

HEAT TRANSFER FROM ELECTRICALLY-
AUGMENTED FLAMES TO METAL SURFACES

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Abstract

An electrically augmented burner has been developed from a previous design^(1) in order to test its application to metal melting. Rates of heat transfer have been obtained from the electrically augmented flame to the surface of a stainless steel slab over a range of surface temperatures from room temperature to 1400°C.

A heat flux meter was designed and constructed to determine stagnation point heat fluxes and radial distributions of heat flux at the slab surface. Electrical augmentation was found to increase the stagnation point heat flux by a factor of about 8 when the input of electrical energy was equal to the chemical energy in the flame. These heat fluxes have also been predicted from existing heat transfer correlations for partially dissociated gases. With augmentation experimentally determined values have been found to be 5 to 7 times greater than the predicted values. This discrepancy has been found to be due to non-uniform distribution of electrical energy in the flame.

The heat fluxes have been found to decrease as the surface temperature increases. Melting times have been predicted from the experimentally determined heat fluxes when the burner is installed in a steel melting furnace.

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Chapter 1

Introduction

Introduction

An electrically augmented flame is a combination of a combustion flame and an electric arc.

Many different types of electrically augmented burners have been designed⁽¹⁻³⁾ and rates of heat transfer have been determined from these flames to water-cooled surfaces. These results indicate that a large increase in the rate of heat transfer can be obtained by augmenting the combustion products with an electric discharge. Electrical augmentation can also be used to stabilize the flame. Therefore electrically augmented burners are most attractive for metallurgical processing because high temperature non-oxidising flames could be produced. Their application to flame hardening has already been studied and the present work sets out to investigate their use in melting steel. A burner has been developed for melting based on the design used for flame hardening. This burner employs an a.c. arc striking across a turbulent flame stabilized in a combustion chamber. Pre-mixed air and methane are fed to the combustion chamber and the hot products of combustion emerge at high velocity from a nozzle. Important features of this burner are that seeding the flame with readily ionized salts is unnecessary and refractory electrodes are used which eliminate the need for water-cooling. In the course of developing this burner some flame temperatures, the arc characteristics and power factors were determined.

For melting, it is necessary to determine rates of heat transfer between the combustion products and steel surfaces which are at temperatures up to the melting point of the steel. The water-cooled calorimeters used by other workers cannot provide this

information. It was therefore decided to design a heat flux meter which could be installed in a steel slab and which would be small enough to enable radial distributions of heat flux to be determined at the surface of the slab. This heat flux meter would have to withstand surface temperatures approaching the melting point of the steel.

By solving the unsteady state equation of heat conduction for the heat flux meter, values of heat flux can be determined as the surface temperature increases. The heat flux meter can be used to determine stagnation point heat fluxes and radial distributions of heat flux. These heat fluxes can be obtained over ranges of electrical power input, gas flow rate and stoichiometric factor.

Stagnation point heat fluxes can be predicted for partially dissociated gases impinging on solid surfaces using equations developed by various workers⁽⁴⁻⁸⁾. These equations have usually been applied to space vehicle re-entry problems. The major difference between applying these equations to augmented flames and to dissociated air is that dissociated hydrogen exists in the flames. This can be expected to enhance the heat flux because the hydrogen atom has a high mobility in the rest of the gas and can carry its recombination enthalpy to a surface.

The objectives of the research can be summarized as follows:

- 1 - To obtain heat fluxes from the flame to the surface of a steel slab at various surface temperatures, by experiment.
- 2 - To predict these heat fluxes at the stagnation point and to compare them with the experimentally determined values.
- 3 - To assess the application of the burner for melting steel.

Chapter 2

Previous Work

- 2-1. Electrically augmented burners.
- 2-2. Electrical discharges in gases.
- 2-3. Calculation of composition of flame product.
- 2-4. Free submerged jet impinging on a flat plate.
- 2-5. Heat transfer measurement from the flames.

2-1. Electrically augmented burners.

The idea of augmenting a combustion flame by an electrical discharge is not new. Almost 50 years ago, Southgate^(9) first passed burning gas through an arc discharge. However there was little immediate development because of the technical difficulties. The subject was taken up again in the early 1960s by Karlovitz^(2) in U. S. A. and Weinberg^(3) and co-workers in London. A brief review of the relevant work is given below.

A - Burner design

a - Burners of the Karlovitz type

Karlovitz^(2) showed that a high voltage, low current a.c. discharge could be passed through the flame and as a result a very high volumetric heating rate could be achieved, due to increases in both the specific enthalpy and the temperature of the gas mixture. He claimed to have produced a diffuse discharge throughout the hot combustion products which were highly turbulent and were apparently seeded with readily ionizable salt. A typical drawing of the burner is shown in figure 2-1.

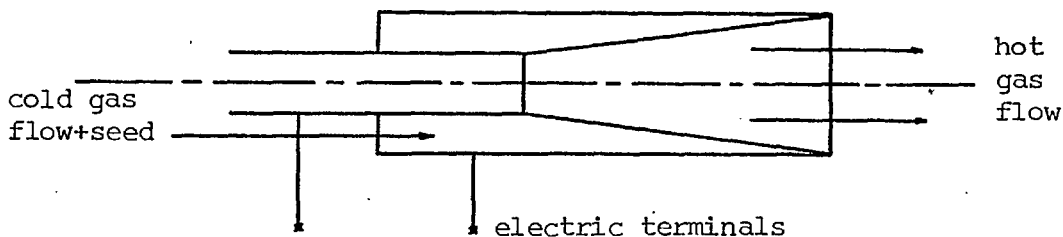


Figure 2-1.

The burner operated at 100 KW of electrical power and equal chemical power. A ballast resistance was used to limit the current as will be explained on page 21.

Karlovitz's idea was further demonstrated in a series of experiments which are described in references ⁽¹⁰⁾ and ⁽¹¹⁾.

The result showed that with 70 percent of the input energy provided by electrical augmentation the following occurred:

- 1 - The output specific enthalpy increased by about 50 percent.
- 2 - The overall heat transfer to a cold surface increased almost three fold.
- 3 - The flame temperature increased by 26 percent.

Marynowski, Karlovitz and Hirt⁽¹²⁾ then stated that the discharge produced by the burner above was not diffuse. A modified burner was developed in which the discharge zone occurred down stream of the combustion zone, and high speed photography showed that the discharge was diffuse.

Uhlherr and Walsh⁽¹³⁾ since stated that d.c. discharges in seeded flames can be diffuse if the current is low and the seed concentration is sufficiently high. At high currents the discharge contracts to an arc and seeding is then unnecessary.

Experiments with a similar type of burner were carried out by Davies⁽¹⁴⁾ who used a tunnel burner equipped with an axial electrode. He found that the exit gas was not heated uniformly by the a.c. discharge.

b - Burners of the Weinberg type

Weinberg's⁽³⁾ type of burner was based on a plasma-jet design and is illustrated in figure 2-2.

The combustion and the arc both occurred between the tip

of the cathode and the anode, and in this case the arc helps to stabilize the flame because combustion occurs in the same region as the arc. In order to minimize chemical attack on the cathode and to prevent ignition within the burner body, the cathode was shielded by a low flow rate of an inert gas. In another design the combustible mixture was intro-

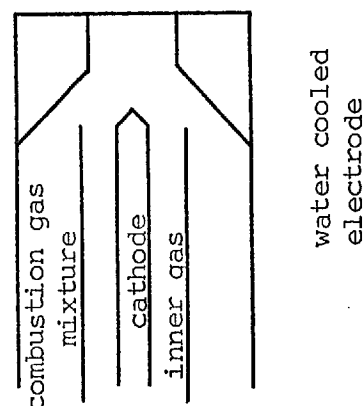


Fig. 2-2.

duced into the discharge from a ring of nozzles positioned horizontally above the burner to create a highly turbulent region just above the arc. A further design involved the use of a porous cavity burner⁽³⁾ to force reactants into extended contact with an arc channel. It is shown in figure 2-3.

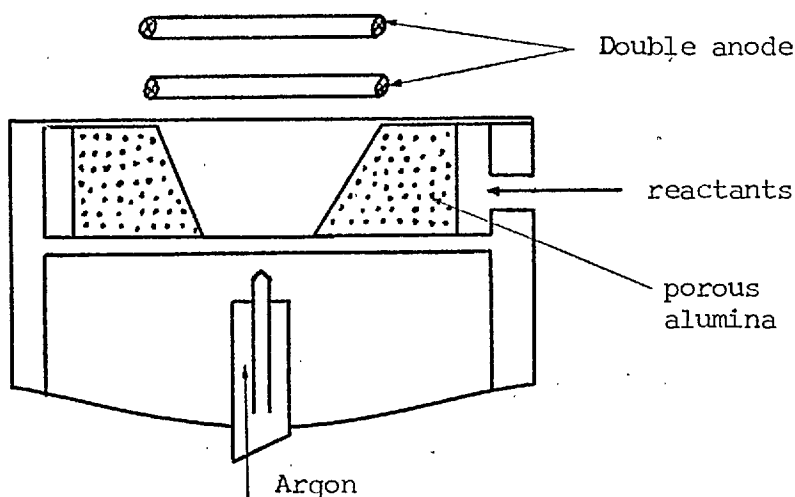


Figure 2-3.

The methods of spreading the discharge throughout the gas in order to heat the gas uniformly have been examined in a subsequent investigation⁽³⁾ and they are:

- 1 - Inducing turbulence in the gas stream.
- 2 - Seeding the gas stream with readily ionized salts.
- 3 - Moving the arc using a magnetic field.

4 - The use of a high frequency discharge.

Methods 1, 2 and 3 are all possible means of spreading the discharge and a combination of methods 2 and 3 have been recommended (3). Method 4 is not as successful in heating the gas uniformly over the cross section of the flame as appears to the eye. Whilst the central luminous region appears to extend over most of the flame, the peripheral annulus of cooler gas carries a disproportionately large fraction of the mass flow to by pass the plasma^(3). Johnston⁽¹⁵⁾ and Lawton showed that for seeded high frequency discharge the skin depth or width of the discharge increased as the frequency was reduced e.g. at 10 K HZ it should be possible to produce discharge 0.5 m in width. However the discharge must still be contained and it is likely that cool gas will by pass the discharge.

c - Fells and co-workers

Fells⁽¹⁶⁾ and co-workers developed a seeded propane-air burner augmented with a d.c. electrical discharge. The cathode was placed outside the burner at some distance from the anode. The authors found that the initiation voltage is a function of seed concentration but seeding has no significant effect on the voltage required to maintain the arc. The discharge seemed to be more diffuse in the d.c. system than when an a.c. discharge was used. Seeding was required constantly when a.c. power was used.

2-2. Electrical discharges in gases.

In this work of electrically augmented burners it is appropriate to give a brief account of electrical discharges in gases. The information has been obtained from standard texts and reviews (17, 18).

Figure 2-4 shows the voltage-current characteristics of three main types of self-sustained discharges.

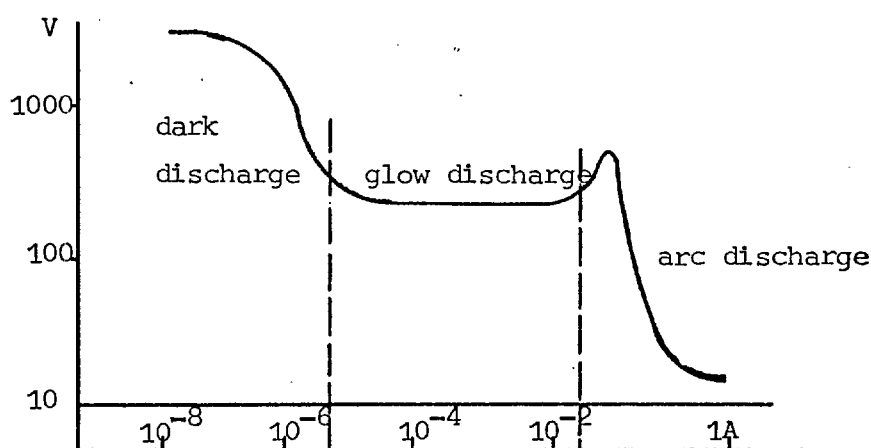


Figure 2-4.

The dark discharge and glow discharge are not relevant to electrically augmented flames mainly because they pass a very low current, and they are associated with reduced pressure. Arcs occur at atmospheric pressure and pass higher currents. They exist in the ambient gases or in the vapour of their own volatilized electrodes. They are applicable in this work and will be considered here in detail.

A - Arc discharge

Considerable discussion has taken place to define the arc, and a suitable definition of a fully developed arc may be given as (19) a steady state discharge having a positive column in thermal

equilibrium and a cathode fall of small voltage and high current density as shown in figure 2-5. The positive column is a luminous region of ionized gas which has zero net space charge, therefore it satisfied the definition of a plasma. At low pressure the gas temperature T_g in the positive column is equal to ambient temperature, whereas the electron temperature T_{e1} is high, and with increasing pressure T_g increases and T_{e1} decreases. This is shown in figure 2-6.

a - Arc characteristics:

(i) D.C. arc. Figure 2-7 shows the static characteristic of a D.C. arc. The precise relationship between V and I will depend upon the electrode materials, the electrode gap, the gaseous medium and the pressure of the gas.

(ii) A.C. arc. Oscillogram of A.C. arc current and voltage is shown in figure 2-8⁽²⁰⁾.

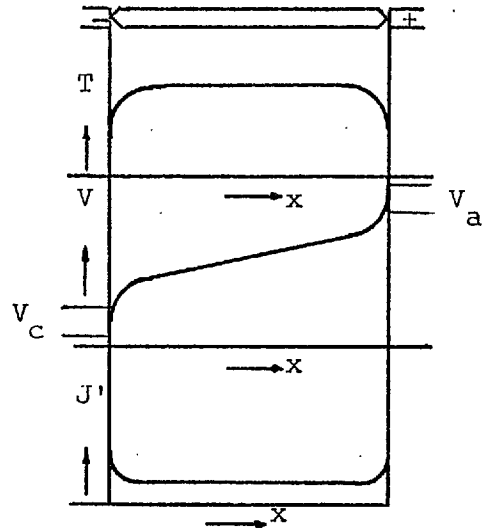


Figure 2-5.

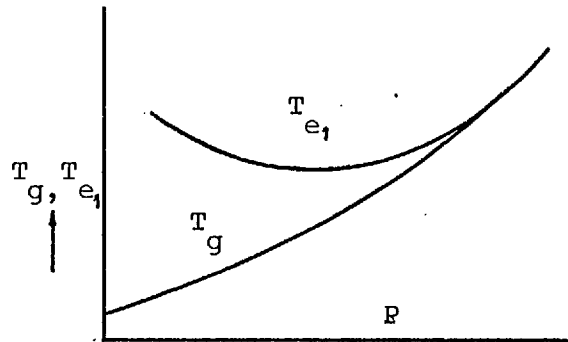


Figure 2-6.

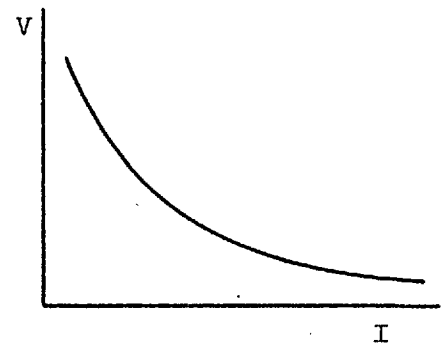


Figure 2-7.

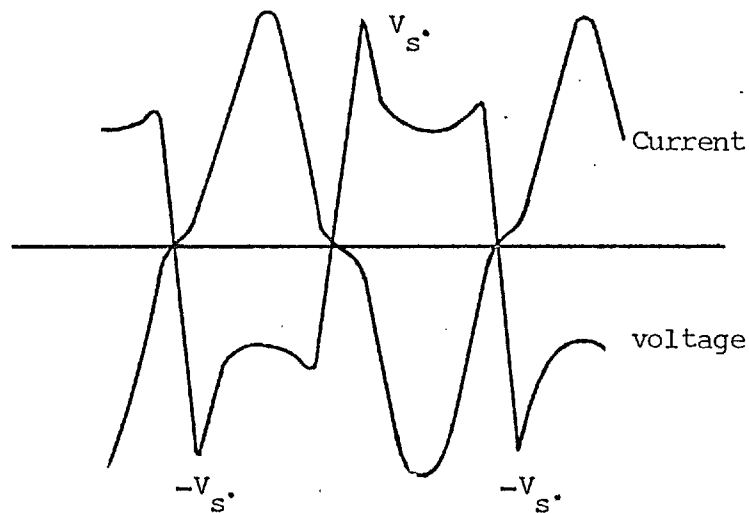


Figure 2-8.

The characteristic of the arc is clearly seen in the fall of voltage as current rises and vice versa. The arc goes out as the current passes through zero, and does not ignite again until the voltage reaches the initiation voltage V_s . This initiation voltage increases with:

- 1 - Increasing arc length.
- 2 - Increasing external resistance.
- 3 - Reduction in frequency.
- 4 - All temperature-reducing factors.

Because of the difference between the current and voltage curves an area is enclosed in the V-I plane as shown in figure 2-9. This area represents the power expended by the arc. Self induction increases the sinusoidal nature of the arc and makes the periods of extinction shorter.

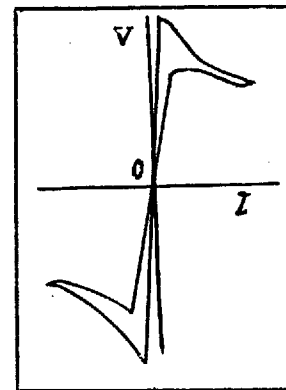


Figure 2-9.

The characteristic of a 60 cycle, 40 mm arc in hydrogen is shown in figure 2-10⁽²¹⁾. The current is limited to 6.4 amps. R.M.S. The same process will occur with V and I both negative.

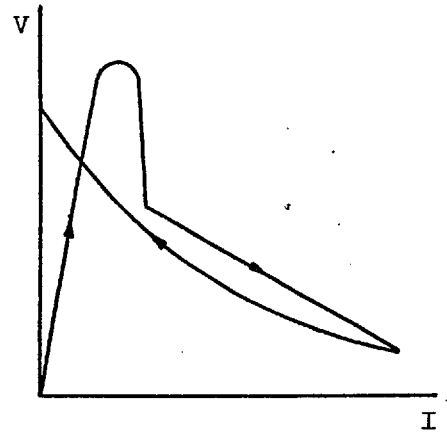


Figure 2-10

b - Striking an arc:

Arcs can be initiated by contacting the electrodes, by melting or vaporizing thin wires joining the electrodes, by the transition from a glow discharge or by exceeding the breakdown voltage of the gas between the electrodes.

c - Arc stability:

The conductivity of the gas heated by the electric discharge increases rapidly, as the temperature of the gas increased and therefore the resistance of the arc path will decrease. As a result the current will increase until a short circuit occurs. To prevent this, a large resistance must be placed in series with the arc to control the current. An example of the use of a ballast resistance is given by Browne⁽²¹⁾.

d - Electrodes:

The nature of the discharge depends on the material of the electrode. There are two types of cathode, the cold cathode and the refractory. Materials which emit electrons at high temperature often make suitable refractory cathodes. A discussion of thermionic emission and the choice of electrodes for electrically augmented

burners is made elsewhere (22).

2-3. Flame calculations.

A brief description of the well known method of calculating the composition of the flame products, together with the concept of boost ratio is given below:

A - Composition of flame products

Methane-air mixtures burning at 1 atmosphere pressure, give rise to an equilibrium mixture of ten gaseous constituents up to a temperature of 4000 K. These are CO, CO₂, O₂, H₂, H₂O, NO and N₂ molecules, the OH radical and the O and H atoms. Therefore we can formulate ten equations in order to find the composition of the flame at a given temperature. The initial air-methane mixture comprises



where e is the stoichiometric factor and is defined as the moles of air in the mixture per mole of air required for stoichiometric combustion in the expression (2-1). The ratios of the numbers of gram atoms

$$n_{\text{C}}/n_{\text{H}}, \quad n_{\text{O}}/n_{\text{H}} \quad \text{and} \quad n_{\text{N}}/n_{\text{H}}$$

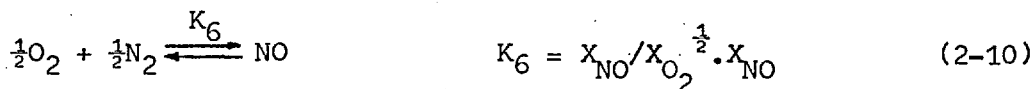
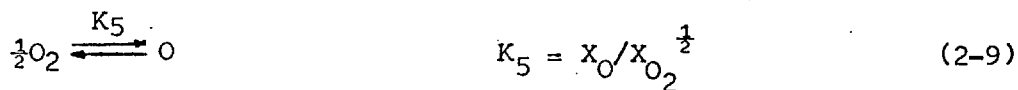
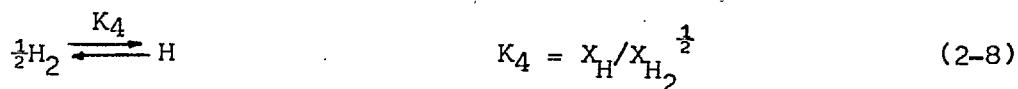
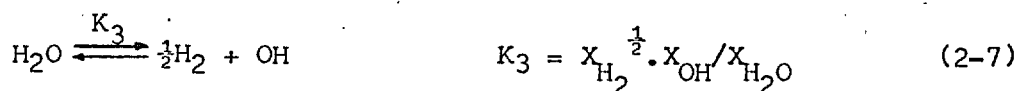
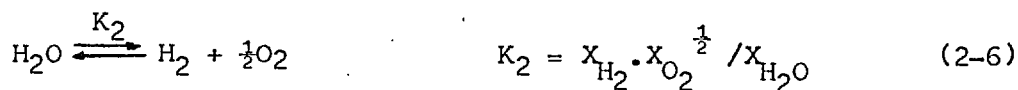
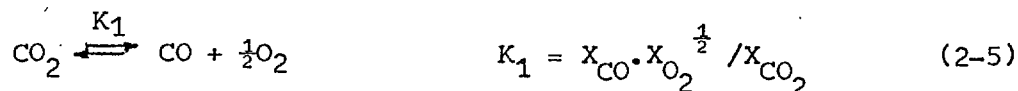
are obtained from the methane-air mixture and are equated to those of the product gas, thus:

$$n_{\text{C}}/n_{\text{H}} = 0.25 = (x_{\text{CO}} + x_{\text{CO}_2}) / (2x_{\text{H}_2} + 2x_{\text{H}_2\text{O}} + x_{\text{OH}} + x_{\text{H}}) \quad (2-2)$$

$$n_{\text{O}}/n_{\text{H}} = e = (x_{\text{CO}} + 2x_{\text{CO}_2} + 2x_{\text{O}_2} + x_{\text{H}_2\text{O}} + x_{\text{O}} + x_{\text{NO}} + x_{\text{OH}}) / (2x_{\text{H}_2} + 2x_{\text{H}_2\text{O}} + x_{\text{OH}} + x_{\text{H}}) \quad (2-3)$$

$$n_N/n_H = e(78.9/21.1) = (X_{NO} + 2X_{N_2})/(2X_{H_2} + 2X_{H_2O} + X_{OH} + X_H) \quad (2-4)$$

The remaining equations are provided by considering the chemical equilibria. For the methane-air mixture, the dissociation equilibria are:



Furthermore at atmospheric pressure:

$$\sum_{i=1}^{10} X_i = 1 \quad (2-11)$$

There will be ten unknown partial pressures or mole fractions and ten equations. It should be mentioned that other reactions are occurring and the choice of these reactions is arbitrary.

Karp et al⁽²⁷⁾ replaced reactions (2-5), (2-6) and (2-10) by



In addition the nitrogen molecule dissociates as the temperature increases. The partial pressure of nitrogen atoms at 3500°C is approximately 0.0002 atmosphere and at 3000°C it is 0.00001 atmosphere. At high temperatures molecules tend to ionize, and at equilibrium ionization may be considered to be a simple chemical reaction. For instance for species A



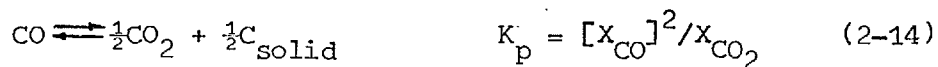
and the degree of ionization of a molecule is given by the Saha equation.

$$\frac{X^2}{1-X^2} \cdot P = 2 \frac{\omega_+}{\omega} \left(\frac{2\pi m_e}{h^2} \right)^{\frac{3}{2}} (K'T)^{\frac{5}{2}} \exp\left(-\frac{e'V_i}{K'T}\right) \quad (2-13)$$

where X is the fraction of the original molecules that are ionized.

All the species except NO have ionization potentials of about 13 e'V. The Saha equation indicates that at 2000 K, 0.2% of any of these species will be ionized and at 4000 K, 1% will be ionized. NO with an ionization potential of 9e'V will be 10% ionized at 4000 K. The enthalpy of the ionized species at temperatures below about 3500 K can therefore be neglected.

For rich flames at low temperatures less than 1000 K there is a likelihood of free carbon being produced, therefore equation (2-2) no longer holds. In such a case equation (2-2) is replaced by equation (2-14)



values for K_p from Gaydon and Wolfhard ⁽²⁴⁾, and the equilibrium constants for the other reactions were from many sources as compiled by Harker ⁽²⁵⁾.

Many systems have been devised for solving the ten equations mentioned above. Simplified methods due to Damköhler and Edse⁽²⁶⁾ (1943), Weinberg⁽²⁸⁾ (1957), Hottel et al⁽²⁹⁾ (1949) and Harker⁽²⁵⁾ (1967) can be used.

A computer solution has been performed by T. F. Wall⁽²³⁾. Programme from the Harwell subroutine library (subroutine NS01A) was used to solve equations (2-2) to (2-11) over the temperature range 1500 to 3500 K and for stoichiometric factor $e = 0.7$ to 1.3. This subroutine solves a system of non-linear equations by a combination of Newton-Raphson iteration and steepest decent approaches coupled with Broyd's⁽⁴⁷⁾ method for improving Jacobian matrices. The equilibrium composition of flame products have been calculated by the above method and is shown in figure 2-12. Literature values at the adiabatic flame temperature under stoichiometric conditions agreed with the values from the calculation.

B - Enthalpy of flame

The total enthalpy of the mixture, and its average molecular weight was found from:

$$H = \sum_{i=1}^{10} (H^0 - H_{298}^0)_i X_i + \sum_{L=1}^4 X_L \Delta H_L \quad (2-15)$$

$$\bar{M}_p = \sum_{i=1}^{10} X_i M_i \quad (2-16)$$

The adiabatic flame temperatures of the combustion flame and of the boosted flame have also been calculated⁽²³⁾ at various stoichiometric factors e and boost ratios B by the following procedure:

The chemical energy released per mole of combustion products formed is:

$$H_{\text{chem}} = - \sum_{i=1}^{10} \Delta H_{f,i}^{\circ} X_i - \Delta H_{f,\text{CH}_4}^{\circ} \cdot \frac{1}{F} \quad (2-17)$$

where X_i is the mole fraction of the species in the products and $\Delta H_{f,i}^{\circ}$ is the standard heat of formation. The heat absorbed by the decomposition of one mole of methane, $\Delta H_{f,\text{CH}_4}^{\circ}$, is included in the final term, F being the moles of product formed per moles of CH_4 burnt. F can be evaluated from the average molecular weights of products ($\bar{M}_p$) and reactants ($\bar{M}_r$) by:

$$F = (\bar{M}_r / \bar{M}_p) [1 + 2e + 2e(78.9/21)] \quad (2-18)$$

$$\text{where } \bar{M}_r = \frac{M_{\text{CH}_4} + 2eM_{\text{O}_2} + 2e(78.9/21.1)M_{\text{N}_2}}{1 + 2e + 2e(78.9/21.1)} \quad (2-19)$$

and $\bar{M}_p$ is obtained from the solution of equation (2-16). An energy balance therefore gives, on the basis of one mole of products,

$$H_{\text{chem}} + H_{\text{elec}} = \sum_{i=1}^{10} (H_i^{\circ} - H_{298}^{\circ})_i X_i + \sum_{i=1}^4 X_i \Delta H_i \quad (2-20)$$

(diss)

For a methane-air mixture fed at 298 K equation (2-20) gives the total enthalpy of the flame, and the adiabatic flame temperature of the augmented flame.

C - Boost ratio

There is some confusion in the literature regarding the concept of boost ratios. Karlovitz and Richardson⁽¹¹⁾ and Fells and Harker⁽¹⁶⁾ used a boost ratio B_I defined by the ratios of electrical input to chemical input. This chemical input refers to combustion to CO_2 and H_2O for the reaction



Davies⁽¹⁴⁾ defined a boost ratio as the fraction by which the heat content of the combustion products is increased during augmentation with the electrical discharge. He might have used this statement for his theoretical treatment and used B_I in his experimental treatment. However as B_I does not give any information about the combustion products, any study related to the products (either heat or mass transfer from products) should not use B_I . It would be preferable to use an effective boost ratio B_E which accounts variation in the stoichiometry and for the fact that the products of combustion are not entirely made up of CO_2 and H_2O .

D - Physical properties

The physical properties of the combustion products can also be determined. The thermal conductivity may be calculated by adding the frozen thermal conductivity and the reacting thermal conductivity as will be explained on page 33.

For the multi component mixture the frozen thermal conductivity can be determined by the Mason and Saxena⁽³⁰⁾ approximation at low density, to an accuracy of 5%.

$$\lambda_f = \frac{\sum_{i=1}^{10} \frac{X_i \lambda_i}{\sum_{J=1}^{10} X_J \varphi_{iJ}} \quad (2-22)$$

$$\text{where } \varphi_{iJ} = \frac{1}{\sqrt{8}} \left(1 + \frac{M_i}{M_J} \right)^{-\frac{1}{2}} \left[1 + \left(\frac{\mu_i}{\mu_J} \right)^{\frac{1}{2}} \left(\frac{M_J}{M_i} \right)^{\frac{1}{4}} \right]^2 \quad (2-23)$$

This approximation allows calculation of λ_f from a knowledge of the thermal conductivities of the pure components present. Similar equations apply for the viscosity. For the calculation, the ten components were approximated to four by T. F. Wall⁽²³⁾ as detailed

in table 2-1.

i	Components	Represented by	Reference
1	H	H	Vauderslice et al ⁽⁵¹⁾ 1962
2	H ₂	H ₂	
3	O, OH	O	
4	N ₂ , CO ₂ , CO, H ₂ O, O ₂ , NO	N ₂	yuw et al ⁽⁵²⁾ 1962

Table 2-1. Representation of species in flame by four components.

The thermal conductivity and viscosity of each of the four species were represented as functions of temperature, as follows:

$$\lambda_i = a + bT + cT^2 \quad (2-24)$$

$$\mu_i = d + eT + fT^2 \quad (2-25)$$

The constants a, b, c, d, e and f are given in the table 2-2.

i	a	b x 10 ³	c x 10 ⁷	d x 10	e x 10 ³	f x 10 ⁸
	λ -cal/cm.sec.deg K			μ -poise		
1	0.18642	0.88893	-0.23571	0.264	0.1191	-0.3
2	0.17871	0.85379	0.13571	0.85428	0.11464	0.10000
3	0.06340	0.16310	-0.07000	1.14628	0.38008	-2.42857
4	0.03731	0.12632	-0.02714	1.162328	0.24285	-0.42142

Table 2-2. Constants in equations (2-24) and (2-25)

The molecular weight and therefore the density of the gas can be calculated from

$$\bar{M} = \sum_{i=1}^{10} X_i M_i \quad (2-26)$$

2-4. Free submerged jet impinging on a flat plate.

The fluid dynamics of a flame can be approximated to those of a free submerged jet. Studies have been carried out on free submerged jets impinging on to solid surfaces mainly for the purpose of measuring heat transfer coefficients, in which case the principal resistance is confined to a boundary layer in the fluid phase adjacent to the solid surface. Results have been expressed in terms of standard dimensionless groups. Poreh and Cermak (31) used a submerged water jet impinging normally on to a flat surface to investigate the pressure distribution and velocity profile in the resulting wall jet. Bradshaw and Love (32) studied on air jets.

The flow pattern of a circular submerged jet impinging normally on a plane solid boundary is shown in figure 2-12.

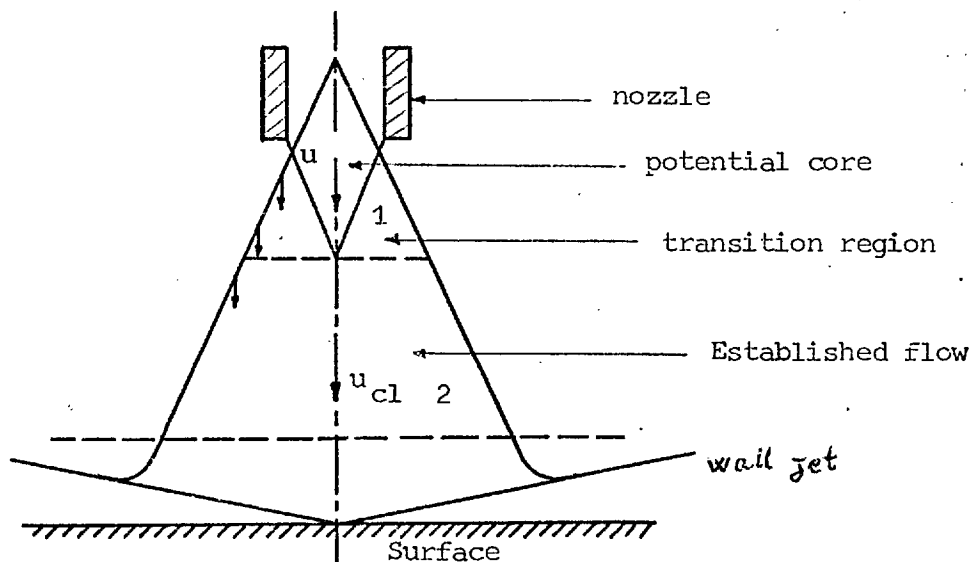


Figure 2-11.

Close to the nozzle exit a region of intense shear exists between the jet fluid and its surroundings. This results in an acceleration of the surrounding fluid and a deceleration of the

jet. In most practical cases the flow is turbulent and eddies are produced which diffuse towards the centre of the jet giving rise to mass entrainment of the surrounding fluid.

Since the momentum is conserved, the increase in mass transfer with distance from the nozzle due to entrainment is associated with a decrease in both jet velocity and kinetic energy. The flow pattern can be conveniently divided into two different regions.

The potential core is contained in the transition region 1 immediately outside the nozzle and is unaffected by diffusion of eddies. The axial velocity at any point in this region is constant. The length of the potential core has been variably reported to be between 3 to 7 times the nozzle diameter.⁽³³⁾ In the established flow region 2 eddies reach the jet axis and the axial velocity decreases as the distance from the nozzle increases. In the established flow region 2 the velocity profiles in the jet are kinematically similar and the radial spread of the jet is almost linear with the distance between the jet and the plate. The angle of spread of the submerged jet has been found to be 21° ⁽³⁴⁾. A stagnation point exists on the jet axis where the jet impinges on the plate. The velocity gradient at the stagnation point is given by ⁽³⁵⁾

$$\left(\frac{du}{dr}\right)_s = \frac{u_{cl}}{r'} \quad (2-27)$$

2-5. Heat transfer from flames to surfaces.

In convective heat transfer from flames, a large increase in heat flux can be obtained by the use of temperatures in excess of 2000°C . This increase is partly the result of changes in the

transport properties of the gas caused by dissociation. Exothermic recombination of the dissociated species at or near the surface being heated also increases the heat flux. Kilham⁽³⁶⁾ showed that the heat flux from a hydrogen-air flame to a body placed in the flame gases could not be attributed to ordinary convection alone. Ziebland⁽⁴⁸⁾ reached the same conclusion by carrying out a series of experiments on heat transfer from combustion gases to the cooled walls of rocket engines. The heat transfer from an oxy-acetylene flame to a flat plate has been investigated more recently by Geidt⁽³⁷⁾ et al. They postulated that recombination of hydrogen atoms, either in the gas phase or on the solid surface, enhanced the heat transfer rate by 30 to 90%. Cookson and Kilham⁽³⁶⁾ determined the heat transfer from a hydrogen-air flame stabilised on a burner of Botha, Spalding⁽³⁹⁾ design. They confirmed Kilham's conclusion that convection was not the only mechanism of energy transfer in the region near the reaction zone.

A - Recombination

Recombination reactions are generally recognized to involve a third body e.g.



The third body could be a gas, a solid or a liquid. If recombination occurs in the gas phase it is homogeneous while recombination at a solid or liquid surface is heterogeneous.

Heat transfer calculations from dissociated gases to surfaces have been mainly carried out assuming two limiting cases as follows:

a - Equilibrium boundary layer

If the reaction rates are sufficiently rapid compared to the rates of diffusion of species through the boundary layer, then the boundary layer may be assumed to be in a state of thermochemical equilibrium. The composition of the mixture at every point within the boundary layer is then only a function of temperature and pressure at that point.

b - Frozen boundary layer

If the reaction rates are slow enough so that the transfer processes at a wall are governed mainly by molecular and atomic diffusion then the boundary layer is frozen. One important question in connection with a frozen boundary layer is whether or not appreciable recombination occurs at the wall. Recombination will only occur if the wall is made of a material that catalyzes recombination. The probability that an atom incident on a surface will recombine is called the heterogeneous recombination coefficient γ . Typical values of γ for oxygen atoms on various surfaces at room temperature are given in table I page 163.

Scala⁽⁴⁰⁾ has concluded that at low pressure the surface can be perfectly catalytic if $\gamma > 40 \times 10^{-4}$.

It has been found by Rosner⁽⁴¹⁾ that at low pressures γ is independent of surface temperature up to 1000 K for metals.

The most general situation lies somewhere between the frozen and equilibrium cases outlined above and will exist when the gas phase recombination rate is finite.

B - Heat transfer correlations

The enhanced rate of heat transfer obtained from partially dissociated gas in equilibrium has been described⁽⁴⁾ in terms of an effective thermal conductivity.

If we consider that the gas consists of an atomic species A and a molecular species B, then the heat flux is given by

$$q = \lambda_f \text{ grad. } T - \Delta H_A D_{AB} \rho_A \text{ grad } x_A \quad (2-30)$$

The first term on the right hand side of equation (2-30) is the heat conducted by molecular collisions, and the second term is the transfer of chemical enthalpy by diffusion of species A. Thermal diffusion and radiation have been ignored as being of secondary importance.

Equation (2-30) is developed further on page 164 in appendix C to give

$$\frac{\lambda_E}{\lambda_f} = 1 + \text{Le} \left(\frac{C_{pe}}{C_{pf}} - 1 \right) \quad (2-31)$$

where λ_E is the effective thermal conductivity, λ_f is the frozen thermal conductivity, C_{pe} is the equilibrium specific heat and C_{pf} is the frozen specific heat. The non-dimensional quantity Le is known as the Lewis number. The Lewis number is shown to be of significance in partially dissociated gases particularly when H atoms are present. Equation (2-30), originated by Butler and Brokaw⁽⁵⁾, was used by Anderson and Stresino⁽⁴¹⁾ and Davies⁽¹⁴⁾. Average values of the effective thermal conductivity and specific heat were used by Anderson and Stresino⁽⁴²⁾ to calculate λ_E for hydrogen/oxygen and acetylene/oxygen flames with reasonable success, but more than a two

fold difference was found between the calculated and experimental values of λ_E for an oxy/propane flame. They pointed out that improved agreement could be obtained by more careful calculation of the effective thermal conductivity. Davies⁽¹⁴⁾ used the same method to calculate the heat flux from electrically augmented flames to a cylindrical probe in cross flow. He used the recommended low temperature heat transfer correlation from McAdams⁽⁴³⁾ with a weighted mean value $\bar{\lambda}_E$ of the effective thermal conductivity λ_E , where

$$\bar{\lambda}_E = (T_e - T_w)^{-1} \int_{T_w}^{T_e} \lambda_E dT \quad (2-32)$$

T_e and T_w are gas and probe temperatures respectively. The heat flux to the probe was then determined using Newton's law of cooling which is expressed as:

$$q = h'(T_e - T_w) \quad (2-33)$$

or

$$q = st_f \rho_e u_e \bar{C}_p (T_e - T_w) \quad (2-34)$$

The agreement between predicted values and measured values was within 20%.

A multiplication factor was used by Rosner⁽⁴⁴⁾ and by Davies⁽¹⁴⁾ to modify values of heat flux q calculated by the above method when the Lewis number is greater than unity. This factor is:

$$\left[1 - \left(1 - \frac{1}{Le} \right) \frac{\Delta\psi_{chem}}{\Delta\psi} \right]^{1/3} \cdot \left[1 + (Le - 1) \frac{\Delta H_{chem}}{\Delta H} \right] \quad (2-35)$$

ψ is the heat flux potential and is defined as $\psi = \int_0^T \lambda(T) dT$ and

$\psi_{chem} = \psi - \psi_f$, the heat flux potential due to chemical reaction.

The first part of the factor accounts for the change in Prandtl

number, and the second part is for recombination of hydrogen atoms

which are likely to have a Lewis number which is far greater than unity. $\Delta H_{\text{chem}}/\Delta H$ is the fraction of total enthalpy due to recombination of hydrogen atoms.

