature gradient with counter flow was not as significant as it originally appeared, since the maximum temperature rise of water above room temperature was only about 10^{o}C. This temperature difference, is clearly negligible (as far as the gas-water temperature gradient is concerned) when considering that the gas temperature could be a few thousand degrees.

A thermocouple was used for measuring the air temperature at the exit of the calorimeter. Radiation baffles were not used since the thermocouple was of the self-shielded type. Restriction of the flow was controlled by varying the diameter of the exit of the calorimeter. The restriction effect should be just adequate since, over-restriction of the flow increases the gas pressure and a back-pressure could develop that affects operation conditions. Also, the back-pressure, could force the arc downwards,

FIGURE 5.5. Insulation failure to back pressure
(a) before, (b) after.

a case that results in burning some of the electrical insulations inside the torch. Fig. 5.5. illustrates the effect of excessive flow restriction on bakelite insulations.

5.3. The Need for Using a Calorimeter in an Energy Balance

Due to the limitations imposed on the temperature measuring techniques discussed in Section 4.4.2., it was suggested to use a calorimeter to account for the heat in the gas and also to help in reducing the temperature of the air at its exit to a value that can be, more accurately, measured by temperature measuring instruments. This section, therefore, investigates the validity of such a claim by performing an electro-thermal energy balance with and without the use of a calorimeter. Another point of interest will be to observe the accuracy of the energy balance when using the electronic multiplier system (Fig. 3.14.) that had been recommended in Chapter 3.

The exterior view of the plasma torch is shown in Fig.5.6. It can be seen that the magnetic field coil fully surrounds the electrodes. The actual position of the nozzle is about the middle of the coil. It is clear that the exhaust system has to be changed, depending on which method is used for the energy balance.

When the energy balance was to be made by measuring the temperature of the plasma jet, an asbestos chimney was used to direct the gas flow round an inserted thermocouple as shown in Fig. 5.7. The thermocouple used was of the self-jacketed type to reduce the effects of direct radiation pick-up from the arc. Although the thermocouple should ideally be as near the plasma jet as possible, it was not possible to do this due to mechanical difficulties. Possible errors due to this arrangement were thought to have been small, since the jet is pushed vertically upwards by the air flow and thus nearly reaches the thermocouple.

The calorimeter system for heat energy assessment is shown in Fig. 5.8. The air discharges to atmospher via the air channel of the calorimeter. Inlet and outlet water temperatures were recorded by resistance thermometers and the outlet air temperature measured by the same thermocouple already described.