Most of the heat transfer problems associated with flames, involve a stagnation point. In an incompressible fluid and at a laminar boundary layer, the Stanton number at the stagnation point is given by^(7).

$$St_{f,s} = 0.76 Pr_f^{-0.6} (\rho_s u_s)^{-1} \sqrt{\rho_s \mu_s \left(\frac{du}{dr}\right)_s} \quad (2-36)$$

Equation (2-36) is developed further in appendix page 165 to give

$$q_s = 0.76 Pr_f^{-0.6} (\rho_s \mu_s)^{0.5} \left[1 + (Le_f - 1) \frac{m_{A,e} \Delta H}{h_s - h_w}\right]^{0.6} \times (h_s - h_w) \left(\frac{du}{dr}\right)_s \quad (2-37)$$

where $\left(\frac{du}{dr}\right)_s$ is the stagnation point velocity gradient.

Fay and Riddell^(8) used an alternative approach. They integrated the laminar boundary layer equation using numerical methods and obtained solutions for an equilibrium boundary layer and for a frozen boundary layer with both catalytic and non-catalytic walls. They fitted an equation of a similar type to equation (2-37) to their results and obtained the correlation.

$$q_s = 0.76 Pr_f^{-0.6} (\rho_w \mu_w)^{0.1} (\rho_s \mu_s)^{0.4} \left[1 + (Le_f^y - 1) \frac{m_{A,e} \Delta H}{h_s}\right] \times (h_s - h_w) \left(\frac{du}{dr}\right)_s^{0.5} \quad (2-38)$$

For an equilibrium boundary layer $y = 0.52$ and for a frozen boundary layer with fully catalytic surface $y = 0.62$.

In deriving equations (2-37) and (2-38) the following assumptions have been made:

- 1 - No bulk flow.
- 2 - No thermal diffusion.
- 3 - No radiation from the gas.
- 4 - Binary gas model of atoms and molecules.
- 5 - Laminar boundary layer.
- 6 - Either equilibrium or frozen boundary layer.
- 7 - Perfect catalytic surface in frozen case.

Comfort, O'Connor and Cass⁽³⁶⁾ compared the stagnation point heat flux from a high enthalpy dissociated nitrogen jet impinging normally on a large flat plate with predictions obtained using equation (2-38). They found that measured values were more than twice the predicted values. They attributed this to turbulence in the boundary layer. The authors then modified equation (2-38) to provide agreement. The equation is given below:

$$q_s = 0.442 \text{ Pr}_f^{-0.6} \left(\frac{\rho_W \mu_W}{\rho_s \mu_s} \right)^{0.1} (\rho_s \mu_s \beta \frac{x}{r'})^{\frac{1}{2}} [1 + (Le_f^{0.52} - 1) \frac{h_D}{h_s}] (h_s - h_W) \quad (2-39)$$

$$\text{where } \beta = \frac{u_{cl}}{r'} \quad (2-40)$$

C - Heat conduction in a slab

The heat flux from an electrically augmented flame to a slab can be calculated from the temperature distribution in the slab. The heat conduction equation and its solution for a semi-infinite slab is given below:

a - Heat conduction equation: Consider a solid extending from

$x = 0$ to infinity. The YZ plane is heated and conduction occurs in the X direction only, as indicated in figure 2-11. The slab temperature is initially zero throughout, and then increases with time. The equation of one-dimensional unsteady state conduction in an isotropic region of uniform thermal conductivity, and uniform surface heat flux is given below:

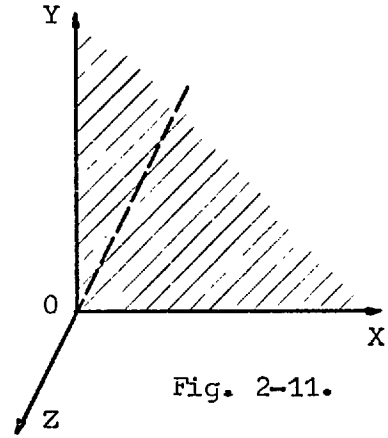


Fig. 2-11.

$$\frac{\partial}{\partial x} \left[k \cdot \frac{\partial t}{\partial x} \right] = \rho \cdot C_p \cdot \frac{\partial t}{\partial \tau} \quad (2-41)$$

In the case that ρ , C and k are independent of temperature equation (2-41) becomes

$$\frac{\partial^2 t}{\partial x^2} = \frac{1}{\alpha} \cdot \frac{\partial t}{\partial \tau} \quad (2-42)$$

where $\alpha = \frac{k}{\rho C_p} \quad (2-43)$

b - Exact solution of the heat conduction equation: Equation (2-42) has been solved analytically by Carslaw and Jaeger⁽⁴⁵⁾.

The local heat flux in terms of local temperature gradient in the X direction is:

$$q_x = -k \frac{\partial t}{\partial x} \quad (2-44)$$

Equation (2-44) satisfies the same differential equation as (2-42)

$$\frac{\partial^2 q_x}{\partial x^2} = \frac{1}{\alpha} \cdot \frac{\partial q_x}{\partial \tau} \quad (2-45)$$

The boundary equation is

$$\text{at } \tau > 0 \text{ and } x = 0, \quad q_x = q_o$$

where q_o is a constant heat flux at the surface.

The solution of equation (2-45) is

$$t = \frac{2q_x}{k} \left[\left(\frac{\alpha \tau}{\pi} \right)^{\frac{1}{2}} e^{\frac{-x^2}{4\alpha}} - \frac{x}{2} \operatorname{erfc} \frac{x}{2\sqrt{\alpha \tau}} \right] \quad (2-46)$$

$$\text{or} \quad t = \frac{2q_x}{k} \sqrt{\alpha \tau} \left[\operatorname{Ierfc} \frac{x}{2\sqrt{\alpha \tau}} \right] \quad (2-47)$$

The temperature at the surface ($x = 0$) is given by:

$$t_s = \frac{2q_o}{k} \left(\frac{\alpha \tau}{\pi} \right)^{\frac{1}{2}} \quad (2-48)$$

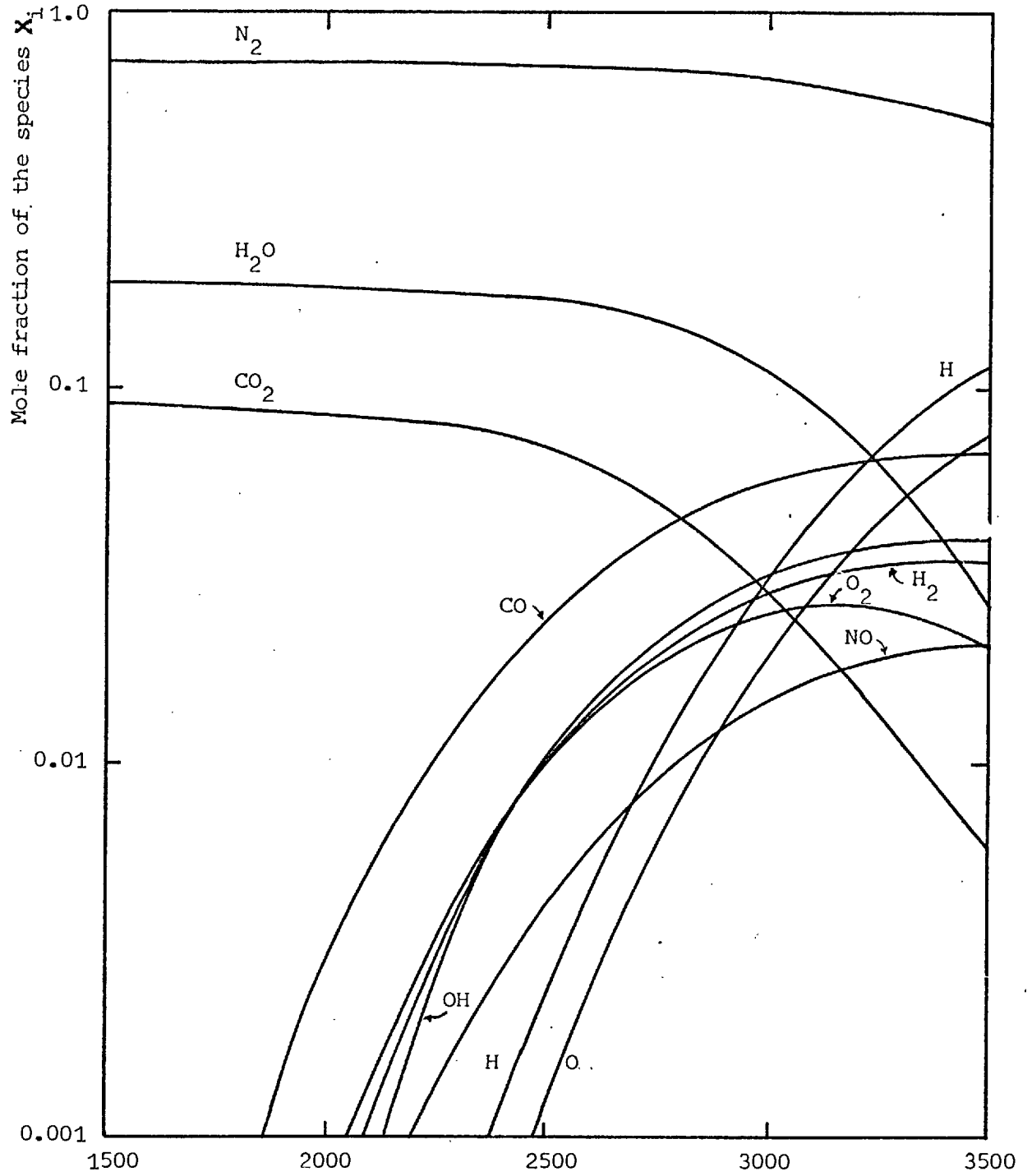


Figure 2-12. Equilibrium composition of a stoichiometric methane-air flame.

Chapter 3.

Prediction of heat fluxes

- 3-1. Boundary layer.
- 3-2. Effective boost ratio.
- 3-3. Flame temperature.
- 3-4. Calculation of stagnation point heat flux.

3-1. Boundary layer.

The decision as to whether the boundary layer is in equilibrium or is frozen can be made by evaluating a recombination rate parameter C_1 , which is the ratio of the life time of a species ($\tau_{\text{recomb.}}$) to the time for it to diffuse through the boundary layer $\tau_{\text{(diff.)}}$ i.e. $C_1 = \tau_{\text{recomb.}} / \tau_{\text{diff.}}$. If C_1 is large the layer can be considered to be frozen. In this case it is important to know whether or not appreciable recombination occurs at the wall. If atoms do not recombine at the wall their concentration will build up at the wall. If they do recombine, because the wall is made of a material that catalyses recombination, they will give up their heat of recombination which will contribute largely to the heat flux. If C_1 is small then the layer approaches thermodynamic equilibrium, and the composition of the mixture at any point can be calculated as a function of temperature and pressure at that point.

However, in order to eliminate entrainment of the cold surrounding atmosphere, it is intended to carry out experiments when the nozzle to plate distance is within length of the potential core of the jet. In this case the results of Comfort et al⁽³⁵⁾ can be extrapolated to give

$$\left(\frac{du_e}{dr}\right)_s = \frac{u_{cl}}{d_1} \quad (3-1)$$

where u_{cl} the gas velocity on the centreline of the jet is approximately equal to the mean jet velocity and can be evaluated from Q the volumetric flow rate at STP, i.e.

$$u_{cl} = \bar{u} = \frac{4Q}{\pi d_1^2} \cdot \frac{T_s}{298} \cdot \frac{27.7}{M_s} = 118 \times 10^{-6} \times \frac{Q}{d_1^2} \cdot \frac{T_s}{M_s} \text{ m.sec}^{-1} \quad (3-2)$$

so we have

$$\left(\frac{du}{dr}\right)_s = 118 \times 10^{-6} \times \frac{Q}{d_1^3} \cdot \frac{T_s}{M_s} \text{ sec}^{-1} \quad (3-3)$$

The time for diffusion ($\tau_{\text{diff.}}$) is given by:

$$\tau_{\text{diff.}} = \left(\frac{du}{dr}\right)_s^{-1} = (118 \times 10^{-6} \times \frac{Q}{d_1^3} \cdot \frac{T_s}{M_s})^{-1} \quad (3-4)$$

C_1 now becomes

$$C_1 = \frac{\tau_{\text{recomb.}}}{\tau_{\text{diff.}}} = \frac{K_1^2 T^3}{3 \times 10^{-41} (X_H \cdot X_M) \cdot (118 \times 10^{-6} \times \frac{Q}{d_1^3} \cdot \frac{T_s}{M_s})^{-1}} =$$

$$7.25 \times 10^{-20} \times \frac{T^3 \cdot T_s}{X_H X_M \cdot M_s} \times \frac{Q}{d_1^3} \quad (3-5)$$

For a stoichiometric mixture values of X_H can be obtained from figure 2-1 and

$$X_M = 1 - X_H \quad (3-6)$$

H atoms have the highest value of diffusivity of all the species in the gas, and therefore have Lewis number which is greater than unity. For the purpose of predicting heat fluxes from the gas we can therefore consider the gas to consist of two "species", H atoms and the rest of the gas. The time for recombination is calculated from available data (35) for the recombination of H atoms according to:



The method of calculating $\tau_{\text{recomb.}}$ is given in appendix page 167.

$$\tau_{\text{recomb.}} = \frac{K_1^2 T^3}{3 \times 10^{-41} (X_H X_M)} \quad (3-8)$$

The time for hydrogen atoms to diffuse to the surface ($\tau_{\text{diff.}}$) is given by⁽³⁵⁾

$$\tau_{\text{diff.}} = \left(\frac{du}{dr} \right)_s^{-1} \quad (3-9)$$

As given on page 166

$$\left(\frac{du}{dr} \right)_s = \frac{u_{cl}}{r'} \quad (3-10)$$

in the established flow region of the jet.

For an equilibrium boundary layer X_H must be evaluated at temperature T whilst in the frozen case, X_H must be determined at temperature T_s . Calculations were carried out for both of these cases and the results are shown in figure 3-1 as plots of C_1 against temperature for two values of $\frac{Q}{d_1^3}$ of 500 and 1000 sec^{-1} to cover the likely range of experimental work. These curves were plotted at stagnation temperatures between 2500 K and 4000 K and at film temperatures 1000 K below these stagnation temperatures. Calculations carried out for equilibrium conditions always gave $C_1 > 1$. Hence the boundary layer was never in equilibrium. Figure 3-1 shows that the boundary layer is either frozen or in a transition region.

3-2. Effective boost ratio

The enthalpy of the boosted products is compared with the enthalpy of the products at the adiabatic flame temperature without electrical boosting. The ratio of these two enthalpies is:

$$B_E = \frac{\sum_{J=1}^{10} (H^0 - H_{298})_J X_J + \sum_{i=1}^4 x_i \Delta H_i \text{ at } T_{Af. Aug.}}{\sum_{J=1}^{10} (H^0 - H_{298})_J X_J \text{ at } T_{Afo}} = \frac{H_{elec.} \text{ at } T_{Af. Aug.}}{H_{chem.} \text{ at } T_{Afo}} \quad (3-11)$$

where $T_{Af. Aug.}$ is the augmented adiabatic flame temperature and T_{Afo} is the adiabatic flame temperature without augmentation. H_{chem} decreases in a boosted flame as the flame temperature is increased because the proportions of H_2O and CO_2 decrease whilst the proportions of the dissociated species increase. In fact H_{chem} eventually becomes negative (at *more* than 3180 K for a stoichiometric methane-air flame). This decrease in enthalpy is recovered when the dissociated species recombine.

The ratio of the input boost ratio B_I to the effective boost ratio B_E , depends only on the air fuel ratios, and has been calculated for a methane-air flame in terms of e (stoichiometric factor). The ratio B_I/B_E is shown in table 3-1.

e	1.2	1.1	1.0	0.9	0.8
B_I/B_E	0.975	0.959	0.928	0.844	0.730

Table 3-1.

3-3. Flame temperature.

The adiabatic flame temperature for the combustion flame and for the flame with boost ratio were calculated as explained on page 25. The results are shown plotted in figure 3-2 as the effective boost ratio against temperature for $e = 0.8$, $e = 1$ and $e = 1.2$.

3-4. Calculation of stagnation point heat flux.

The heat flux from electrically augmented flames can therefore be calculated by equations (2-37) and (2-38). The assumptions made in applying these equations to predict stagnation point heat fluxes from electrically augmented flames are given below:

- 1 - Uniform distribution of electrical energy across flame.
- 2 - No radiation from arc.
- 3 - No entrainment in jet.
- 4 - No turbulence induced by arc.
- 5 - Centreline velocity = mean jet velocity at nozzle exit.
- 6 - Adiabatic flame.
- 7 - Only H atoms have $Le_H > 1$.

For a boundary in equilibrium the gas composition and therefore the physical properties such as viscosity, density and enthalpy will be a function of temperature only. Molecular weight and therefore density, as well as enthalpy of the gas were calculated using the I.U.P.A.C. data ⁽⁵⁰⁻⁵²⁾. These properties are shown in figure 3-3 as a function of temperature for $e = 1$.

As mentioned previously on page 42 a binary gas was assumed which consists of H atoms diffusing in the rest of the gas. In order to evaluate the Lewis number, the diffusivity of H atoms in nitrogen was taken as the best available data ⁽⁵⁰⁾.

$$Le_f = \frac{D_{H,N_2} \rho C_p}{\lambda_f} \quad \text{at } T \quad (3-12)$$

The diffusivity varies with temperature according to

$$D_{H,N_2} = 2.63 \times 10^{-8} T^{1.75} \text{ m}^2 \cdot \text{sec}^{-1} \quad (3-13)$$

The specific heat for hydrogen atoms was found from the JANAF data⁽⁴⁹⁾. H atoms were considered to be an ideal gas in order that the density could be found at any temperature, according to:

$$\rho = 273/22.4 T \text{ moles lit}^{-1} \quad (3-14)$$

The Lewis number was then calculated and is plotted against temperature in figure 3-3. The Lewis number should be calculated at the mean film temperature T_F but it can be seen from figure 3-3 that the Lewis number does not vary appreciably with temperature. Therefore it was calculated at T_s in all cases. The Prandtl number was considered to be constant at $P_{r,f} = 0.71$.

The proportion of the enthalpy due to dissociation $\frac{m_{A,e} \Delta H}{h_s}$ was calculated considering the heat of recombination of hydrogen to be 104 K cal/mole and assuming that all the hydrogen atoms recombine, i.e.

$$\Delta H_{\text{chem}} = 104 X_H \text{ K cal} \quad (3-15)$$

The value of $(\frac{du}{dr})_s$ is given by equation (3-3). Taking $\frac{Q}{d_1^3}$ to be 500 sec.⁻¹ and 1000 sec.⁻¹ for the reason explained on page 43 $(\frac{du}{dr})_s$ can be calculated at temperature T_s .

$\mu\rho$ is also shown in figure 3-3 and was used for equation (2-37) at the wall and stagnation temperatures. For a frozen boundary layer $\rho_s \mu_s$ is dependent upon both the wall temperature and the stagnation point temperature, as the latter determines the gas composition within the boundary layer. In other words, $\rho_s \mu_s$ has to be calculated at T_w with a composition at the stagnation temperature T_s .

The stagnation flux q_s has been calculated for both the equilibrium and the frozen boundary layer using equations (2-37) and (2-38) at values of T_s between 2220 K and 3050 K which correspond to $B_E = 0$ to 1.20 for both $\frac{Q}{d_1^3}$ of 500 sec.⁻¹ and 1000 sec.⁻¹ and are shown in figure 3-4 for $e = 1.0$. As the two values of the equations agree to within 4 percent, further calculations have been carried out using equation (2-37). It was also found that the values of q_s are similar for both equilibrium and frozen boundary layer. The heat flux for $B_E = 1.2$ and $\frac{Q}{d_1^3}$ of 1000 for three stoichiometric factors of 0.8, 1, 1.2 was also calculated and is shown in figure 3-4.

It can be seen from figure 3-4 that B_E , $\frac{Q}{d_1^3}$, T_W and e in the range of 1 to 1.2 have a considerable influence on the heat flux whilst e in the range 0.8 to 1 has little effect.

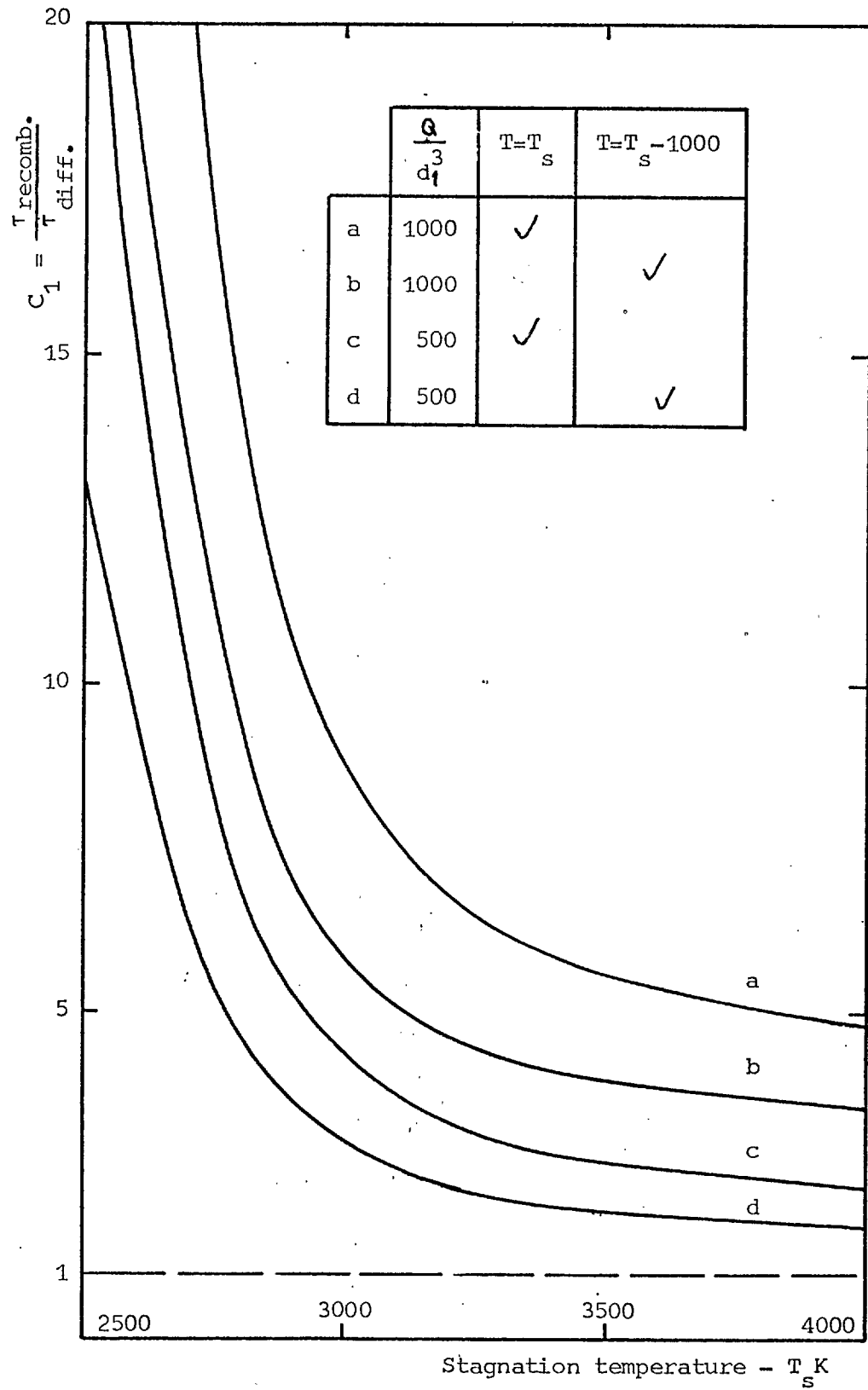


Figure 3-1. Effect of temperature and $\frac{Q}{d_1^3}$ on non-equilibrium in the boundary layer for hydrogen atoms.

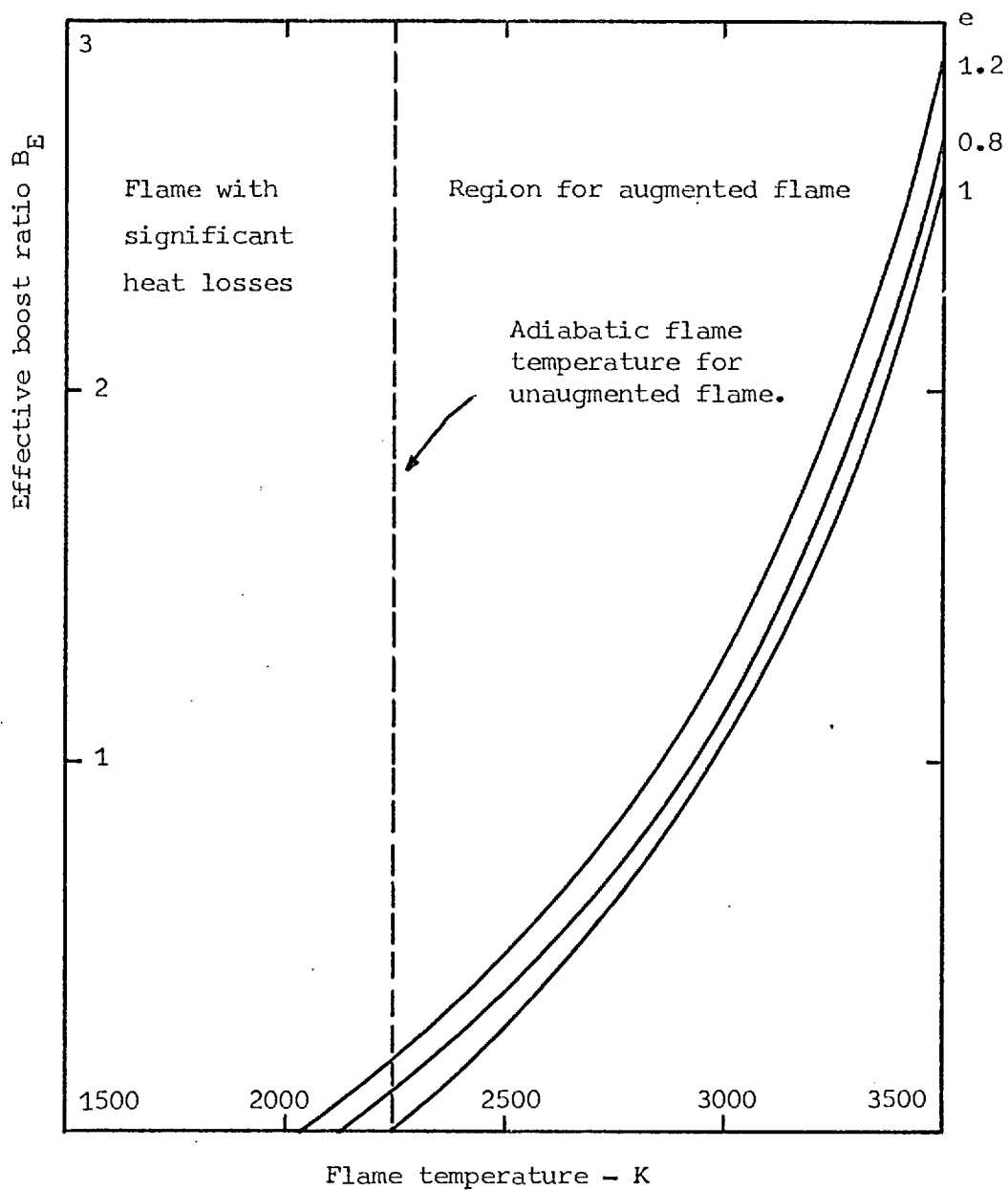


Figure 3-2. Flame temperatures of methane-air flame at three stoichiometric factors.

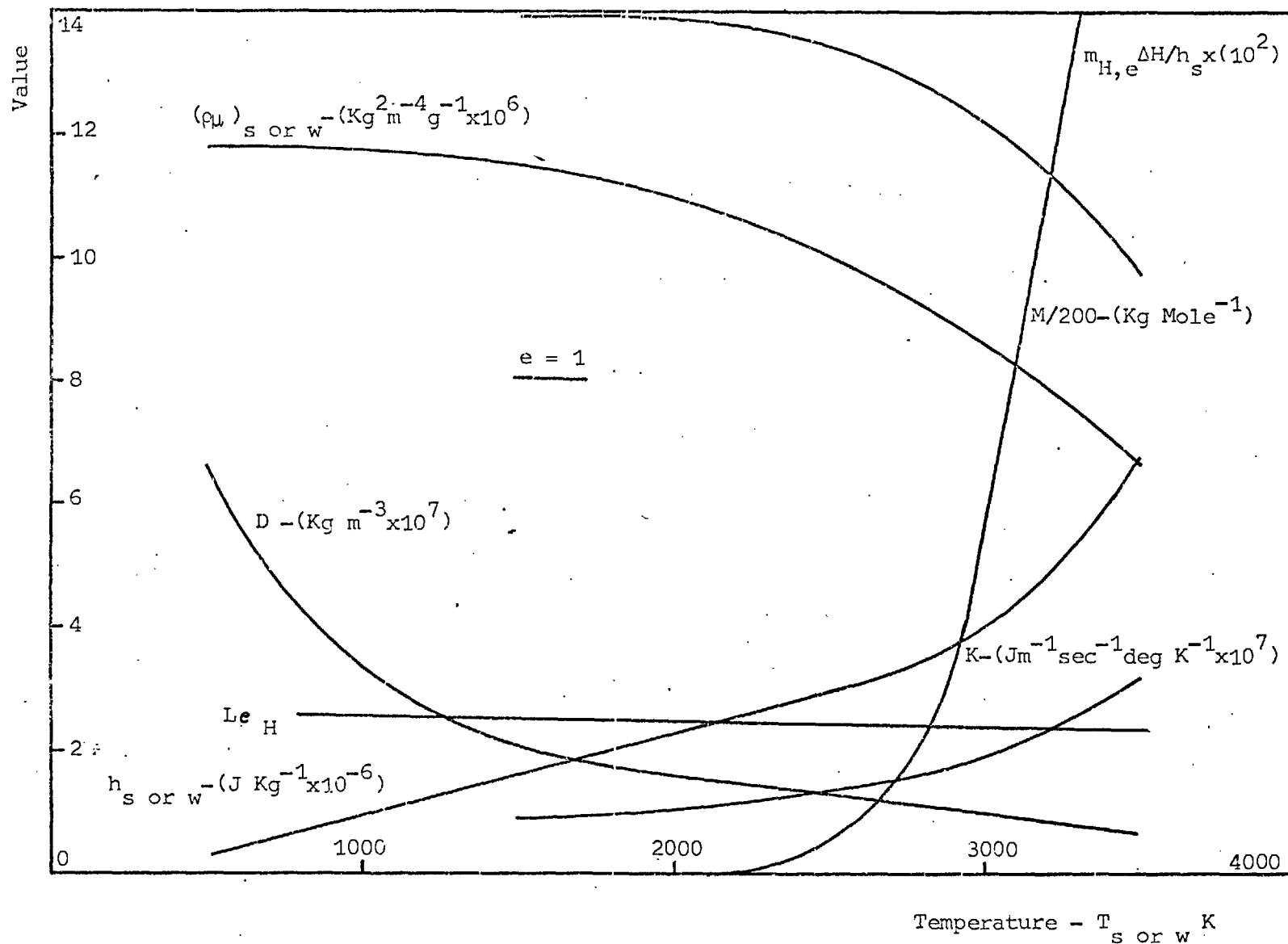
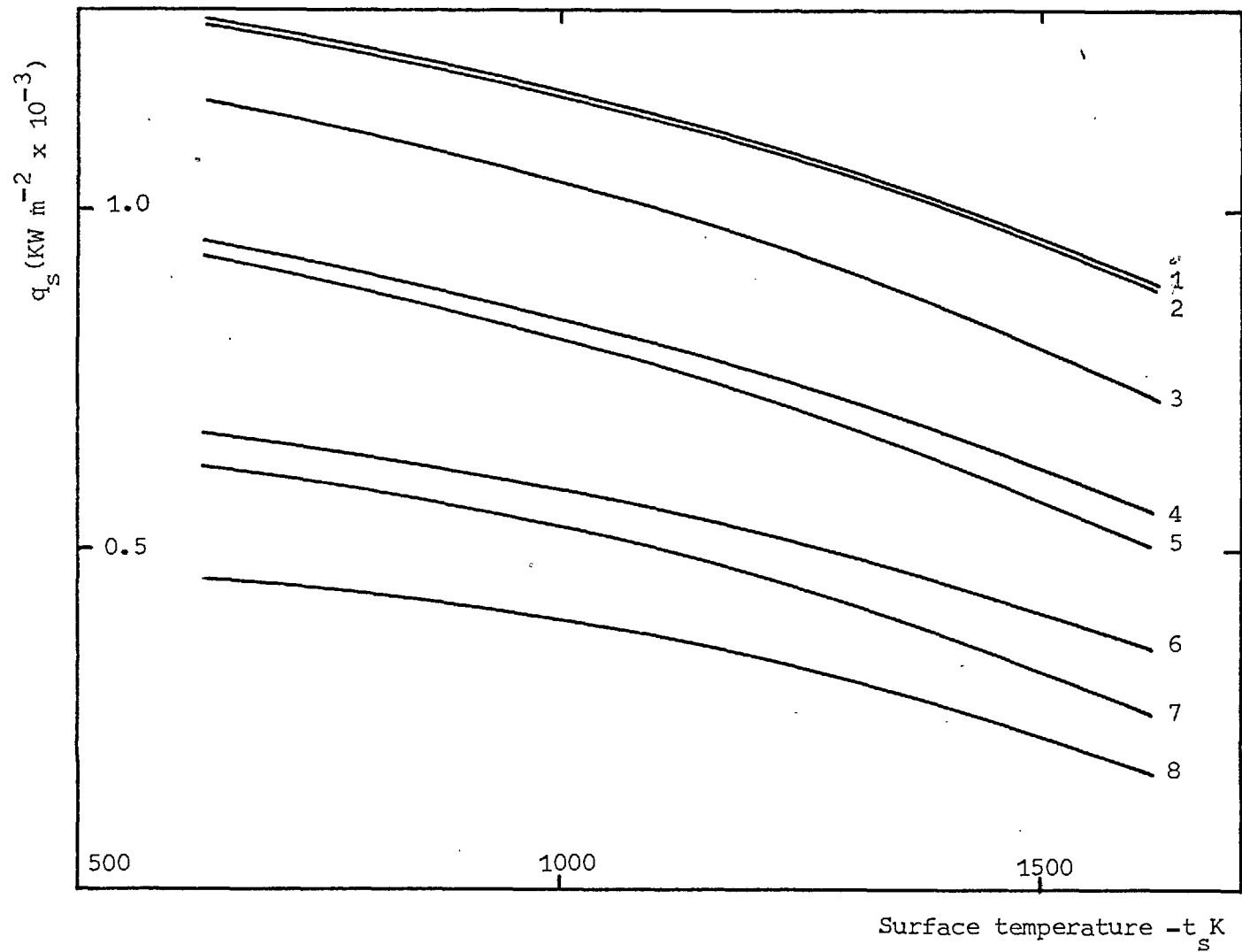


Figure 3-3. Property values required to evaluate equations (2-37) and (2-38)



Curve No.	B_E	$\frac{Q}{3d_1}$	e
1	1.2	1000	1
2	"	"	0.8
3	"	"	1.2
4	"	500	1
5	0.5	1000	"
6	"	500	"
7	0	1000	"
8	"	500	"

Figure 3-4. Predicted values of stagnation point heat fluxes.

Chapter 4

Experimental Apparatus

- 4-1. Description of final states of small and large burners.
- 4-2. Description of cage, power, gas supplies and meter circuits.
- 4-3. Design and construction of heat flux meter.

4-1. Description of small and large burners.

The burners which have been developed previously (1) have been modified and improved and are described below:

A - Small burner

Full scale drawings of the burner are shown in figure 4-1. A mixture of methane and air enters the swirl chamber from the tangential inlet and then flows into the combustion chamber where the gas is burnt. An a.c. or d.c. electric arc is struck between the central electrode and the annular electrode and the arc heated products of combustion then emerge from the nozzle. This burner is capable of burning $16.7 \times 10^{-6} \text{ m}^3 \text{ sec}^{-1}$ of methane. The central electrode was made from a variety of materials and is described later. The central electrode is capable of being moved vertically along the axis of the annular electrode. The annular electrode was made by casting lime-zirconia cement inside an alumina tube, which was also connected to the power supply by platinum wire. The walls of the combustion chamber were formed by a tube of re-crystallized alumina. The horizontal gas inlet tube was brazed in a tangential position to a vertical tube of larger diameter to comprise the swirl chamber and two flanges of syndanyo were held above and below the swirl chamber by three securing bolts. This burner operated without the necessity of seeding..

B - Larger burner

The larger burner was similar in design and construction

to the small burner and a sectional elevation and a plan of this burner are shown in figure 4-2 and a photograph is shown in plate 1. The differences between the two designs are detailed below:

a - Combustion chamber:

An alumina tube by itself is no longer suitable as the combustion chamber, because the tube will not withstand the thermal shock. This was overcome by using an alumina tube of longer diameter which was lined with a 50:50 mixture of alumina cement and lime-zirconia cement.

b - Electrodes:

(i) Annular electrode: Two tungsten rods were fitted at opposite sides of the annular electrode of compressed lime-zirconia to make electrical contact with the electrode. Both rods were connected to the earthed side of the transducer. They were covered with alumina cement to ensure that the rate of oxidation was kept at a low level.

The top two centimeters of the electrode were filled with alumina cement. This acted as an electrical insulator and therefore prevented the arc from attaching itself to the top surface of the electrode, as shown in figure 4-3.

A shield was made to prevent entrainment of cold air into the jet of hot combustion products. This shield was cemented above the annular electrode. The shield is shown in 4-4. The jet angle was assumed to be 21° (34).

(ii) Central electrode: The ceramic central electrode of the

small burner was replaced by a tungsten rod and the reasons are given on page 73.

c - Ignition system:

The methane-air mixture was ignited by a spark generated by a 12 volt ignition coil from a motor car connected across the two electrodes at the bottom of the combustion chamber. These electrodes are shown in figure 4-5.

4-2. Power and gas supplies and meter circuits.

A - Electrical power supplies

Two different sizes of electrical power supply were used for the burners described above. One, of about 0.5 KVA output, supplied power to the small burner. The other provided an output of up to 66 KVA and was used as a supply for the larger burner.

a - 0.5 KVA supply.

A single phase transformer supplied power to the electrodes of the small burner at up to 3.2 KV from a mains input of 240 v. The output could be connected directly to the electrodes of the small burner to provide an a.c. arc. Instruments were provided in the circuitry to measure the current, voltage, and power supplied to the burner. A ballast resistance of 6 K Ω were placed in series with the burner electrodes in order to limit the current supplied to the arc; the necessity for this procedure is explained in section 2, page 21.

b - 66 KVA supply.

The Foster transductor which was used to supply power to

the larger burner consisted of a single phase transformer, providing a controlled current at voltage up to 6.6 KV. The current could be set at any value between 0 and 10 amps. and could remain at this value even if the transformer output was short-circuited.

The transducer and burner were enclosed in an earthed cage. The door of the cage was interlocked with the mains supply in such a way that the operator was prevented from gaining access to the high voltage side of the equipment when the supply was switched on. The output terminal which was connected to the annular electrode of the burner was also earthed, and the other terminal was connected to the central electrode.

B - Air and methane supply

Methane was used as the fuel gas for the burners and was supplied by Mogden Sewage Treatment Works to the approximate analysis:

CH ₄	97 %
CO ₂	(3-4) %
O ₂	(0.1-0.2) %
N ₂	(0.2-0.4) %

The method of supplying air and methane depends on the size of the burner in operation.

a - The small burner was supplied with air and methane from cylinders. The gas flows were individually metered and then mixed and dried in a column which was packed with silica-gel. The gas mixture was then passed into the burner.

b - The larger burner was supplied with air from the atmosphere and methane from cylinders. A Selas Mini Mixer was used to mix the

air with the methane and to control their proportions at a set value. The gas system had to be designed so that the total pressure drop did not exceed the pressure head developed by the Mini Mixer, otherwise flash-back would occur. A flame trap was installed which would automatically disconnect the methane supply in the case of flash-back. A diagram of the large burner system is given in figure 4-6 and a photograph of the transductor, earthed cage, meters, gas flow meters, and large burner appears as plate 2.

C - Circuitry for obtaining current and voltage transients

Figure 4-7 shows the circuitry that was used to obtain a.c. current and voltage transients from the electrodes using an Oscilloscope. A potential divider (R'_1 and R'_2) was used to reduce the operating voltage of the burner to suitable levels in order that it could be displayed on the oscilloscope. The voltage drop across resistance R'_3 enabled the current in the electrode circuit to be calculated. The values of R'_1 , R'_2 and R'_3 for both burners are given on table 4-1.

Burner	R'_1 ohm.	R'_2 ohm.	R'_3 ohm.
small	4.63×10^4	1.065×10^6	39
large	991	10^7	4

Table 4-1

4-3. Design and construction of heat flux meter.

The heat flux can be determined by finding the temperature distribution produced in a semi-infinite slab. The exact solution of the unsteady heat conduction equation page 36 can be applied to find the heat flux at the surface of the slab if the following assumptions are made:

- 1 - Heat flow is linear and normal to the surface of the slab.
- 2 - Heat flux is constant at the surface.
- 3 - No heat of transformation occurs in the steel.
- 4 - The slab is isotropic.
- 5 - Thermal properties of the steel do not vary with temperatures.