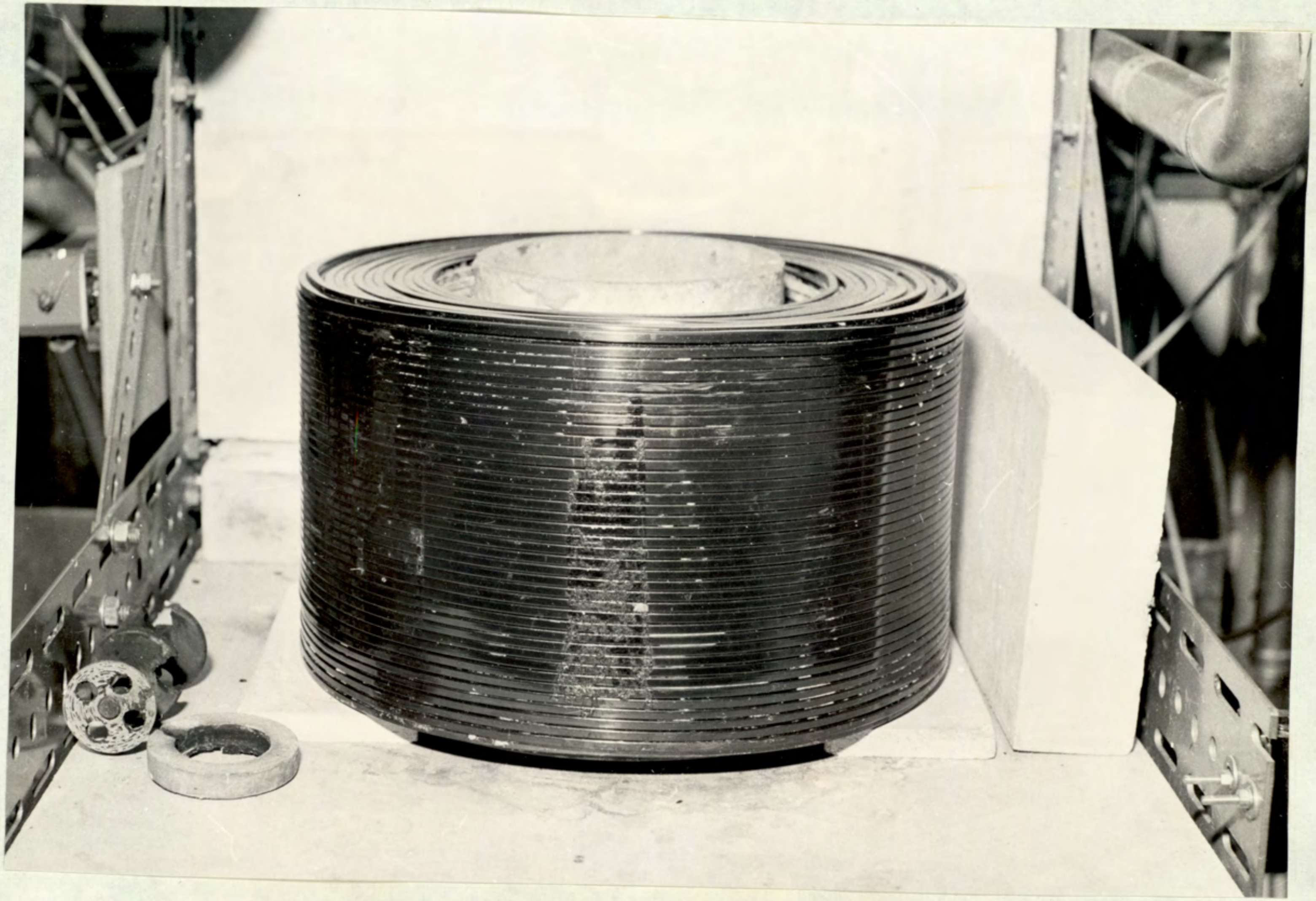


FIGURE 5.6. The exterior view of the plasma torch

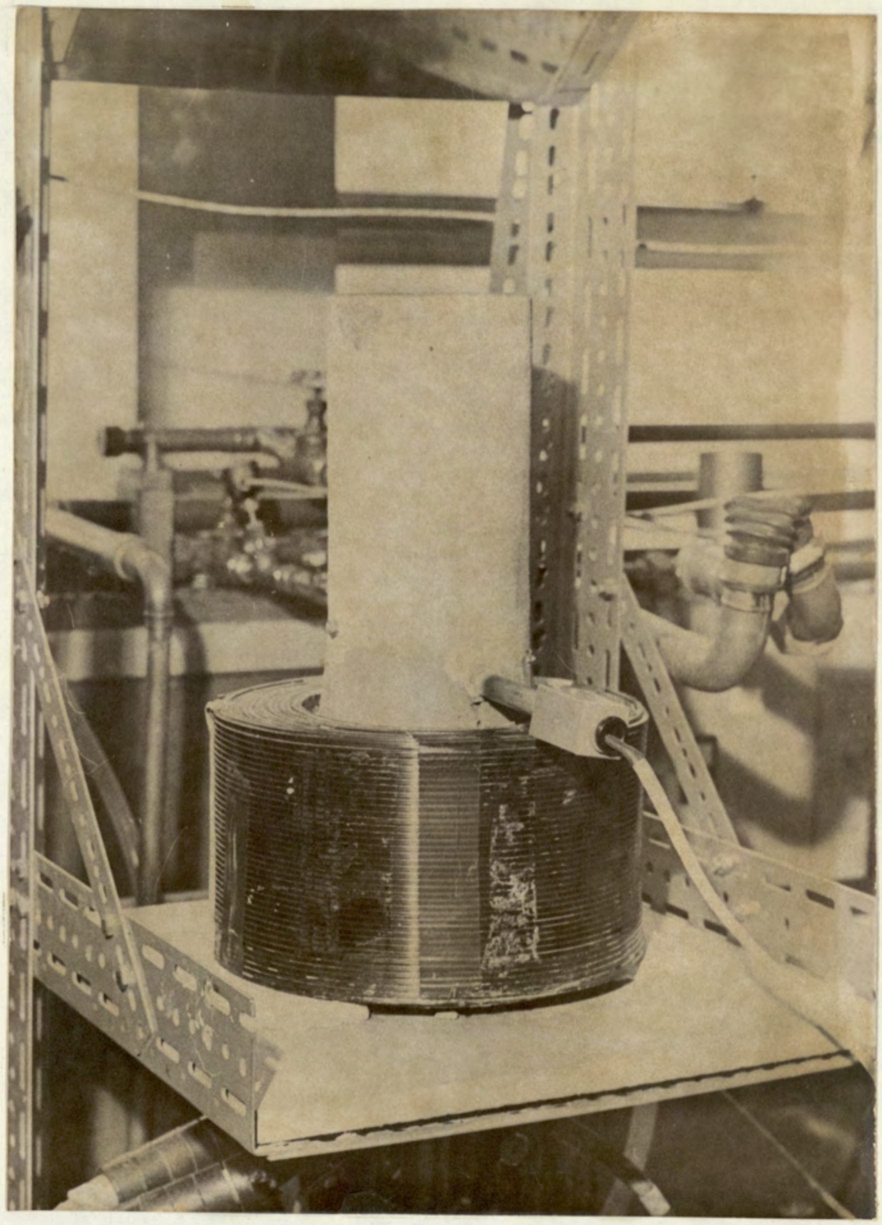


FIGURE 5.7. The plasma torch, chimney and thermocouple

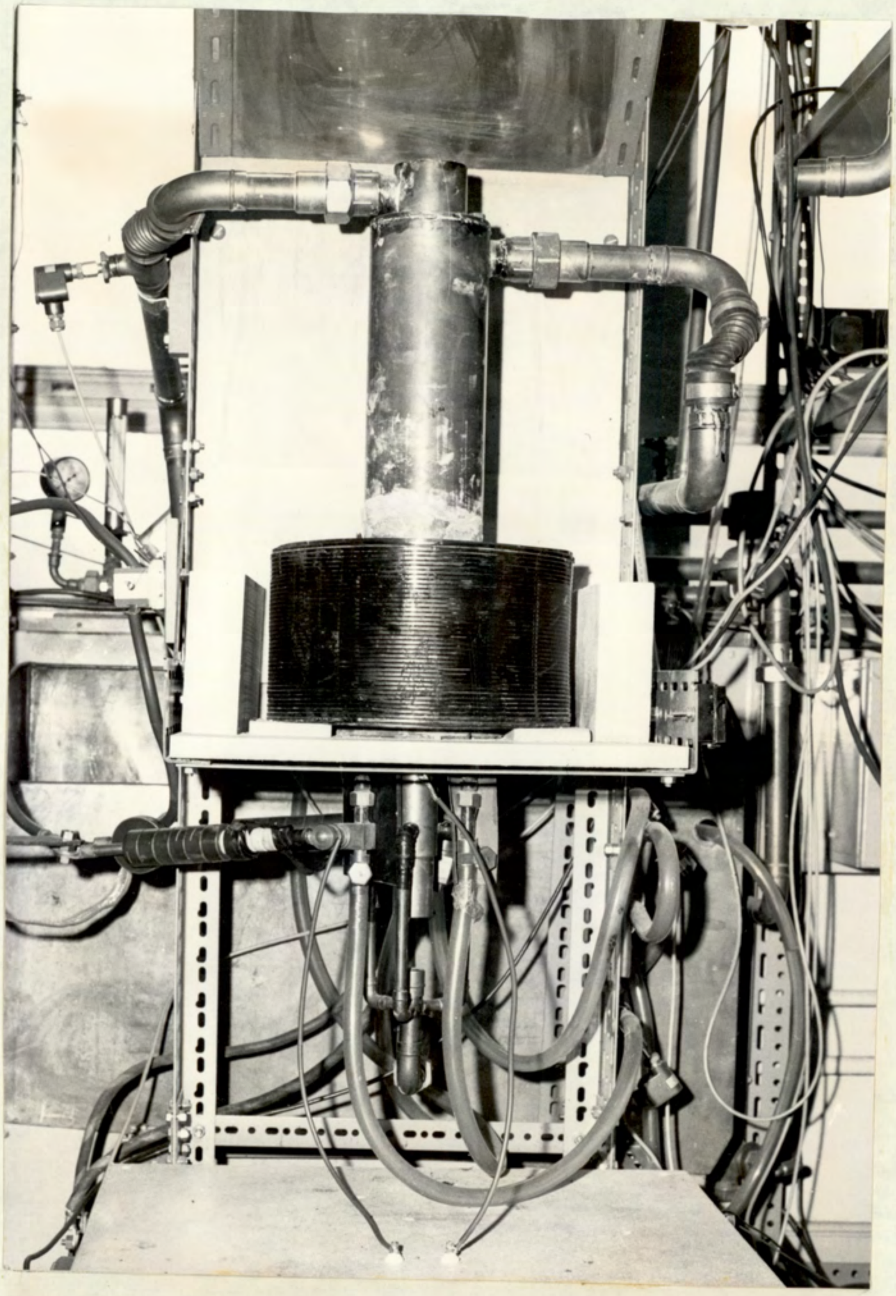


FIGURE 5.8. The plasma torch with calorimeter in position

The results obtained by the two methods are shown in Fig. 5.9. and Fig. 5.10. respectively. It can be seen that, with no calorimeter, no proper balance was achieved. The deficit in the balance showed that an average of 10 kW were unaccounted for. In contrast, the energy balance using a calorimeter was very accurate. The maximum error in the balance was 5.5%. Errors as low as 1.25% were also obtained.

The positioning of the thermocouple in the first method could have resulted in recording lower temperatures than the actual plasma jet temperature. This differs from what was thought previously. The calorimeter served to minimise the heat losses to the surroundings.

The accuracy of the energy balance in the second case indicated the advantage of using a multiplier for input power assessment.