A heat flux meter was designed to determine the surface heat flux, when the flame impinged on the surface of a large slab. This heat flux meter was designed to satisfy the above assumptions and is shown in figure 4-8.

The central rod of E_n 58A stainless steel was made as thin as possible. The surface of the rod was insulated with flame sprayed alumina and was fitted with four mineral insulated chromelalumel thermo-couples with junctions bonded to stainless steel sheathes of 0.5 mm diameter. The position of the thermo-couples and the length of the rod were chosen by first assuming that the surface heat flux would be $3.5 \times 10^3 \text{ KW/m}^2$ and the maximum surface temperature would be 1300°C. Equation (2-48) gives the time at which the surface temperature reaches 1300°C as 10.24 second. For these values of heat flux q and time t , the temperature profile in the rod is shown in figure 4-9. For lower heat flux of $0.8 \times 10^3 \text{ KW/m}^2$ and a maximum surface temperature of 600°C the time at which the surface temperature

reaches 600°C was calculated to be 35 seconds. A plot of the temperature in the rod against distance from the surface x is also shown in figure 4-9.

From the above curves the positions of the thermo-couples from the surface of the slab were chosen to be 1.5, 5, 15 and 25 mm from the surface and the length of the rod was chosen to be 50 mm. Two stainless steel cylinders insulated with flame-sprayed alumina acted as guard rings. The slab consisted of a disk of stainless steel of diameter 105 mm and thickness 30 mm. When the flame impinges on the slab the temperature at various positions along the axis of the central rod were measured using the thermo-couples which were connected to a data logger. The method of connecting the thermo-couples to the data logger, including an ice point reference junction, is shown in figure 4-10 for one of the thermo-couples. This procedure eliminated the use of compensating cable and provided a reference junction at 0°C . The central rod and the slab were earthed in order to obtain stable emf. outputs when the slab was heated by the augmented flame. A gantry was constructed over the burner to support a pair of rails. The slab was suspended from these rails in a trolley which was traversed horizontally over the flame. The trolley was connected to a 0.5 meter long pneumatic cylinder equipped with air cushioning at each end to reduce the shock at the limit of the stroke. The connecting rod from the cylinder was attached to an adjustable slide which allowed the position of the heat flux meter relative to the burner axis to be varied. A measuring rule was attached to the slide and this adjustment was used in order to determine the radial distribution of heat flux. The burner to slab distance could be varied by adjusting the height of the burner. A photograph of the heat flux meter, slab and trolley is given in plate 3.

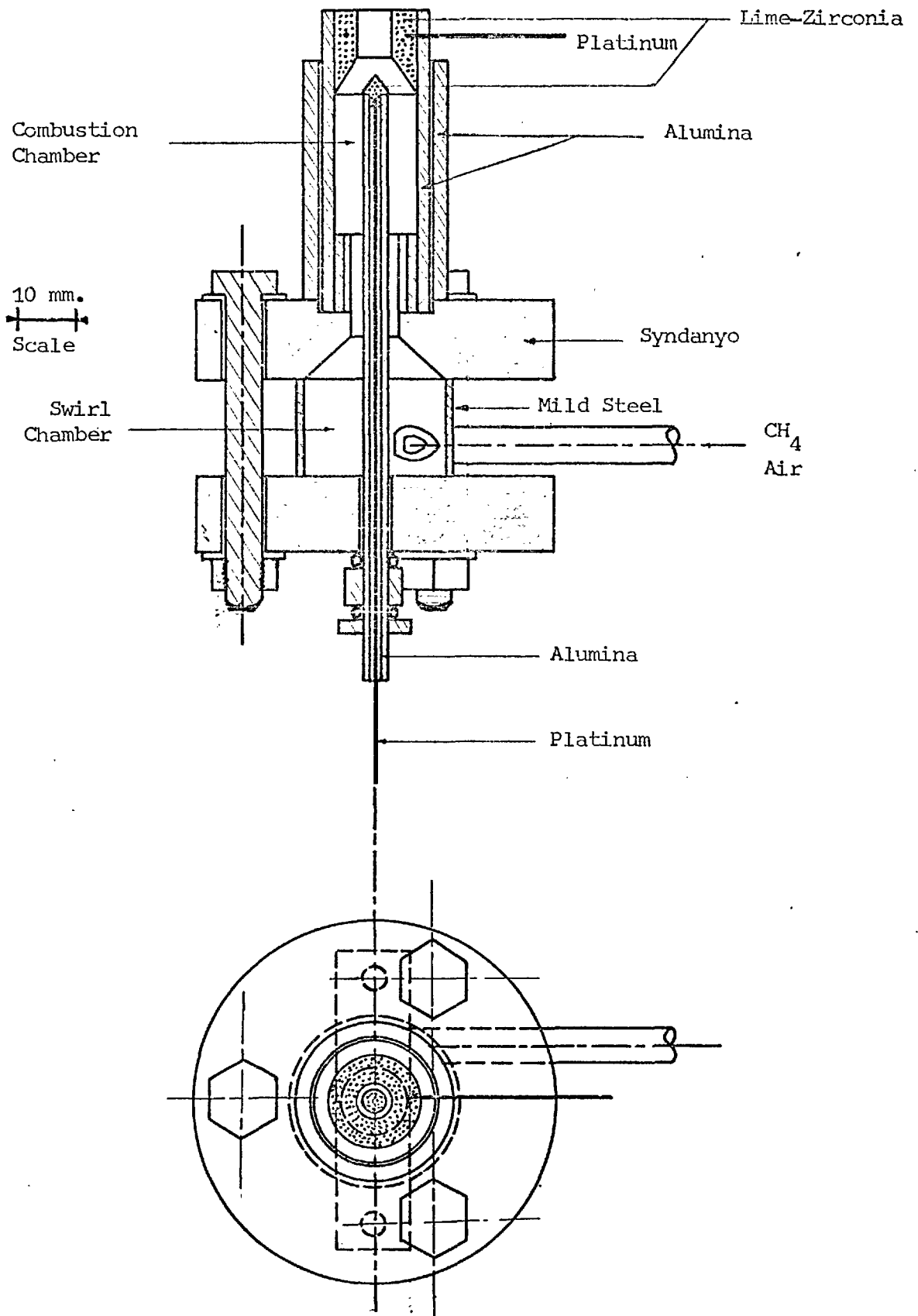


Figure 4-1. Small burner

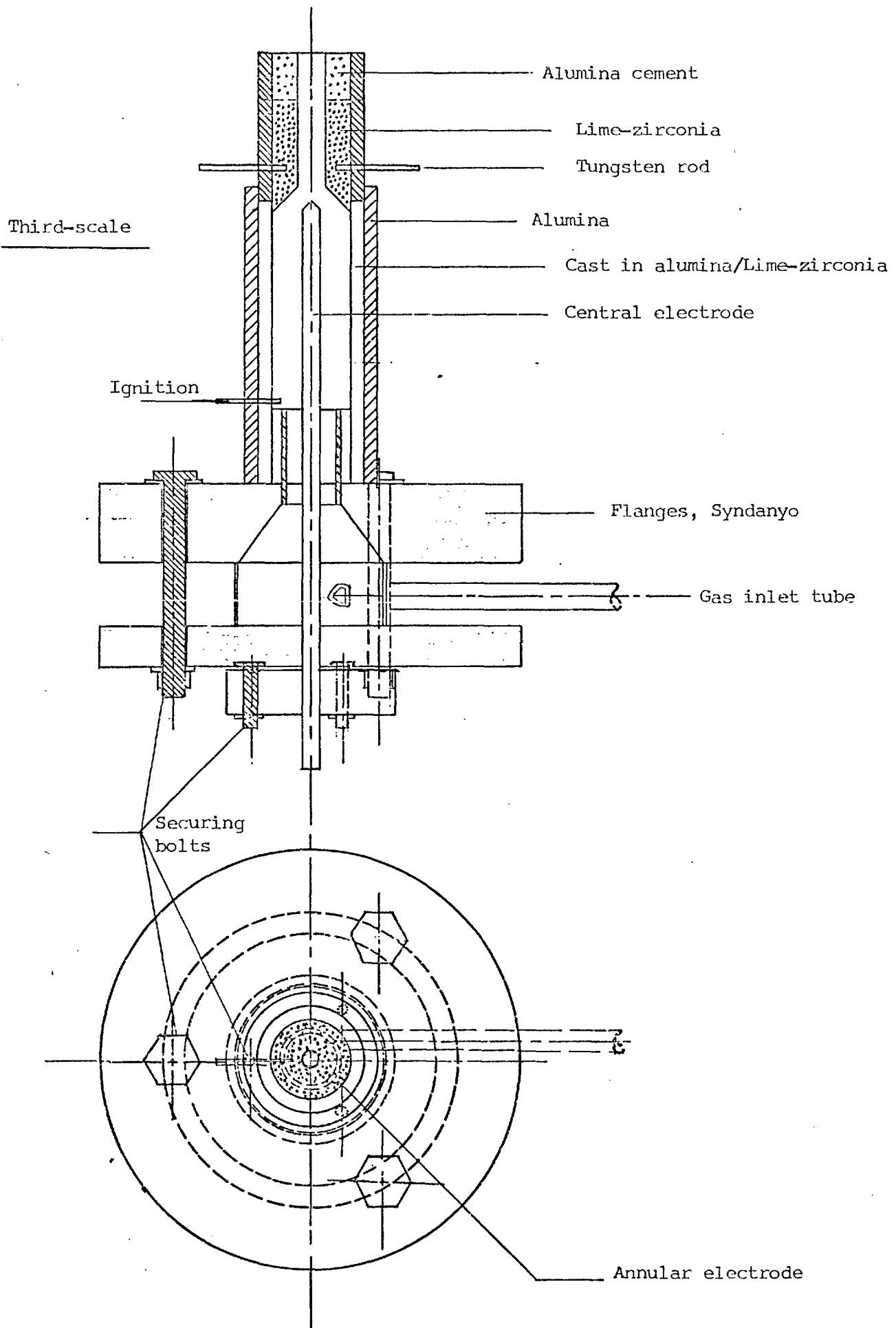


Figure 4-2. Large burner.

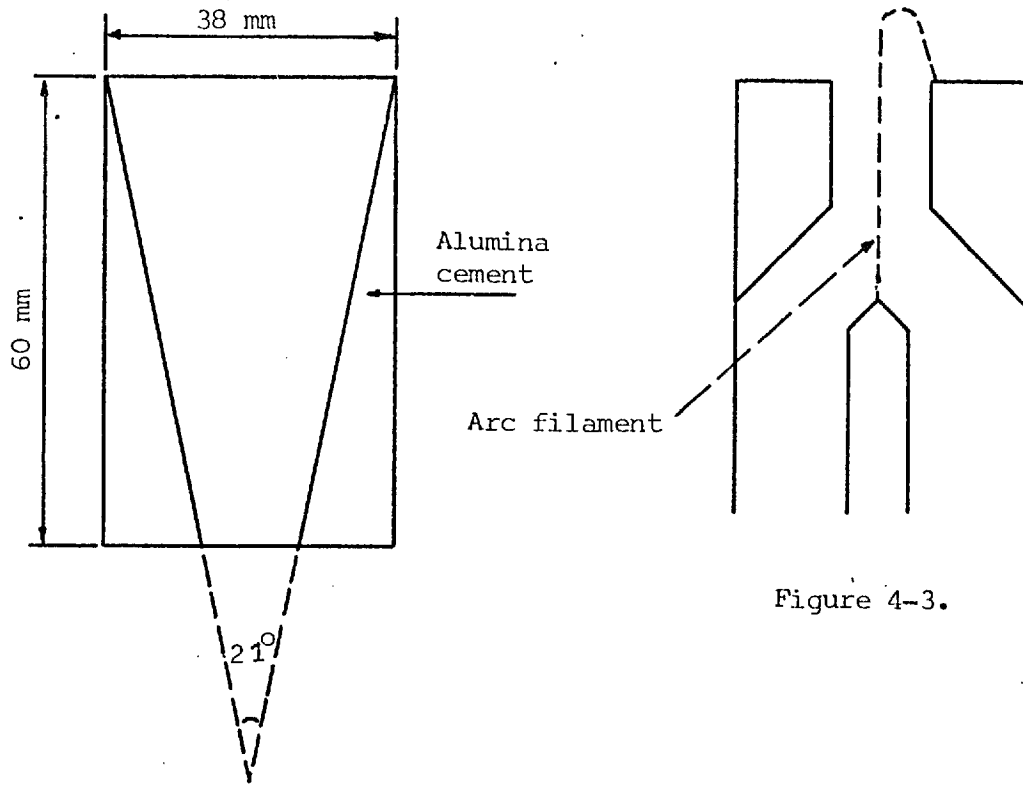


Figure 4-3.

Figure 4-4.

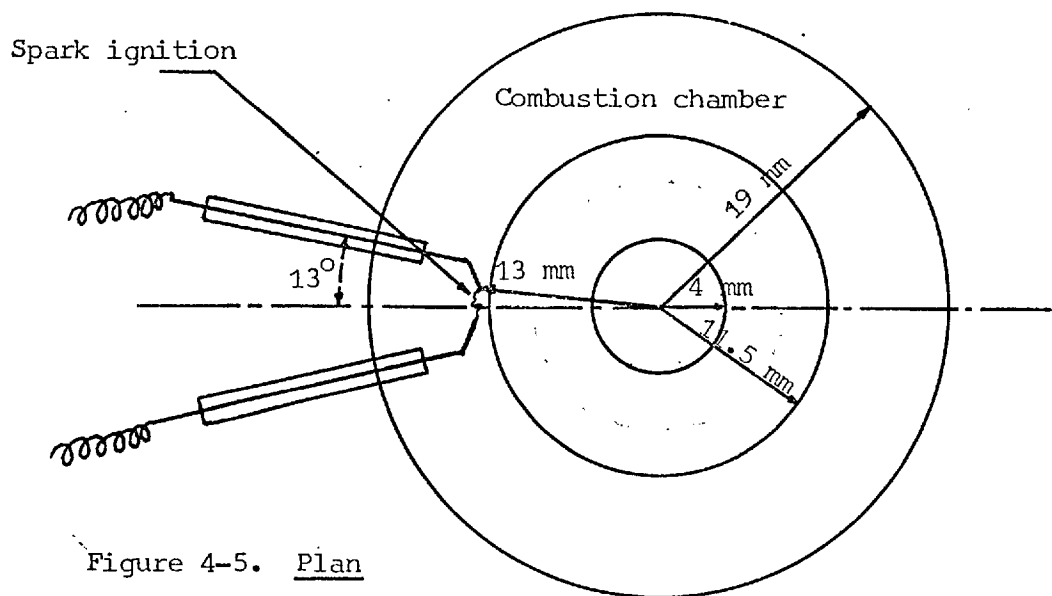


Figure 4-5. Plan

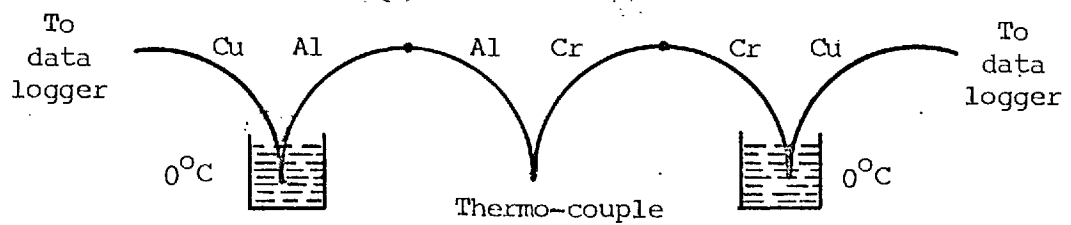


Figure 4-10.

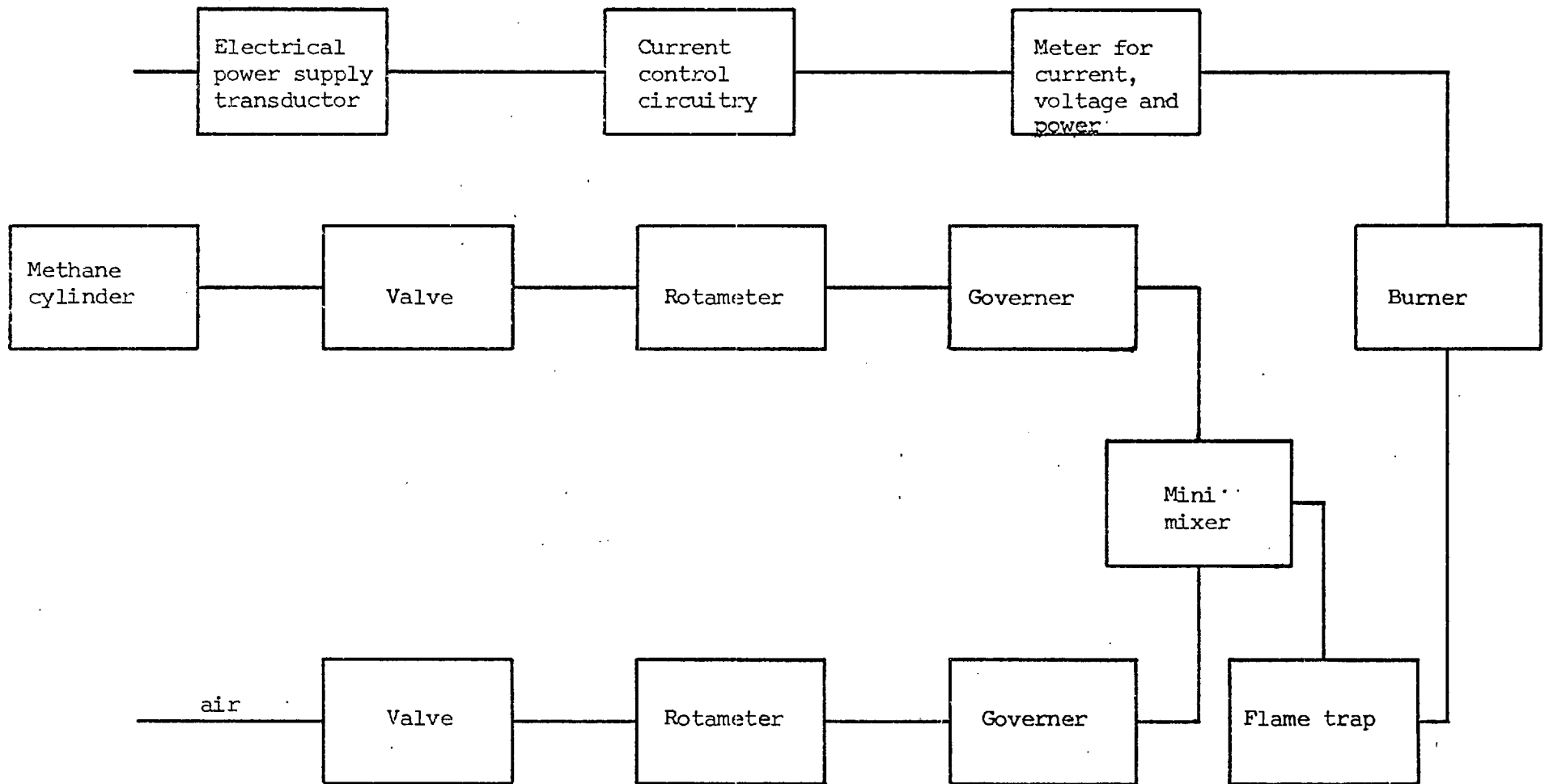


Figure 4-6. A block diagram of the large burner system.

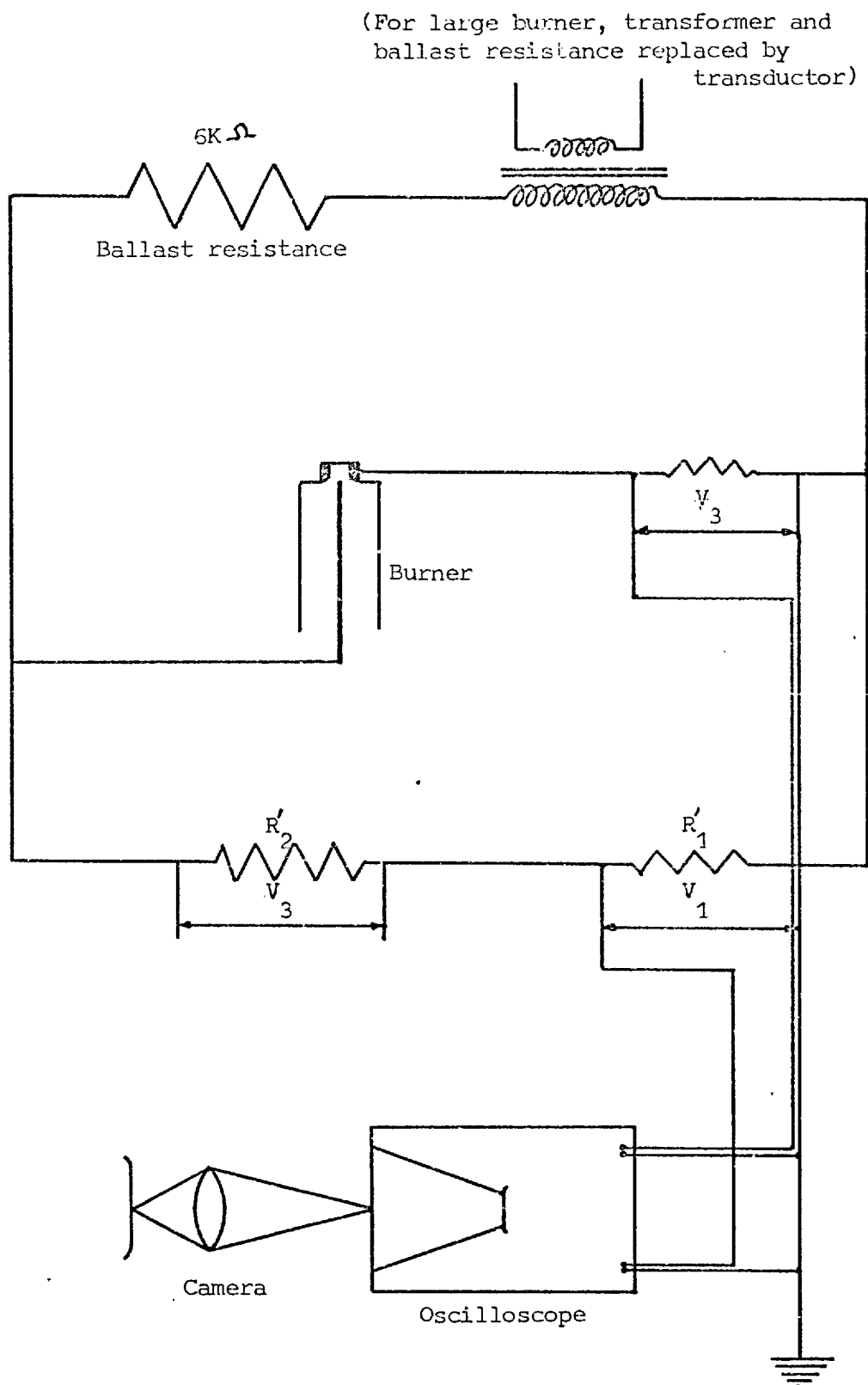


Figure 4-7. Circuitry for obtaining voltage and current.

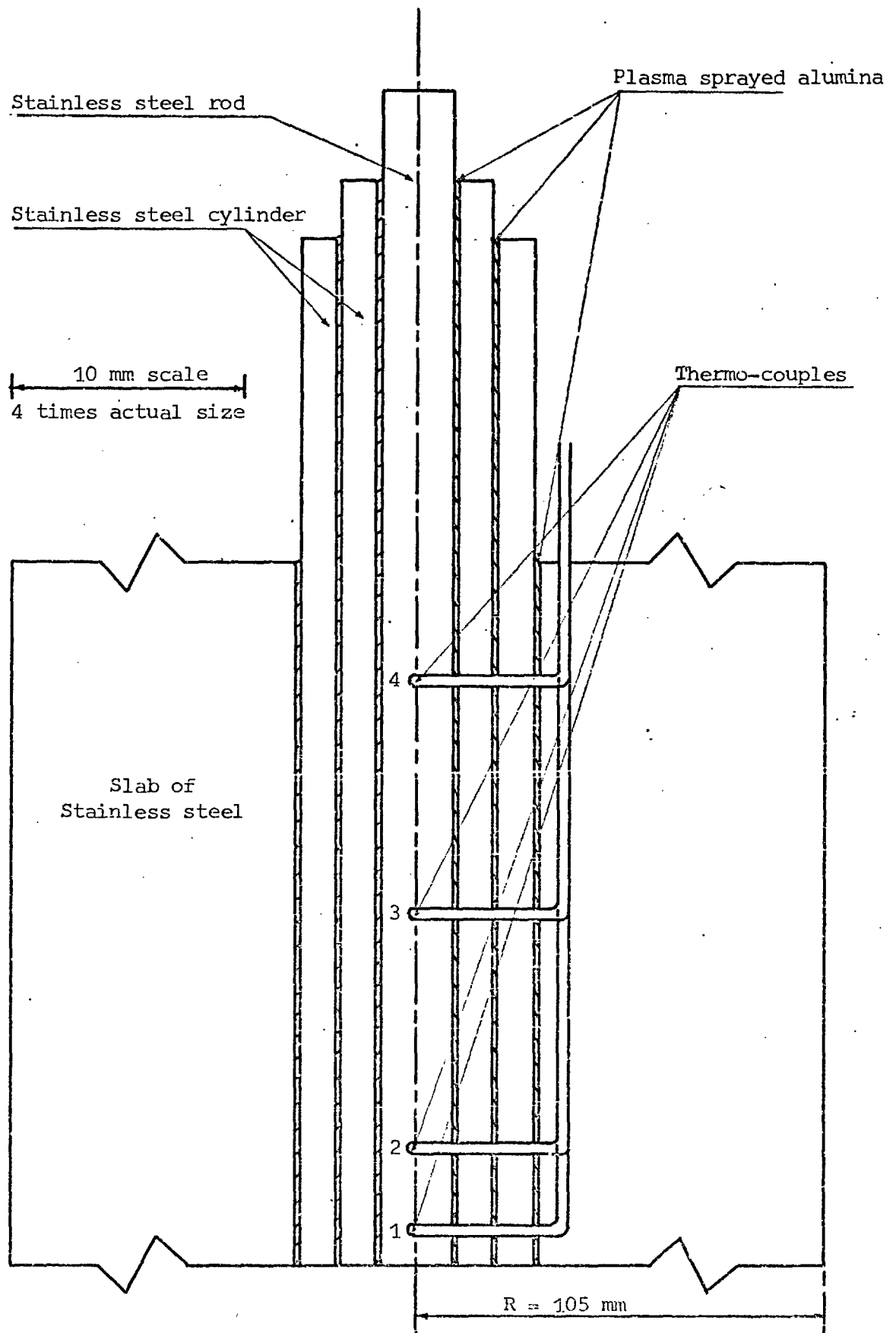


Figure 4-B. Heat flux meter in slab.

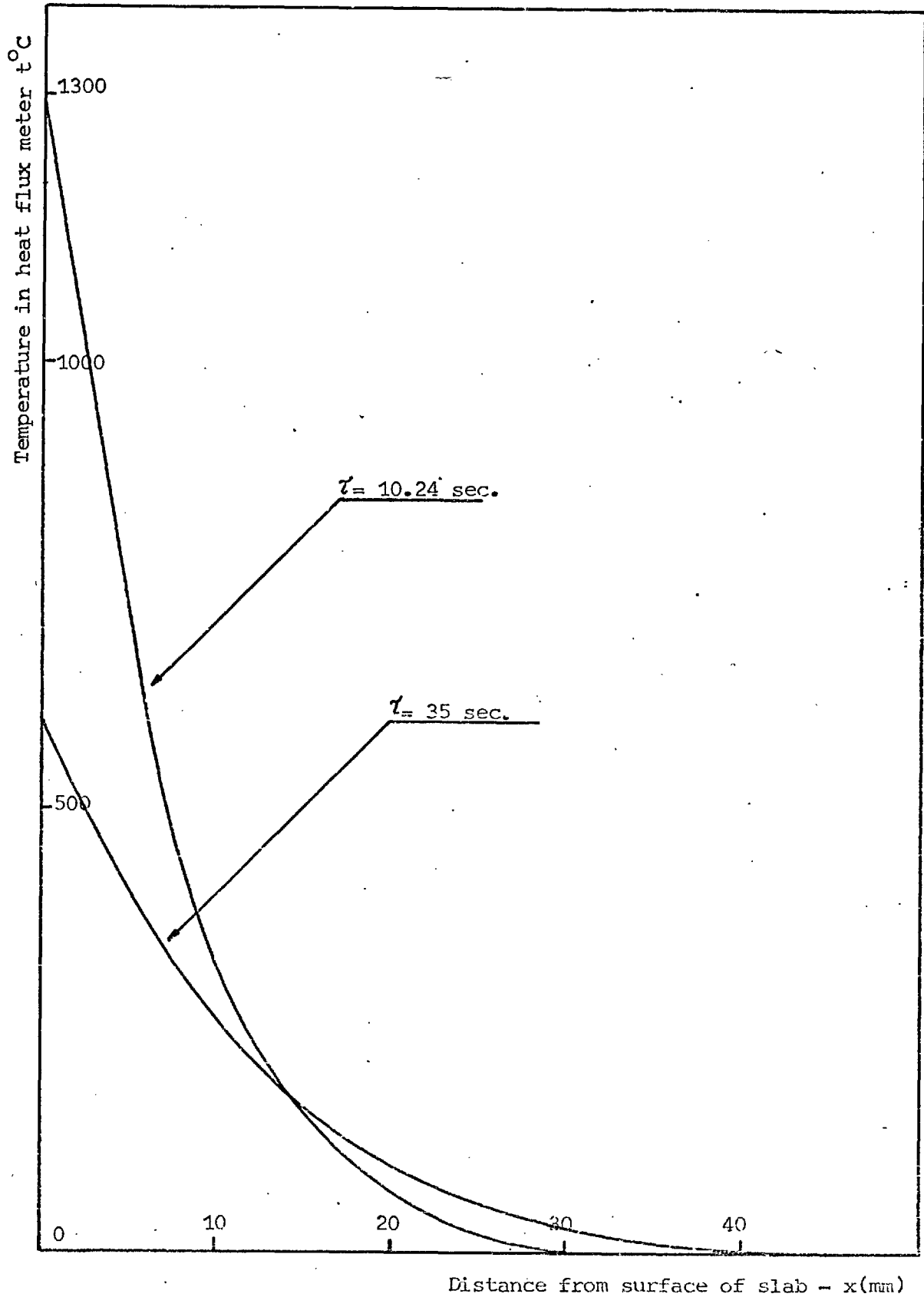


Figure 4-9. Temperature profile in the heat flux meter

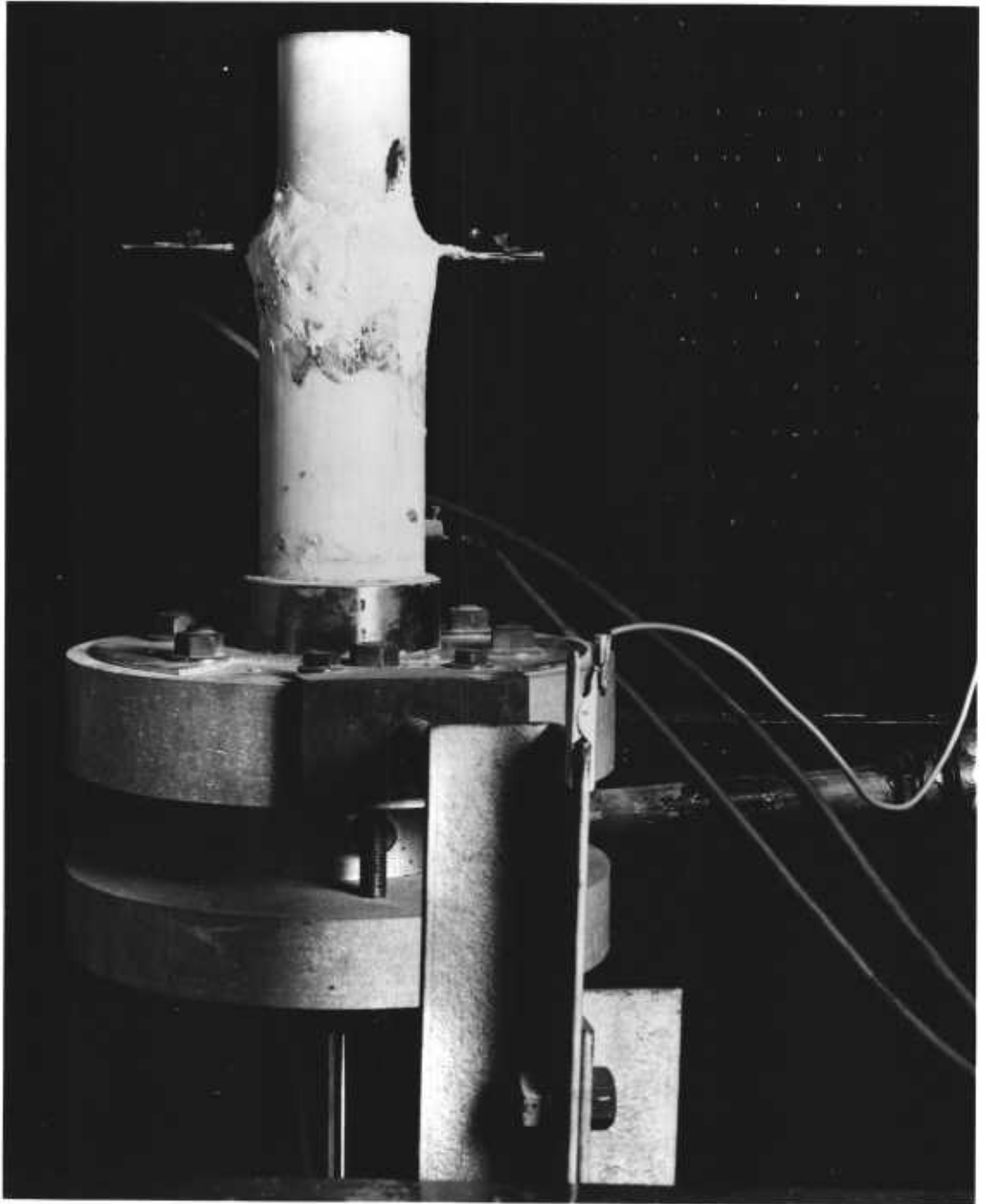


PLATE 1. Large burner

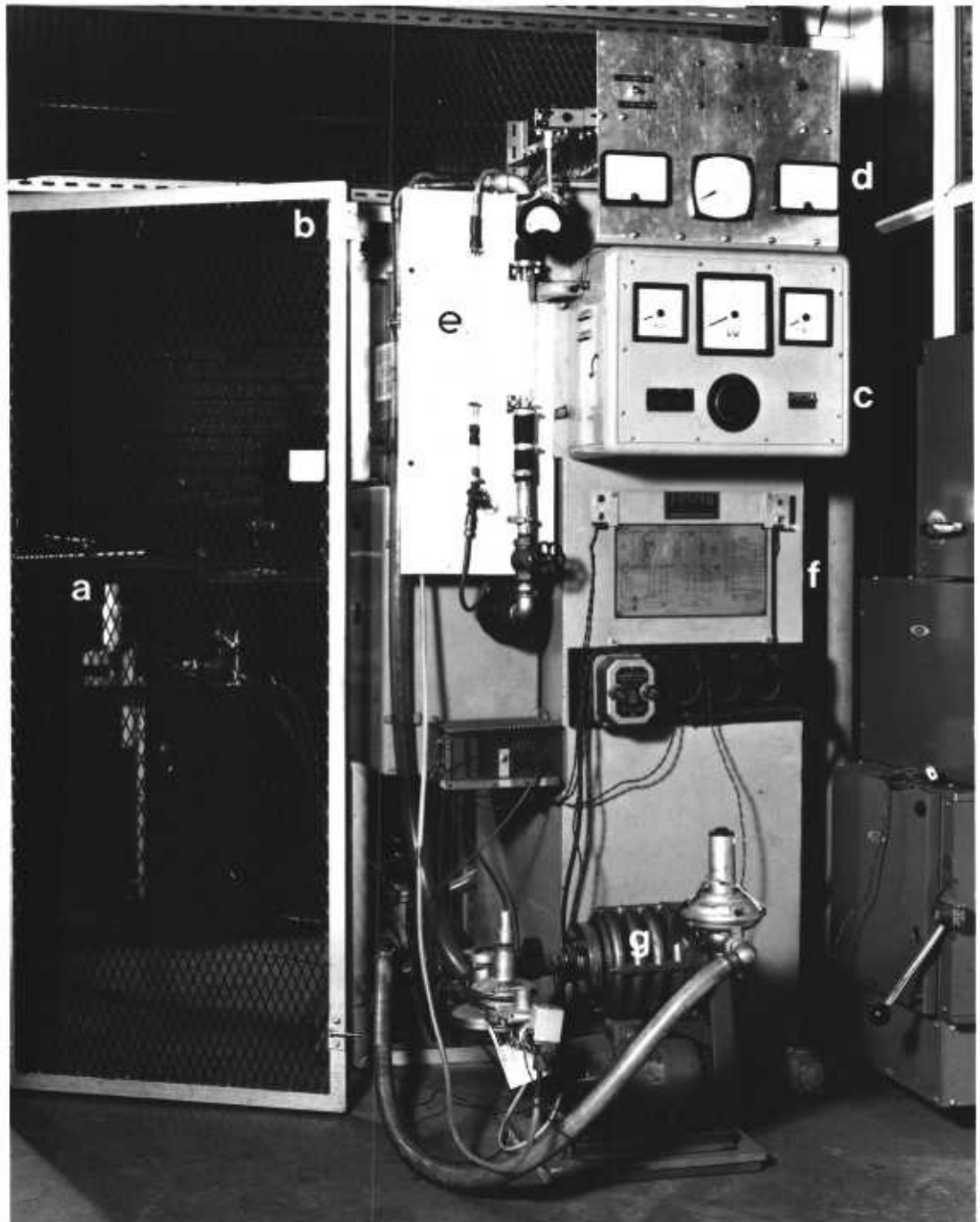


PLATE 2. Transducer, earthed cage and large burner.

- a) burner b) cage door interlock
c) high range meters d) low range meters
e) gas flow meters f) transducer
g) mini mixer

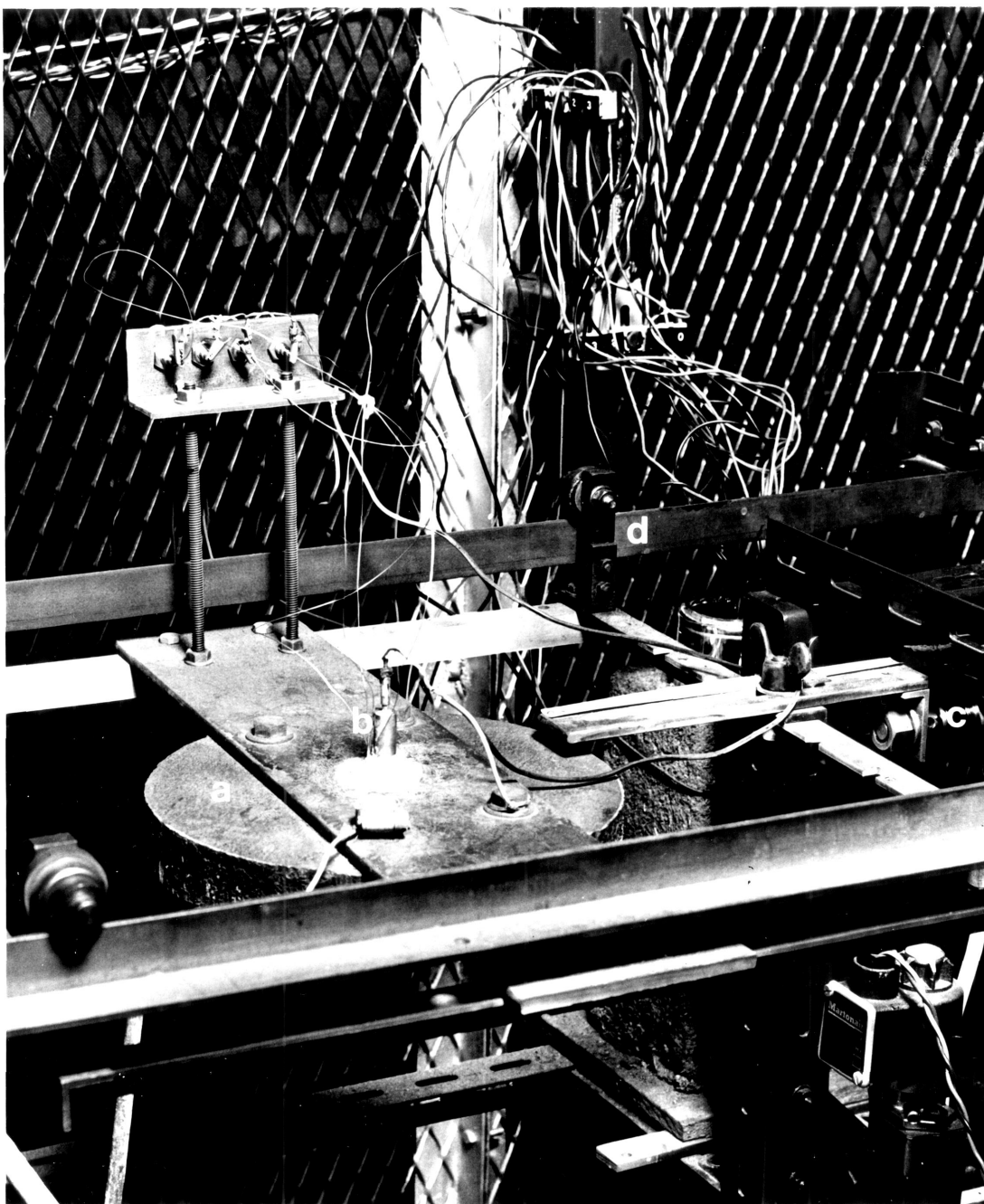


PLATE 3. Heat flux meter

- a) slab b) heat flux meter c) air cylinder
d) trolley

Chapter 5

Experimental Techniques

- 5-1. Development of both burners.
- 5-2. Flame temperature.
- 5-3. Use of oscilloscope to obtain voltage and current.
- 5-4. Use of heat flux meter.