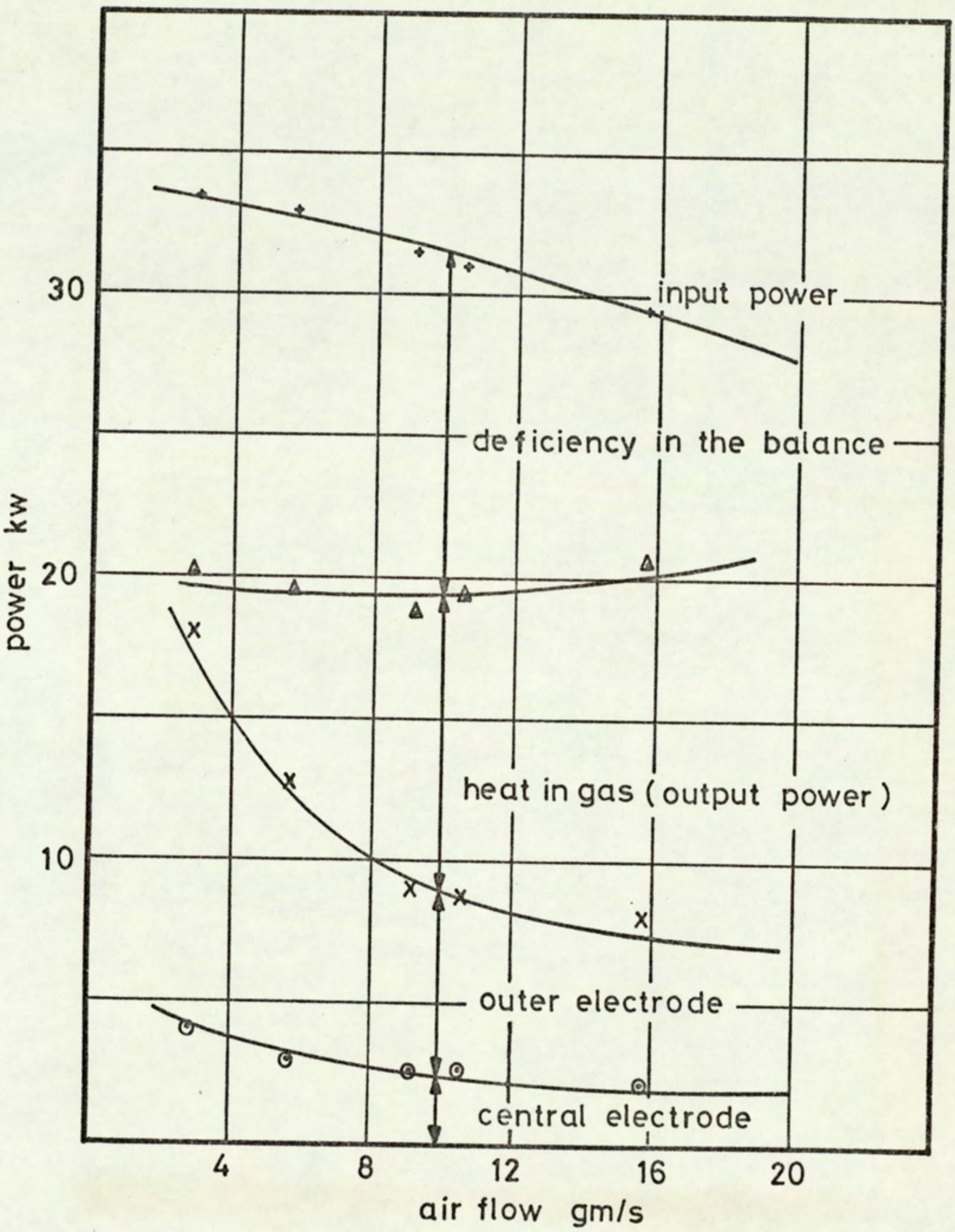


FIGURE 5·9. Energy balance without a calorimeter

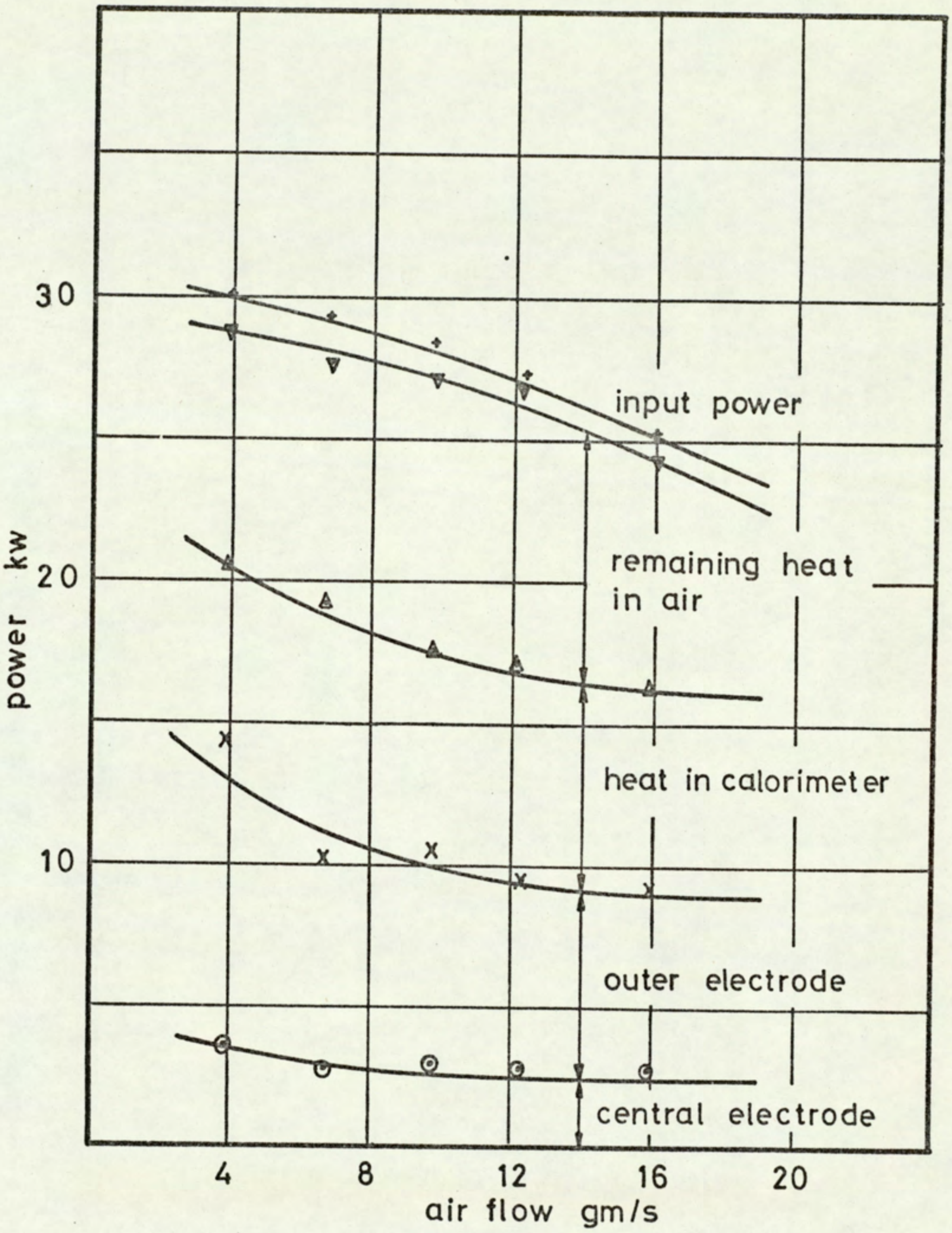


FIGURE 5·10. Energy balance with the calorimeter

CHAPTER 6.

THE OVERALL ENERGY BALANCE.

An electro-thermal energy balance, has already been achieved in the preceding chapter. It indicated that it was possible to obtain a good degree of accuracy if the electrical input to the torch was measured by an electronic multiplier and the thermal energy accounted for by a calorimeter. In this chapter, it is intended to follow up this by an overall energy balance. A critical study of the efficiency, temperature, enthalpy and electrical characteristics of the torch is also made.

6.1. Factors Affecting an Energy Balance Test

Computation of an energy balance test is an extensive and time-consuming operation. For a complete test, the following quantities will have to be measured.

1 -	Total input power.	(KW)
2 -	Input power to field coil.	(KW)
3 -	Input power to ignition system.	(KW)
4 -	Main arc current.	(A)
5 -	Magnetic field.	(Wb/m^2)
6 -	Room temperature.	(^oC)
7 -	Electrodes and calorimeter cooling water temperatures.	(^oC)
8 -	Outlet, air temperature.	(^oC)
9 -	Electrodes and calorimeter water flow rates.	(gm/s)
10 -	Air flow rate.	(gm/s)

Each test (one particular flow rate), takes about 30 minutes to complete. Most of the actual measurements are made during the final stages when the whole system has reached steady conditions.

At present the torch cannot be operated longer than 30 minutes at a time due to possible heating damage to the field coil. This was the main time-consuming part of the system, since up to 6 hours of cooling time had to be allowed before another test could be made. In effect, this permitted an average of not more than two daily tests.

A further source of delay is the possibility of electrode failure. In this case, the main torch assembly has to be stripped down and new electrodes substituted, an operation that could last a few days.

For a detailed energy balance, tests must be made for a range of air flow rates. In addition, each set should be made for different magnetic fields and series resistances. Measurements for the complete energy balance could, therefore, extend over several weeks, during which period special attention must be made to ensure that the desired operating conditions remain unaltered.

6. 2. Electrical Characteristics

In its original design, the plasma torch performed as a semi-constant current device. By this, it is meant that the current does not vary appreciably throughout the air flow range. As the air flow increases, the arc column gets elongated, and the arc voltage rises. Therefore, since the current remains nearly constant, the overall effect of this is to increase the power input to the torch.

Several external factors combine to affect the electrical characgeristics of the plasma torch. These include electrode geometry, external circuit parameters, exhaust system and the re-ignition unit. Very little, if any, modifications were made to all but the last factor. The performance of the ignition system was examined and slightly modified, by a co-worker[44], to make it consume less power. In particular, the breakdown voltage across the gap was reduced and the current intake of the system limited. As a result, the main arc current was no longer semi-constant with air flow.

Typical, current, voltage, power and equivalent arc resistance characteristics for the present torch are shown in Fig. 6. 1. Throughout the air flow range, the variations of current and