5-1. Development of both burners.

A - Small burner

a - Electrodes:

Various materials were used as the central and annular electrodes for the small burner which are described below:

- (i) Tungsten rod as a central and lime-zirconia as annular electrode.
- (ii) Carbon in the form of rods of dense graphite as the central and annular electrode.
- (iii) Various compositions of lime-zirconia and ceria as central and annular electrode.
- (iv) Lime-zirconia as central and annular electrode.
- (v) Carbon as the central and lime-zirconia as annular electrode.
- (vi) Zirconium diboride as central and annular electrodes.

All the electrode materials suffered from erosion. The graphite was oxidised rapidly at flame temperatures. Ceria was mechanically unstable. Zirconium diboride changed from black to white possibly indicating a chemical change to zirconia. The tungsten rod was gradually oxidised and a yellow powder (tungstic oxide) was formed. Zirconia-lime was found to be stable although some melting occurred at the arc attachment point. Zirconia electrodes were therefore used for experiments with the small burner.

b - Burner operation:

The gas mixture, comprising $16.7 \times 10^{-6} \text{ m}^3 \cdot \text{sec}^{-1}$ of methane

and at least $167 \times 10^{-6} \text{ m}^3 \cdot \text{sec}^{-1}$ of air, was ignited in the combustion chamber with the annular electrode removed. When the flame had become stable in the combustion chamber, the electrode was replaced and a few minutes were allowed for the electrodes to become sufficiently hot for thermionic emission to occur. The supply of 3.2 KV a.c. was switched on across the electrodes and the arc was initiated. The arc could be switched on and off repeatedly without damaging the electrodes.

When the arc had been initiated and the methane flow was $13.3 \times 10^{-6} \text{ m}^3 \cdot \text{sec}^{-1}$ the air flow could be reduced to $65 \times 10^{-6} \text{ m}^3 \cdot \text{sec}^{-1}$ before the flame lifted out of the combustion chamber and became a diffusion flame stabilized on top of annular electrode. Without the arc this phenomenon occurred at an air flow of $101 \times 10^{-6} \text{ m}^3 \cdot \text{sec}^{-1}$. In a similar fashion the air flow could be increased to $224 \times 10^{-6} \text{ m}^3 \cdot \text{sec}^{-1}$ before blow off occurred but without the arc blow off occurred at $200 \times 10^{-6} \text{ m}^3 \cdot \text{sec}^{-1}$ of air. These limits can be seen in figure 6-6 page 103.

B - Large burner

The larger burner which was designed for the heat transfer studies was capable of burning at least $167 \times 10^{-6} \text{ m}^3 \cdot \text{sec}^{-1}$ of methane instead of $16.7 \times 10^{-6} \text{ m}^3 \cdot \text{sec}^{-1}$ burnt in the small burner, and so the diameters of the components of the smaller burner were increased by a factor of $\sqrt{10}$. The modifications required to scale-up the small vortex stabilized burner are detailed below:

a - Central electrode:

- (i) First of all, the central electrode was made in three parts

from alumina, metamic and zirconia. Metamic is a cermet of molybdenum and alumina which contains 80% metal by weight and will stand up to 1900°C . The zirconia tip was pressed at up to 3000 MN/m^2 pressure and was fired at 1400°C for two hours and was mounted in the metamic tube by a tungsten rod and alumina cermet. Figure 5-1 shows the construction of the electrode. After a few minutes of running the burner a yellow gas was emitted from the burner which indicated that the molybdenum was oxidizing. The metamic was then easily broken and was found to be nonconducting.

(ii) Then the zirconia tip was cemented to the top of an alumina tube. Electrical connection to the zirconia was made using a tungsten rod and a platinum wire, as shown in figure 5-2. As a result of augmentation with a relatively low current of about 2 amps. for about 1 hour, a small hole appeared in the side of the tip near the tungsten rod and in fact the arc had struck between the tungsten and the annular electrode.

(iii) Finally the tungsten rod was replaced by platinum wire. This seemed to be satisfactory for low currents over about 2 hours. Figure 5-3 shows this electrode.

(iv) A more durable electrode was achieved by using a tungsten rod of 8 mm diameter. The rate of oxidation could be kept low by burning the methane with less than its stoichiometric air requirement.

b -- Annular electrode:

The platinum wire used in the annular electrode of the small burner was found to be unsatisfactory in the large burner. This problem was solved by using two tungsten rods fitted into two holes

on the opposite sides of the annulus.

The technique of removing the annular electrode for igniting the mixture in the small burner was unsatisfactory for the large burner. The annular electrode had to be cemented in position to prevent leakage caused by the upward force on the annular electrode due to the flow of the combustion products.

The arc which was produced in the larger burner was observed to attach itself to the top surface of the annular electrode as shown in figure 4-3. In order to prevent this attachment a larger tube was chosen for the annular electrode and the top of the electrode was filled with alumina cement. A longer annular electrode also had the advantage of giving more opportunity for the hot combustion products to mix and obtain a more uniform temperature, but had the disadvantage of increasing the heat loss from the burner.

c - Burner operation:

The mixture was ignited by a spark which was passed between two electrodes in the combustion chamber. Ignition could only be achieved when the methane and air flow rates were controlled at 108.5×10^{-6} to $1400 \times 10^{-6} \text{ m}^3 \cdot \text{sec}^{-1}$ respectively. The burner was then operated at $14.2 \times 10^{-6} \text{ m}^3 \cdot \text{sec}^{-1}$ of methane and $1420 \times 10^{-6} \text{ m}^3 \cdot \text{sec}^{-1}$ of air for 15 minutes in order to heat the electrodes before electrical power was supplied to the electrodes from the transducer. The flow rate could be varied from 50×10^{-6} to $265 \times 10^{-6} \text{ m}^3 \cdot \text{sec}^{-1}$ methane for the stoichiometric mixture. The potential applied to the electrodes was about 1.2 KV for a distance between the electrodes of 8 mm.

5-2. Flame temperature

The temperature of the flame of the small burner with and without augmentation was measured by the line reversal technique, the apparatus for which is shown in figure 5-4. Light from a strip-filament tungsten lamp T is focused with a lens L₁ to give an image of the filament in the flame F. A second lens L₂ then forms an image of both flame and lamp on the slit of a spectroscope. Sodium was introduced into the flame by entraining particles of sodium chloride in the combustion mixture entering the burner.

A correction has to be made to the calibration of the lamp. A five percent decrease in emissivity was necessary (24) because the light from the background source is weakened by reflection losses in passing through the lens L₁ whereas that from the flame is not.

5-3. Use of oscilloscope to obtain voltage and current.

A twin beam oscilloscope was used to display voltage and current transients during the a.c. discharge in the burners. The method is described below:

A - Small burner

From photographs of the oscilloscope traces, the R.M.S. values of voltages and currents under different operating conditions were calculated. Method of calculation is given in chapter 6. The initiation voltage and also the proportion of the a.c. cycle during which arcing occurred were determined. According to figure 4-7 the voltage between the two burner electrodes can be calculated as follows:

$$\frac{V_1}{V} = \frac{R'_1}{R'_1 + R'_2} \quad \text{or} \quad V = V_1 \cdot \frac{R'_1 + R'_2}{R'_1} \quad (5-1)$$

and the current passing through the electrodes can be calculated from,

$$A = \frac{V_3}{R_3} \quad (5-2)$$

where V is the potential between the two electrodes and A is the current passing through the electrodes V_1 and V_3 can be calculated from the oscilloscope traces, and R'_1 , R'_2 and R'_3 for both burners are given on page 57.

B -- Large burner

The voltage between the burner electrodes was monitored on the oscilloscope using a potential divider as explained earlier on page 57. A series of electric fire elements was used in place of the burner and from photographs of the oscilloscope traces, the existing meters on the power supply were calibrated. The calibration was found to be difficult at low voltages and currents because of the large range of meters. A further range of meters were added to the previous ones in order to measure low values of voltage, current, and power. A schematic diagram of this set-up is shown in figure 5-5 and they appear on plate 3 page 69.

A step down transformer is used to reduce the output voltage of the transducer by $\frac{1}{60}$ in order that low voltage meters can be used. A 0-50 volt moving iron meter was installed in parallel with the existing 0-80 KV meter. Similarly, a current transformer is used to reduce the current by a half and a 0-2 ammeter was put in series with the existing 0-10 ammeter. The power was measured using 0-100 watt transducer type wattmeter which was installed to supplement the existing 0-80 KW instrument.

5-4. The use of the heat flux meter.

The heat flux meter described in section 4 was used to determine the surface heat flux from the larger burner to a slab, as described below. The slab was adjusted to a height h above the burner with the heat flux meter at a known position relative to the burner axis. The slab was then retracted. The burner was ignited and controlled under known operating conditions for about 10 minutes so that it reached the steady state. The data-logger was then switched on to register the emf of the thermo-couples in the slab at room temperature. The thermo-couples were scanned at a rate of 10 per second. Then the slab was moved rapidly into position over the burner by operating the air cylinder using a switch situated outside the earthed cage. The time taken for the heat flux meter to remain above the burner varied between 30 and 90 seconds depending on the maximum value of the temperature of the surface of the slab that was required. After that time the slab was removed from the flame by operating the air cylinder. Prior to the next run the surface of the slab was cleaned and polished with fine emery paper when it was at room temperature. Plate 4 shows a plan view of the larger burner and the heat flux meter ready to move over the burner.

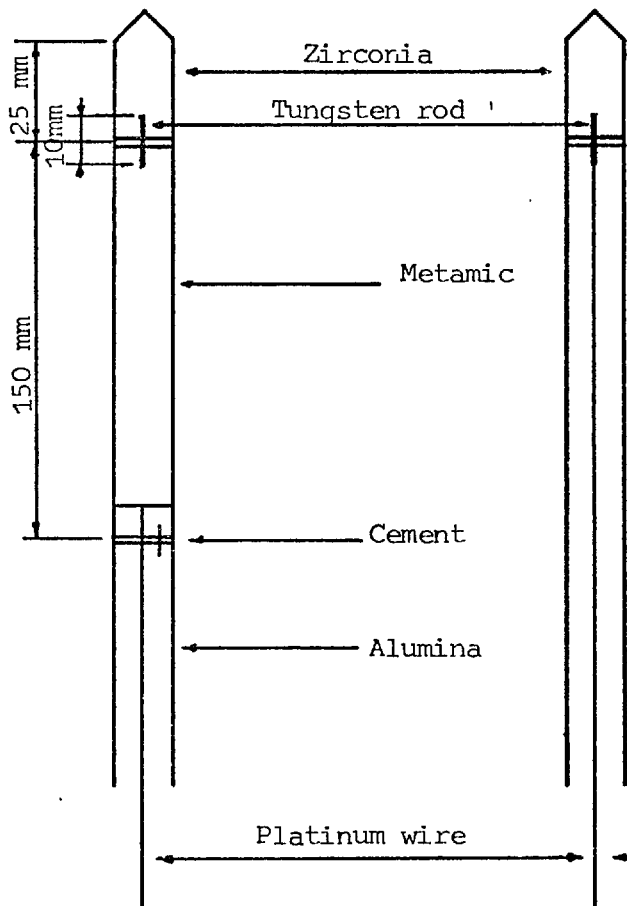


Figure 5-1.

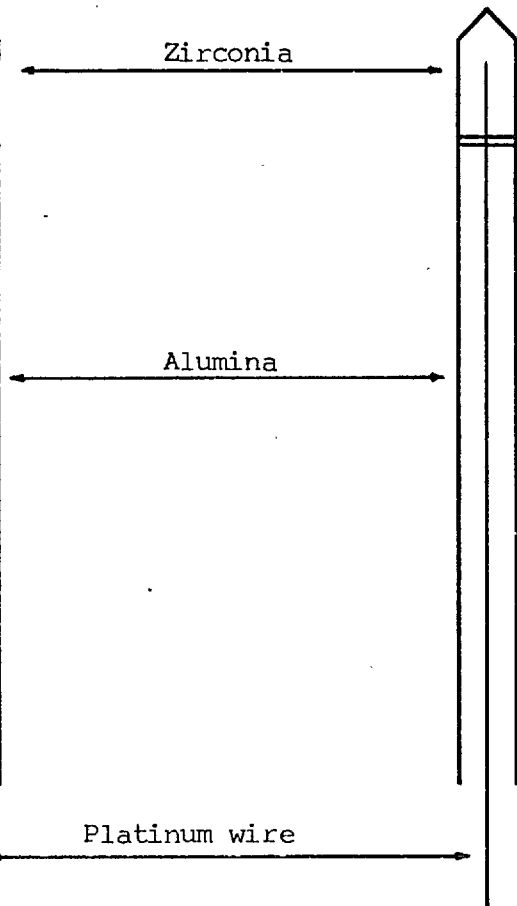


Figure 5-2.



Figure 5-3.

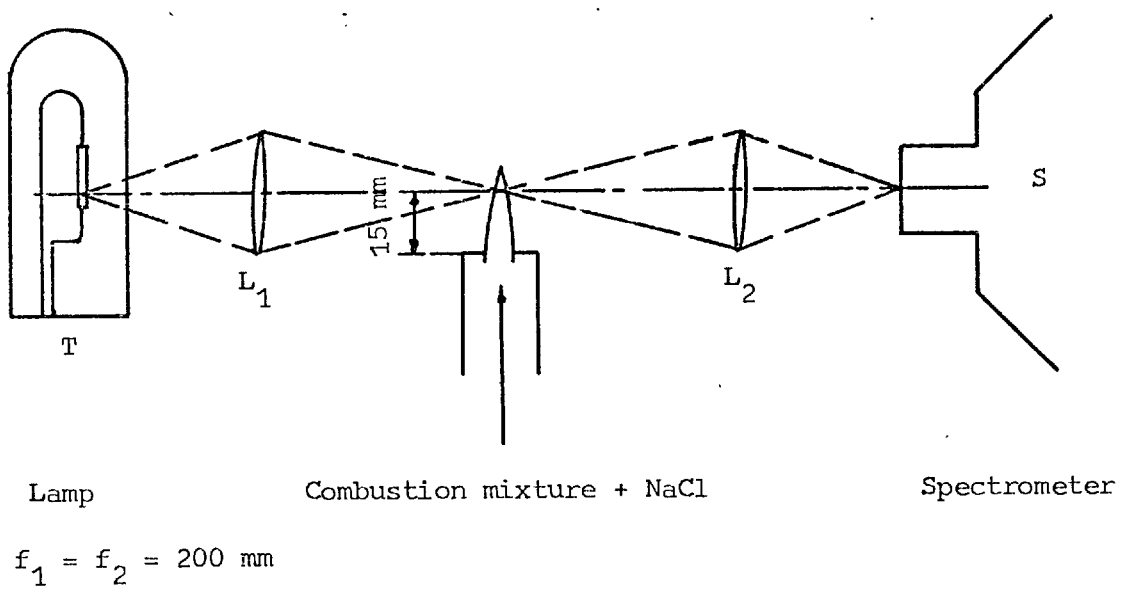


Figure 5-4.

- 1,2 - Switches
 3,4 - Fuse
 5 - Ammeter 0-2 amps.
 6 - Wattmeter 0-100 watts
 7 - Voltmeter 0-50 volts
 8 - Ammeter 0-750 milliamps
 9 - terminal connection
 10 - Ammeter 0-10 amps.
 11 - Wattmeter 0-80 KW
 12 - Voltmeter 0-8 KV
 M and L - Current
 V_1 and V_2 - Voltage

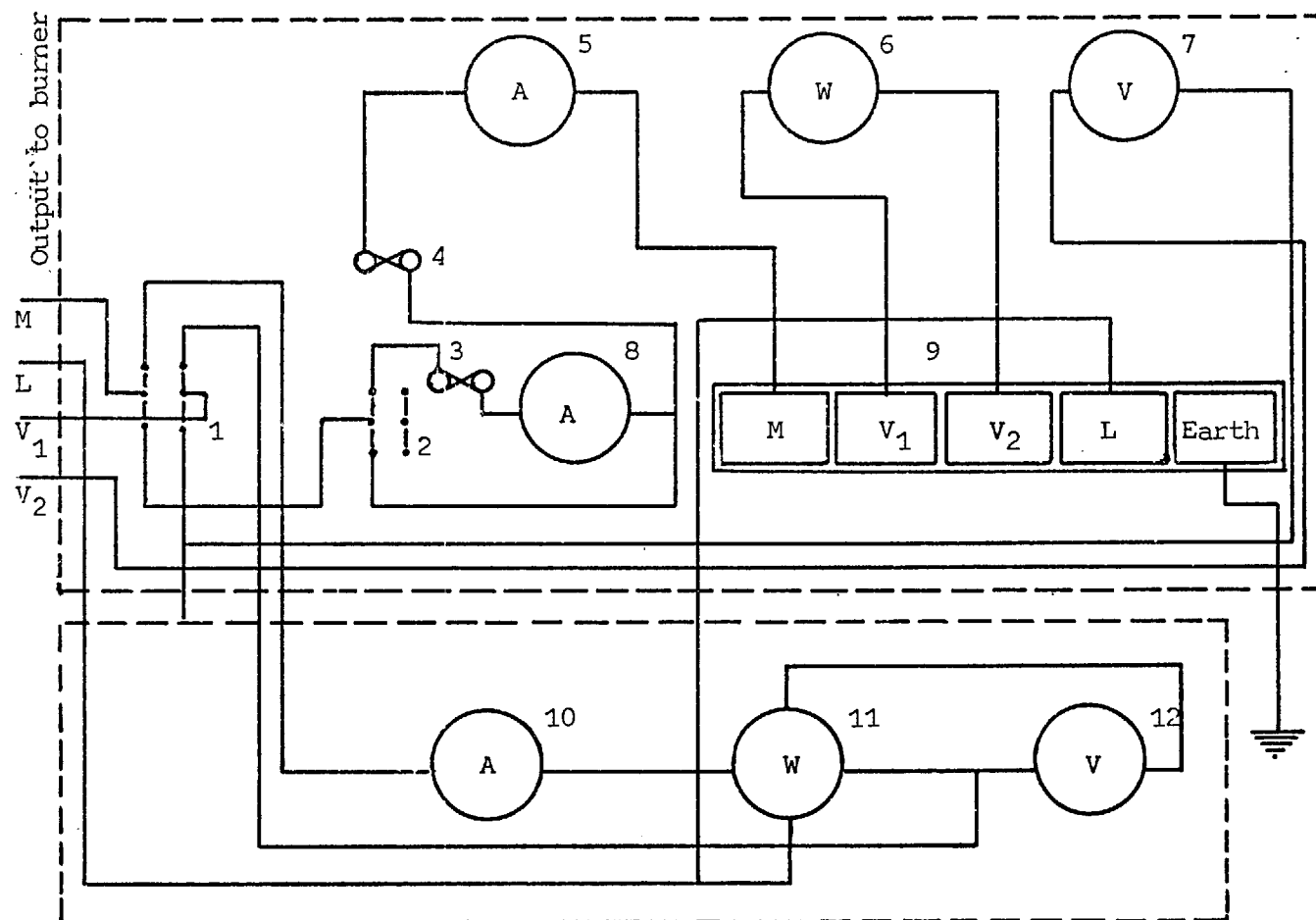


Figure 5-5. Circuit diagram of meters.

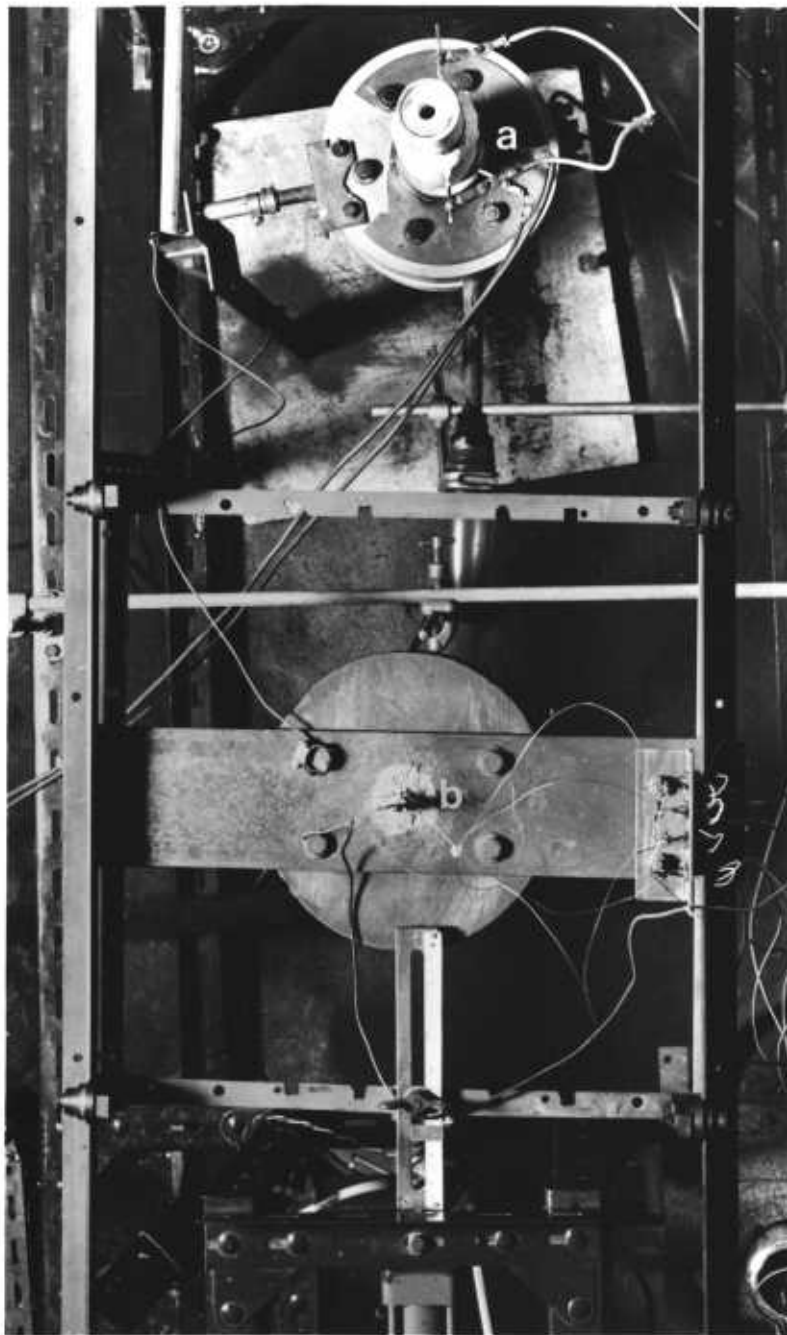


PLATE 4. Plan of burner and heat flux meter

a) burner b) heat flux meter

Chapter 6

Results

6-1. Burner operation.

- A - Electrode life.
- B - Voltage and current transients.
 - a - Effective voltage and current.
 - (i) Variation of electrode gap.
 - (ii) Variation of air flow rate.
 - (iii) Variation of total gas flow rate.
 - (iv) Zirconia-ceria mixtures.
- C - Flame temperature.
- D - Current and voltage output from the transducer.
- E - Stability limits of larger burner.

6-2. Heat transfer to the surface of the slab.

- A - Axial distribution.
- B - Radial distribution.
- C - The effect of gas flow rate on the heat flux.
- D - The effect of the ratio of air to fuel on the
heat flux.
- E - Boost ratio.

6-1. Burner operation.

Some of the experimental observations which were made during the operation of the small and large burner have been described in section 5. The electrode life, voltage and current transients, stability limits, and flame temperature are given below:

A - Electrode life

The life of the zirconia electrode in the small burner was about 50 hours. During this time one replacement central electrode was necessary. The burner was operated on about 300 occasions before it was necessary to replace the central electrode.

The large burner was operated for longer times of about 25 minutes. The annular electrode required replacement after about 20 hours, because a small hole appeared in the zirconia near the tip of one of the tungsten rods and in fact the arc struck between the tungsten rod in the annular electrode and the tungsten central electrode.

The central electrode of tungsten was found to erode at an average rate of 0.1 mm reduction per hour, and 2 per cent reduction in weight.

B - Voltage and current transients for the small burner

Plate 5-a shows photographs of the oscilloscope traces obtained for a 50 HZ, 3.2 KV arc across the burner electrodes with a 6 kilohm resistance in series. The voltage and current scale is shown beside the photographs and each half-cycle corresponds to 0.01 second. A stoichiometric gas flow rate of $13.3 \times 10^{-6} \text{ m}^3 \cdot \text{sec}^{-1}$ methane was used and the gap between the zirconia electrodes

was 3.7 mm.

a - Effective voltage and current:

The effective R.M.S. values of voltage and current are given by:

$$V_{R.M.S.} = \sqrt{\frac{1}{T} \int_0^T V^2 dt} \quad (6-1)$$

$$I_{R.M.S.} = \sqrt{\frac{1}{T} \int_0^T I^2 dt} \quad (6-2)$$

where T , the periodic time of the wave, is equal to $\frac{2\pi}{\omega}$.

Consider one half-cycle only, and divide this into n equal parts of $\frac{0.01}{n}$ second each to give n ordinates of $i_1, i_2, i_3 \dots$ etc. The R.M.S. values of voltage and current were then calculated as follows:

$$V_{R.M.S.} = \sqrt{\frac{v_1'^2 + v_2'^2 + v_3'^2 + \dots}{n}} \quad (6-3)$$

$$I_{R.M.S.} = \sqrt{\frac{i_1'^2 + i_2'^2 + i_3'^2 + \dots}{n}} \quad (6-4)$$

In the following experiments the half-cycle was divided into ten equal parts ($n=10$) as is shown in plate (6-a and b). Owing to variation between consecutive half-cycles, the average (R.M.S.) voltage and current for one complete cycle was calculated.

Various experiments were done to find the effect of various operating conditions on the voltage and current. They are explained below:

(i) Variation of electrode gap: Experiments were performed with methane and air flow rates of 15×10^{-6} and $150 \times 10^{-6} \text{ m}^3 \cdot \text{sec}^{-1}$ respectively using zirconia electrodes. The distance between the

electrodes was varied as explained on page 53 . The results are expressed graphically in terms of voltage, current and average striking voltage in figure 6-1. The proportion of the cycle during which arcing occurs is plotted against distance between the electrodes in figure 6-2.

(ii) Variation of air flow rate: In these experiments the methane flow rate was kept constant at $15 \times 10^{-6} \text{ m}^3 \cdot \text{sec}^{-1}$. The air flow rate was varied from 60×10^{-6} to $195 \times 10^{-6} \text{ m}^3 \cdot \text{sec}^{-1}$. The results are expressed graphically in figure 6-3 in terms of voltages and currents against the stoichiometric factor e in the gas flow. The distance between the zirconia electrodes was 3.2 mm.

(iii) Variation of total gas flow rate: Further experiments were carried out over a range of gas flow rates in which the methane to air ratio was maintained at the stoichiometric proportion. The separation between the zirconia electrodes was 3.7 mm. The R.M.S. values of voltage and current are plotted against the gas flow rate in figure 6-4.

(iv) Zirconia-ceria mixtures: Experiments were also done with various mixtures of zirconia and ceria as the material of construction of the central and annular electrodes. The R.M.S. values of voltage and current, at various zirconia-ceria compositions, were obtained and are plotted against composition in figure 6-5. The electrode gap was 3.7 mm and a stoichiometric mixture was used at a methane flow rate of $15 \times 10^{-6} \text{ m}^3 \cdot \text{sec}^{-1}$.

C - Flame temperature

The temperature of the flame in the small burner was measured using the sodium D-line reversal method which was described

on page 75. Figure 6-6 shows flame temperature plotted against stoichiometric factor e in the mixture both with and without the arc at a distance of 10 mm above the nozzle of the burner. The methane flow rate was kept constant at $13.3 \times 10^{-6} \text{ m}^3 \cdot \text{sec}^{-1}$ and the air flow rate was varied from 101 to $200 \times 10^{-6} \text{ m}^3 \cdot \text{sec}^{-1}$ for the flame without augmentation and from 65 to $224 \times 10^{-6} \text{ m}^3 \cdot \text{sec}^{-1}$ for the flame with augmentation.

D - Current and voltage output from the transducer

When the large burner was replaced by a resistance, the current and voltage reproduced by the oscilloscope can be seen in plate 5-b. This photograph was taken when a resistance of 660 ohms was used. The voltage and current traces have an approximately triangular shape as shown in figure 6-7. The R.M.S. values of voltage and current can be calculated on this basis using equations (6-1) and 6-2) as follows:

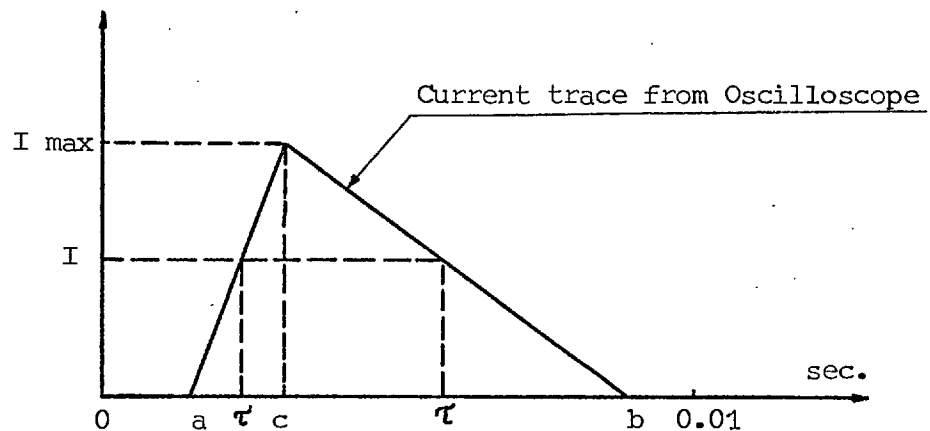


Figure 6-7.

$$I \text{ R.M.S.} = \sqrt{\frac{1}{\tau} \int_0^{\tau} I^2 dt} \quad (6-2)$$

$$\text{For } a < \tau < c \quad I = I \text{ max.} \cdot \frac{\tau - a}{c - a}$$

$$\text{For } c < \tau < b \quad I = I_{\max} \cdot \frac{b-\tau}{b-c}$$

$$\text{and } \int_a^b I^2 d\tau = I_{\max}^2 \left(\int_a^c \left(\frac{\tau-a}{c-a} \right)^2 d\tau + \int_c^b \left(\frac{b-\tau}{b-c} \right)^2 d\tau \right) =$$

$$I_{\max}^2 \left(\frac{c-a}{3} + \frac{b-c}{3} \right) = I_{\max}^2 \cdot \frac{b-a}{3}$$

$$\text{so we will have } I \text{ R.M.S.} = I_{\max} \sqrt{\frac{1}{\tau} \cdot \frac{b-a}{3}} \quad (6-5)$$

$$\text{and similarly } V \text{ R.M.S.} = V_{\max} \sqrt{\frac{1}{\tau} \cdot \frac{b-a}{3}} \quad (6-6)$$

From the above equations the R.M.S. values of voltages and currents when a number of different resistors replaced the burner were calculated and compared with the meter readings. The comparison is shown in table 6-1.

Actual readings of voltage, current and power are given in table 6-2 for various boost ratios. The run numbers correspond to run numbers given in table 6-3. The power factor $\cos \phi$ has been calculated from

$$\cos \phi = \frac{W}{VI} \quad (6-7)$$

and is also shown in table 6-2.

Run No.	B _E	V	I	W	Cos ϕ
7	0.27	1320	1.36	1.26	0.70
59	0.62	1300	2.8	2.93	0.82
44	0.81	1350	3.1	3.79	0.90
45	1.2	1380	4.2	5.66	0.98

Table 6-2.

E - Stability limits

The limits at which the flame was stable in the combustion chamber for the large burner with and without augmentation were determined by experiment. In each experiment the air flow rate was kept constant and the methane flow rate was varied between two limiting cases. The electrical power input was kept constant at 1.25 KW. The limits at which the flame blows off or forms a diffusion flame above the nozzle are shown in figure 6-8 where the limiting methane flow rate is plotted against the air flow rate. A line representing the stoichiometric mixture and the mixture required for ignition are also shown in the figure 6-8.

6-2. Heat transfer to the surface of the slab.

The heat flux meter which was used to measure the rates of heat transfer from the larger burner to the metal surfaces is described in section 4. The technique which was used to obtain results from this heat flux meter is explained in section 5. The experimental measurements and derived results are given below:

The emfs from the four thermo-couples were recorded on paper tape, using a data-logger at a rate of ten readings per second. The first increase in any of the emf readings above that corresponding to the initial slab temperature indicated that the slab had reached the region over the burner. This first increase in emf was recorded by the no. 1 thermo-couple at a point in time which was a minimum of 0.1 second and a maximum of 0.4 second after the time when the flame first impinged on the heat flux meter, because the data-logger was also scanning thermo-couples 2, 3 and 4 at 0.1 second intervals. Hence an average value of the time at which thermo-couple no. 1 first indicated a temperature above that the initial slab temperature was 0.25 second. Starting from this point for the augmented flame every tenth set of emf readings from the four thermo-couples was used in a computer program to be converted to temperatures in $^{\circ}\text{C}$, i.e. readings from the four thermo-couples were taken every four seconds. For the un-augmented flame readings were used from twentieth set of emf readings, therefore the first temperature profile was obtained at 8.25 second. Each set of four temperatures was fitted to a polynomial of temperature expressed in terms of distance from the surface of the slab. This gave a series of temperature profiles in the slab at various times. It should be noted that, if the polynomial is a quadratic, it cannot be fitted until at least three thermo-couples show temperatures above that of the initial slab temperature. A cubic can only

be fitted if all four thermo-couples show a rise in temperature.

These polynomials were then extrapolated to the surface of the slab to find the surface temperatures. The conductivity and the mean specific heat of the stainless steel (En 58A) at each surface temperature have already been found by fitting a third order polynomial to the data in table Ap.D to give equation (6-7) and a straight line to the data in table Ap.D to give equation (6-8) respectively.

$$k = 0.03752 + 0.9486 t \times 10^{-5} + 0.7551 \times 10^{-7} t^2 - 0.5685 \times 10^{-10} t^3 \quad (6-8)$$

$$\bar{c} = 0.120 + 0.232 \times 10^{-4} t \quad (6-9)$$

Since the thermal conductivity and the mean specific heat at any temperature have been calculated, the thermal diffusivity α can be found using equation (2-43).

The heat flux at various surface temperatures was then calculated using equation (2-48), and a computer programme developed in the course of this study. A flow chart of this programme is on pages 95 and 96, and a complete programme is in the appendix B. A typical series of ten temperature profiles by the computer is given in figure 6-9. A plot of experimental heat fluxes against surface temperature for different boost ratios is given in figure 6-10. Experiments were carried out with the slab at three different initial temperatures because it was found that when the slab is at room temperature, water vapour from the combustion products condensed on the surface of the slab at the beginning of an experiment. At higher surface temperatures this condensation did not occur. Figure 6-11 shows the heat flux plotted against surface temperature at three different initial temperatures of 26.2, 50 and 86.7°C.

Fifty experiments were done to determine heat fluxes under varying conditions of burner operation. Each experiment was identified by a run number. The conditions under which the burner was operated during each of the experiments are given in table 6-3 page 93 and and the emf readings corresponding to each run are given in the appendix A.

The heat flux from the flame to the slab with and without augmentation, was determined in the following experiments.

A - Axial distribution

The variation of heat flux with distance between the burner and the surface of the slab, with and without augmentation, and also with shield as described in section 4, was determined and is described below:

It was observed that without the shield flash back occurred for slab to burner distances less than 4 mm, and that the visible flame did not reach the surface of the slab for distances more than 50 mm.

The heat fluxes from the flame, without and with augmentation, to the surface were calculated from run numbers (1-6) and (7-10) and were plotted against surface temperature. From these results, the heat fluxes were plotted against slab to burner distance in figure 6-12. Run numbers (11-12) were carried out to find the effect of using a shield above the nozzle of the burner on the heat flux. The gap between the exit from the shield and the slab was 2.5 and 5 mm. The results are shown in the figure 6-12.

B - Radial distribution

Radial distributions of heat flux were determined by taking measurements along two flame diameters at right angles to each other. The gap between the nozzle of the burner and the surface of the slab was fixed at 5 mm. because the axial distributions shown in figure 6-12 indicate that the greatest heat fluxes occur at this distance. The heat fluxes obtained along two diameters at right angles both without augmentation (run numbers (13-16) and run number 1) and with augmentation (run numbers (17-20) and (21-24) and run number 7) are plotted against surface temperature. Radial distributions were obtained from these results and are shown in figure 6-13.

C - The effect of gas flow rate on the heat flux

Run numbers (25-29 and 1) and (30-34) were carried out in order to investigate the effect of various gas flow rates on the heat flux both without and with electrical augmentation.

Plots of heat flux against surface temperature without and with electrical augmentation were obtained and from them the effect of various stoichiometric gas flow rates on the heat flux at different slab temperatures is shown in figure 6-14.

D - The effect of the ratio of air to fuel on the heat flux

A further series of experiments was conducted to determine the heat fluxes that could be expected when the proportion of air in the gas mixture both with and without augmentation was varied. The heat fluxes were plotted against surface temperatures from run numbers (35-38 and 1) for the flame without augmentation and run numbers (39-43) for the flame with augmentation. From these plots

the heat fluxes were then plotted against stoichiometric in figure 6-15.

E - Boost ratio

The effect of boost ratio on the heat flux was found from run numbers (44-45, 41, 7 and 1). The heat fluxes were plotted against surface temperature and from them plots of heat flux against boost ratio are shown in figure 6-16.