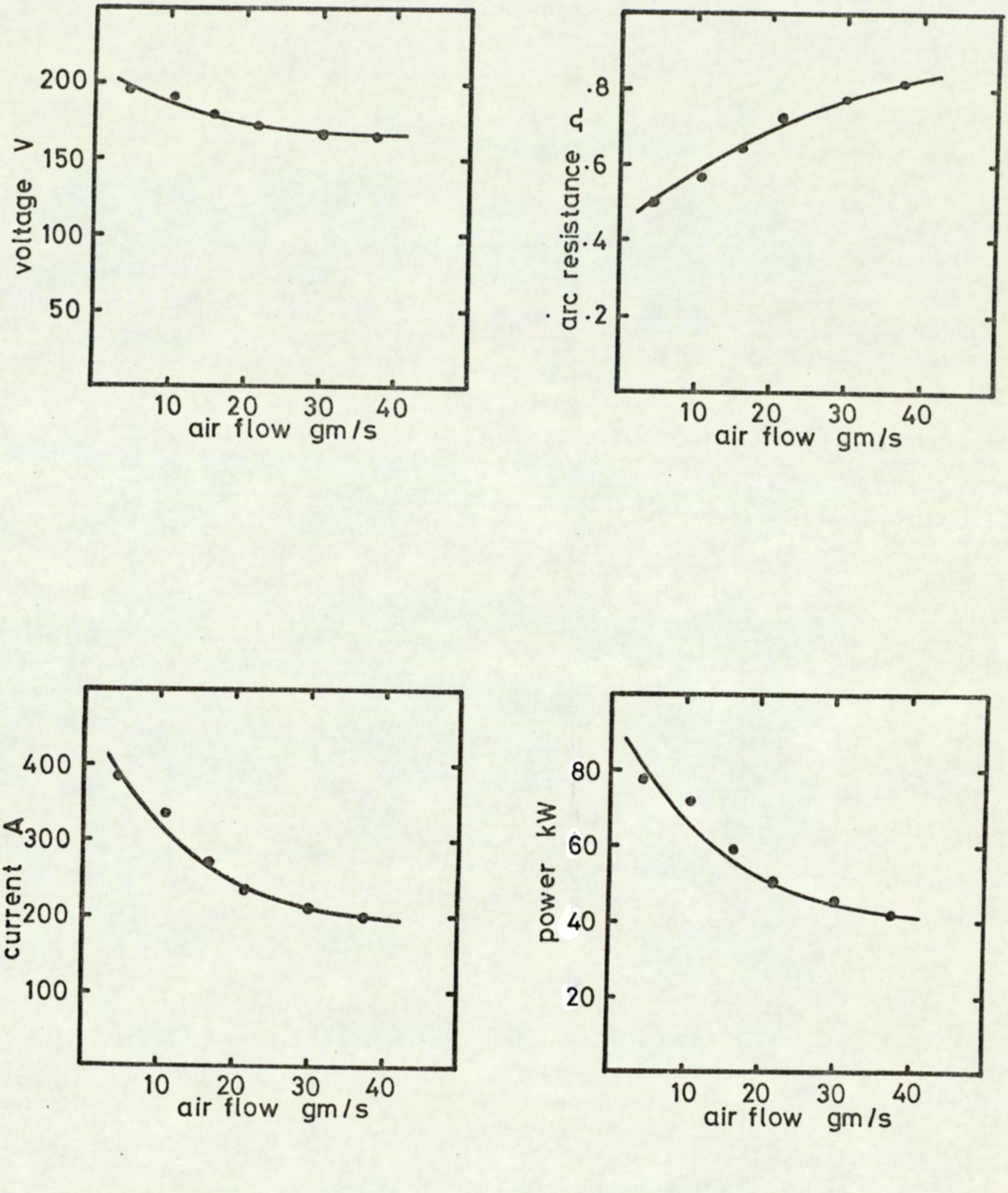


FIGURE 6·1· variation of electrical arc characteristics with air flow.

voltage, measured as percentages of their initial values, were :

current = 47%

voltage = 15%.

Of these two parameters, the voltage appears to be the least liable to large changes. Perhaps it is appropriate to describe the plasma torch with its present characteristics as a semi-constant voltage device.

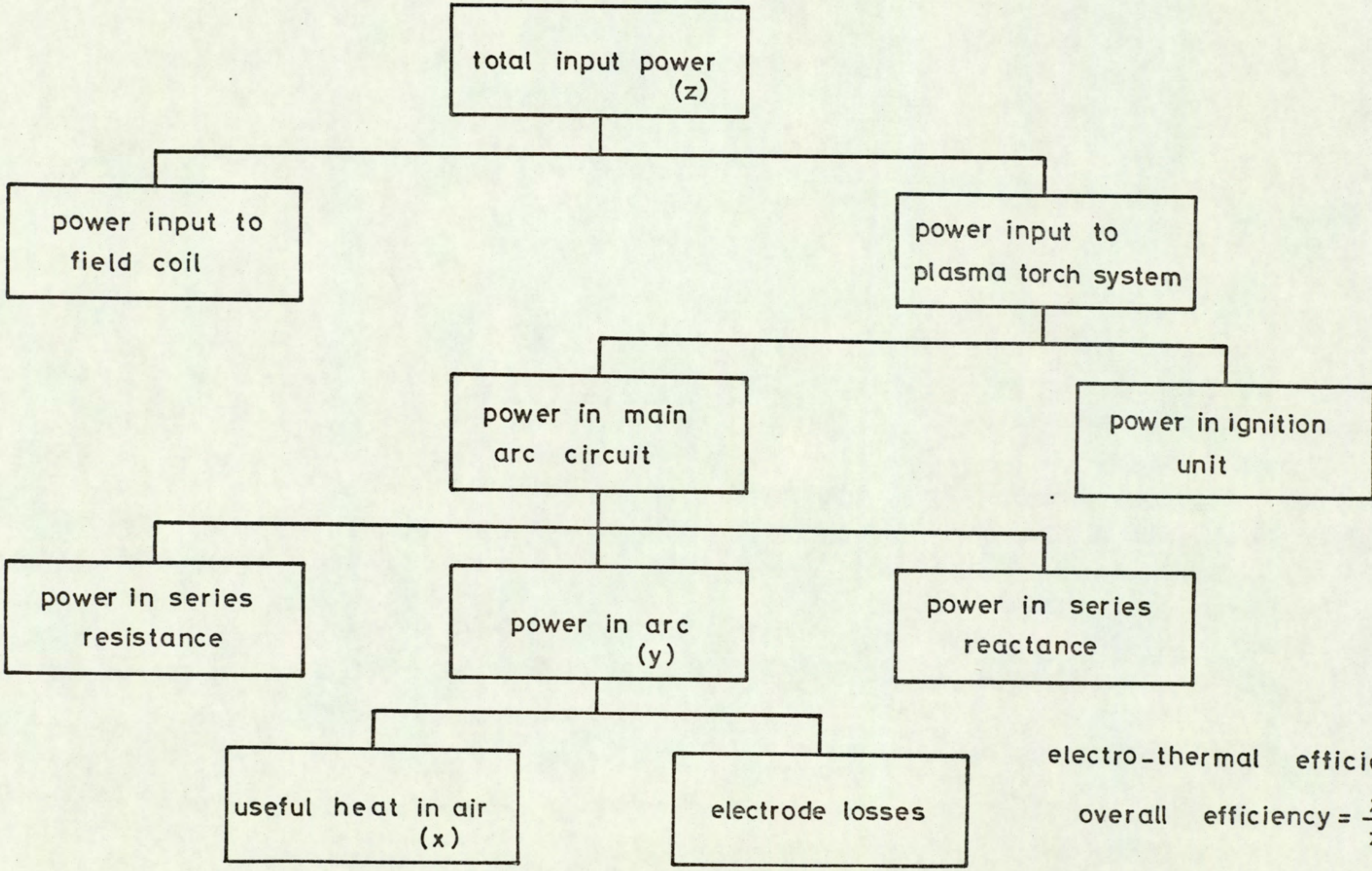
6.3. The Energy Balance

A general impression of the overall power distribution can be made by examining Fig. 6.2. The total input power was divided into two independent parts. The field coil was supplied separately in order to maintain the magnetic field as an independent variable. The second part supplied the rest of the plasma torch system. This included the ignition unit. The remainder of the flow diagram is self-explanatory.

The overall energy balance is shown in Fig. 6.3. Individual power quantities were added to each other to show how the balance was accounted for and to indicate its accuracy.

The ignition power and the reactance power (due to the small resistance of the inductance) were too small to be included on the diagram, and were included with the power in the series resistance.

The power in each part of the system can be seen to depend largely upon air-flow rate. Above about 30 gm/s, the characteristics are generally constant, and the plasma torch is therefore quite suitable for use at, and above, this flow rate. The main losses, expressed as percentages of the total input power, and for small and large flow rates, are indicated in Table 6.1.



electro-thermal efficiency $= \frac{x}{y}$

overall efficiency $= \frac{x}{z}$

FIGURE 6·2. overall power distribution

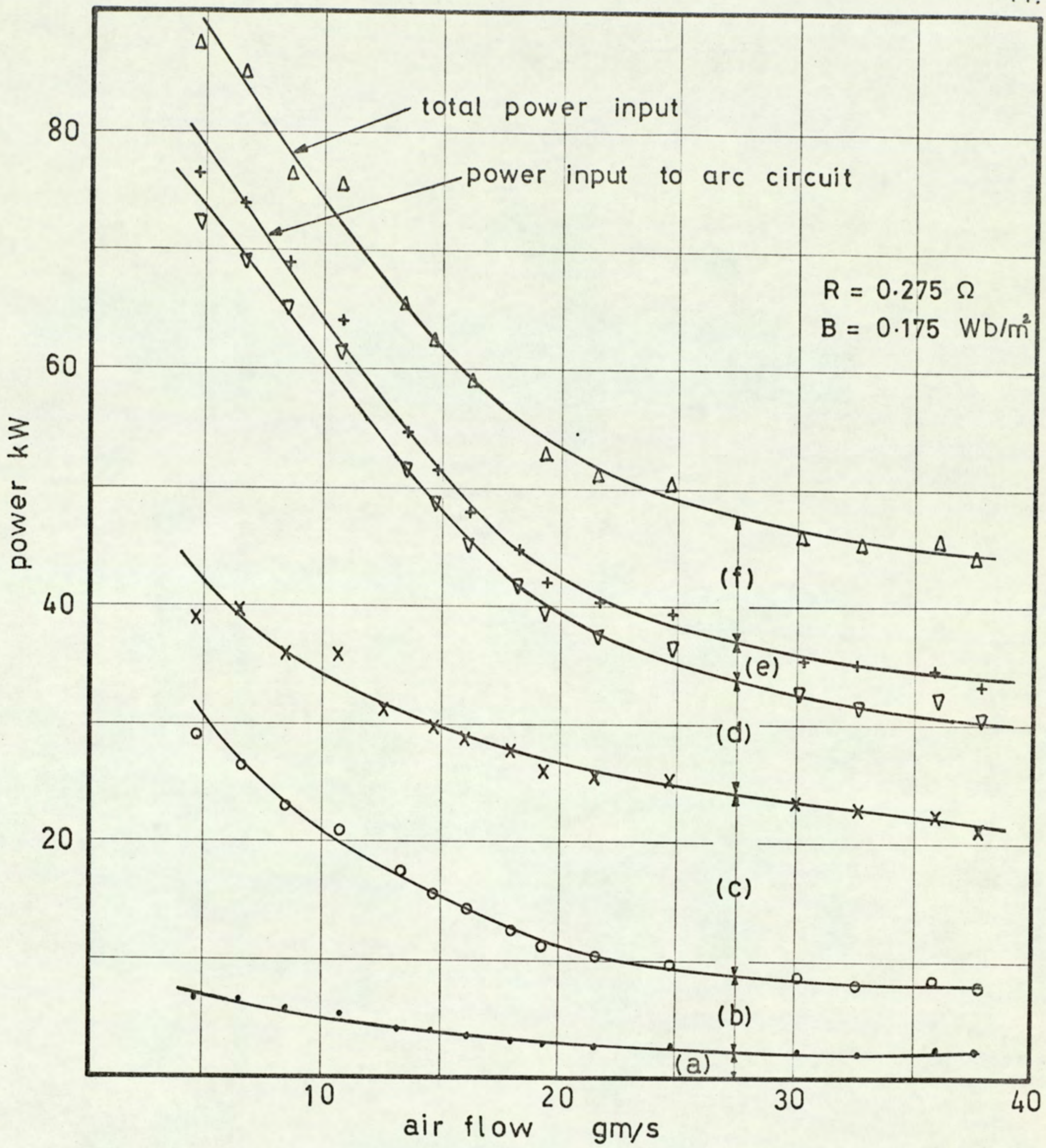


FIGURE 6·3. Overall energy balance

(a) Heat lost to central electrode

(b) Heat lost to outer electrode

(c) Useful heat in air

(d) I^2R and ignition losses

(e) Deficiency in balance

(f) Field coil power

Air flow	Field power loss	Resistive power loss	Electrode losses
5 gm/s	12.5%	37.7%	33.2%
30 gm/s	24.8%	20.3%	17.2%

TABLE 6.1.

As the efficiency of the torch is of prime importance in industrial applications, the low air-flow range will only be used if special applications are required, since the percentage losses are quite high. These special applications require high temperatures and specific enthalpies which might not be possible to achieve at higher flow rates.

With the present plasma torch being no longer a constant current device, the resistive losses vary excessively throughout the range due to the current variation. The excessive losses could be reduced by decreasing the value of the series resistance. This, however, could affect stability.

Since the power input to the field system was constant, its variation (as a percentage of total input power) was governed entirely by the power characteristics of the torch. If, on the other hand, the operation is that of a constant current nature, the input power will generally increase with increasing gas flow[45]. Thus, the field power share of total power will, in this case, decrease with increasing flow rates, thus making the overall efficiency higher.

Therefore, for a more consistent torch behaviour, it can be seen that a return to the constant-current operation mode is desirable.

The field power can be reduced if higher overall efficiency is required. This, however, could affect the stability and increase electrode erosion. In such cases, a compromise should be made when choosing the operating conditions.

6.4. Efficiency Analysis

Published results on the thermal efficiency of plasma torches were normally made relative to d.c. operation. Recently, however, a.c. operated devices have received increased attention, and some efficiency assessments are also available. For both type of operation the efficiency has been quoted as relative to the device itself, rather than the system as a whole, i.e. reference is usually made to the electro-thermal efficiency and not the overall efficiency. The thermal efficiency values range from 10 to 90%, depending on the design and operating conditions. Okada et al[3], obtained a maximum thermal efficiency of 75%, and attributed most of the heat losses to the electrodes. They also expected higher efficiency by further increase in the flow rate. This, however, can only mean a marginal increase, since their results showed a level below which no further reduction in the electrode losses occurred.

In analysing the plasma generator as a cutting tool, Kelly and Scott[39] obtained efficiencies higher than 75%. Jahn[38] reported a maximum efficiency of 81.6% . Efficiencies higher than 80% were easily obtained by using transpiration electrodes. Values as high as 90% were reported using this method[42].

In all these examples, reference was made to electro-thermal efficiencies for d.c. operated plasma torches that were only suitable for special applications. When plasma torches are used in industrial applications, the efficiency rating drops; this mainly due to the bulky design. 40 to 60% efficiency is the normal rating for a 1-MW d.c. torch[1].

For a.c. operation, efficiencies as low as 7-10% are common for 5 - 10 MW torches. Some three-phase torches, used in wind tunnels, have a reported efficiency of between 10 and 20%.