Table 6-3. Series of heat flux experiments

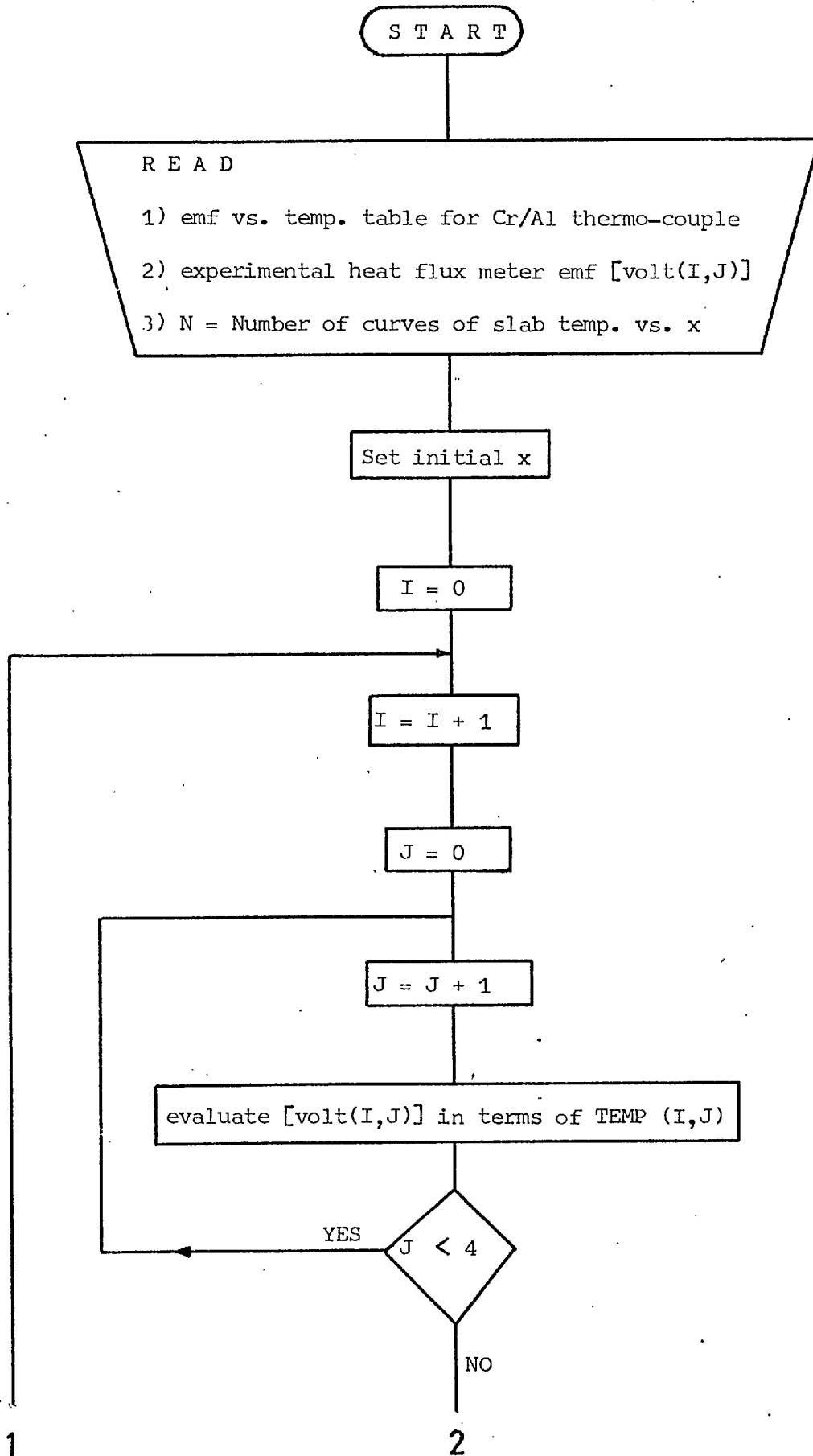
Run No.	Methane flow rate $\text{m}^3 \cdot \text{sec}^{-1} \times 10^6$	Air flow rate $\text{m}^3 \cdot \text{sec}^{-1} \times 10^6$	Axial position h(mm.)	Radial position R(mm.)	Boost ratio B_E	Stoichiometric factor e
1	142	1420	5	0	0	1
2	"	"	1	"	"	"
3	"	"	15	"	"	"
4	"	"	20	"	"	"
5	"	"	25	"	"	"
6	"	"	35	"	"	"
7	"	"	5	"	0.27	"
8	"	"	10	"	"	"
9	"	"	20	"	"	"
10	"	"	40	"	"	"
11*	"	"	5	"	"	"
12*	"	"	2.5	"	"	"
13	"	"	5	+10	0	"
14	"	"	"	-10	"	"
15	"	"	"	+20	"	"
16	"	"	"	-20	"	"
17	"	"	"	+10	0.27	"
18	"	"	"	-10	"	"
19	"	"	"	+20	"	"
20	"	"	"	-20	"	"
21	"	"	"	+10	"	"
22	"	"	"	-10	"	"
23	"	"	"	+20	"	"
24	"	"	"	-20	"	"

* gap between nozzle of the shield and heat flux meter

Table 6-3. (Continued)

Run No.	Methane flow rate $\text{m}^3 \cdot \text{sec}^{-1} \times 10^6$	Air flow rate $\text{m}^3 \cdot \text{sec}^{-1} \times 10^6$	Axial position h(mm.)	Radial position R(mm.)	Boost ratio Be	Stoichiometric factor e
25	111.6	1116	5	0	0	1
26	124.9	1249	"	"	"	"
27	158.3	1583	"	"	"	"
28	186.6	1866	"	"	"	"
29	211.6	2116	"	"	"	"
30	111.6	1116	"	"	0.27	"
31	124.9	1249	"	"	"	"
32	158.3	1583	"	"	"	"
33	169.9	1699	"	"	"	"
34	186.6	1866	"	"	"	"
35	142	1016.3	"	"	0	0.72
36	"	1282.8	"	"	"	0.90
37	"	1616	"	"	"	1.1
38	"	1857.6	"	"	"	1.27
39	"	1846	"	"	0.62	1.30
40	"	1704	"	"	"	1.20
41	"	1420	"	"	"	1
42	"	1136	"	"	"	0.80
43	"	994	"	"	"	0.70
44	"	1420	"	"	0.81	1
45	"	"	"	"	1.2	"
46	"	"	"	"	"	"
47	"	"	"	"	0	"

Block diagram of computer program



Block diagram of computer program (Continued)

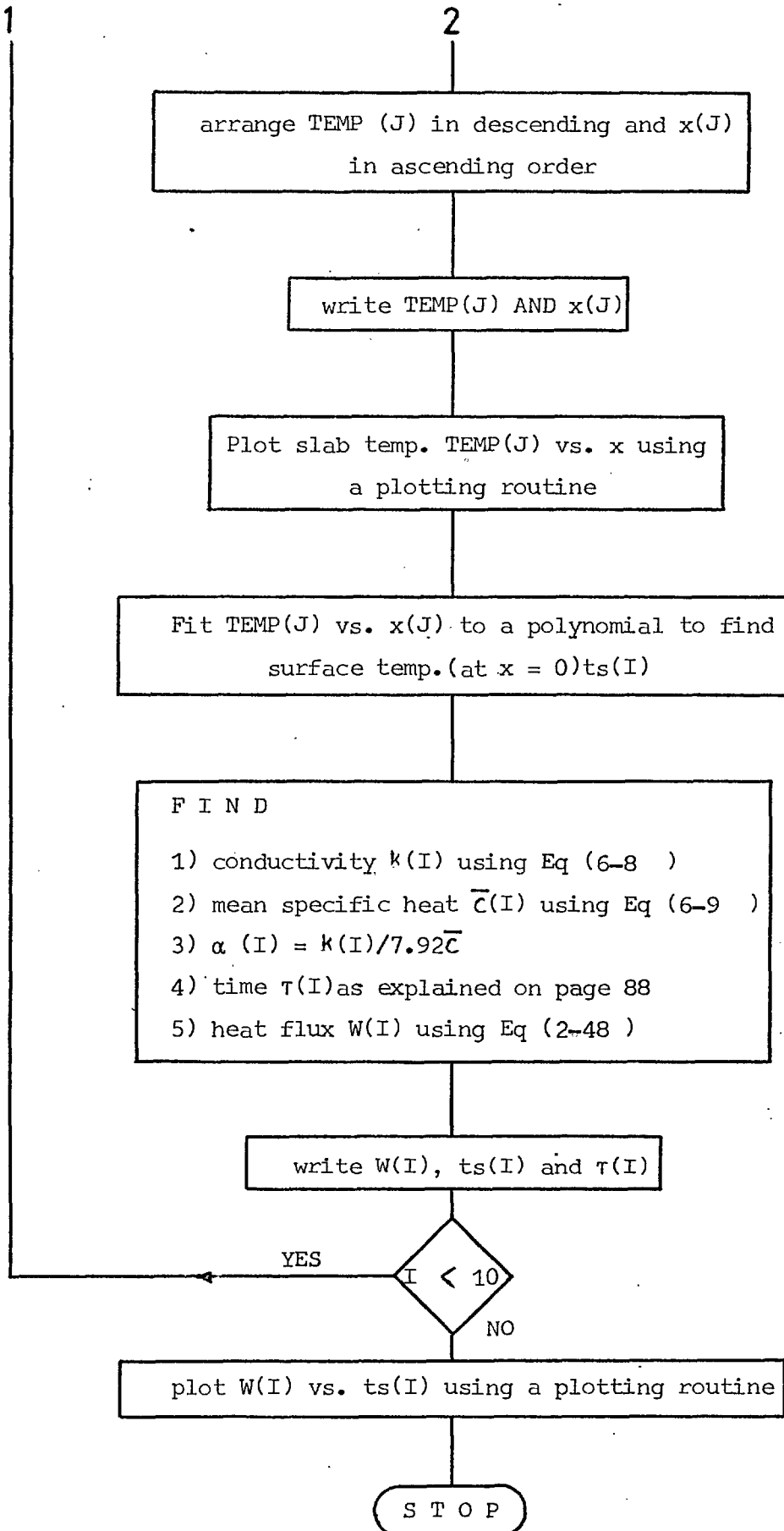


Table 6-1. Comparison between meter readings
and R.M.S. values based on Oscilloscope traces

	Resistance replacing Burner	Meter reading			R.M.S. values calculated from Oscilloscope traces		
No.	R Ohms	V Volts	I Amps	W KW	V Volts	I Amps	W KW
<u>1</u>	1650	1710	1.00	1.80	1740	1.00	1.74
<u>2</u>	1360	960	0.73	0.72	1000	0.76	0.76
<u>3</u>	1220	996	0.80	0.84	941	0.80	0.75
<u>4</u>	1220	2400	2.10	5.15	2450	2.00	4.9
<u>5</u>	880	2400	2.80	0.69	2420	2.90	0.70
<u>6</u>	660	1965	3.00	6.20	2030	2.90	5.90
<u>7</u>	430	1410	3.20	4.56	1370	3.1	4.32

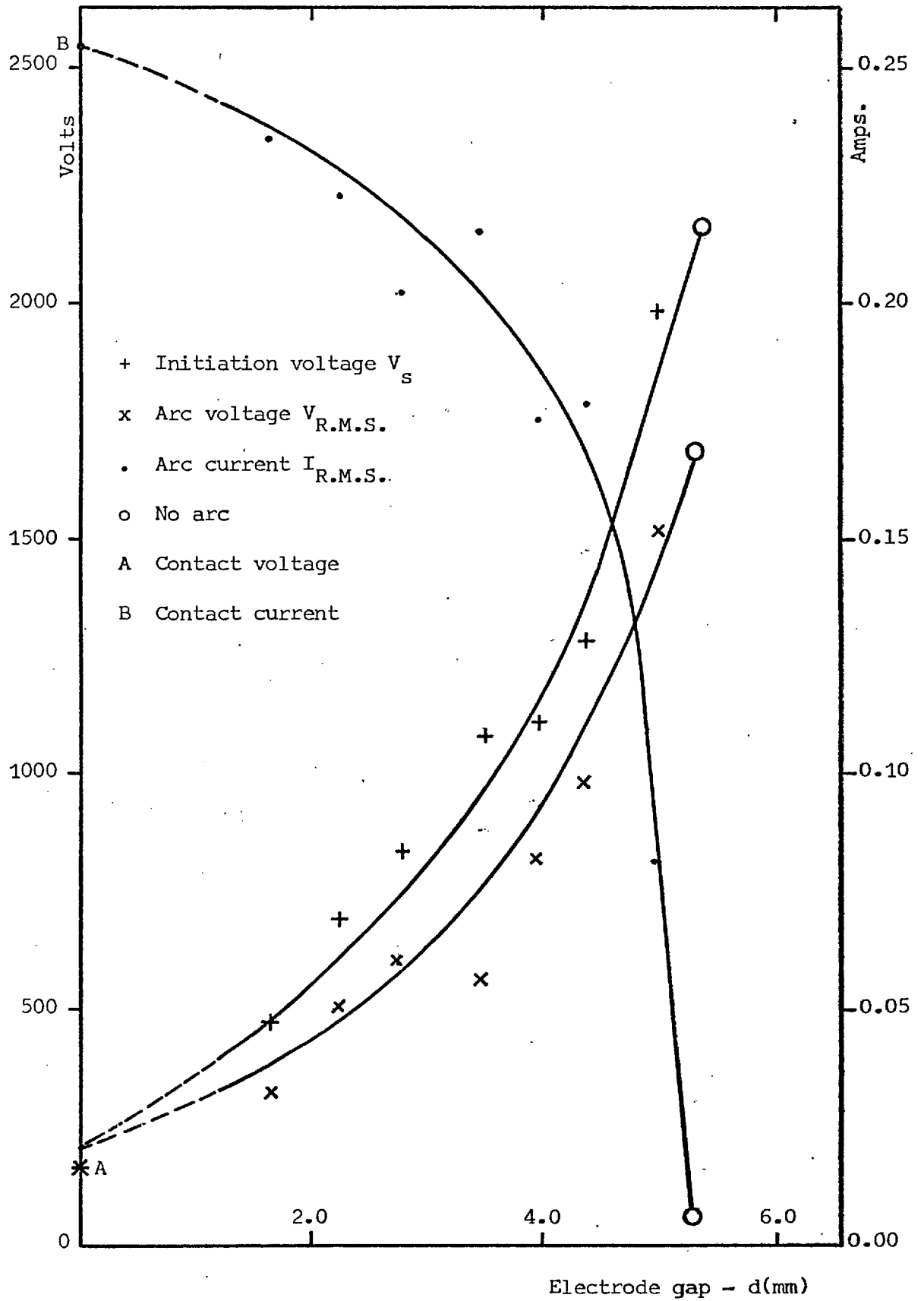


Figure 6-1. Effect of distance between the electrodes on voltage current, and initiation voltage.

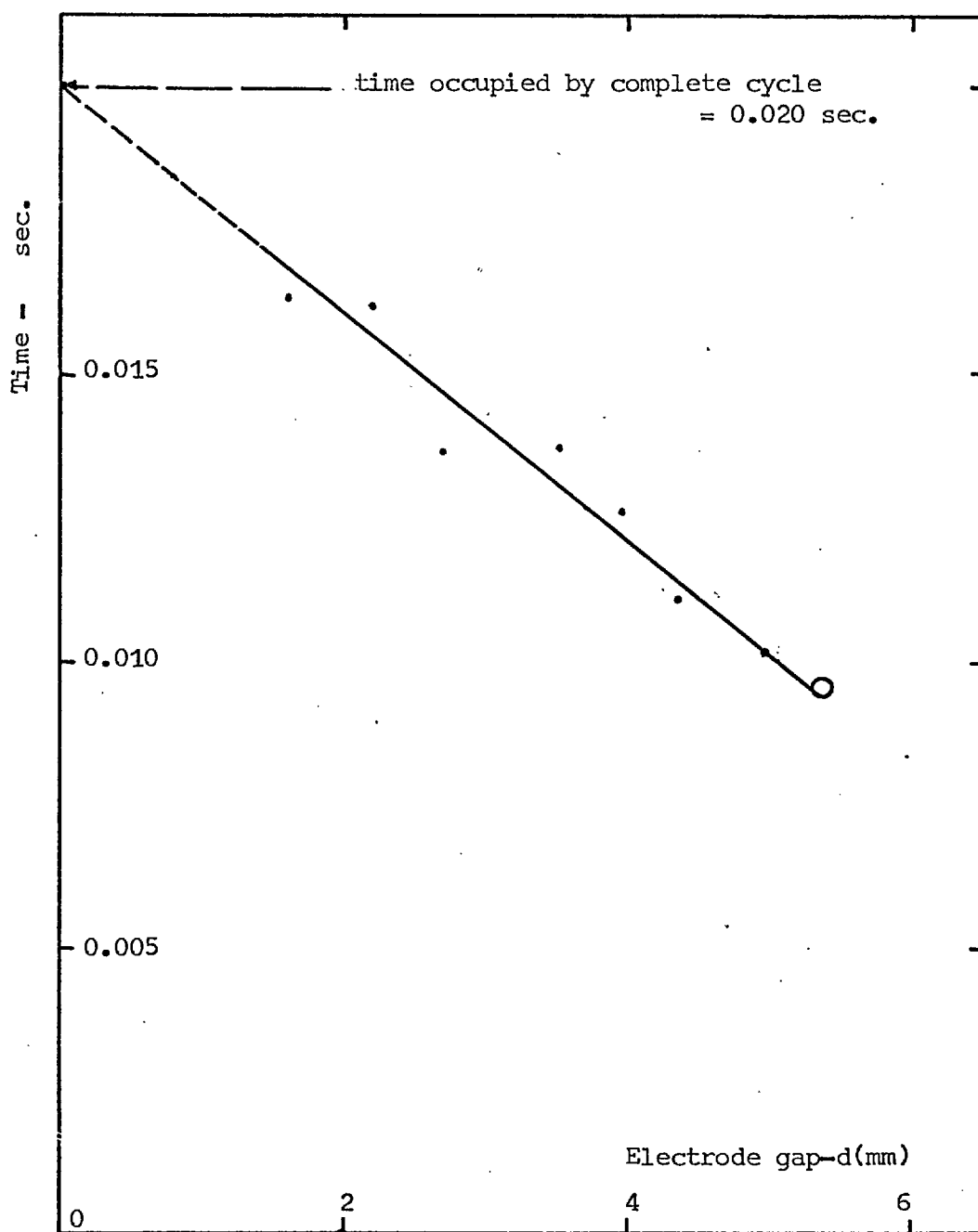


Figure 6-2. Average time in one cycle during which arcing occurs

- 100 -

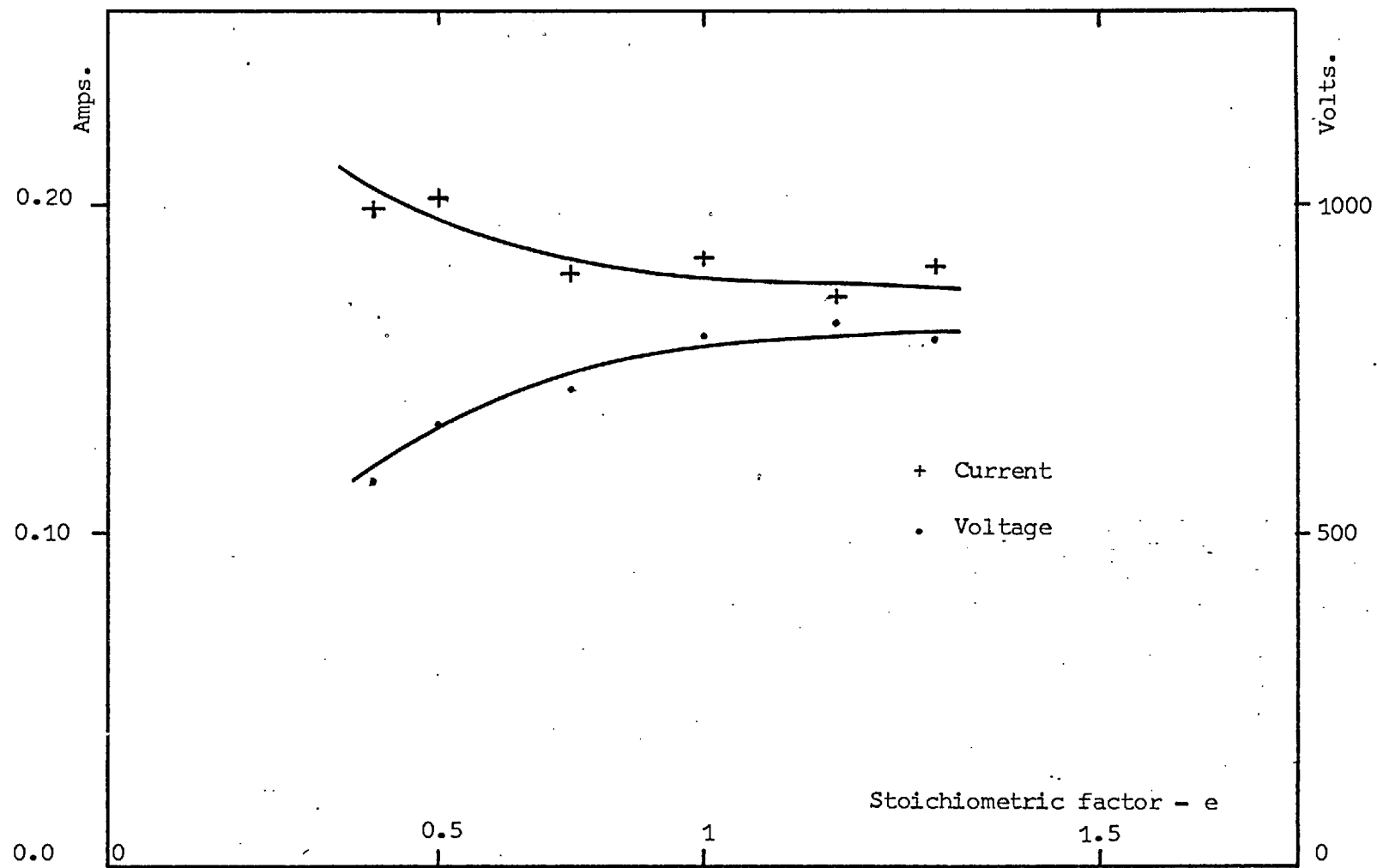


Figure 6-3. Variation in voltage and current with stoichiometric factor.

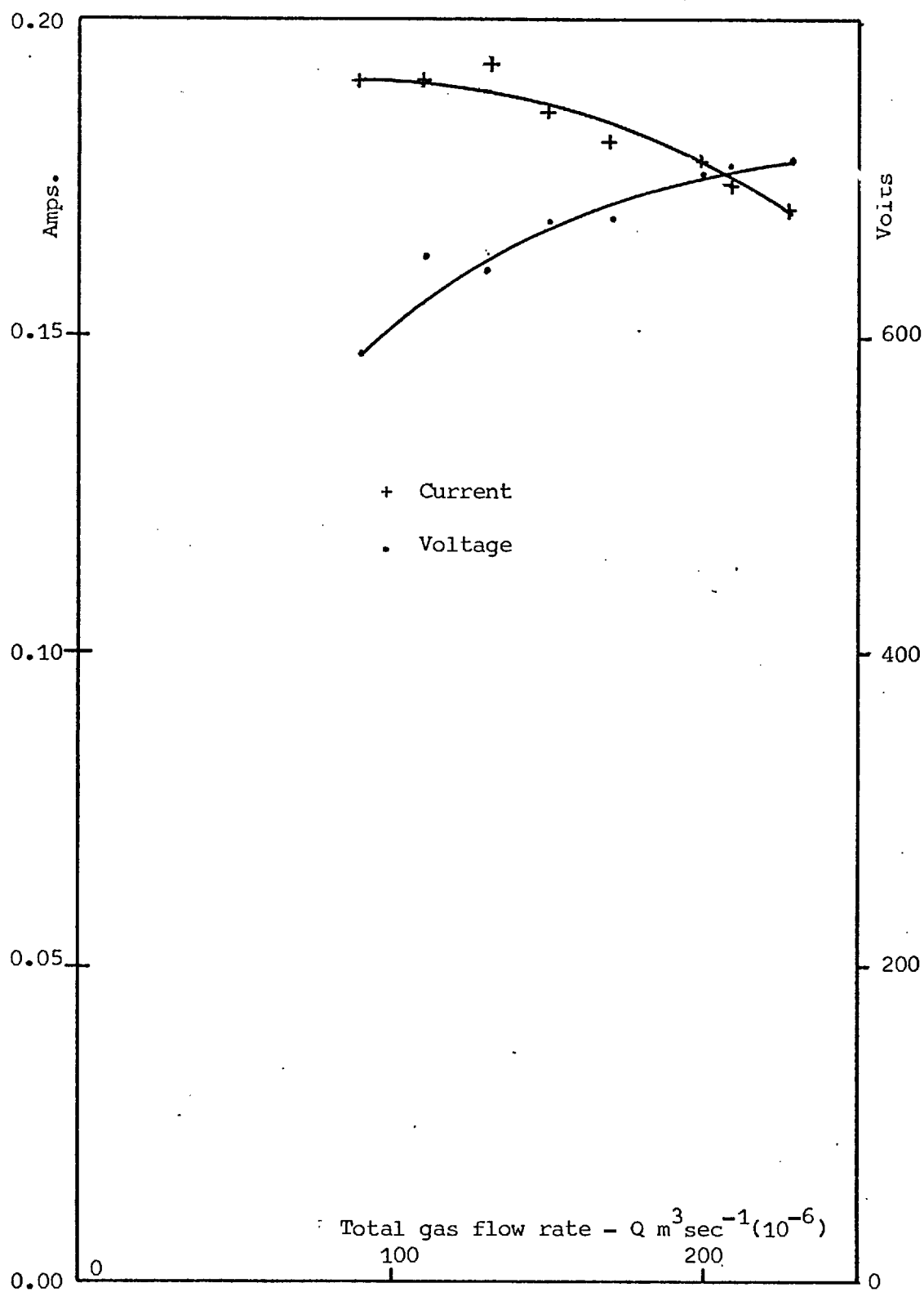


Figure 6-4. Effect of total gas flow rate on voltage and current.

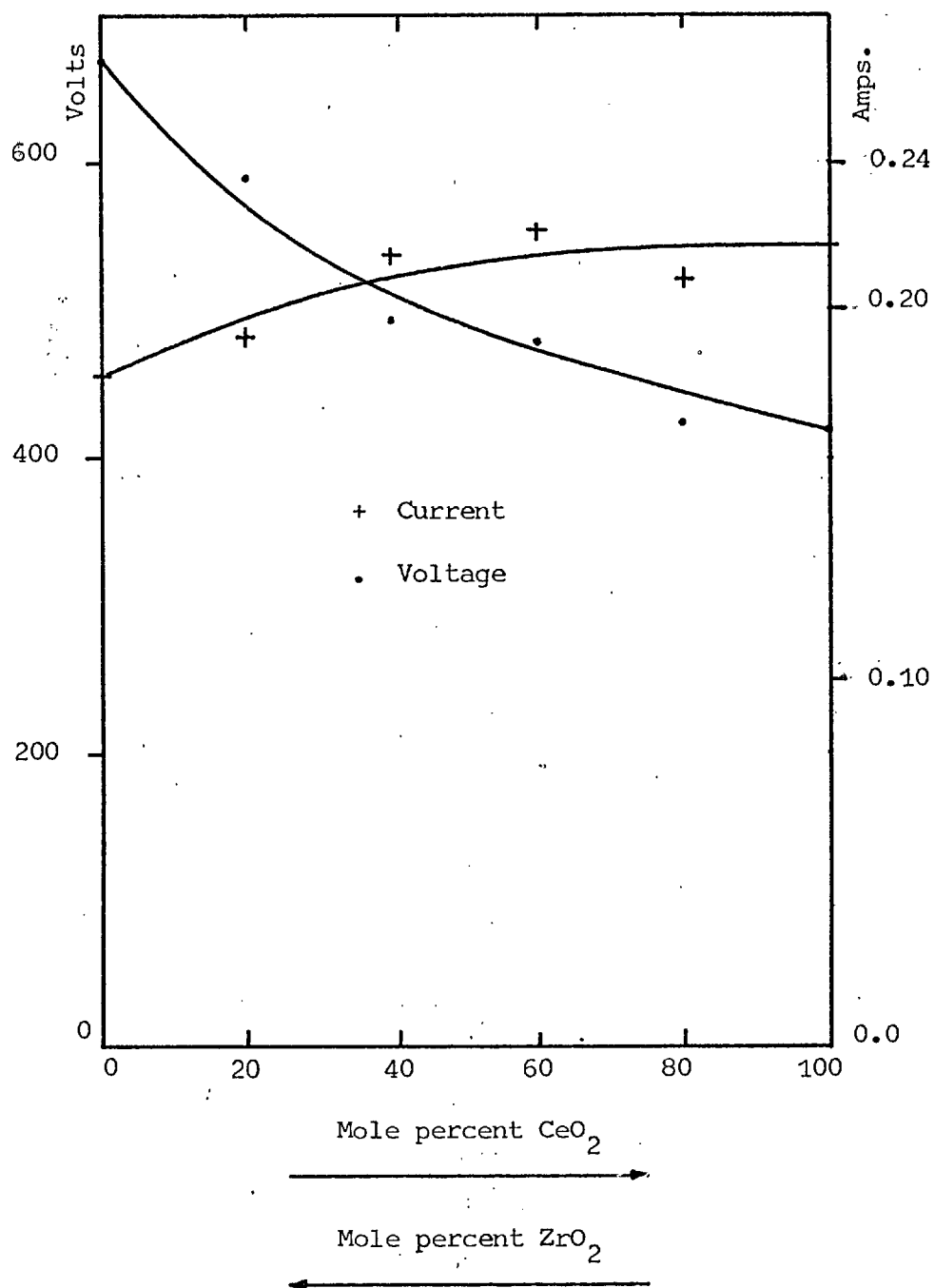


Figure 6-5. Effect of ceria-zirconia content on voltage and currents.

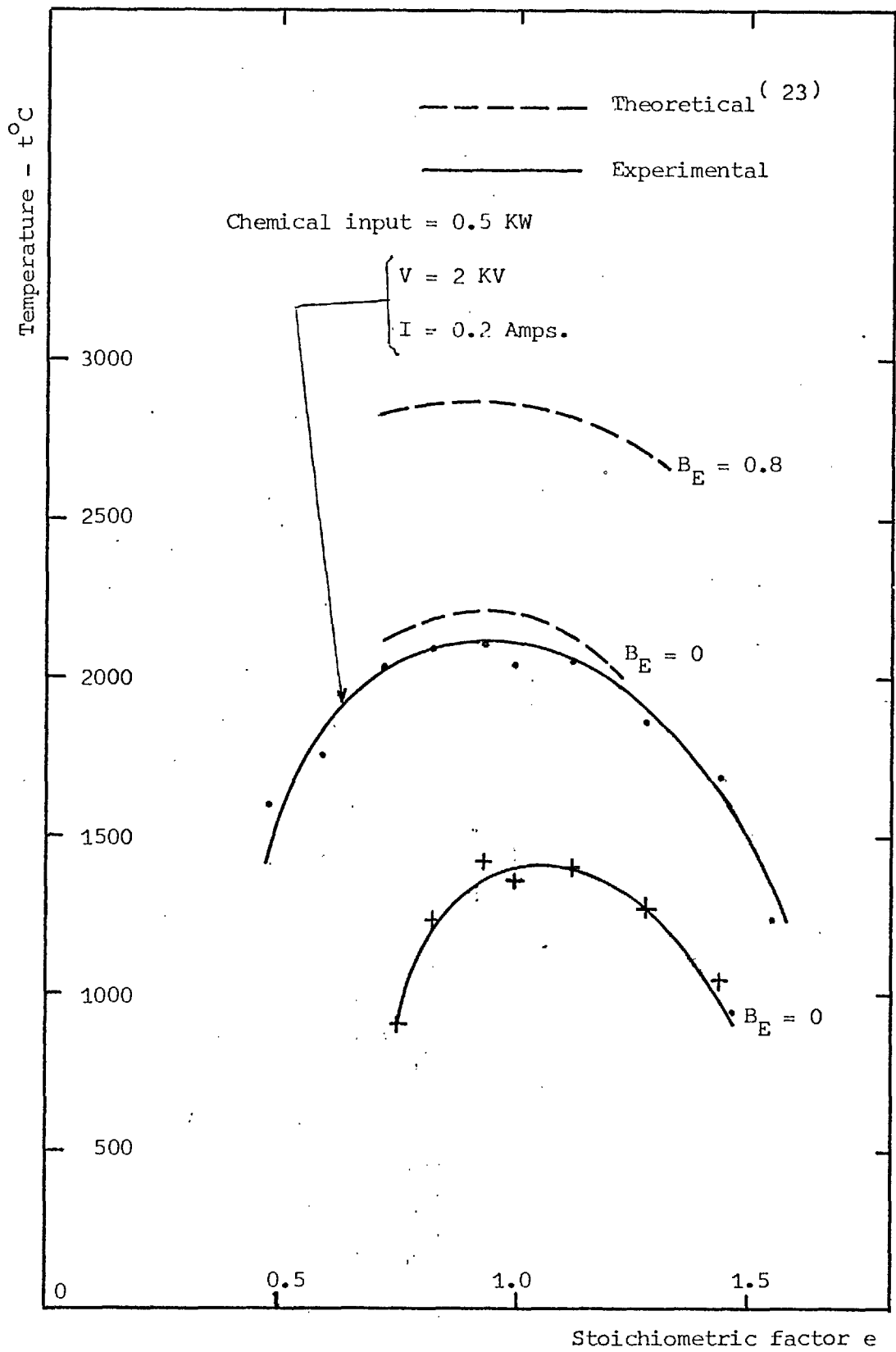


Figure 6-6. Effect of stoichiometric factor on flame temperature.

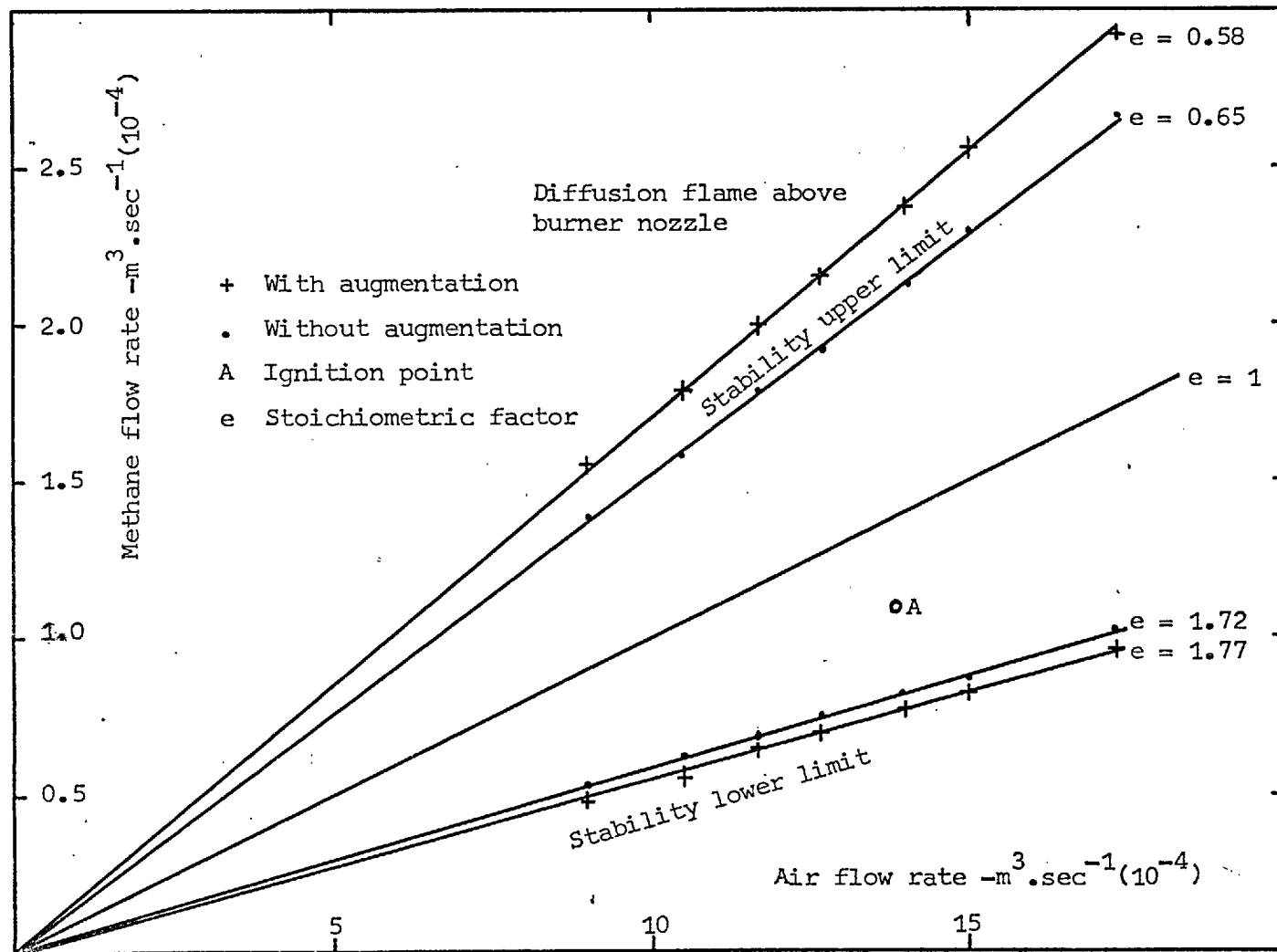


Figure 6-8. Stability limits for methane-air mixtures in the large burner

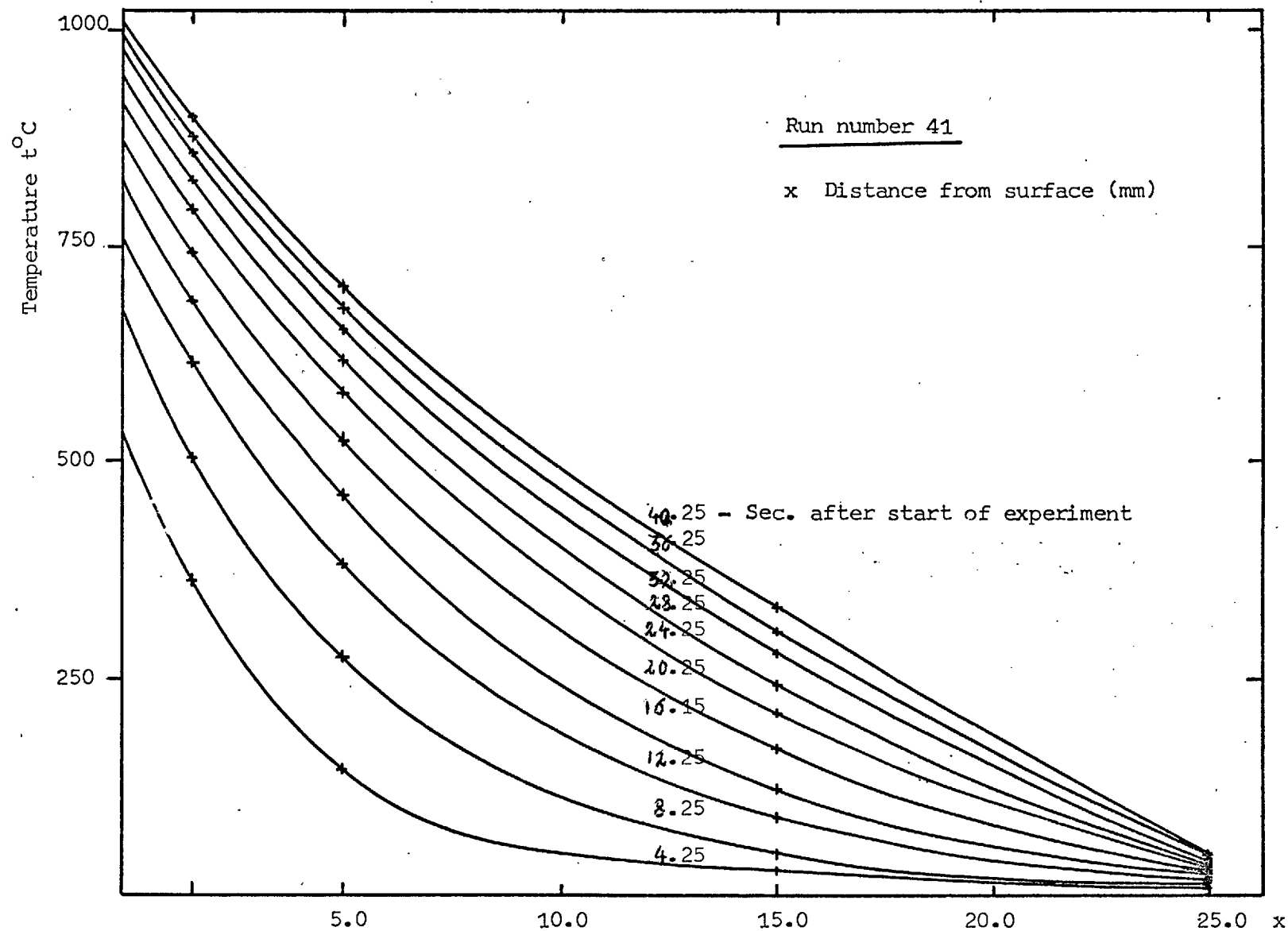


Figure 6-9. Typical temperature profiles in heat flux meter.

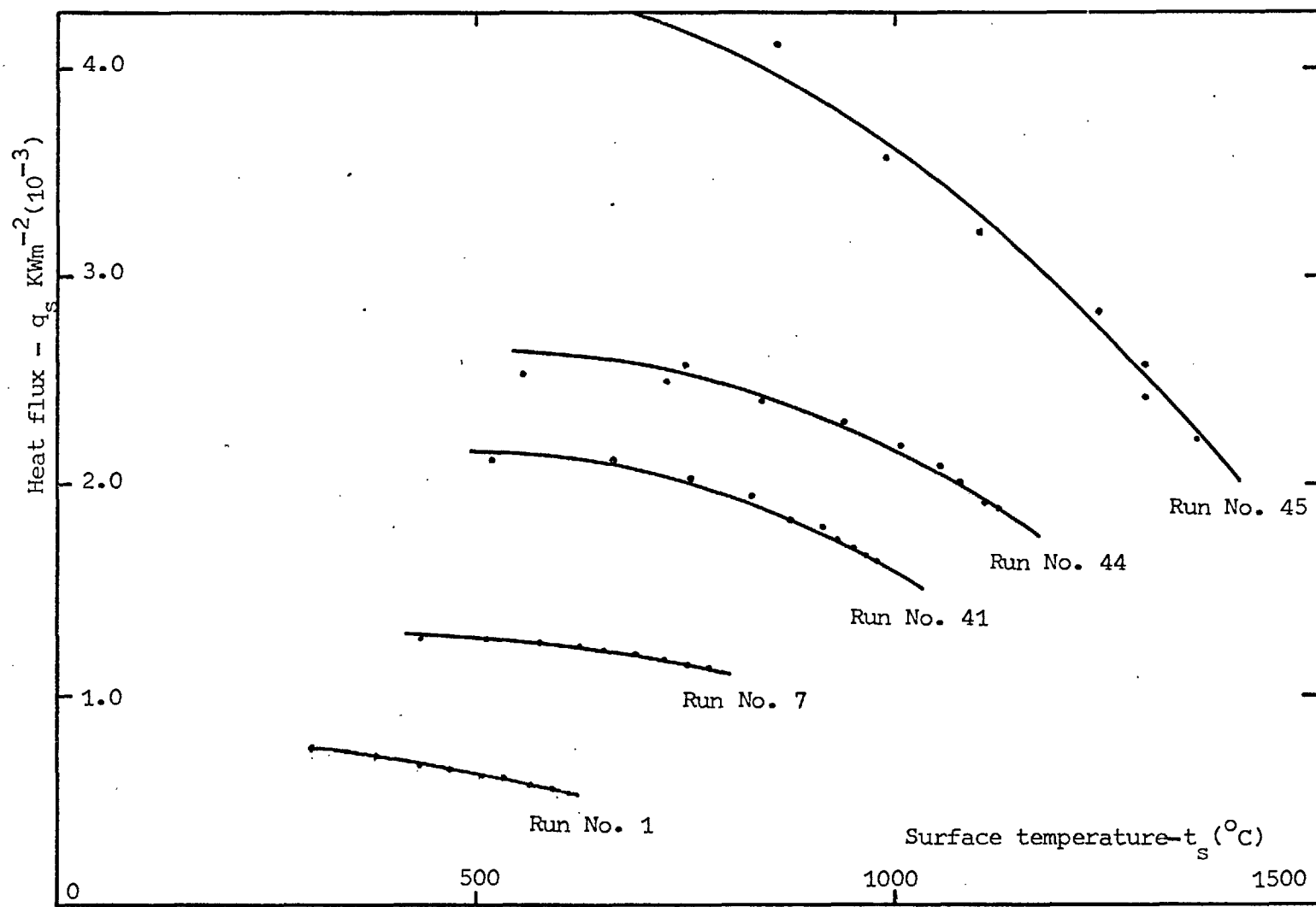


Figure 6-10. Experimental heat flux against surface temperature.