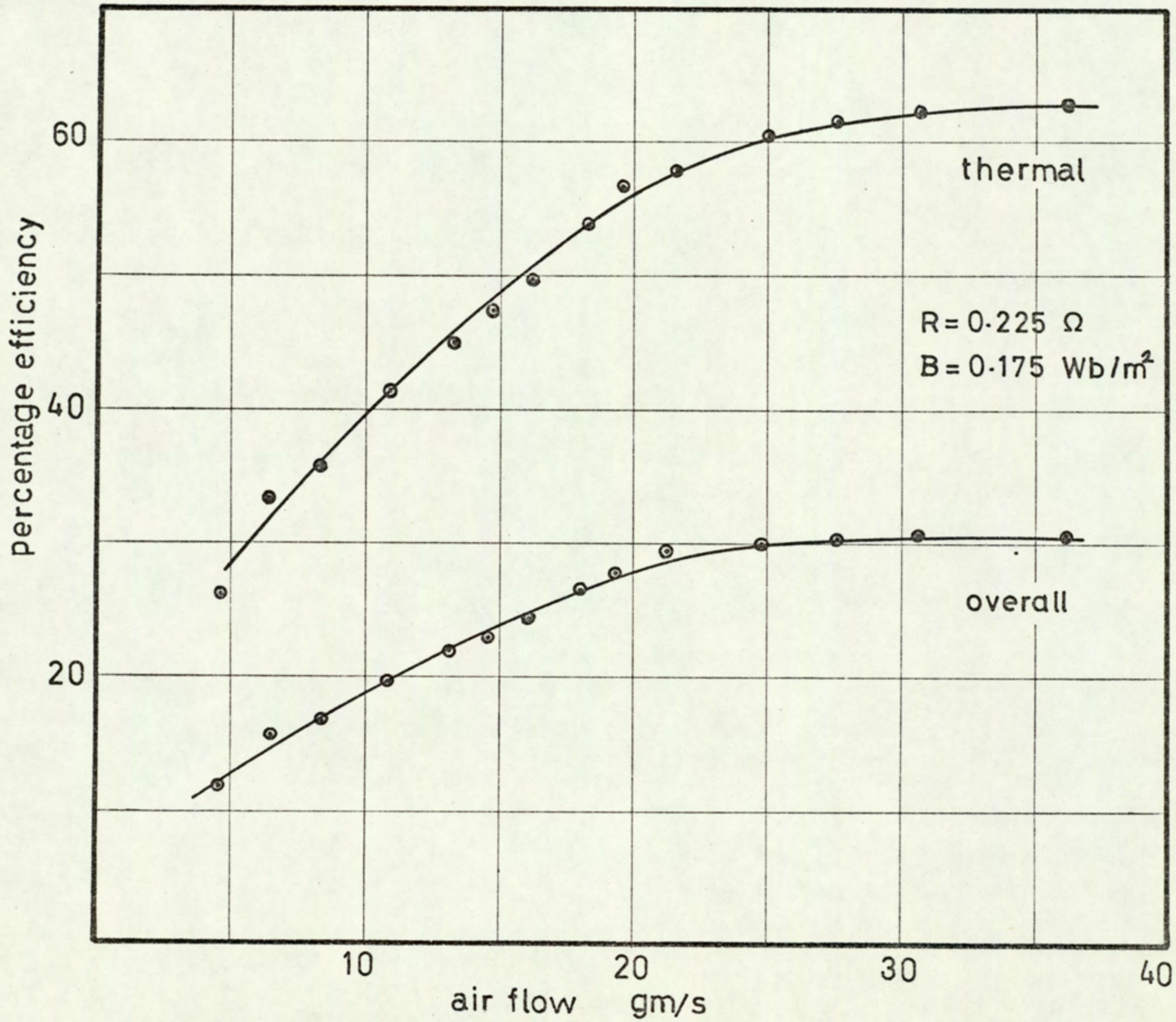


FIGURE 6·4. Variation of efficiency with air flow

Fig. 6.4. represent typical efficiency curves for the Aston Torch. It can be seen that the thermal efficiency figure could attain values that are higher than 60%. This, in itself, is very encouraging since it is quite comparable to some of the highest efficiencies obtained for industrial plasma torches. In addition, this is at least three times as efficient as some of the best values reported for a.c. operation. No overall-efficiency comparison with other a.c. plasma devices could be made at this stage since no current information on this is available. However, with the "Aston" values exceeding 30%, a favourable comparison could be made with the reported electro-thermal efficiencies of other a.c. torches.

The efficiency curves rise sharply with low values of air flow and then reach steady values, throughout which, constant-efficiency operations are possible for the rest of the flow range. The shape of these curves is largely dependent upon the variation of electrode losses. Fig. 6.5. shows the effect of adding the percentages of electrode losses and heat in gas. This accounts

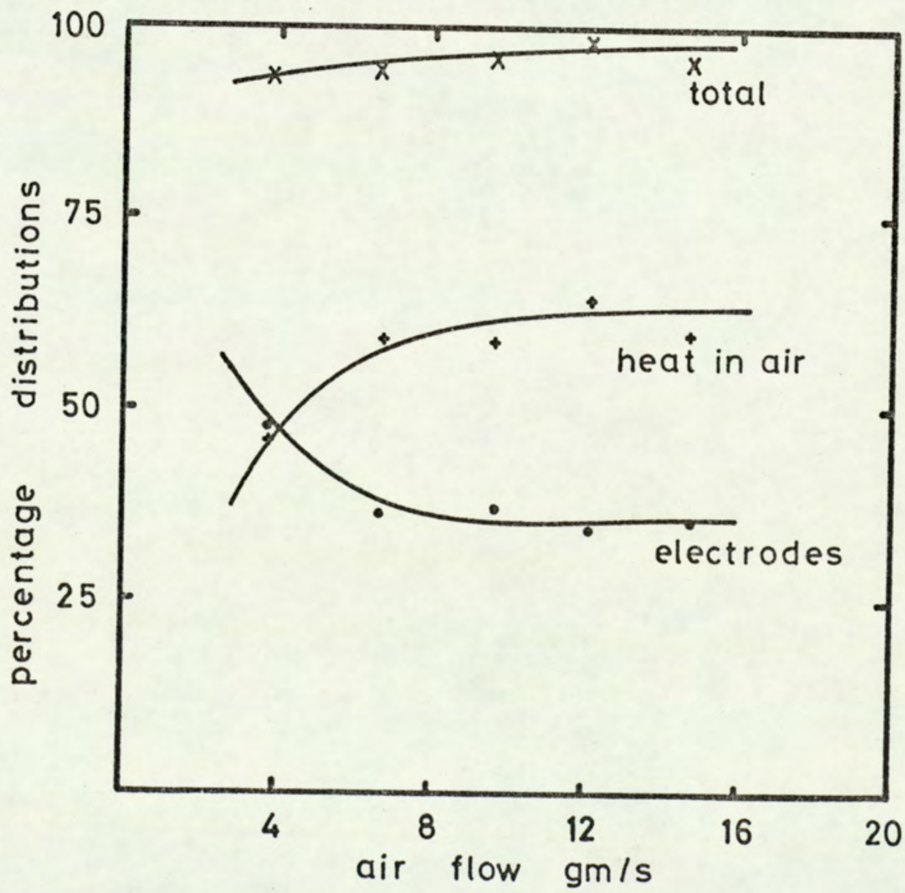


FIGURE 6.5.

to more than 95% of the input to the torch, and indicates that other losses within the torch are very small, and with improved design can be even neglected. Consequently, the electrode losses, heat in gas and electrical input are related such that, knowing any two parameters, the third may be calculated.

The effects of varying the series resistance and magnetic field on the thermal and overall efficiencies are shown in Figs. 6.6. and 6.7. respectively. At constant magnetic fields, the effect of decreasing the series resistance is to increase the efficiency initially, but reaches an ultimate level (lower than that with higher resistance) at the region where theefficiencies are semi-constant. The decrease in series resistance appears to be a good method of improving the efficiency if the torch is to be operated at low gas flow rates. This effect can be explained as follows :

As the series resistance is decreased, so will the voltage drop across it, thus a higher voltage across the arc gap is available. Since the fall voltages remain approximately constant, the effect of this is to increase tne arc column power which, in turn, increases the heat given to the air.

If the series resistance is kept constant, the effect of increasing the magnetic field is to lower the efficiency, with the new curves being parallel to the original. This is explained by the increased electrode losses at higher magnetic fields as a result of the increased rotation of the arc. In addition to this, the increased power taken by the field system results in lowering the overall efficiency.

6.5. Enthalpy and Temperature

One of the main motives behind the original development stages of plasma generators was the need to achieve re-entry simulation (of space vehicles) where high enthalpy conditions are met. A typical enthalpy range for a 1-MW torch (1 Atm.) used for such purposes[8] is 20-30 KJ/gm.