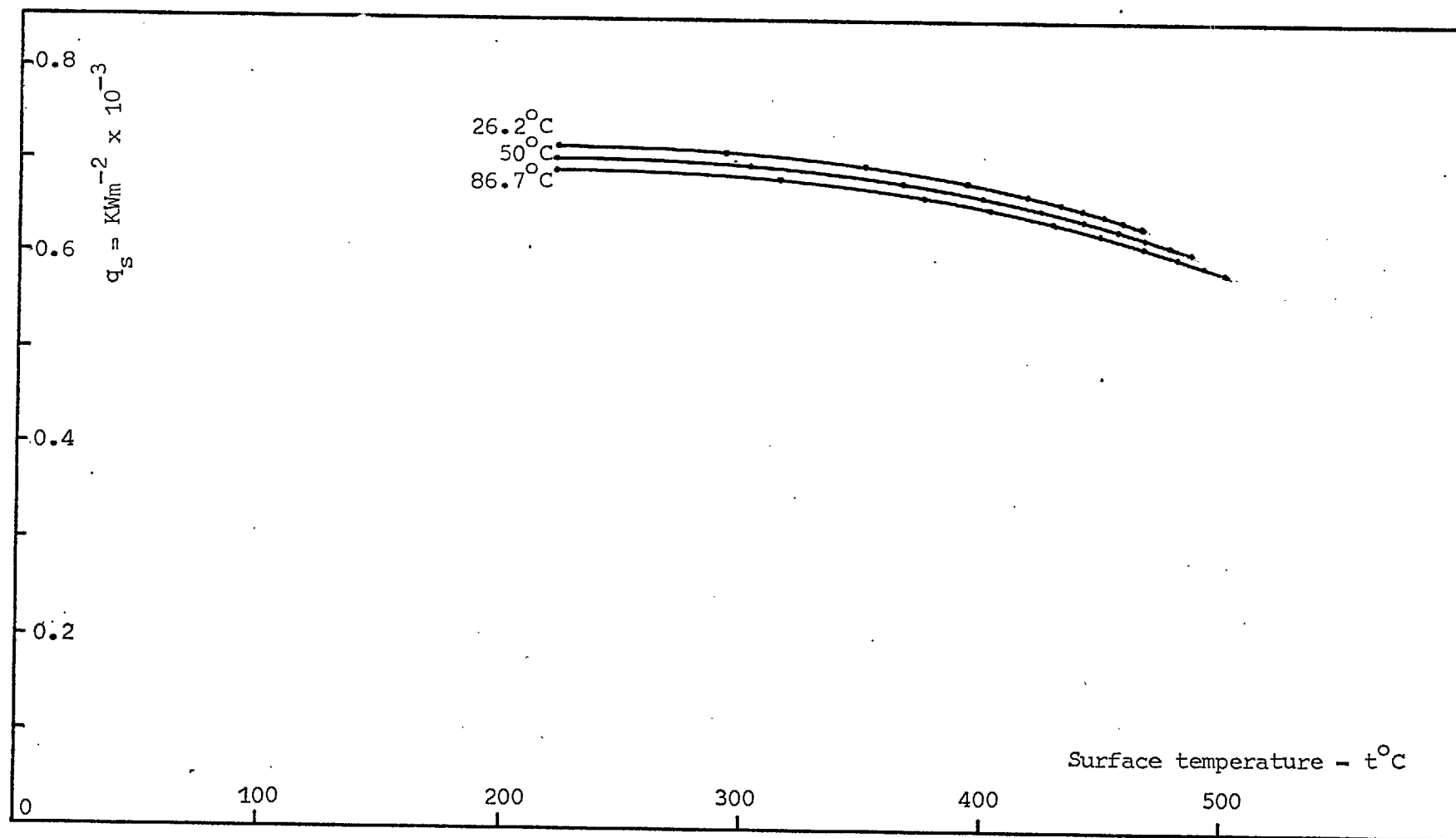


Figure 6-11. The effect of initial slab temperature on heat flux.

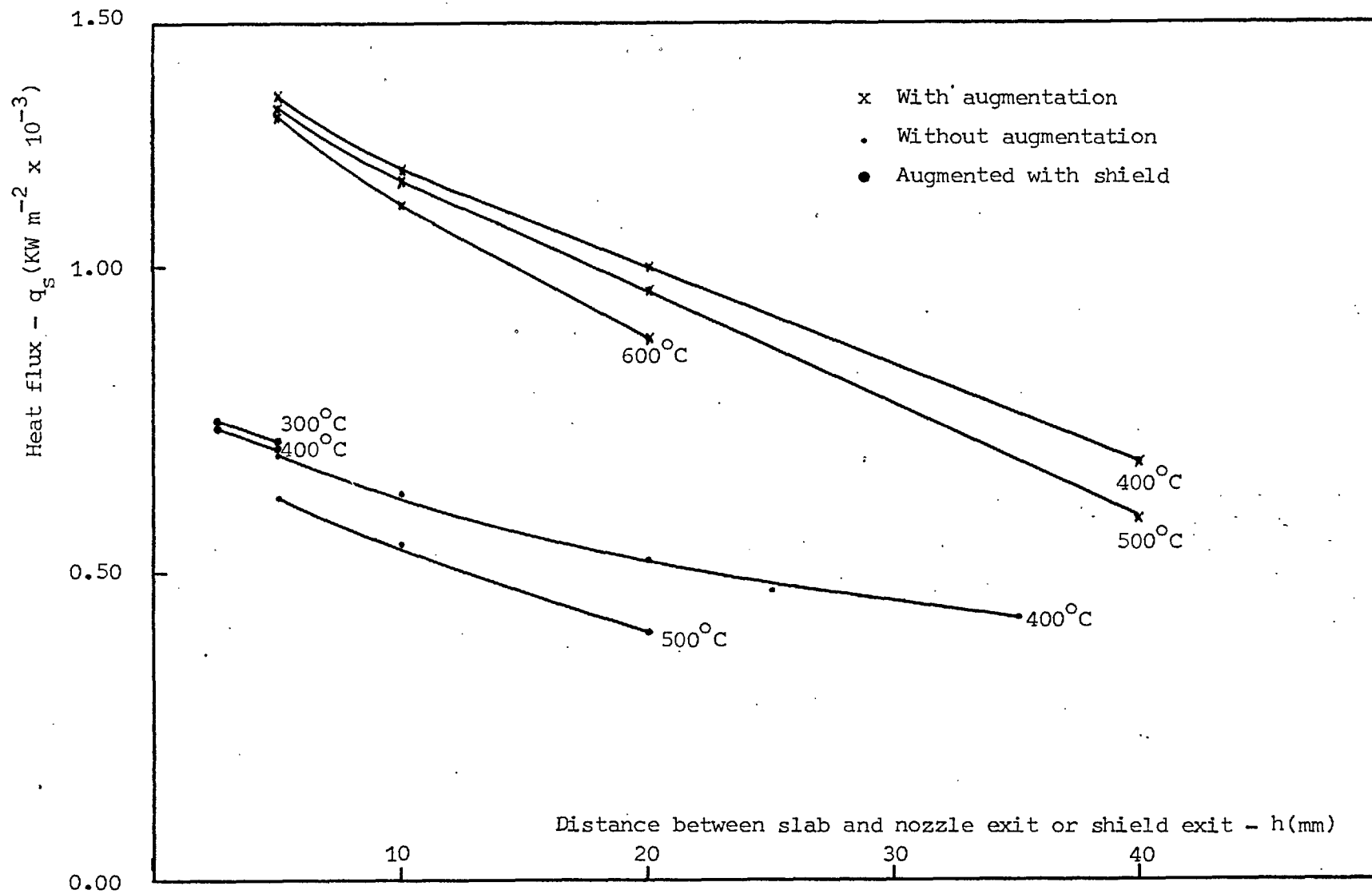


Figure 6-12. Axial distribution of heat flux at various surface temperatures.

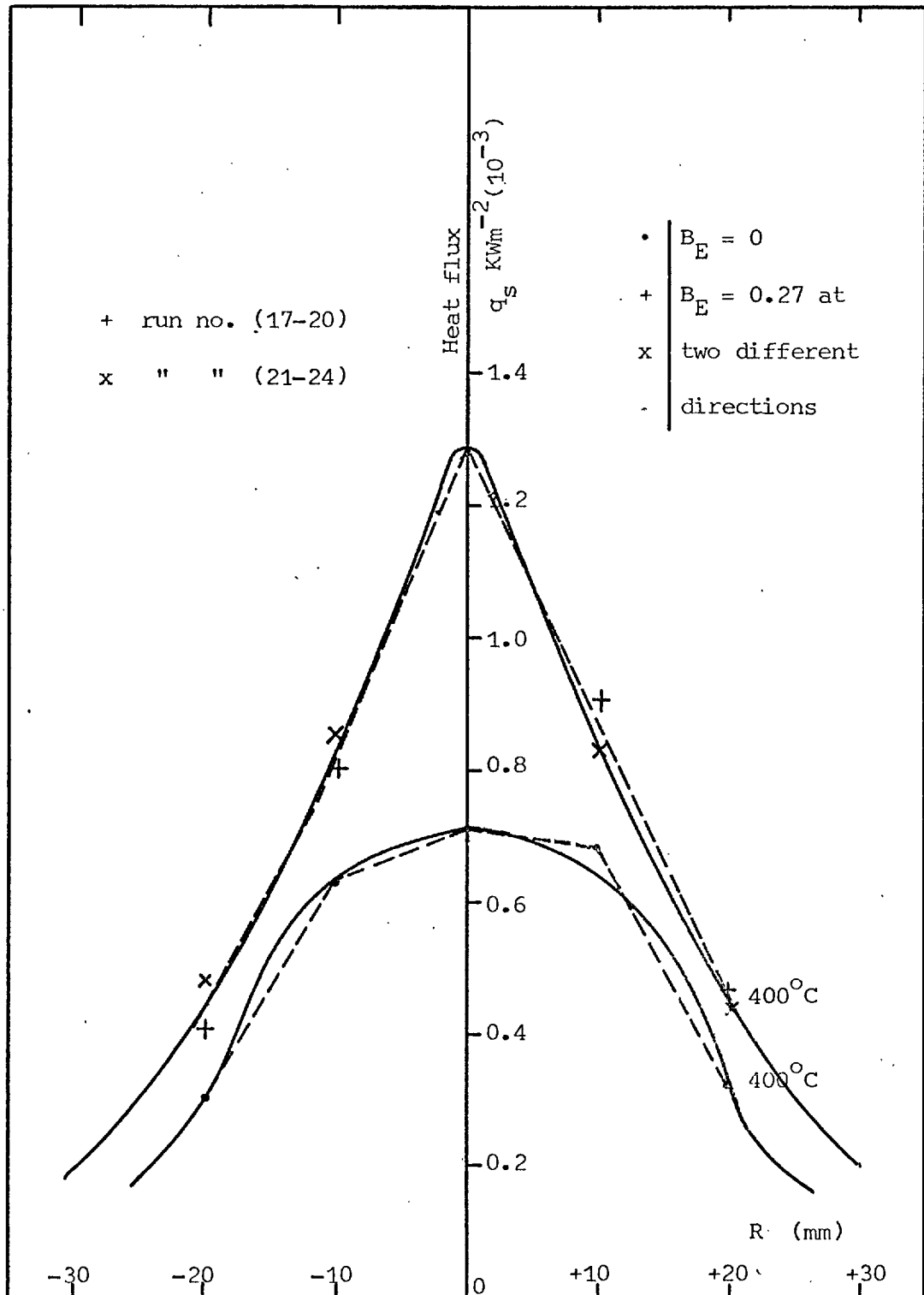


Figure 6-13. Radial distribution of heat flux at $t_w = 400^\circ\text{C}$

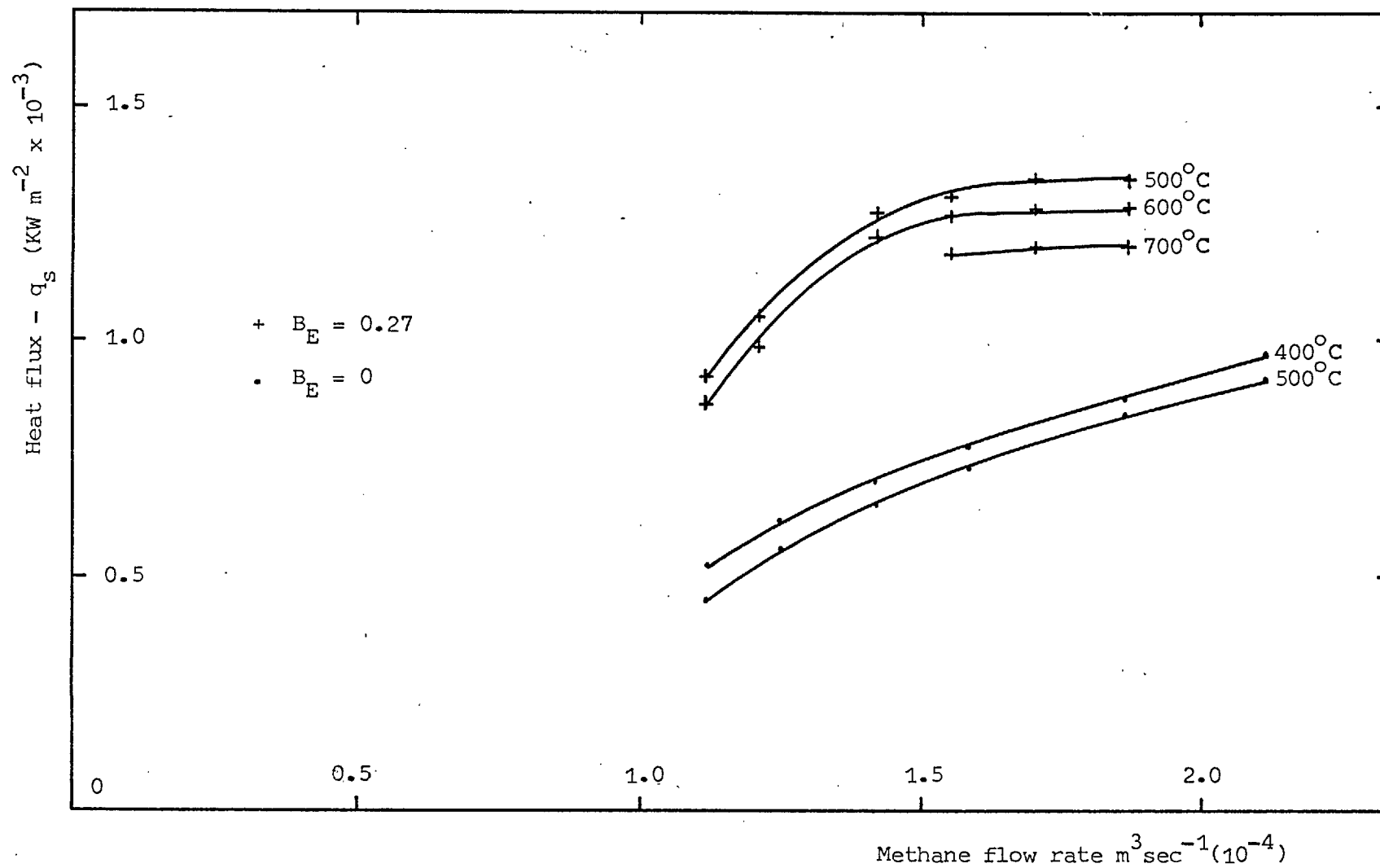


Figure 6-14. Variation in heat flux with flow rate for stoichiometric methane air flame.

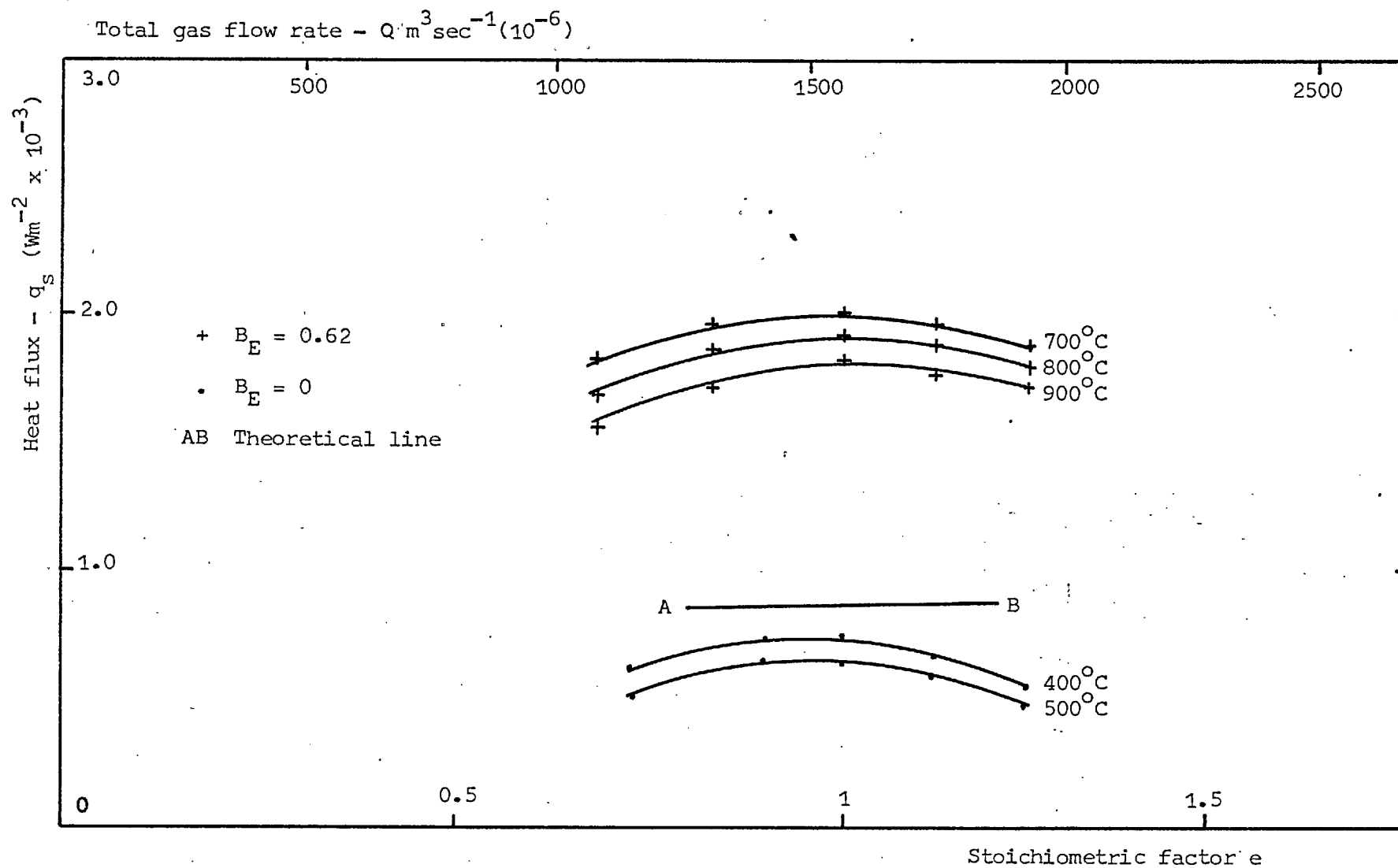


Figure 6-15. Variation of heat flux with stoichiometric factor.

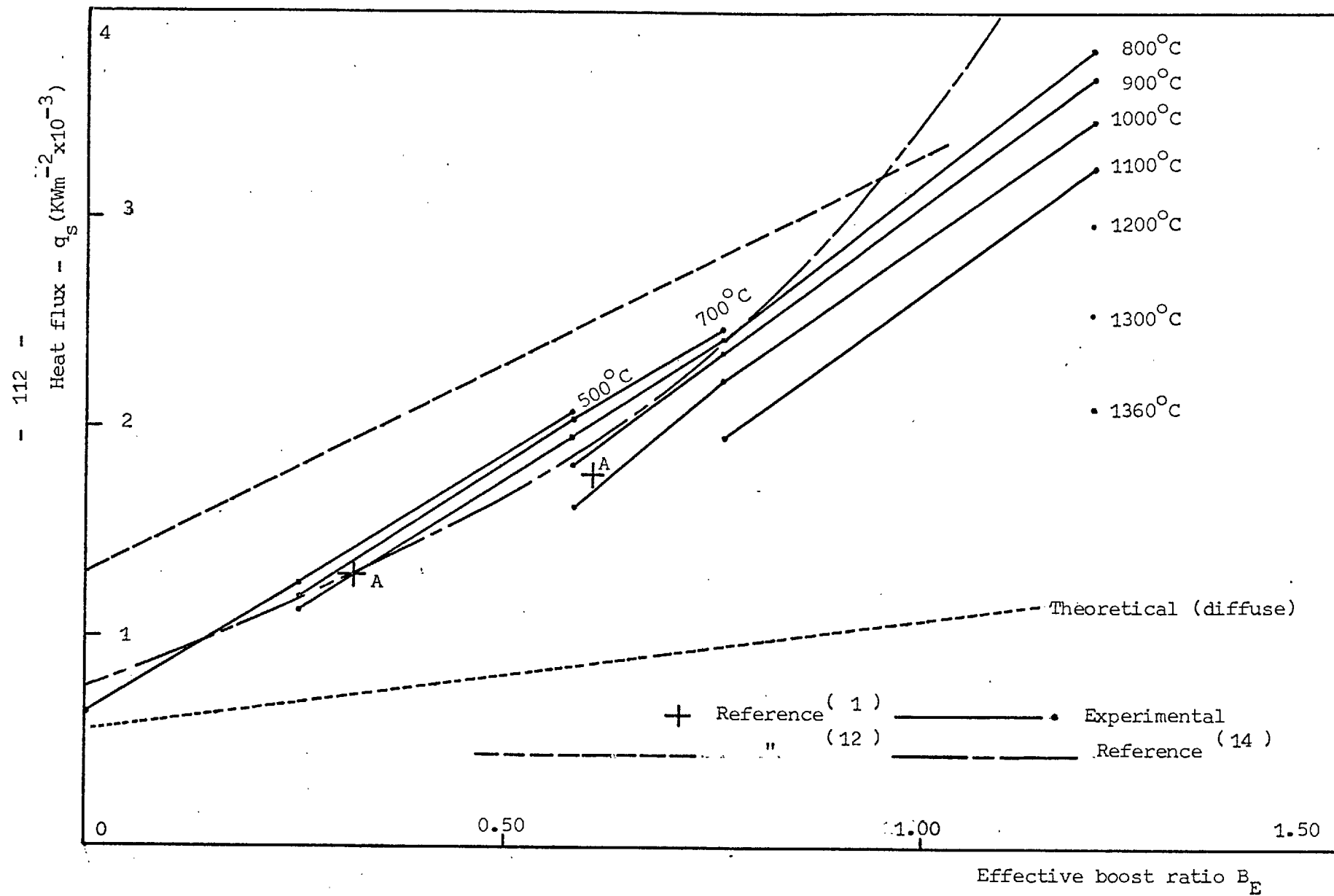
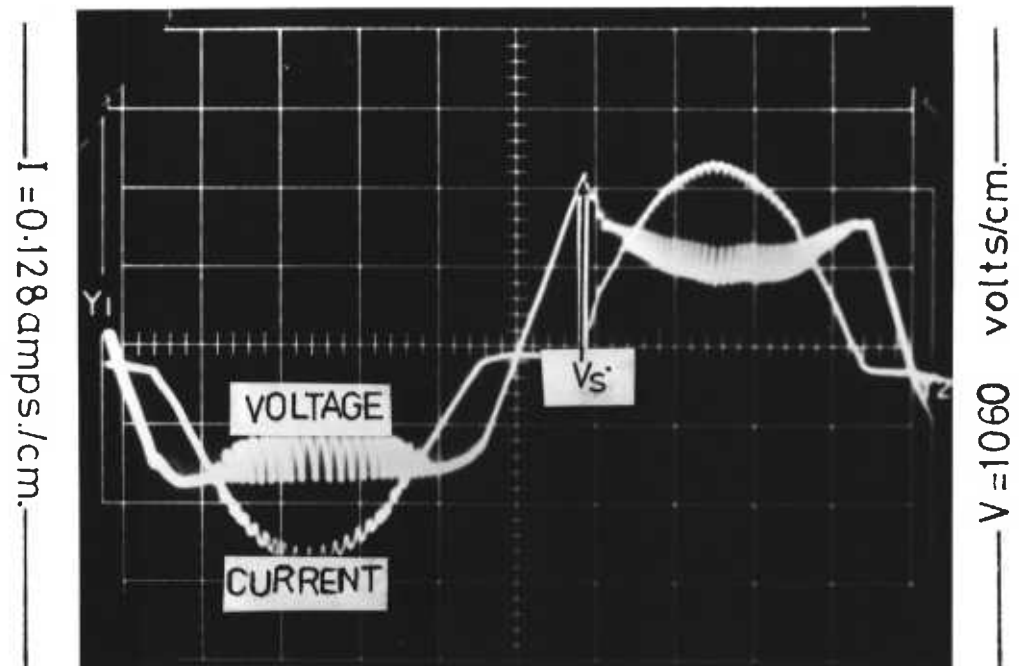
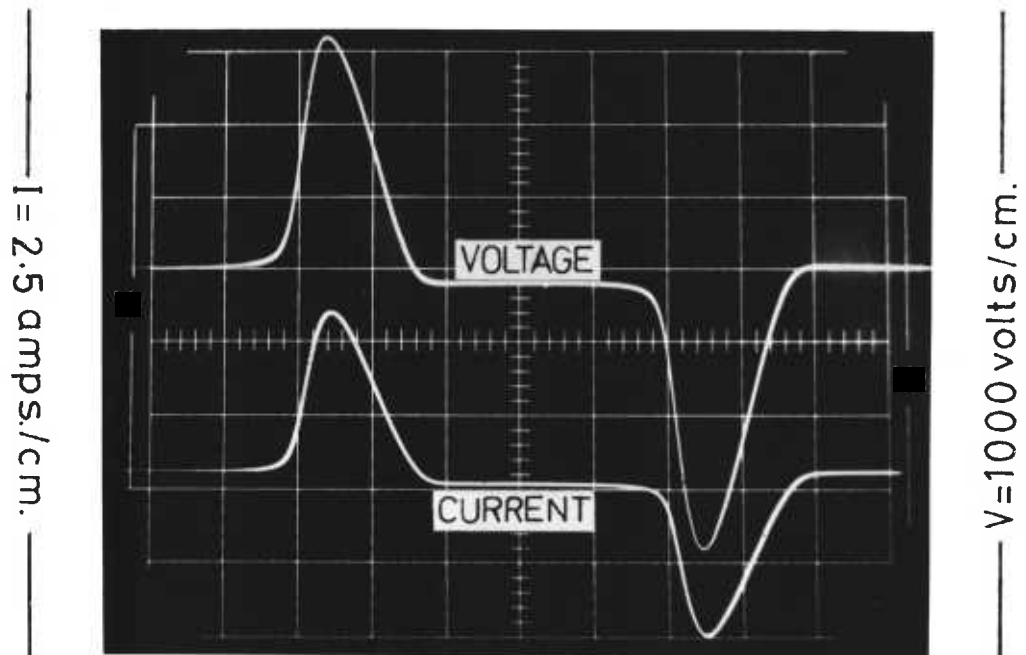


Figure 6-16. Variation of heat flux with effective boost ratio at various temperatures.

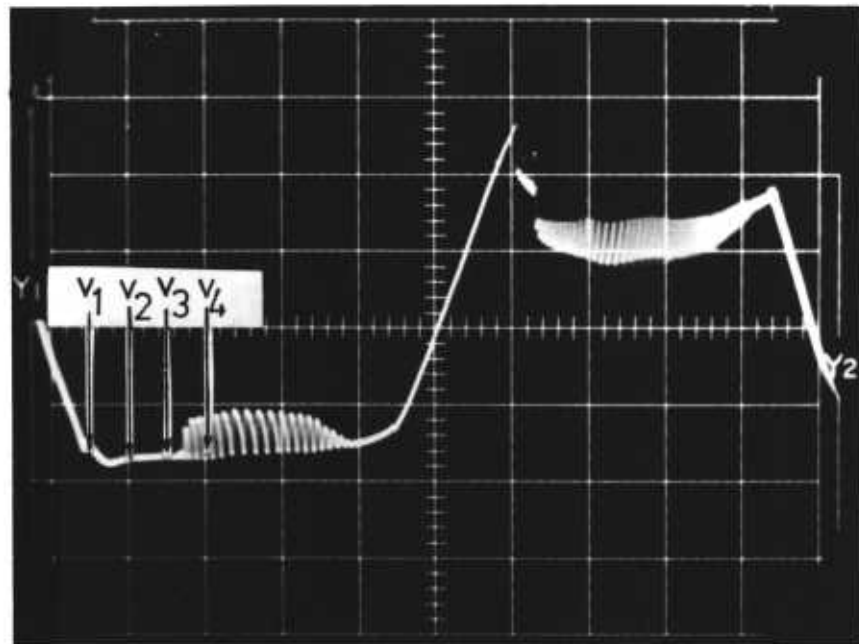


a) burner.

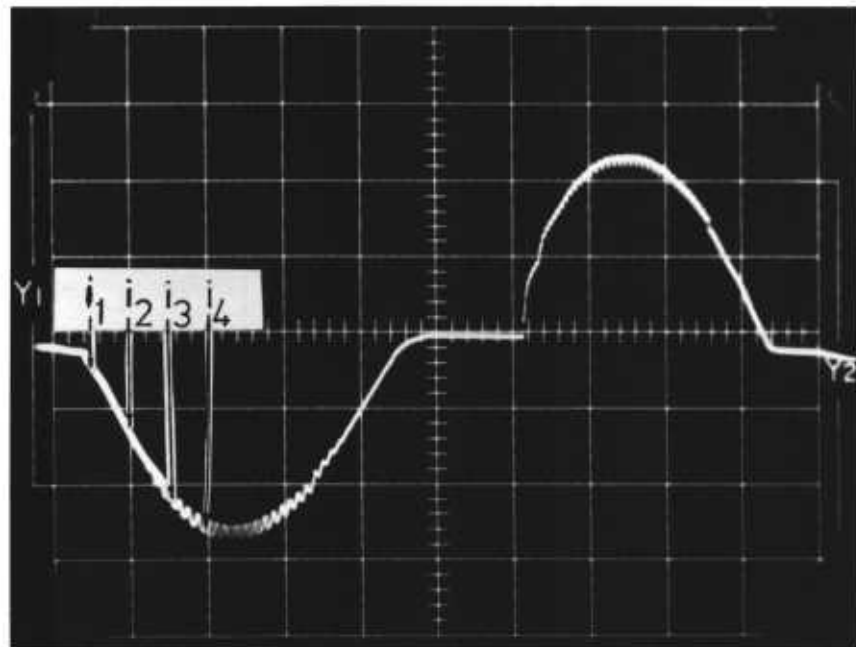


b) substitute resistor.

PLATE 5. VOLTAGE AND CURRENT TRANSIENT
OBTAINED FROM OSCILLOSCOPE.



a) voltage.



b) current.

PLATE 6. CALCULATION OF (r.m.s.) EFFECTIVE
VALUE OF VOLTAGE AND CURRENT.

Chapter 7

Discussion

- 7-1. Characteristics of the a.c. discharge.
- 7-2. Flame stability.
- 7-3. Flame temperature.
- 7-4. Experimental determination of heat flux.
- 7-5. Axial distribution of heat flux.
- 7-6. Radial distribution of heat flux.
- 7-7. Effect of process variables on heat flux.
- 7-8. Effect of surface temperature on the heat flux.
- 7-9. Comparison between experimental and predicted heat fluxes.
- 7-10. Application of the burner for melting.

7-1. Characteristics of the a.c. discharge.

A - Small burner

The characteristics of the a.c. discharge in the small burner are shown in plate (5-a). These characteristics are similar to those given in figure 2-8 on page 20 for hydrogen. When there is no arc, i.e. current is zero, the voltage increases until the initiation voltage V_s is reached. At V_s the arc is struck and the voltage then drops while the current rises first to a maximum and then falls. The arc goes out when the current reaches zero and does not reignite until the voltage reaches the initiation voltage again. The initiation voltage V_s and the R.M.S. voltage $V_{R.M.S.}$ can be expected to increase when the electrode gap is increased and figure 6-1 shows this effect. The variation of current I with electrode gap is also shown in figure 6-1. It can be seen that the arc no longer exists when the electrode gap exceeds 5.3 mm.

The initiation voltage was limited to about 2500 volts by the power supply. It can be seen that as the electrode gap is increased a correspondingly greater increase in voltage is required to initiate the arc, i.e. the initiation voltage rises steeply with increasing electrode gap. In an a.c. arc, the time during which the arc exists in each half-cycle will become less as the initiation voltage increases as shown in figure 6-2. Therefore the R.M.S. value of the current will decrease as the time of arcing becomes less, because the maximum value of the current does not change. It can be seen from figure 6-1 that the R.M.S. current falls off rapidly as the initiation voltage increases.

In order to achieve a stable arc which exists over a large

proportion of each half-cycle it would appear that V_s should be as small as possible. This can be achieved by using small arc gaps and electrode materials which have low work functions. The power dissipated by the arc is given by

$$V_{R.M.S.} \cdot I_{R.M.S.} \cdot \cos \phi \quad (7-1)$$

where $\cos \phi$ is the power factor. The variation of power with electrode gap can be calculated from the data given in figure 6-1 assuming $\cos \phi = 1$ but the scatter is too great to enable power to be plotted against electrode gap. This scatter is due to three causes:

- 1 - The electrode gap was set to an accuracy of ± 0.3 mm.
- 2 - Values of V and I were obtained to an accuracy of $\pm 10\%$ from the oscilloscope.
- 3 - R.M.S. values were calculated by an approximate method, see page 83, to an estimated accuracy of within $\pm 5\%$.

The voltage between the electrodes when they are in contact is given by point A, and point B represents the current in the circuit under these conditions.

Extrapolation of the V_s , $V_{R.M.S.}$ and $I_{R.M.S.}$ curves indicates that they cut the ordinate at point A and B, approximately. The potential drops at both electrodes can therefore be considered to be negligible compared to the voltage drops due to the resistances of either the electrodes or the positive column. This is the reverse of the situation in low voltage arcs, see figure 2-5, page 19, where the potential drops at the electrodes are significant.

Figure 7-1 has been derived from plate (5-a) and shows the voltage-current characteristics of the a.c. discharge. In this

circuit the current was limited to 0.3 amps. Figure 7-1 is similar to figure 2-10 on page 21. Figure 6-3 shows that the current rises and the voltage drops when the proportion of methane in the mixture is increased. The stability of the arc is improved when the gas flow rate is low and the methane content is high, e being less than unity.

It can be seen in figure 6-4 that increasing the gas flow rate causes the voltage to increase and the current to decrease. This effect is probably due to the lengthening of the arc path when the gas flow rate is increased as shown in figure 4-3 on page 62.

The effect of the proportion of ceria in the zirconia on the voltage and on the current is shown in figure 6-5. It can be seen that as the mole percent of ceria increases, the current increases and the voltage decreases. This is due to the fact that the work function of zirconia is higher than that of ceria. The ratio of these work functions is

$$\frac{\phi_{\text{Zr}}}{\phi_{\text{Ce}}} = \frac{3.9}{2.3} = 1.7$$

and the ratio of the voltages due to zirconia and ceria is

$$\frac{V_{\text{Zr}}}{V_{\text{Ce}}} = \frac{670}{415} = 1.62$$

From this calculation it appears that the arc voltage V is directly proportional to ϕ .

B - Large burner

Large fluctuations in the oscilloscope traces of the voltage and current transients for the large burner occurred, presumably because the arc was less stable than in the small burner. The

large burner was a scaled up version of the small burner and the larger electrode gap could have been responsible for the decrease in stability. The only means of determining current, voltage and power during electrical augmentation in the large burner was by means of meters. These meters were checked using a fixed resistance as described on page 85. Table 6-1 on page 97 shows that the meter readings agreed with R.M.S. values obtained from an oscilloscope to within $\pm 5\%$. Table 6-1 shows that the power factor for all values of V and I is approximately unity and it can be concluded that the transduction has no significant influence on the power factor. Table 6-2 gives the power factors for various boost ratios. It can be seen that the power factor increases as the boost ratio is increased. This is of considerable importance economically because electrical augmentation can be achieved without large power losses.

7-2. Flame stability

The stability of the flame from the large burner is given in figure 6-8. It can be seen that electrical augmentation increases the stability of the flame, particularly for fuel rich mixtures when the stoichiometric factor e can be reduced from 0.65 to 0.58. This upper limit represents the situation when the flame leaves the combustion chamber and burns above the nozzle as a diffusion flame. The lower limit is barely changed by the augmentation. The flame is blown out of the combustion chamber and extinguished when $e = 1.7$ to 1.8 . Point A represents the well-defined flow condition required for ignition. The upper and lower stability limits lie on lines of constant e and are therefore independent of the total gas flow rate. All lines pass through the origin of figure 6-8.

7-3. Flame temperature.

The results of measuring the flame temperature for the small burner both without and with electrical augmentation are given in figure 6-6. These experiments were carried out when the methane flow rate was kept constant and the air-flow rate was varied. At $\phi=0.8$ i.e. a stoichiometric mixture, the flame temperature has been increased due to augmentation by about 50%. The adiabatic flame temperatures were obtained from reference (23). Generally the experimentally determined temperatures are lower than the theoretical values because the flame has entrained cool air and has also lost some enthalpy to the surrounding atmosphere. This has occurred because the flame gases have travelled 5 nozzle diameters between the nozzle exit and the point of measurement.

Various problems occurred with this method of measuring flame temperatures. In addition to the problems normally encountered (46), such as the presence of soot particles, there were other problems. These were:

- 1 - The flame had to be seeded and so flame temperatures were unlikely to be representative of an unseeded electrically augmented flame.
- 2 - It was experimentally difficult to obtain temperatures close to the nozzle.
- 3 - Temperature gradients in the flame were very steep.
- 4 - A pocket spectroscope was available but this only enabled approximate temperatures to be measured.

7-4. Experimental determination of heat flux.

The exact solution of the heat conduction equation for a semi-infinite slab has been given in chapter 2 page 72. The justification for using this solution and the assumptions that have to be made will be discussed.

A - Assumptions involved in using the heat flux meter

1 - Conduction of heat occurs in the X direction only

The temperature distribution in as thin a rod as was practically possible and this rod was insulated from the rest of the slab by guard rings to ensure that conduction was mainly taking place in the X direction.

2 - Physical properties

Physical properties of stainless steel En 58A used in making the heat flux meter vary considerably with temperature. The thermal conductivity and the mean specific heat are given in appendix D. The variation of these physical properties has been used as explained in chapter 6 page 89.

3 - Heats of transformation

Using En 58A steel enables assumptions to be made that the slab is isotropic and that no heat of transformation occurs in the slab because the steel is isotropic from room temperature to its melting point.

4 - The heat flux is constant at the surface

Equation (2-48) enables a constant heat flux at the surface

to be determined in terms of surface temperature and time. This heat flux is not constant however, as shown in figure 6-10 where surface heat flux depends on surface temperature. Figure 7-2 shows that the temperature gradient at the surface $(\frac{dt}{dx})_{x=0}$ decreases with increasing time. This implies that the heat flux also decreases with time, and therefore with increasing surface temperature, because

$$q_{x=0} = -k \left(\frac{dt}{dx} \right)_{x=0}$$

For run number 41, heat flux was calculated by this method and are compared in figure 7-2.

B - Fitting polynomials to temperature profile

In order to solve equation 2-48 for heat flux q , it is necessary to find the temperature at the surface of the slab. A polynomial is used to represent the temperature profile as described in section 6. The effect of choosing quadratic and cubic curves to fit the experimentally determined temperatures from the heat flux meter is shown in figure 7-4. It was always found that heat fluxes decreased as polynomials were used in the following order:

- 1 - Cubic fitted to 4 points.
- 2 - Quadratic fitted to 3 points.
- 3 - Quadratic fitted to 4 points.

Case 1 was chosen to determine all heat fluxes except run numbers 39, 40, 42, 43, 45 and 46 when case 2 had to be chosen because number 4 thermo-couple failed.