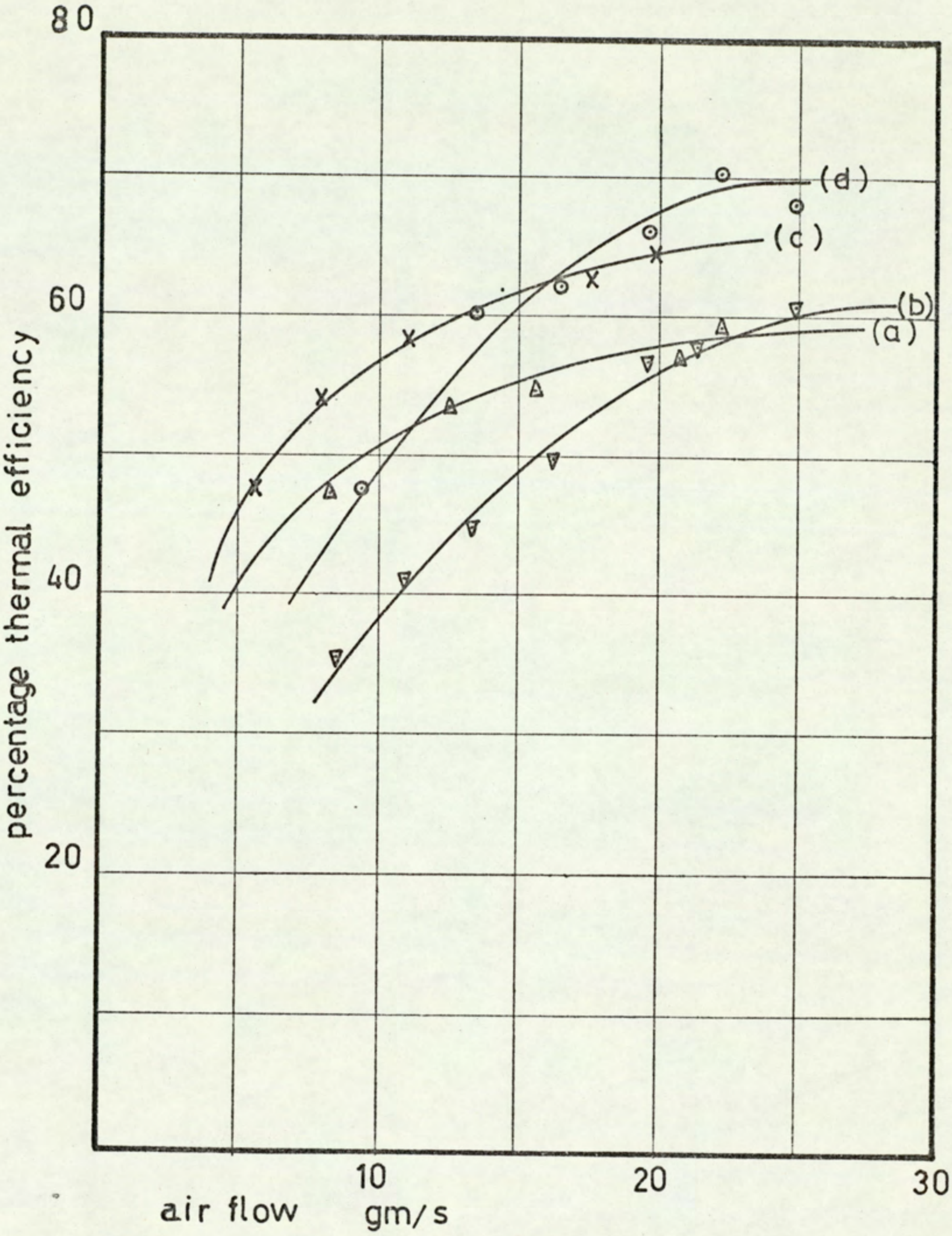


FIGURE 6.6. Variation of thermal efficiency with air flow

(a) R = 0·117 Ω B = 0·175 Wb/m^2

(b) R = 0·225 Ω B = 0·175 Wb/m^2

(c) R = 0·117 Ω B = 0·055 Wb/m^2

(d) R = 0·225 Ω B = 0·055 Wb/m^2

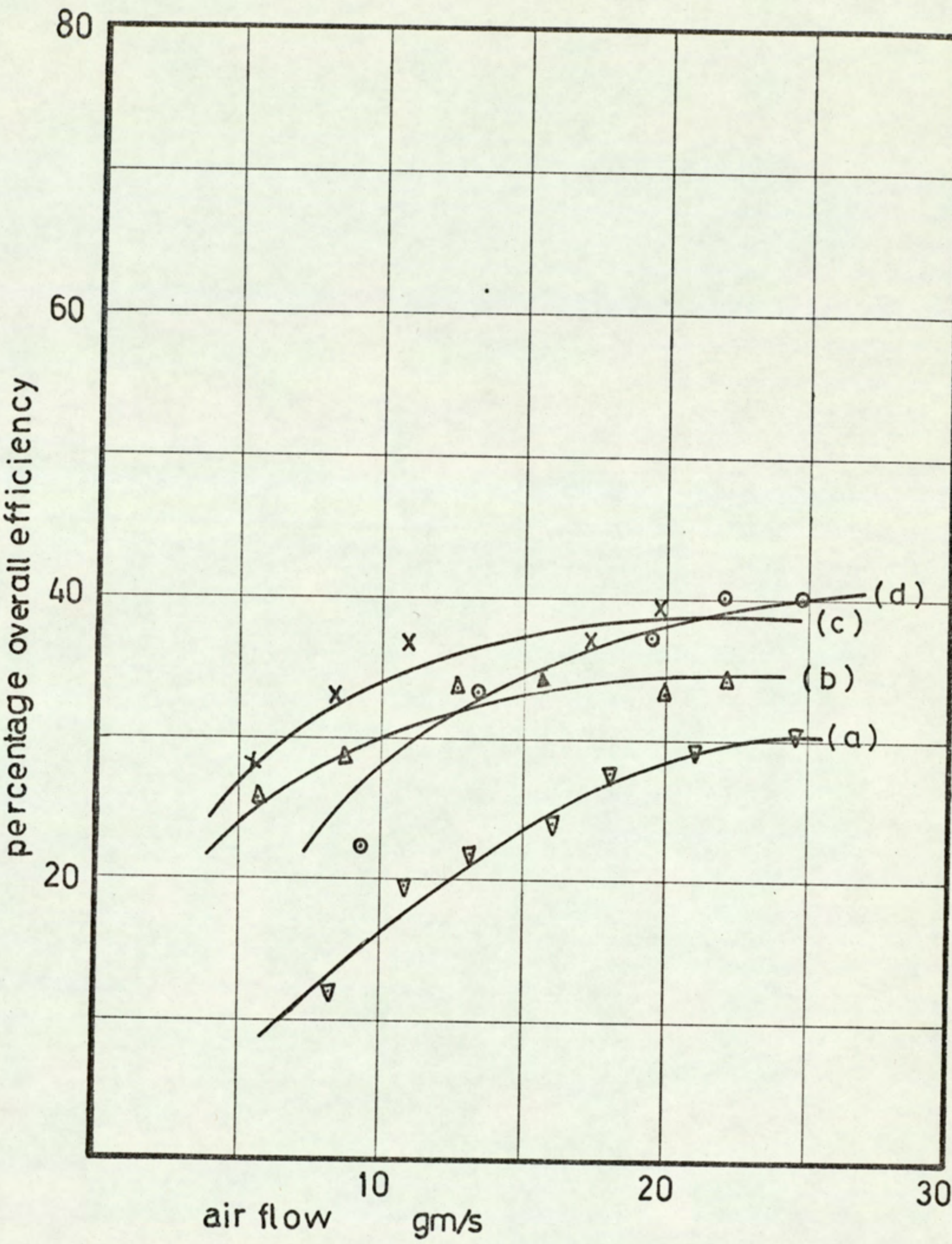


FIGURE 6·7. Variation of overall efficiency with air flow

(a) R = 0·225 Ω B = 0·175 Wb/m²

(b) R = 0·117 Ω B = 0·175 Wb/m²

(c) R = 0·117 Ω B = 0·055 Wb/m²

(d) R = 0·225 Ω B = 0·055 Wb/m²

Due to their high enthalpy capabilities, plasma generators are also competitive commercially as shown in Table 6.2., where a comparison is made between a number of possible heat sources[1].

Heat Source	Maximum Air Enthalpy KJ/gm
Open flames	3.08
Enclosed flames	3.08
Open arc, low intensity	2.36
Open arc, high intensity	18.9
Plasma jet, arc contained within device	78

TABLE 6.2.

It can clearly be seen that the plasma generator is capable of supplying much higher enthalpies than other possible heat sources. This table however, shows only maximum values and therefore should not be taken to indicate usual operating enthalpies. It must also be stated that a high-enthalpy plasma torch normally has operating times that are for below other sources.

A typical example is shown by the 1 MW plasma torch used by Raelson and Dickerman[41], where 16.7 KJ/gm was available at 70 gm/s of air flow. This plasma torch, however, had an operating time of 90 seconds, after which the cathode has to be replaced.

Values as low as 0.74 KJ/gm have been reported[30] for a transpiration-cooled anode, argon arc generator, at power inputs of 6.7 KW, and 7.95 gm/s of air flow.

It can therefore be seen that the enthalpy rating of plasma devices vary largely with the design, power input, gas-flow rate and type of gas.

When a.c. plasma torches are used, enthalpy values are inferior to their d.c. counterparts. The maximum reported[1] air enthalpy for an a.c. unit is about 8.3 KJ/gm, and is believed to be a reflection of the designs.

In Fig. 6.8., typical enthalpy-air flow characteristics for the Aston Torch are shown. From the shape of the curves, it can be deduced that values as high as 3 KJ/gm can be obtained if lower air flows are used. This, however, is accompanies by low efficiencies.

The a.c. plasma torches also suffer from producing only low temperatures (3,000°C)[1] at low efficiencies. The Aston Torch is not claimed to be an exception. Temperature variations with arc flow are shown in Fig. 6.9.

Improvement of the enthalpy and temperature ratings of the Aston Torch are not thought to be impossible if improvements in design are made, the width of the air gap and the shape of the outer electrode (which could dissipate 4-times as much power than the central electrode) being the main parts to be considered.