C - Time taken for number one thermo-couple to indicate

The average time taken for the number one thermo-couple to provide a reading with augmentation in the tenth set of readings

is 4.25 seconds as explained on page 88. (Without augmentation this time is 8.25 seconds.) The effect of using times of 4.1, 4.25 and 4.4 seconds is given in figure 7-3. This figure shows that there is very little difference between the heat fluxes for the various times and therefore an average value of 4.25 seconds is justified. A method of checking the accuracy with which the various polynomials will predict surface temperature is given below:

Two cases of high and low heat fluxes were chosen as explained on page 58 in order to design the heat flux meter. Heat fluxes of 3.5×10^3 and $0.85 \times 10^3 \text{ K W.m}^{-2}$ with surface temperatures of 1300 and 600°C respectively have been chosen. Putting these values in equation 2-48 gives the time taken for the surface temperature to reach the values mentioned above as 10.24 and 35 seconds respectively. Inserting these values into equation 2-47 enabled the temperature in the slab at $x = 1.5, 5, 15$ and 25 mm to be calculated. These temperatures are given in table 7-1 and are shown in figure 4-9. A second order polynomial was fitted to three and to four of the thermo-couples and a third order was fitted to four thermo-couples as explained above. The results are given in table 7-1. The best results were obtained with the following:

A second order polynomial can be fitted to three points to predict the high surface temperature of 1300°C to within 0.5%. The accuracy of predicting surface temperature by fitting a third order polynomial to four points in case of the lower surface temperature is 0.8% of the theoretical value. The worst case involved an error of 3.7% in predicting the surface temperature.

Third order polynomials were used wherever possible, second

order polynomials were also fitted in order to be certain that a maximum or minimum in the cubic temperature profile did not occur close to the surface. It can be seen from figure 7-4 that the values of heat fluxes are all within about 10% and that the cubic temperature profile predicts higher heat fluxes than the quadratic temperature profile.

D - Reproducibility

Several experiments were repeated under identical conditions in order to test reproducibility of the results. Flames with and without augmentation are compared in table 7-2. It can be seen from the table that heat fluxes and surface temperatures are producible to within $\pm 9\%$.

According to the manufacturer the thermo-couples are accurate to within $\pm 0.75\%$, and respond to about 300°C temperature rise in 0.25 second. The maximum rise in temperature recorded by a thermo-couple is about 800°C in 4 seconds (run number 45) which corresponds to 50°C in 0.25 second. The response time of the thermo-couple is therefore unlikely to influence the results.

The position of the axis of the heat flux meter relative to the axis of the burner will influence reproducibility. The heat flux meter could be positioned to within an estimated ± 1 mm.

A further error is likely because the position of the arc inside the burner nozzle is uncertain and is likely to change during an experiment. This error is impossible to estimate.

Other errors that will affect the heat flux values will be the errors in nozzle to slab distance, methane flow rate, stoichiometric

factor and boost ratios.

By the theory of errors, the error in the heat flux is given by:

$$\delta q = \frac{dq}{dt} \cdot \delta t + \frac{dq}{dR} \cdot \delta R + \frac{dq}{dh} \cdot \delta h + \frac{dq}{dQ} \cdot \delta Q + \frac{dq}{de} \cdot \delta e + \frac{dq}{dB} \cdot \delta B \quad (7-2)$$

In order to evaluate this equation the functions

$$q = f_1(t), \quad q = f_2(R) \text{ etc.}$$

must be known. The estimated errors δt , δR etc. are given in table 7-3 as the functions f_1 , f_2 , which have been approximated to straight lines from the figures given in the table. 7-3.

Experimental Variable	Error	q K Wm ⁻² as approx. function of	Source From figures
t	+0.75%	-3.4t	6-10
R	+10 ⁻³ m.	4.5 x 10 ⁴ R	6-13
h	+0.5mm.	-16.3 x 10 ³ h	6-12
Q	+9 x 10 ⁻⁷ m ³ sec ⁻¹	7.0 x 10 ⁴ Q	6-14
e	+0.02	-	6-15
B	+3%	2.6 x 10 ³ B	6-16

Table 7-3

$$\text{For } B_E = 1.2, \quad t_s = 1000^\circ\text{C}$$

(7-3)

$$\delta q = -3.4\delta t + 4.5 \times 10^4 \delta R - 16.3 \times 10^3 \delta h + 7 \times 10^4 \delta Q + 2.6 \times 10^3 \delta B \quad (7-4)$$

Hence equation (7-2) gives the maximum error in q as

$$\delta q = 171 \text{ KWm}^{-2}$$

As q in this case is 4000 KWm^{-2} the error in $q = \pm 4\%$.

7-5. Axial distribution of heat flux.

The effect of distance between the burner and the slab on the heat flux for flames without and with electrical augmentation is given in figure 6-12. Generally, both with and without augmentation, it can be seen that the heat flux decreases as the burner to slab distance is increased. This can be explained by considering two distinct effects.

At the plane of the nozzle exit there is likely to be a steep temperature gradient across the jet because of the existence of the arc at this plane. Heat will therefore be transferred in a direction normal to the centre line of the jet, having the effect of establishing a more even temperature profile across the jet downstream from the nozzle exit. Therefore irrespective of velocity considerations the centre line heat flux to a surface will tend to decrease as the nozzle to slab distance is increased. The heat flux will decrease even further because the jet of combustion products will entrain more and more cold air as this distance increases.

These two effects have been separated by using a shield as explained on page 54. In this case entrainment of cold air is eliminated. The stagnation point heat flux obtained with the shield is considerably lower than the corresponding heat flux obtained at a nozzle to slab distance of 5 mm. This suggests that a steep temperature gradient does exist at the nozzle exit and consequently that the electrical energy is concentrated on the axis of the flame

and is not uniformly distributed across the flame. If we consider the flame to be a free submerged jet (see page 29) then all the results shown in figure 6-12 lie within the potential core of the jet i.e. at h less than 40 mm. Entrainment cannot occur if this is the case. The main differences between the flame and the jet are that the flame is not isothermal and incorporates swirl.

The importance of keeping the burner to slab distance at a minimum in order to maximize the stagnation point heat flux can be seen from figure 6-12.

7-6. Radial distribution of heat flux.

Figure 6-13 shows radial heat flux distributions obtained at various surface temperatures for flames without and with electrical augmentation. The effect of electrical augmentation is to increase the heat flux gradient $\frac{dq}{dR}$ obtained from the central region of the flame and again it can be seen that the electrical energy is not uniformly distributed in the flame.

Insufficient results are available to give the exact shape of the distribution. The dotted line gives a triangular distribution for the augmented flame but previous work⁽¹⁾ using water-cooled surfaces has suggested that a better approximation to the distribution is given by:

$$q = \frac{q_s}{1 + \left(\frac{R}{b}\right)^2} \quad (7-5)$$

The *full* lines were drawn using equation (7-5) for the flame both without and with electrical augmentation. An overall heat balance can be drawn up using equation (7-5). The overall rate of heat

transfer is given by:

$$q' = 2\pi q_s \int_0^R \frac{RdR}{1 + \left(\frac{R}{b}\right)^2} \quad (7-6)$$

Integrating gives:

$$q' = \pi b^2 q_s \ln\left[1 + \left(\frac{R}{b}\right)^2\right] \quad (7-7)$$

In figure 6-13 equation (7-5) can be fitted to both of the radial distribution. The overall rate of heat transfer due to electrical augmentation can be estimated from equation (7-7) for both distributions, i.e.

$$q'_{\text{elec.aug.}} = q'_{B_E = 0.27} - q'_{B_E = 0}$$

$$\text{For } B_E = 0, \quad q_s = 0.7 \text{ KW m}^{-2} \times 10^{-3} \quad b = 30 \text{ mm.}$$

$$\text{For } B_E = 0.27, \quad q_s = 1.28 \text{ KW m}^{-2} \times 10^{-3} \quad b = 13.3 \text{ mm.}$$

It can be assumed that $R = 20 \text{ mm.}$ for both cases because electrical augmentation only effects the distribution significantly at $R < 20 \text{ mm.}$

This gives

$$q_{\text{elec.aug.}} = 0.345 \text{ KW}$$

At $B_E = 0.27$, the input boost ratio = 0.25. The inputs to the flame are 1.26 KW of electrical power and 5.05 KW of chemical power.

Percentage of chemical power recovered in the slab at $R = 2 \text{ cm} = 14.8\%$. Percentage of electrical power recovered in the slab at $R = 2 \text{ cm} = 31.5\%$. Within a radius of 20 mm, the proportion of electrical power recovered in the slab is double the proportion of chemical power recovered in the slab.

7-7. Effect of process variables on heat flux.

A - Total gas flow rate

The effect of methane flow rate on the heat flux from a stoichiometric flame is seen in figure 6-14. The heat flux from the flame without and with augmentation increases when the gas flow rate is increased. For the augmented flame, an optimum value of the methane flow rate appears to exist at about $1.4 \times 10^{-4} \text{ m}^3 \text{ sec}^{-1}$. Beyond this value, there is little increase in heat flux whilst below this value, the heat flux falls off sharply. For this reason all experiments were carried out at a methane flow rate of $1.4 \times 10^{-4} \text{ m}^3 \text{ sec}^{-1}$.

In the case of the flame without augmentation there is no longer an optimum value of the methane flow rate in the range under consideration. The heat flux increases about linearly with gas flow rate. These trends can be explained approximately using equation (2-38) in which it is shown that

$$q \propto \left(\frac{du_e}{dr} \right)_s^{0.5} \quad (7-8)$$

From equations (3-1) and (3-2)

$$\left(\frac{du_e}{dr} \right)_s \propto Q \quad (7-9)$$

Hence

$$q \propto Q^{0.5} \quad (\text{Methane flow rate})^{0.5} \quad (7-10)$$

B - Stoichiometric factor

Figure 6-15 shows the effect of stoichiometric factor e on the heat flux. In this experiment the methane flow rate was kept constant and the air flow rate was varied. As e increases, the total gas flow rate will also increase and so figure 6-15 also includes

the effect of gas flow rate which has already been explained immediately above.

a - For lean flames $e > 1$, all the curves show that the heat flux decreases as e increases, despite the fact that the total gas flow rate increases. This effect is due to dilution of the combustion products.

b - For $e < 1$, all the curves show that the heat flux decreases. This effect will be due to the decrease in total gas flow rate. It is probable that this effect will be modified according to the proportion of dissociated hydrogen present. Figure 7-5 shows theoretically how the hydrogen atom concentration varies with stoichiometric factor e and gas temperature t . This plot was obtained from figure 2-12 and shows that the hydrogen atom concentration increased as e reduced. Equation 2-38 indicates that the heat flux increases when the hydrogen atom concentration increases. The combined effect of gas flow rate and hydrogen atom concentration has been obtained theoretically for a frozen boundary layer from equation 2-38 and is shown plotted in figure 6-15 as the line AB. This theoretical line gives lower heat fluxes than the experimental values, probably due to non-uniform distribution of electrical energy as discussed on page 126. There is also no noticeable dependence of heat flux on e and total gas flow rate Q in the range of e between 0.8 and 1.2.

C - Boost ratio

The effect of boost ratio on the heat flux is shown in figure 6-16. It can be seen that as a result of augmentation the heat flux increases considerably.

From figure 6-16 the approximate relationship is true

$$\frac{q_{B_E}}{q_{B_E=0}} \approx 8 B_E \quad (7-11)$$

i.e. the stagnation point heat flux is increased by a constant factor of $8 B_E$ when the flame is augmented with a boost ratio of B_E .

The stagnation point results of other workers have also been plotted on figure 6-17. These were obtained under similar conditions to the present work except that all the surfaces were water-cooled. All these results are in reasonable agreement with the present work. It is interesting to note that Karlovitz et al⁽¹²⁾ claim that their discharge is diffuse. However their stagnation point results indicate that the distribution of electrical energy across the flame must be similar to that obtained by other workers, including the present work. This suggests that Karlovitz et al also obtained a filamentary arc discharge and not a diffuse discharge.

7-8. Effect of surface temperature on the heat flux.

The decrease of heat flux as surface temperature increases becomes more rapid as the boost ratio B_E increases. Figure 3-1 shows that the boundary layer is largely frozen. The magnitude of the heat flux from a frozen boundary layer is dependent upon the heterogeneous recombination coefficient γ . For metals at room temperature γ is high⁽⁴¹⁾. At surface temperatures above 1000 K desorption of hydrogen atoms from the surface occurs before recombination⁽⁴¹⁾. This will result in a decrease in the heat flux. Consequently the heat flux will exhibit a greater dependence on surface temperature than can be expected by consideration of the enthalpy driving force $(h_s - h_w)$ given in equation 2-48 because this equation

assumes that $\delta = 1$ in the case of the frozen boundary layer.

7-9. Comparison between experimental and predicted heat fluxes.

A comparison between figures 6-10 and 3-4 indicates that for augmented flames the experimental values of stagnation point heat flux are considerably higher than the theoretical values. The agreement is reasonable when the flame is not augmented. The extent of this discrepancy can be obtained from the ratio

$$\eta = \frac{q_s - q_{s,B_E=0} \text{ Experimental}}{q_s - q_{s,B_E=0} \text{ Predicted}} \quad (7-12)$$

Values of η at various boost ratios and surface temperatures which have been obtained from figures 6-10 and 3-4 are given in table 7-4.

B_E	η at T_W	
	750	1000
0.27	5.5	6.2
0.62	5.1	5.8
0.81	5.6	6.2
1.21	5.9	7.4

Table 7-4.

Table 7-4 suggests that the experimental values of heat flux due to electrical augmentation exceed the predicted ones by a factor of between 5 and 7. To predict heat fluxes from electrically augmented flames some assumptions have been made. These are explained on page 45. The only assumptions that are likely to influence the heat flux sufficiently to account for $\eta = 5$ to 7 are assumptions 1 and 2.

Assumption 1 is invalid as discussed on page 126

because a large proportion of the flame gases by-pass the arc. The enthalpy driving force on the flame axis will be much greater than that predicted assuming a uniform distribution of electrical energy. Also, the flame will contain a larger proportion of hydrogen atoms on its axis than predicted using assumption 1 and hence thermal diffusion could then become significant. A flame temperature of 3700 K gives good agreement between predicted and experimental heat fluxes at a boost ratio of 1.2. This indicates that the flame temperature must be well-defined if equations (2-37) and (2-38) are to be used to predict heat fluxes, because a small increase in temperature causes a large increase in enthalpy h_s and heat flux q_s .

The validity of assumption 2 on page 45, that thermal radiation from the arc is negligible has been discussed on page 169 in appendix.

7-10. Application of the burner for melting.

An example of the use of the burner for melting steel, will now be considered, assuming $B_E = 1.2$ and the gas flow rates that are given in run number 45.

Electrical power input to burner	= 6 KW
Power input from combustion	= 5 KW
Total power input	= 11 KW

A possible design of furnace which incorporates the burner is shown in figure 7-5.

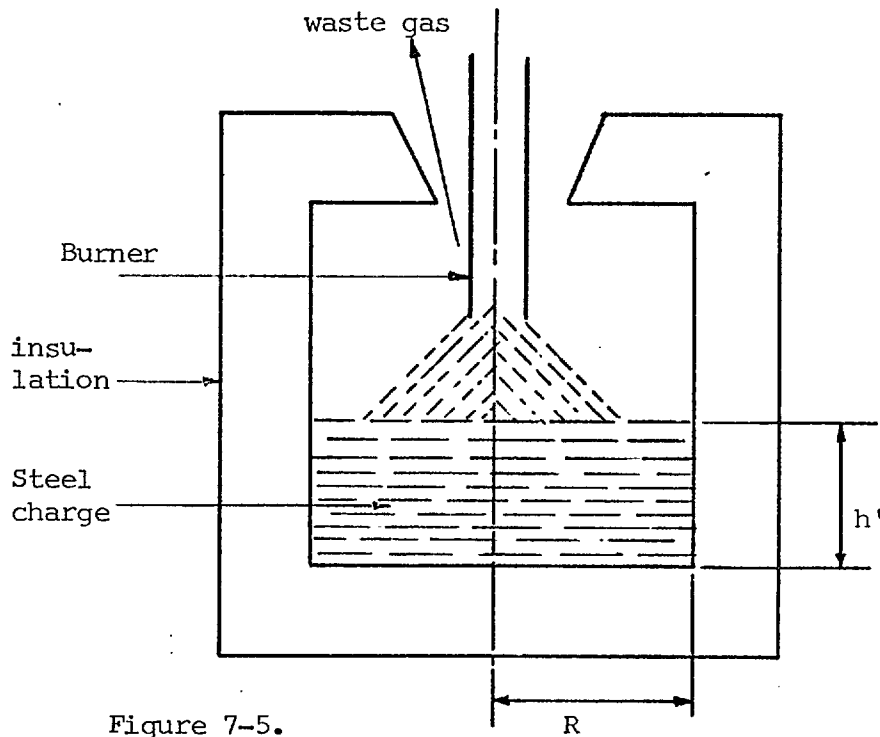


Figure 7-5.

A heat balance on this furnace at the melting point of the charge will enable the diameter and depth of the charge to be calculated.

A - Heat balance

a - Overall rate of heat transfer to charge

Equation 7-5 gives overall rate of heat transfer as

$$q' = \pi b^2 q_s \ln \left[1 + \left(\frac{R}{b} \right)^2 \right] \quad (7-7)$$

At the melting point of steel (1600°C), the stagnation point heat flux can be found by extrapolation from figure 6-10. A value for b can be found by assuming that the distribution of heat flux is similar to that shown in figure 6-12 and that at $R = 20 \text{ mm}$,

$$q_{B_E} = 1.2 \quad \sim \quad q_{B_E} = 0$$

$$\text{From this } q_s = 2000 \text{ KWm}^{-2} \quad (7-6)$$

b - Heat lost in waste gas

Figure 2-12 shows the composition of the waste gas at 1600°C. This composition can be approximated to

$$X_{H_2O} = 0.2$$

$$X_{CO_2} = 0.1$$

$$X_{N_2} = 0.7$$

Total gas flow rate at 20°C is $1560 \times 10^{-6} \text{ m}^3/\text{s} = 0.07 \text{ mole/s}$

X	P _X	Moles/sec.	KJ/mole	KW
H ₂ O	0.2	0.014	77	1.08
CO ₂	0.1	0.007	96	0.67
N ₂	0.7	0.049	61	2.99
				4.74

Table 7-5.

Table 7-5 gives the mole fractions of the major constituents of the waste gas and their enthalpies. The total heat lost in the waste gas is 4.7 KW.

c - Radius of charge

The radius of the charge R can be calculated from equation 7-6 because the value of q' is given by

$$\begin{aligned} q' &= \text{total power input} - \text{heat lost in waste gas} \\ &= 11 - 4.7 = 6.3 \text{ KW} \end{aligned}$$

However, values of R calculated from equation 7-6 are found to vary strongly with b, as shown in table 7-6.

b mm	R mm
10	380
13	250
16	107

Table 7-6.

A reasonable value for R is given when b = 16 mm.

d - Heat loss from walls of furnace

During melting, the unsteady state heat loss through the furnace walls from the charge can be calculated if the thermal diffusivity and the thermal conductivity of the refractory are known.

$$\text{Heat flux through the walls } q = \frac{k \Delta t}{\sqrt{\pi \alpha \tau_m}} \quad (7-13)$$

where τ_m is the time for melting. .

Temperature difference across wall, Δt = Mean charge temperature -
outside furnace wall temperature

$$\Delta t \approx 800^\circ\text{C}$$

$$k = 1.7 \times 10^{-4} \text{ W m}^\circ\text{C}^{-1}$$

$$\alpha = 2.2 \times 10^{-5} \text{ m}^2\text{sec}^{-1}$$

$$\text{Hence wall heat flux } q = \frac{16.4}{\sqrt{\tau_m}}$$

$$\text{Wall area enclosing charge} = \pi R^2 + 2\pi R h'$$

$$\text{Heat loss from charge } Q = \frac{16.4}{\sqrt{\tau_m}} [\pi R^2 + 2\pi R h']$$

e - Depth of charge

A heat balance over melting time τ_m allows h' to be expressed in terms of τ_m .

Heat input to the charge = Heat required to raise charge to melting point + Heat lost from charge through walls.

Heat input to the charge = 6.3 KW

Heat required to raise charge to melting point =

$$\frac{\pi R^2 h' \rho}{\tau_m} (C_{\text{steel}} \times 1600 + L_{\text{steel}})$$

where

$$C_{\text{steel}} = 0.71 \text{ KJ K}_g^{-1} \text{ } ^\circ\text{C}^{-1}$$

$$L_{\text{steel}} = 240 \text{ KJ k}_g^{-1}$$

$$\rho_{\text{steel}} = 7.9 \times 10^3 \text{ K}_g \text{ m}^{-3}$$

From this heat balance, the depth of steel melted can be obtained together with the time of melting. Typical values are shown in table 7-7.

Depth of charge h' mm	Time for melting τ_m sec
1.8	10^2
18.0	10^3
180.0	10^4

Table 7-7.

From figure 6-10 it can be seen that the heat flux without augmentation is approximately zero at 1600°C . Steel cannot therefore be melted by the flame without augmentation. This can be seen from figure 7-6 on which surface temperature is plotted against time.

$q_{x=0} = 0.8 \times 10^3 \text{KWm}^{-2} \quad t_s = 600^{\circ}\text{C} \quad \tau = 3.5 \text{ sec.}$					$q_{x=0} = 3.5 \times 10^3 \text{KWm}^{-2} \quad t_s = 1300^{\circ}\text{C} \quad \tau = 10.24 \text{ sec.}$				
x mm	Slab temp. from equation 2-47 $^{\circ}\text{C}$	Order of Polynomial			Slab temp. from equation 2-47 $^{\circ}\text{C}$	Order of Polynomial			
		2		3		2		3	
		3 points	4 points			3 points	4 points		
0.0	600	616	605	618	1300	1307	1252	1315	
1.5	544	544	545	550	1111	1111	1091	1111	
5.0	413	413	420	413	725	725	757	725	
15.0	166	166	162	166	157	157	141	157	
25.0	53.6		54.6	53.6	17.3		22	17	
50.0	1.06				1				

Table 7-1. Calculated temperature profiles in the heat flux meter.

Run No.	$t_s - t_o$ ($^{\circ}\text{C}$)	$q\text{-KWm}^{-2} \times 10^{-3}$	Run No.	$t_s - t_o$ ($^{\circ}\text{C}$)	$q\text{-KWm}^{-2} \times 10^{-3}$
1 Unaug. 520	263	0.75	47 Unaug.	265	0.72
	344	0.71		345	0.70
	395	0.68		397	0.68
	430	0.66		437	0.66
	460	0.64		466	0.64
	484	0.62		489	0.62
	503	0.60		497	0.59
	520	0.58		522	0.58
	534	0.57		535	0.56
	545	0.55		545	0.54
45 Aug.	843	390	46 Aug.	778	373
	981	339		999	355
	1091	310		1127	319
	1226	290		1192	287
	1287	263		1245	261
	1286	241		1308	240
	1345	222		1311	222

Table 7-2. Reproducibility - Comparison between run numbers 1, 47 and 45, 46.

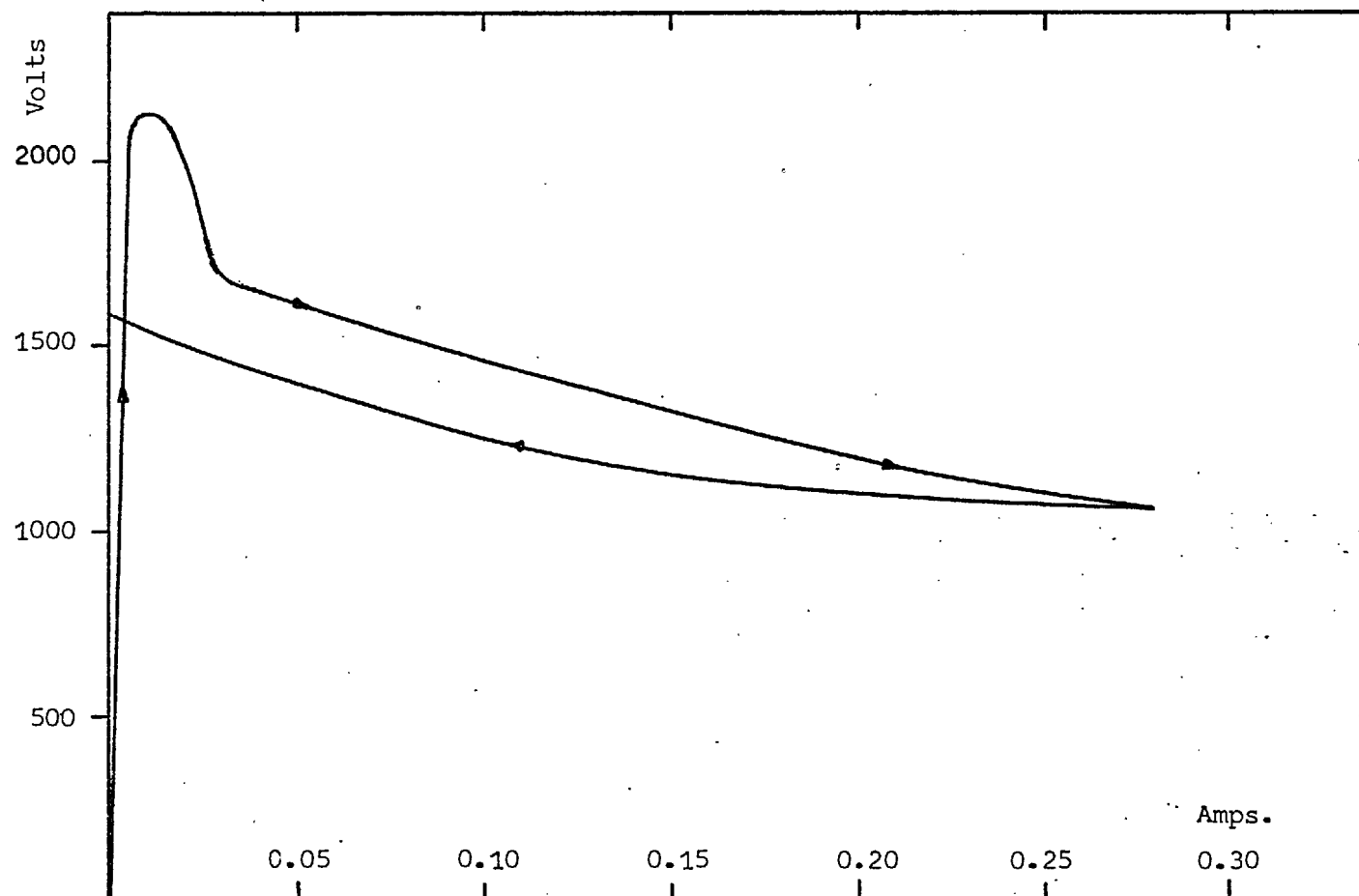


Figure 7-1. Variation of voltage with current obtained from plate 5.a.

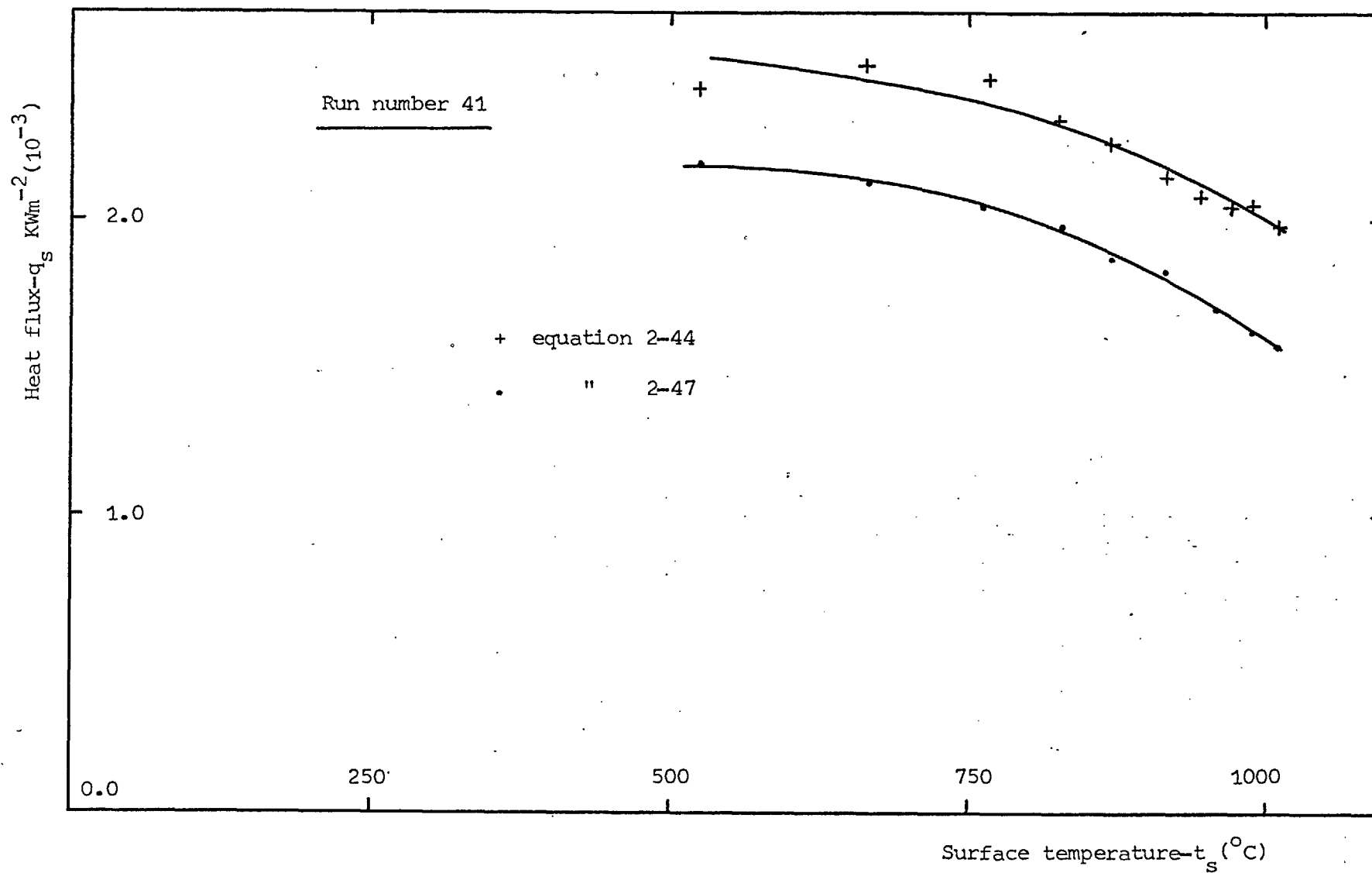


Figure 7-2. Heat fluxes determined from equations (2-44) and (2-47).

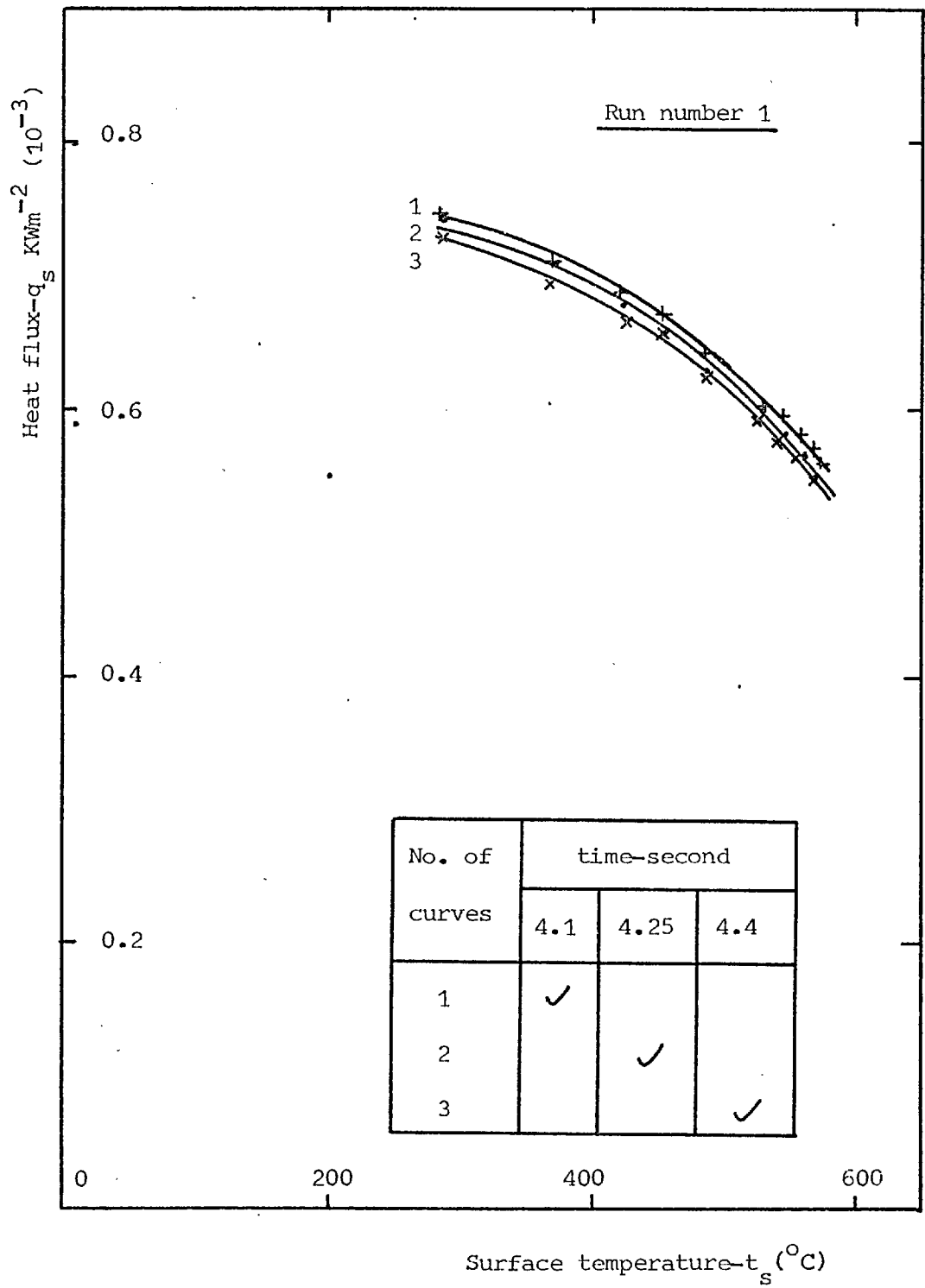


Figure 7-3. Effect of times after starting experiment on heat flux.

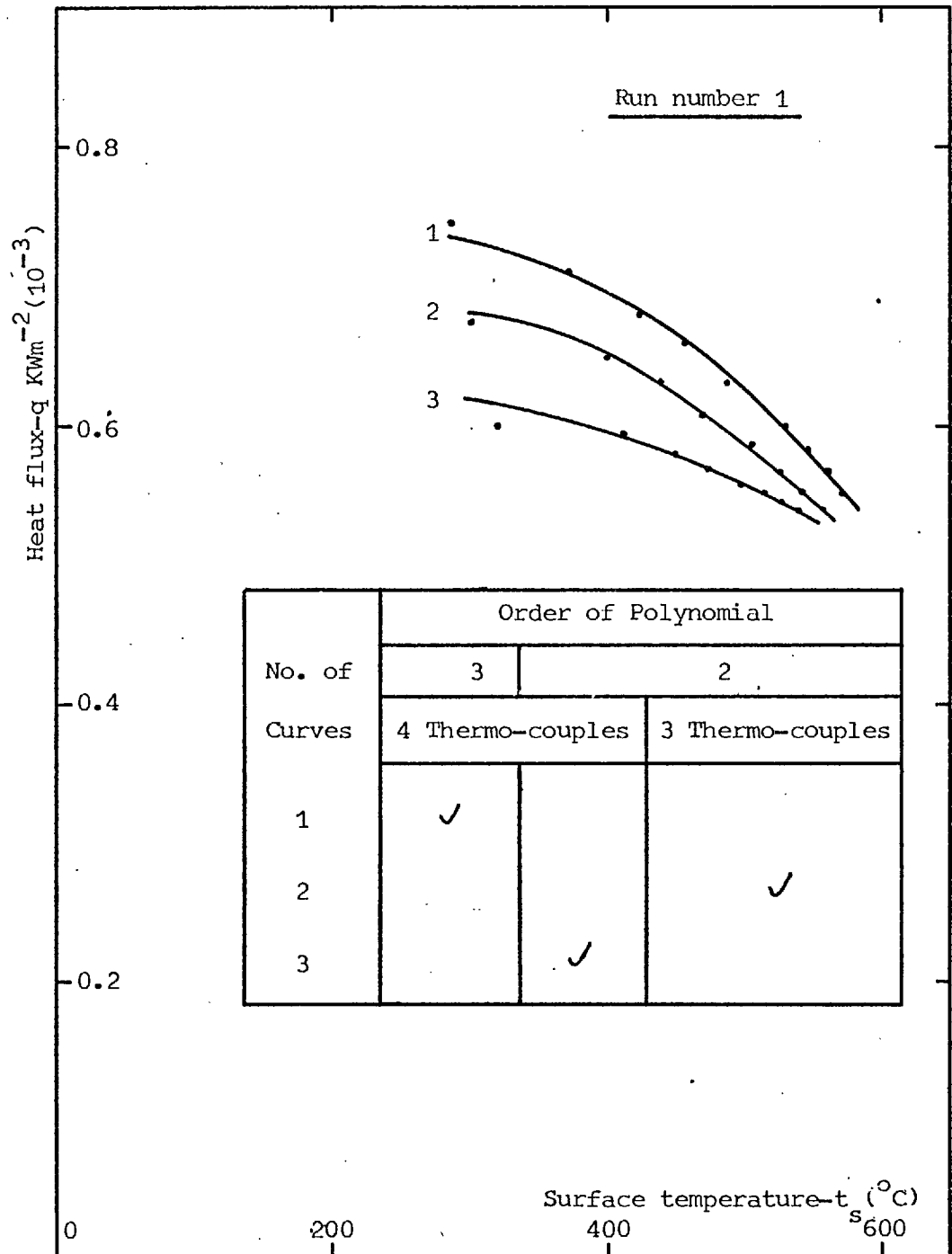


Figure 7-4. Effect of order of polynomial on heat flux.

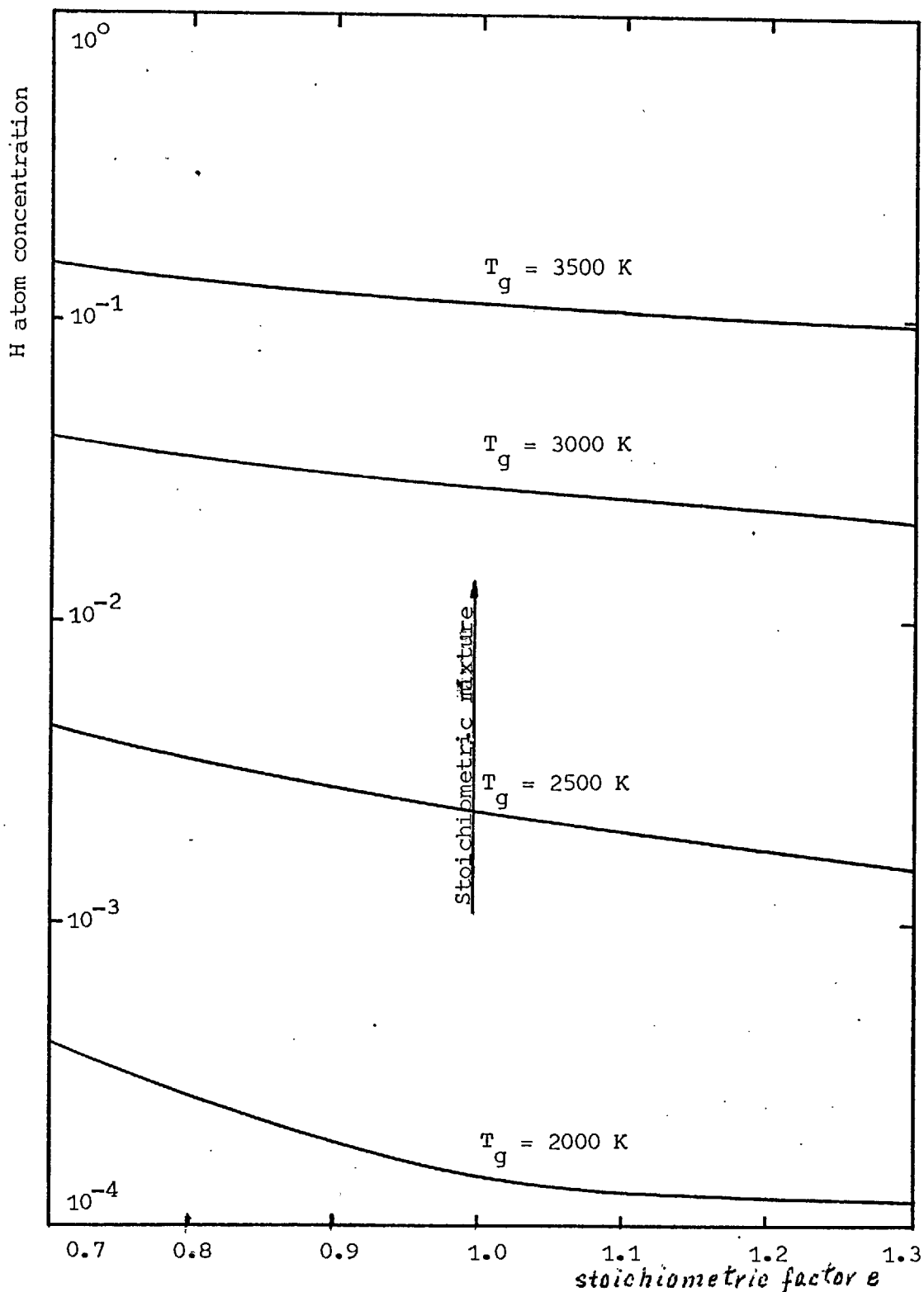


Figure 7-5. Variation of hydrogen atom concentration with stoichiometric factor and gas temperature.