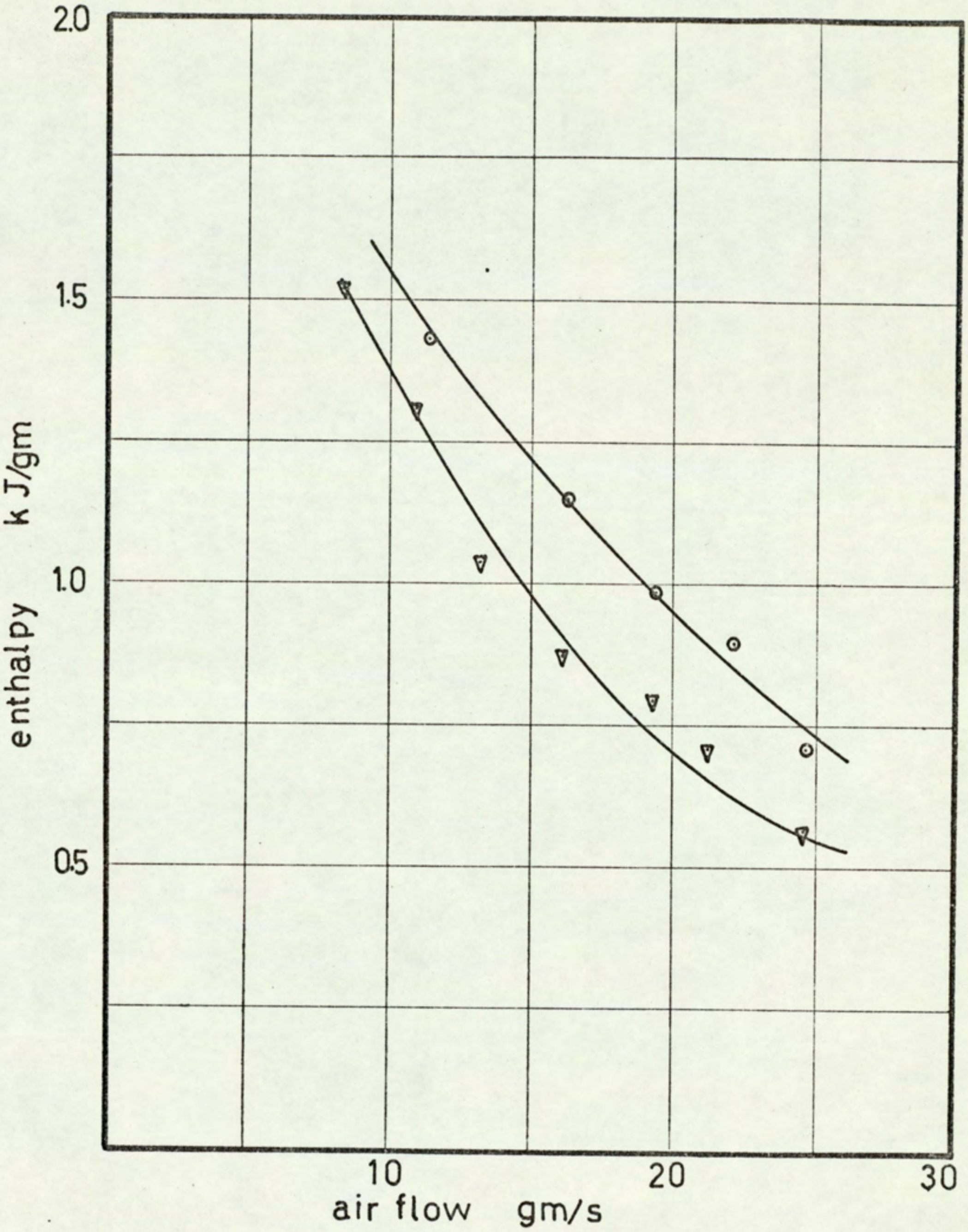


FIGURE 6.8. Variation of enthalpy with air flow

(▼) B = 0.175 Wb/m^2
(⊙) B = 0.055 Wb/m^2

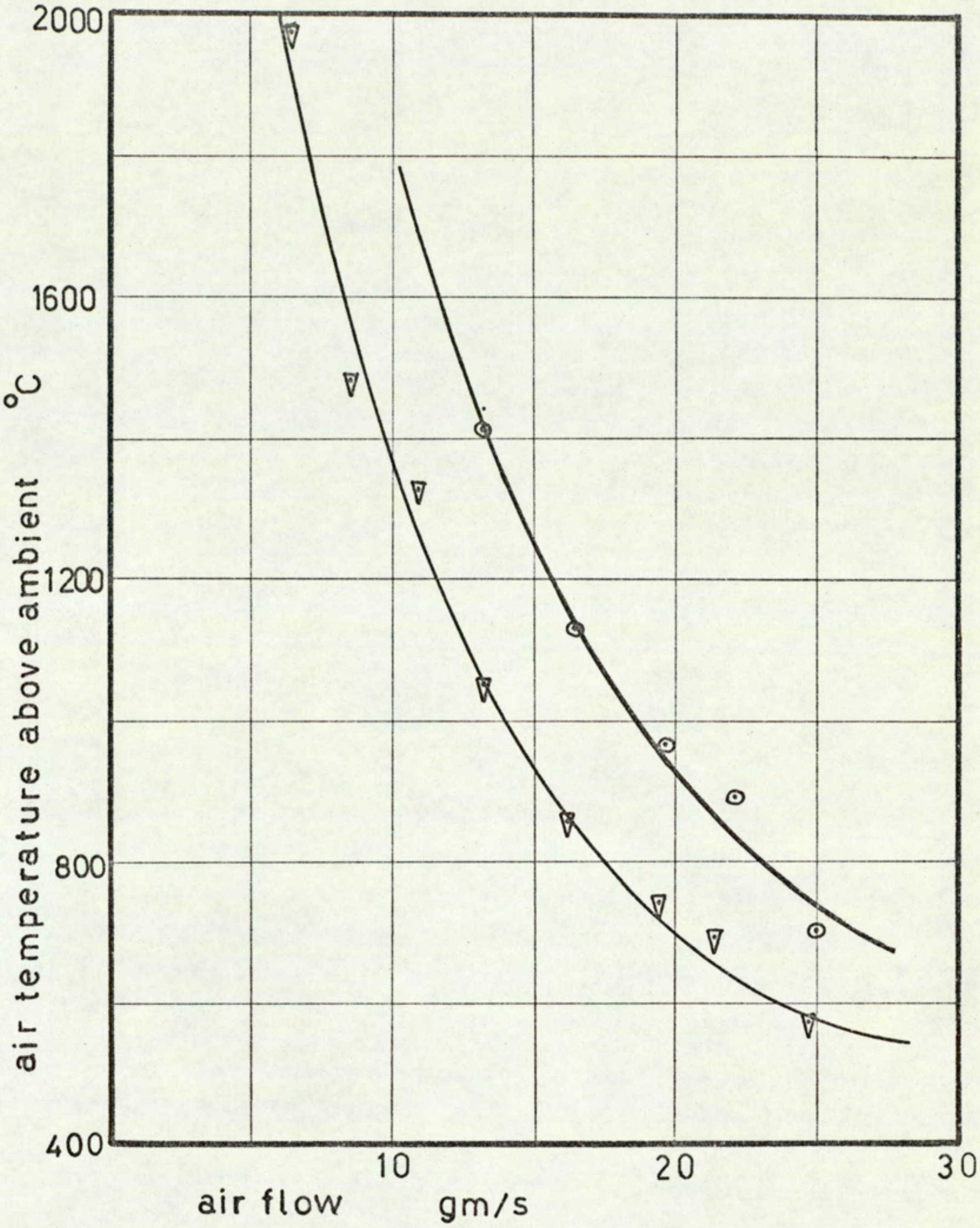


FIGURE 6·9. Variation of air temperature with air flow

(▽) B = 0·175 Wb/m²

(⊙) B = 0·055 Wb/m²

CHAPTER 7.

CONCLUSIONS.

An overall efficiency analysis has been achieved by an accurate energy balance. The whole process involved separate electrical and thermal investigations. Arc waveform studies showed that the fast transient regions (before and after arc extinction) contributed a negligible amount of power to the total wave-form power. When measuring techniques were investigated, the thermal wattmeter proved the most suitable instrument amongst conventional measuring devices. For improved results, an electronic system comprising a multiplier and an integrator is recommended.

The problem of assessing the heat content of the gas was examined by comparing non-calorimetric and calorimetric types of computation. The former was found to be far from satisfactory and a calorimeter was adopted for use in the energy balance.

The electro-thermal energy balance proved that over 95% of the power could be accounted for by adding the heat in the gas and the losses to the electrodes. Radiation and other losses within the torch were therefore shown to be small.

Efficiency analysis indicated the Aston Torch to be capable of converting over 60% of the power input to the arc into useful output. This not only indicated its advantage over other a.c. plasma torches but also made it comparable with d.c. torches. An overall efficiency in excess of 30% was also obtainable. This was well above the reported efficiencies for other a.c. torches.

Suggested improvements for future operation are as follows :

1. An improvement in electrical power assessment could be the use of digital techniques in adding and averaging the multiplier readings over the whole of the operating time.

2. Operating times should themselves not be limited (as at present) by overheating of the field coil. A new water-cooled design should precede further investigations into the characteristics

of the torch when used in semi-continuous operations.

3. A return to operating the torch as a constant current device is recommended; this might lead to modification of the ignition system.

4. The possibility of using a series a.c. field coil in the main arc circuit could have potential advantages in improving the overall efficiency.

5. The electro-thermal efficiency can be improved by modifications to the geometry of the outer electrode (e.g. transpiration cooling).

6. Finally, assessment of the suitability of the device for industrial use could be further investigated by using the torch in conjunction with a prototype furnace.

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