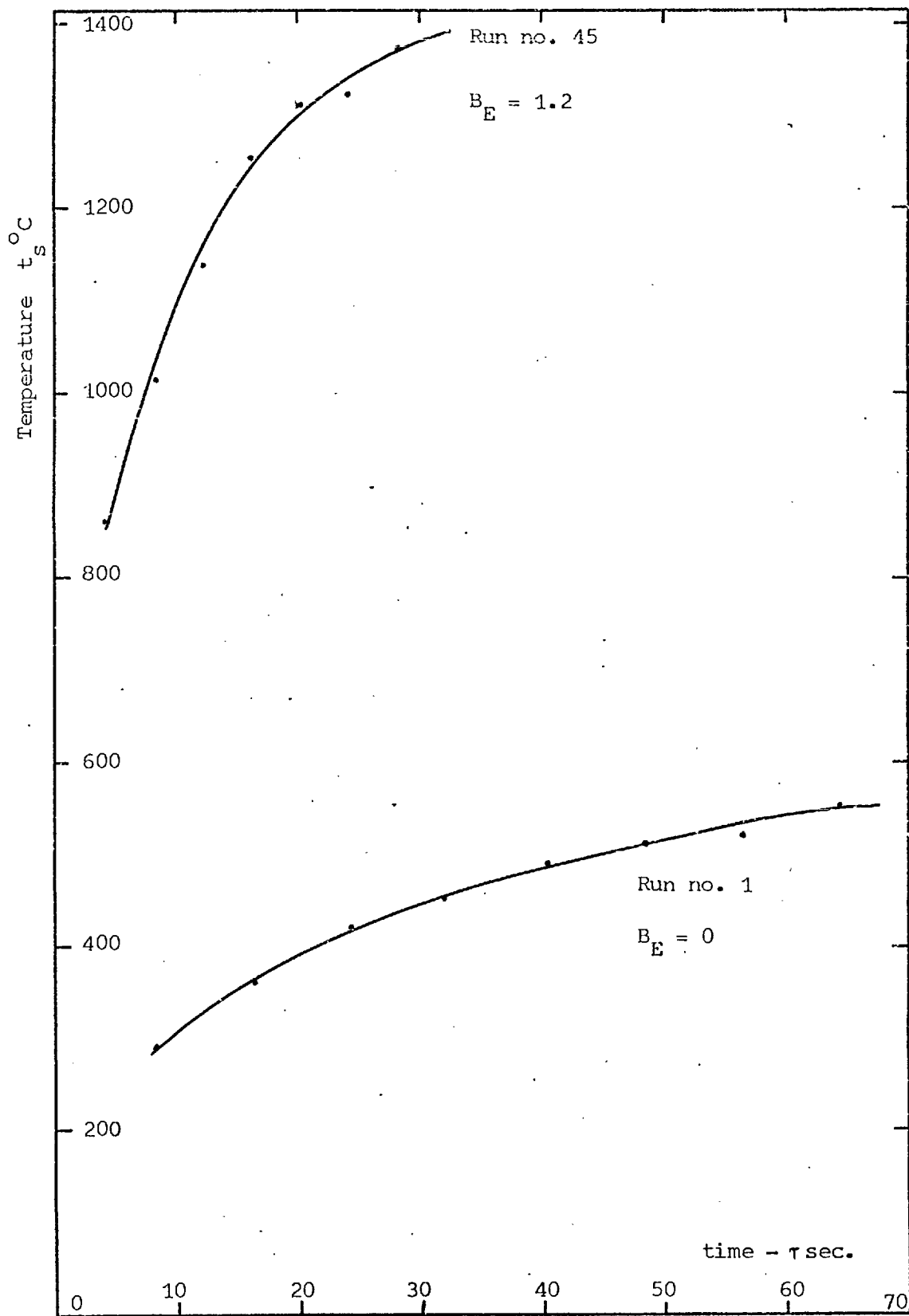


Figure 7-7. Variation of surface temperature with time for flame with and without augmentation.

Chapter 8

Conclusions

Conclusions

A heat flux meter has been developed which has enabled the heat flux from an electrically augmented flame impinging on the surface of a steel slab to be determined as the surface temperature of the slab increases. The following conclusions can be drawn from the results obtained with the heat flux meter.

- 1 - Electrical augmentation greatly increases the heat flux, particularly at the stagnation point.
- 2 - An electrically augmented burner can be used for melting steel at a boost ratio of unity or greater.
- 3 - The heat flux at a steel surface decreases as the surface temperature approaches the melting point of the steel.
- 4 - Heat fluxes obtained at low surface temperatures are in agreement with those obtained by other workers, under similar conditions.

Values of stagnation point heat fluxes were predicted from theoretical equations describing heat transfer from partially dissociated gases to a stagnation point. The augmented flame was represented by a binary gas model involving the diffusion of H atoms in the rest of the gas. In this system the Lewis number is greater than unity and the boundary layer was found to be largely frozen, indicating that the H atoms will recombine on the surface releasing energy. The conclusion that can be drawn from this is that electrical augmentation increases the concentration of H atoms in the flame and will therefore increase the heat flux by a greater amount than can be attributed to an increase in the temperature driving force alone.

A comparison between predicted and experimental stagnation point heat fluxes shows that experimental values greatly exceeded the predicted values based on an uniform distribution of electrical energy in the flame. This leads to the conclusion that the electrical energy is concentrated close to the axis of the flame. The existence of a diffuse discharge by some workers is thought to be unlikely because their heat flux values also greatly exceed the predicted values.

Appendix A

Emfs obtained from
Thermo-couples 1, 2, 3 and 4
in the heat flux meter.

Key -

U = Without augmentation (at 8 second intervals)

A = With augmentation (at 4 second intervals)

* = Starting time 8.25 at 4 second intervals.

** = Fourth thermo-couple failed.

Run No.	mV from the thermo-couple $\times 10^2$				Run No.	mV from the thermo-couple $\times 10^2$			
	1	2	3	4		1	2	3	4
1 U.	0917	0465	0110	0080	4 U.	0752	0363	0064	0044
	1250	0796	0246	0087		1034	0650	0168	0049
	1477	1027	0392	0107		1226	0848	0295	0063
	1648	1210	0481	0135		1366	0996	0407	0085
	1783	1356	0613	0165		1475	1113	0510	0109
	1893	1475	0725	0192		1560	1205	0597	0133
	1031	1573	0819	0216		1628	1279	0669	0156
	2054	1653	0899	0232		1685	0339	0730	0175
2 U.	2114	1719	0967	0253	5 U.	1731	1390	0781	0192
	2163	1775	1029	0273		1770	1432	0825	0205
	0869	0444	0102	0072		0697	0383	0083	0059
	1177	0752	1229	0075		0951	0557	0185	0063
	1358	0953	0366	0097		1119	0733	0323	0078
	1547	1134	0460	0121		1247	0871	0401	0099
	1674	1268	0578	0149		1355	0988	0434	0121
	1772	1376	0679	0176		1445	0185	0470	0142
3 U.	1855	1466	0766	0199	6 U.	1517	1160	0504	0164
	1922	1539	0840	0218		1577	1223	0546	0180
	1976	1560	0901	0238		1627	1277	0617	0197
	2025	1651	0957	0251		1673	1327	0691	0203
	0801	0413	0093	0063		0738	0394	0112	0084
	1086	0698	0208	0062		0985	0641	0210	0089
	1282	0869	0337	0084		1149	0807	0318	0102
	1429	1049	0435	0106		1269	0932	0409	0121
3 U.	1543	1171	0537	0131	6 U.	1362	1030	0493	0141
	1634	1269	0631	0156		1435	1109	0567	0161
	1710	1350	0709	0180		1493	1172	0629	0179
	1772	1416	0775	0200		1542	1225	0682	0195
	1824	1472	0832	0217		1584	1269	0726	0209
	1867	1519	0882	0231		1617	1306	0764	0220

Run No.	mV from the thermo-couple $\times 10^2$				Run No.	mV from the thermo-couple $\times 10^2$			
	1	2	3	4		1	2	3	4
7 A.	0976	0346	0079	0074	10 A.	0663	0272	0088	0086
	1399	0705	0121	0080		0925	0496	0111	0089
	1729	1011	0218	0099		1111	0670	0165	0090
	1976	1264	0338	0112		1255	0812	0233	0092
	2179	1471	0445	0125		1372	0930	0305	0101
	2343	1650	0567	0139		1476	1030	0374	0108
	2507	1804	0683	0149		1543	1116	0437	0118
	2634	1955	0791	0159		1609	1187	0501	0136
2717	2063	0892	0169	1664	1250	0560	0166		
2817	2158	0984	0180	1728	1306	0612	0162		
8 A.	0883	0344	0075	0073	11 A.	0652	0278	0084	0084
	1287	0618	0122	0074		0903	0493	0110	0084
	1572	0884	0239	0078		1082	0667	0160	0084
	1788	1106	0355	0093		1258	0812	0234	0092
	1970	1297	0407	0100		1387	0941	0301	0098
	2114	1461	0447	0119		1520	1050	0376	0108
	2242	1597	0485	0138		1607	1158	0445	0120
	2336	1711	0539	0160		1696	1247	0514	0134
2425	1811	0635	0180	1772	1325	0580	0145		
2504	1898	0743	0200	1841	1395	0641	0154		
9 A.	0827	0341	0083	0081	12 A.	0634	0252	0075	0075
	1169	0609	0121	0087		0925	0485	0102	0076
	1426	0847	0213	0096		1135	0676	0157	0080
	1631	1046	0330	0105		1303	0835	0224	0081
	1796	1218	0410	0116		1440	0972	0303	0086
	1936	1367	0474	0130		1561	1094	0382	0097
	2050	1494	0537	0146		1655	1193	0461	0106
	2152	1602	0601	0164		1766	1295	0551	0118
2258	1699	0714	0184						
2359	1798	0830	0206						

Run No.	mV from the thermo-couple x10 ²				Run No.	mV from the thermo-couple x10 ²			
	1	2	3	4		1	2	3	4
13 U.	0949	0500	0117	0081	16 U.	0524	0283	0084	0069
	1289	0833	0253	0089		0726	0465	0152	0069
	1516	1065	0397	0108		0867	0611	0237	0079
	1682	1240	0531	0135		0979	0724	0319	0095
	1811	1376	0651	0164		1070	0819	0392	0112
	1911	1483	0751	0193		1149	0899	0461	0131
	1990	1571	0837	1218		1215	0969	0525	0150
	2057	1642	0909	0235		1274	1030	0581	0168
	2111	1702	0971	0262		1327	1084	0633	0185
14 U.	2157	1752	1025	0281	17 A.	1373	1131	0679	0202
	0871	0454	0108	0076		0752	0327	0077	0069
	1179	0755	0228	0082		1013	0554	0114	0070
	1391	0971	0367	0099		1207	0736	0174	0073
	1553	1139	0469	0123		1366	0889	0249	0079
	1681	1277	0590	0149		1495	1021	0330	0088
	1787	1390	0693	0175		1606	1135	0410	0098
	1873	1483	0781	0201		1704	1236	0489	0111
	1946	1560	0858	0223		1787	1324	0559	0125
15 U.	2007	1625	0924	0244	18 A.	1859	1403	0626	0139
	2058	1679	0981	0265		1927	1473	0688	0156
	0576	0298	0085	0069		0688	0276	0074	0069
	0785	0501	0159	0074		0966	0513	0103	0070
	0933	0652	0250	0084		1170	0693	0160	0073
	1053	0774	0335	0100		1335	0861	0233	0078
	1147	0872	0410	0118		1471	0996	0313	0085
	1224	0953	0482	0137		1587	1114	0394	0095
	1290	1021	0548	0156		1687	1217	0472	0108
	1346	1081	0605	0174		1771	1307	0545	0124
	1394	1132	0656	0191		1847	1387	0613	0137
	1438	1176	0701	0208		1914	1959	0676	0153

Run No.	mV from the thermo-couple $\times 10^2$				Run No.	mV from the thermo-couple $\times 10^2$			
	1	2	3	4		1	2	3	4
19*	0547	0293	0089	0071	22	0735	0301	0079	0080
	0685	0412	0117	0075		1029	0549	0109	0082
	0803	0521	0162	0077		1259	0756	0171	0086
	0673	0616	0207	0083		1431	0927	0251	0091
	1002	0702	0267	0089		1578	1075	0337	0097
	1085	0782	0308	0134		1699	1200	0426	0105
	1165	0855	0360	0106		1807	1310	0506	0116
	1233	0922	0409	0119		1890	1405	0584	0130
	1300	0986	0458	0128		1968	1483	0654	0148
	1359	1042	0505	0169		2040	1556	0720	0160
20*	0587	0307	0091	0074	23*	0625	0340	0106	0087
	0717	0428	0122	0076		0774	0433	0139	0088
	0821	0531	0164	0079		0894	0544	0184	0090
	0909	0622	0210	0085		1001	0645	0235	0094
	0991	0698	0259	0091		1097	0735	0293	0101
	1062	0769	0308	0099		1182	0818	0357	0109
	1127	0833	0355	0108		1261	0896	0402	0118
	1182	0892	0402	0118		1332	0967	0425	0130
	1243	0947	0446	0128		1398	1034	0443	0142
	1294	0998	0988	0138		1462	1097	0472	0154
21	0725	0295	0079	0075	24*	0551	0345	0107	0085
	1021	0543	0108	0076		0686	0425	0143	0086
	1251	0749	0169	0080		0802	0484	0190	0089
	1423	0920	0249	0086		0909	0581	0242	0094
	1570	1068	0335	0093		0998	0665	0304	0100
	1691	1194	0423	0099		1080	0744	0360	0190
	1798	1303	0504	0111		1155	0817	0399	0120
	1882	1396	0581	0125		1228	0887	0419	0131
	1960	1476	0651	0140		1298	0951	0431	0145
	2031	1549	0716	0156		1362	1015	0444	0159

Run No.	mV from the thermo-couple $\times 10^2$				Run No.	mV from the thermo-couple $\times 10^2$			
	1	2	3	4		1	2	3	4
25 U.	0756	0387	0095	0070	28 U.	1066	0528	0117	0077
	1027	0645	0203	0077		1457	0911	0311	0087
	1216	0837	0332	0093		1719	1187	0433	0114
	1361	0988	0420	0115		1919	1402	0532	0154
	1476	1109	0500	0140		2073	1571	0689	0190
	1569	1208	0600	0164		2195	1708	0823	0211
	1648	1291	0678	0187		2293	1819	0937	0227
	1712	1360	0739	0202		2373	1908	1032	0232
	1766	1417	0797	0218		2438	1981	1115	0273
	1812	1467	0850	0233		2492	2040	1187	0302
26 U.	0847	0433	0093	0065	29 U.	1139	0579	0105	0076
	1157	0730	0224	0075		1525	1003	0280	0083
	1360	0942	0368	0094		1785	1307	0439	0105
	1526	1108	0443	0121		1983	1534	0664	0150
	1650	1240	0523	0151		2136	1708	0782	0187
	1752	1349	0640	0177		2260	1842	0910	0216
	1837	1440	0728	0195		2356	1957	1020	0240
	1908	1517	0809	0212		2455	2035	1115	0274
	1969	1581	0876	0226		2498	2103	1199	0300
	2019	1636	0934	0242		2553	2160	1270	0321
27 U.	0983	0519	0106	0078	30 A.	0769	0321	0089	0087
	1353	0875	0246	0088		1099	0584	0120	0092
	1604	1132	0409	0108		1351	0813	0187	0099
	1789	1327	0562	0137		1561	1004	0276	0109
	1932	1479	0695	0171		1740	1177	0368	0119
	2043	1600	0810	0201		1894	1327	0455	0131
	2133	1697	0906	0224		2008	1454	0548	0144
	2205	0776	0988	0257		2126	1569	0636	0157
	2263	1841	1059	0280		2215	1670	0717	0169
	2315	1895	1119	0301		2300	1757	0792	0181

Run No.	mV from the thermo-couple $\times 10^2$				Run No.	mV from the thermo-couple $\times 10^2$			
	1	2	3	4		1	2	3	4
31 A.	0846	0350	0098	0092	34 A.	1039	0423	0086	0082
	1231	0641	0129	0095		1487	0771	0145	0086
	1517	0901	0210	0099		1811	1068	0281	0093
	1752	1117	0325	0107		2052	1316	0392	0106
	1928	1303	0411	0116		2239	1525	0460	0117
	2078	1464	0479	0127		2598	1706	0559	0129
	2210	1601	0580	0139		2529	1844	0679	0142
	2314	1718	0676	0152		2640	1972	0787	0156
	2414	1824	0766	0165		2739	2082	0890	0171
	2488	1911	0851	0176		2820	2177	0979	0185
32 A.	0970	0414	0092	0085	35 U.	0825	0428	0104	0073
	1413	0722	0151	0088		1123	0725	0223	0082
	1750	1020	0290	0100		1332	0935	0358	0098
	2000	1273	0389	0113		1487	1096	0463	0122
	2209	1496	0448	0125		1611	1225	0578	0148
	2381	1682	0543	0138		1707	1330	0673	0176
	2517	1838	0658	0150		1787	1415	0754	0201
	2633	1966	0770	0165		1852	1485	0824	0220
	2743	2084	0877	0170		1905	1542	0884	0238
	2831	2182	0975	0188		1951	1592	0937	0261
33 A.	0997	0387	0094	0089	36 U.	0907	0464	0098	0066
	1477	0768	0141	0092		1260	0804	0236	0074
	1830	1087	0244	0100		1507	1051	0387	0093
	2073	1351	0370	0112		1690	1241	0512	0120
	2256	1556	0477	0124		1836	1392	0642	0151
	2408	1729	0603	0136		1948	1513	0753	0182
	2551	1875	0721	0149		2038	1610	0845	0208
	2657	2000	0829	0103		2111	1689	0924	0227
	2751	2110	0928	0177		2174	1755	0992	0252
	2835	2197	1016	0190		2222	1810	1053	0274

Run No.	mV from the thermo-couple $\times 10^2$				Run No.	mV from the thermo-couple $\times 10^2$			
	1	2	3	4		1	2	3	4
37 U.	0876	0458	0099	0070	40** A.	1501	0496	0072	
	1198	0768	0231	0079		2105	1049	0143	
	1419	0990	0380	0098		2613	1555	0301	
	1584	1164	0472	0125		2956	1930	0482	
	1717	1304	0591	0155		3226	2246	0682	
	1821	1417	0698	0184		3415	2463	0862	
	1907	1508	0785	0205		3617	2665	1028	
	1977	1584	0863	0223		3733	2827	1179	
	2036	1648	0931	0237		3864	2961	1311	
	2087	1703	0989	0247		3999	3091	1431	
38 U.	0865	0461	0103	0074	41 A.	1546	0579	0103	0095
	1182	0768	0230	0081		2160	1114	0178	0100
	1392	0988	0367	0099		2584	1559	0325	0109
	1558	1157	0492	0126		2929	1904	0497	0120
	1683	1289	0609	0155		3112	2183	0675	0132
	1781	1396	0709	0183		3338	2396	0845	0143
	1863	1483	0795	0205		3468	2571	0998	0156
	1928	1554	0868	0227		3590	2714	1134	0169
	1983	1613	0931	0249		3682	2829	1256	0185
	2027	1662	0986	0269		3761	2929	1361	0201
39** A.	1493	0551	0080		42** A	1409	0486	0078	
	1944	1044	0162			2027	1033	0159	
	2497	1418	0321			2483	1465	0314	
	2888	1830	0445			2824	1827	0449	
	3169	2175	0613			3059	2109	0617	
	3378	2421	0799			3226	2328	0787	
	3588	2625	0969			3346	2492	0947	
	3667	2775	1125			3506	2633	1085	
	3714	2865	1259			3598	2745	1206	
	3801	2956	1371			3657	2857	1311	

Run No.	mV from the thermo-couple x10 ²				Run No.	mV from the thermo-couple x10 ²			
	1	2	3	4		1	2	3	4
43** A.	1398	0488	0090		46** A.	2456	0841	0090	
	1981	1023	0159			3335	1721	0280	
	2386	1449	0311			3960	2437	0478	
	2700	1785	0451			4310	2947	0768	
	2976	2046	0625			4561	3313	1061	
	3136	2263	0784			4798	3579	1372	
	3266	2433	0934			4872	3781	1583	
	3408	2578	1072						
	3511	2701	1222						
3562	2792	1300							
44** A.	1701	0595	0084		47 U.	0899	0466	0106	0079
	2402	1234	0164			12 1	0798	0236	0085
	2937	1783	0338			1474	1032	0381	0105
	3331	2186	0513			1651	1214	0501	0129
	3639	2544	0725			1785	1359	0623	0159
	3841	2797	0936			1890	1473	0732	0189
	3996	2990	1123			1974	1565	0821	0213
	4099	3128	1288			2042	1642	0896	0236
	4184	3242	1424			2096	1699	0963	0258
4300	3336	1541		2151	1769	1023	0270		
45** A.	2487	0781	0089						
	3259	1663	0206						
	3817	2350	0439						
	4348	2900	0718						
	4646	3331	1004						
	4734	3584	1270						
	4924	3767	1497						

Appendix B

Computer programme to solve equation (2-48).

JOB(UMC,J035,J4,CM25000,T24,MT1) REZA-GHASEMZADEH,BARVARZ
FUN(S)
MICFILM(L=LGO)

```

PROGRAM MAIN(INPUT,OUTPUT,TAPE 5=INPUT,
1TAPE6=OUTPUT,TAPE62)
  DIMENSION VOLT(30,4), TEMP(30,4), TEM(55,11)
  CALL START(1)
C   TABLE OF EMF VS TEMP. FOR CR/AL THERMO-COUPLE
  DO 1 I=1,55
    READ(5,2) I,(TEM(I,J),J=1,11)
  1 CONTINUE
  2 FORMAT (15,11F 6.1)
    WRITE (6, 3 ) ((TEM(I,J) , J=1,11) , I=1,55)
  3 FORMAT(1H0,11F10.1)
C   N = NUMBER OF CURVES OF SLAB TEMP. AGAINST X
  READ (5, 4 ) N
  WRITE (6, 6 ) N
  4 FORMAT(110)
  6 FORMAT (1H1,110)
  CALL SUBONE(VOLT,TEMP,TEM,N)
  CALL ENPLOT
  STOP
  END

C   COND = CONDUCTIVITY MSH=MEAN SPECIFIC HEAT
C   ALPHA = THERMAL DIFFUSIVITY
C   X= DISTANCE ON THE X AXIS Y=DISTANCE ON THE Y AXIS
C   COO = SURFACE TEMPERATURE (DEG. C )
C   Q=HEAT FLUX WATT/SQ CM
  SUBROUTINE SUBONE(VOLT,TEMP,TEM,N)
    DIMENSIONTEM(55,11),VOLT(16,4),X(10),Y(10),
  1ATEMP(4),A(16),C(5),TEMP(16,4),COO(20),
  2Q(20),COND(20),MSH(20),ALPHA(20)
    REAL MSH
C   PLOT THE SLAB TEMP. AGAINST X AT VARIOUS TIMES
    CALL PLOT(1.0,1.0,-3)
    CALL FACTOR(0.394)
    CALL AXIS(0.0,0.0,0.1HX,-1,25.0,0.0,0.0,1.0)
    CALL AXIS(0.0,0.0,0.1HTEMPERATURE,11,25.0,90.0,0.0,50.0)
C   VOLT(I,J) = A MATRIX EQUIVALANT TO THE TABLE OF
C   TEMPERATURE VS EMF FOR CR/AL THERMO-COUPLE
    READ(5, 7 ) ((VOLT(I,J) , J=1,4) , I=1,N)
  7 FORMAT(4F10.5)
    WRITE (6, 15) ((VOLT(I,J) , J=1,4) , I=1,N)
  15 FORMAT(1H0,4F10.5)
C   POSITION OF THERMO-COUPLES
    X(1)=1.5
    X(2)=5.0
    X(3)=15.0
    X(4)=25.0
C   EVALUATION OF THERMO-COUPLES EMFS IN TERMS OF TEMPERAT
    URE

```

```

DO 20 I=1,N
DO 30 J=1,4
VOLT(I,J)=VOLT(I,J)/100.0
IVOLT=VOLT(I,J)
XIVOLT=IVOLT
DFLTA=VOLT(I,J)-XIVOLT
IDELTA=DELTA*10.0
DO 40 IJ=1,55
IJJ=IJ-1
IF(IVOLT .NE. IJJ) GO TO 40
DO 50 KJ=1,11
KKJ=KJ-1
IF(IDELTA .NE. KKJ) GO TO 50
SELTA=IDELTA
DELTA=(DELTA-(SELTA/10.0))*100.0
TEMP(I,J)=TEMP(IJ,KJ)+DELTA*0.25
GO TO 30
50 CONTINUE
40 CONTINUE
30 CONTINUE
20 CONTINUE
C   SORTING OUT THE TEMPS IN ORDER OF POSITION
DO 80 K=1,N
DO 90 I=1,4
DO 100 J=1,4
IF (TEMP(K,J) .LE. TEMP(K,I))GO TO 110
GO TO 100
110 BTEMP = TEMP (K,I)
TEMP(K,I)=TEMP(K,J)
TEMP(K,J)=BTEMP
100 CONTINUE
90 CONTINUE
80 CONTINUE
C   PLOT OF SLAB TEMP. AGAINST X
WRITE (6,120) (X(I) , I=1,4)
WRITE(6,120)((TEMP(I,J),J=1,4),I=1,N)
INTEQ=-1
DO 60 I=1,N
DO 70 J=1,4
Y(J)=TEMP(I,J)/50.0
ATEMP(J)=TEMP(I,J)
70 CONTINUE
IF(INTEQ .EQ. 14) INTEQ=-1
INTEQ=INTEQ+1
DO 130 IK=1,4
CALL SYMBOL(X(IK),Y(IK),0.07,INTEQ,0.0,-1)
130 CONTINUE
CALL ARKIST(X,Y,1,4,3,1.0,1.0,0.0,0.0,2,1)

120 FORMAT(1H0,4F12,3)
C   USE LIBRARY SUBROUTIN TO FIT POLYNOMIAL TO SLAB
C   TEMPERATURE AGAINST XTHEN EXTRAPOLATE POLYNOMIAL
C   TO FIND SURFACE TEMPERATURE TS AT (X=0)
CALLPOLYFT(X,ATEMP,4,3,C,CO,A,6)
COO(I)=CO
60 CONTINUE
WRITE(6,160)

```

```

DO 140 NN=1,N
RNN=NN
C THE CHOICE OF ZERO TIME FOR HEAT FLUX DETERMINATION
C WHEN AT LEAST THREE THERMO-COUPLES SHOWS TEMPERATURE
C ABOVE THAT OF INITIAL SLAB TEMPERATURE
TAUE = 4.0*(RNN)+0.25
C THIED ORDER POLYNOMIAL FIT TO THE DATA GIVEN IN TABLE(
COND(NN)=(0.37519E-01)+(0.94862E-05)*(COO(NN))+(0.75510E-7)*
1(COO(NN))**2-(0.56852E-10)*(COO(NN))**3
C BEST STRAIGHT LINE TO THE DATA GIVEN IN TABLE( APP.D Page 177)
MSH(NN)=0.120+0.0000232*(COO(NN))

ALPHA(NN)=COND(NN)/(7.92*MSH(NN))
C CALCULATION OF HEAT FLUX USING EQUATION( 2-49 )
Q(NN)=4.185*((COO(NN)-TEMP(1,4))
1*COND(NN)/(1.1284*SQRT(ALPHA(NN)*TAUE)))
WRITE(6,150)COO(NN),TAUE,Q(NN)
140 CONTINUE
150 FORMAT(1H0,3F10.5)
C PLOT OF HEAT FLUX AGAINST SURFACE TEMP.
CALL PLOT(32.0,0.0,0.-3)
CALL AXIS(0.0,0.0,0.1H0,1,25.0,90.0,0.0,0.10,0)
CALL AXIS(0.0,0.0,0.1HTEMPERATURE,-11,25.0,0.0,0.0,0.50,0)
WRITE(6,160)
DO 170 I=1,N
X(I)=COO(I)
Y(I)=Q(I)
170 CONTINUE
160 FORMAT(////)
180 FORMAT(1H0,2F10.5)
DO 190 I=1,N
X(I) = X(I)/50.0
Y(I) = Y(I)/10.0
190 CONTINUE
INTEQ=-1
DO 200 I=1,N
INTEQ=INTEQ+1
CALL SYMBOL(X(I),Y(I),0.07,INTEQ,0.0,-1)
200 CONTINUE
CALL ARKIST(X,Y,1,10,5,1.0,1.0,0.0,0.0,2,1)
RETURN
END

```

SUBROUTINE POLYFT (X, Y, N, KOR, C, CO, A, NOUT)

Appendix C

Paper presented at Richardson Conference on the
physical chemistry of Process Metallurgy, held
at Imperial College, London, on 23rd - 25th July
1973.

R.G. Barvarz*, R.J. Tait*⁺ and T.P. WallAbstract

A large increase in the rate of heat transfer from a combustion flame can be obtained by augmenting it with an electrical discharge. Electrically augmented flames are therefore most attractive for high temperature metallurgical processing; their application to flame hardening has already been studied⁽³⁾ and the present work is directed at metal melting. Stagnation point heat fluxes have been obtained when a stoichiometric methane-air flame was directed onto a steel slab which contained a heat flux meter. Augmenting the flame with a quantity of electrical energy equal to the chemical energy in the flame was found to increase the stagnation point heat flux by a factor of 8. Heat fluxes have also been predicted from existing heat transfer correlations for partially dissociated gases. The experimental values were found to be 4 to 6 times greater than the predictions owing to non-uniform distribution of the electrical energy in the flame. As the surface temperature approached the melting point of the steel, the heat flux decreased to a greater extent than could be predicted from the enthalpy driving force.

Paper presented at the Richardson Conference on the Physical Chemistry of Process Metallurgy, held at Imperial College, London on 23rd-25th July 1973.

* John Percy Research Group in Process Metallurgy, Department of Metallurgy, Imperial College.

+ Wolfson Research Fellow.

1. Introduction

Electrical augmentation is a convenient method of increasing the enthalpy of a combustion flame. Various burners have been designed to accomplish this^(1,2,3) and they usually depend upon discharging an electric arc between two electrodes situated in the flame. In most cases the electrical energy added to the flame is about equal to the chemical energy released by combustion. In this paper we will not describe the design of the burner but will instead give an account of why electrically augmented flames can produce high heat fluxes. We will also present a method of estimating the magnitude of these heat fluxes and will compare values calculated by this method with values determined during experiments in which we used an electrically augmented burner to heat a slab of steel.

2. Electrical Augmentation

The equilibrium composition of the products of combustion of methane-air flames have been calculated over a wide range of air to fuel ratios and flame temperatures. In Fig.1(a) we show the equilibrium composition for a stoichiometric methane-air flame at temperatures between 1500K and 3500K. At the adiabatic flame temperature of about 2225K, we can see that the degree of dissociation is low. If the flame is electrically augmented, the flame temperature increases but also the degree of dissociation becomes larger as more atoms and radicals are produced. Fig.1(b) is a plot of effective boost ratio B_E .

*Some previous workers in this field^(1,4) have used a boost ratio B defined as
$$B = \frac{\text{electrical energy input}}{\text{chemical energy released if products of combustion were CO}_2 \text{ and H}_2\text{O only.}}$$

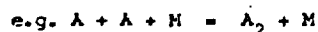
For a stoichiometric methane-air flame $B_E = 1.08B$, and if the richness of the mixture is increased, then B_E/B increases further.

against flame temperature where

$$B_E = \frac{\text{electrical energy input}}{\text{chemical energy of flame prior to augmentation}}$$

At $B_E = 1$, for example, the flame temperature has risen to 2960K. Referring back to Fig. 1(a) we can determine the composition of the combustion products at this temperature and we can see that the flame is now appreciably dissociated. These dissociated species will recombine at lower temperatures and will release a certain quantity of energy.

Recombination reactions are generally recognised to involve a third body, M.



The third body can be either a neutral gas molecule, in which case recombination is homogeneous, or a solid or liquid, when recombination will be heterogeneous. This mode of releasing energy either in the gaseous boundary layer next to a surface or at the surface itself can be expected to give rise to enhanced heat fluxes. This is the basic reason for our present research in which we are determining heat fluxes from electrically augmented flames to solid surfaces, with a view to using an electrically augmented burner to melt metals.

3. Mechanisms of Heat Transfer

Heat transfer from an electrically augmented flame impinging on a solid surface has much in common with the situation when a space vehicle, travelling at hypersonic speed, re-enters the earth's atmosphere. In this case, the polyatomic molecules in the atmosphere dissociate behind the shock wave which precedes the nose of the vehicle. The dissociated species are

predominantly nitrogen and oxygen atoms which recombine at or near the surface of the vehicle, often intensely heating the surface. This class of problem has been studied extensively and most calculations have been based on the assumption that two limiting cases exist, as follows:-

(a) Equilibrium boundary layer

Local thermochemical equilibrium will be approached if homogeneous recombination occurs throughout the boundary layer. This situation will only exist if diffusion rates are slow compared to homogeneous recombination rates. The rate of heat transfer will then be independent of the material forming the surface.

(b) Frozen boundary layer

If diffusion rates are fast compared to homogeneous recombination rates then equilibrium will not be achieved in the boundary layer. The boundary layer is then said to be "frozen" and concentration gradients in it will be independent of temperature. Recombination can only occur at the surface and the extent of recombination will be determined by the catalytic nature of the surface. The probability that an atom incident on a surface will recombine is called the heterogeneous recombination coefficient γ . Table I⁽⁴⁾ gives typical values of γ for oxygen atoms on various surfaces at room temperature.

Surface	$\gamma \times 10^4$
Metals	50 - 2500
Non-metals	2 - 50
Oxides	20 - 200

Table I Heterogeneous recombination coefficients for oxygen atoms at room temperature⁽⁴⁾

Scala⁽⁴⁾ has concluded for the re-entry problem that a surface can be considered to be perfectly catalytic if $\gamma > 40 \times 10^{-4}$. At low pressures γ has been found to be independent of surface temperature up to 1000K for metals.⁽⁵⁾

The most general situation lies somewhere between the two limiting cases outlined above and will exist when the rates of both diffusion and gas-phase recombination are of comparable magnitude.

Hirschfelder⁽⁶⁾ has described the enhanced heat flux obtained from dissociated gases in equilibrium in terms of an effective thermal conductivity. If we consider that the gas consists of an atomic species A and a molecular species B, then the heat flux is given by

$$\vec{q} = -\lambda_f \text{ grad } T - \Delta H_A D_{AB} M_A \text{ grad } x_A \quad (1)$$

Bulk flow, thermal diffusion and radiation have been ignored as being of secondary importance. Equation (1) can be re-written as:

$$\begin{aligned} \vec{q} &= -(\lambda_f + H_A D_{AB} M_A \frac{dx_A}{dT}) \text{ grad } T \\ &= -(\lambda_f + \lambda_R) \text{ grad } T \\ &= -\lambda_E \text{ grad } T \end{aligned} \quad (2)$$

Butler and Brokaw⁽⁷⁾ have shown that

$$\lambda_R = \frac{D_{AB} P}{RT} \cdot \frac{\Delta H_A^2}{RT^2} \cdot \frac{m_A m_B}{n} \quad (3)$$

and that the maximum value of λ_R occurs when

$$m_A = m_B = 0.5 \quad (4)$$

They also obtained an expression for the ratio of the effective thermal conductivity to the frozen thermal conductivity

$$\frac{\lambda_E}{\lambda_f} = 1 + \frac{D_{AB} \rho C_{p,f}}{\lambda_f} \left(\frac{C_{p,eq}}{C_{p,f}} - 1 \right) \quad (5)$$

where

$$\frac{D_{AB} \rho C_{p,f}}{\lambda_f} = Le_f \quad (6)$$

The Lewis number varies widely. For most gases Le_f is approximately unity whilst for dissociated hydrogen Le_f is much higher due to the mobility of the hydrogen atom. Data given by Butler and Brokaw⁽⁷⁾ shows that, for dissociated gases such as hydrogen and oxygen, the ratio λ_E / λ_f can be of the order of 10. Low temperature correlations of the Nusselt and Stanton type can be modified by using this effective thermal conductivity.

4. Heat Transfer Correlations

An electrically augmented flame which is being used to heat a metal can be represented as a jet of partially dissociated gas impinging on an infinitely large flat surface. A stagnation point will exist above the surface on the centre line of the jet.

Stagnation point heat transfer between a dissociated gas and a surface has been studied extensively in re-entry problems and two different approaches have been used. Both assume that air can be considered as a binary gas consisting of "air atoms" and "air molecules". Rosner⁽⁸⁾ has adapted heat transfer correlations obtained for undissociated gases by using the concept of effective thermal conductivity mentioned above. Convective heat fluxes are usually expressed in the steady state by

$$q_f = h' (T_e - T_w)$$

$$\text{or } q_f = St_f \rho_e u_e \bar{C}_p (T_e - T_w) \quad (7)$$

where

$$St_f = \frac{h'}{\rho_e u_e \bar{C}_p}$$

Sibulkin's⁽⁹⁾ incompressible fluid formula applied to the stagnation point in a laminar boundary layer gives the Stanton number as

$$St_{f,s} = 0.76 Pr_f^{-0.6} (\rho_s u_s)^{-1} \sqrt{\rho_s \mu_s \left(\frac{du}{dr}\right)_s} \quad (8)$$

Replacing $\bar{C}_p(T_e - T_w)$ by $(h_e - h_w)$ in equation (7) and combining with equation (8) gives

$$q_{f,s} = 0.76 Pr_f^{-0.6} (\rho_s \mu_s)^{0.5} (h_s - h_w) \left(\frac{du}{dr}\right)_s^{0.5} \quad (9)$$

Equation (9) can now be modified to represent heat transfer from a dissociated gas as follows:-

The ratio of the average values of the frozen and equilibrium specific heats is given by

$$\begin{aligned} \frac{\bar{C}_{p,f}}{\bar{C}_{p,eq}} &= \frac{h_{f,s} - h_{f,w}}{h_s - h_w} \\ &= 1 - \frac{m_{A,e} \Delta H}{h_s - h_w} \end{aligned} \quad (10)$$

Substituting in equation (5) gives

$$\frac{Pr_f}{Pr_{eq}} = 1 + (Le_f - 1) \frac{m_{A,e} \Delta H}{h_s - h_w} \quad (11)$$

For the dissociated case, the corresponding equation to equation (9) is

$$\begin{aligned} q_s &= 0.76 Pr_f^{-0.6} (\rho_s \mu_s)^{0.5} \left[1 + (Le_f - 1) \frac{m_{A,e} \Delta H}{h_s - h_w} \right]^{0.6} \\ &\quad \times (h_s - h_w) \left(\frac{du}{dr}\right)_s^{0.5} \end{aligned} \quad (12)$$

Fay and Riddell⁽¹⁰⁾ used an alternative approach. They integrated the laminar boundary layer equations using numerical methods and obtained solutions for an equilibrium boundary layer and for a frozen boundary layer with both catalytic and non-catalytic walls. They fitted an equation of similar type to equation (12) to their results and obtained the correlation

$$\begin{aligned} q_s &= 0.76 Pr_f^{-0.6} (\rho_w \mu_w)^{0.1} (\rho_s \mu_s)^{0.4} \left[1 + (Le_f^y - 1) \frac{m_{A,e} \Delta H}{h_s} \right] \\ &\quad \times (h_s - h_w) \left(\frac{du}{dr}\right)_s^{0.5} \end{aligned} \quad (13)$$

where $y = 0.52$ for an equilibrium boundary layer and $y = 0.63$ for a frozen boundary layer with a fully catalytic surface such that all atoms diffusing to the surface will recombine at the surface. Again, it should be noted that radiation and thermal diffusion were ignored. Also, equations (12) and (13) strictly apply to a binary mixture of one species of atoms and one species of molecules.

5. Measurement of Heat Flux

A stoichiometric mixture of $1.56 \times 10^{-3} \text{ m}^3 \text{ s}^{-1}$ of methane and air was supplied to the combustion chamber of an electrically augmented burner. An a.c. arc was discharged between two electrodes in the chamber. The augmented products of combustion issued in a jet from the burner nozzle shown in Fig.2 and impinged on the surface of the stainless steel slab. The stagnation point heat flux at the surface of the slab was determined using a heat flux meter incorporated in the slab as shown in Fig.2. The meter consisted of a 3mm diameter central rod of En 58A steel containing four mineral insulated thermocouples in 0.5mm diameter stainless steel sheaths. Two stainless

steel guard rings, insulated with plasma sprayed alumina, surrounded the central rod to ensure one-dimensional heat flow in the meter.

The slab was mounted on a trolley which was rapidly placed in position over the flame so that the heat flux meter was on the centre line of the burner nozzle. The transient output from the thermocouples was recorded by a data logger at 10 readings per second. These temperatures are shown plotted against distance from the surface of the slab in Fig.3 to give profiles at 4 second intervals. The experimental points in the figure were fitted to third order polynomials to give the surface temperature by extrapolation. The exact solution of the linear unsteady heat conduction equation⁽¹¹⁾ then gives the surface heat flux by

$$q = \frac{(T_w - T_o)\lambda}{2\sqrt{\frac{\alpha t}{\pi}}} \quad (14)$$

Here T_o is the initial temperature of the slab and α is its thermal diffusivity.

Insertion of the thermal properties of En 58A steel⁽¹²⁾ gave the experimental heat flux values which are plotted as dash lines against the surface temperature T_w for various boost ratios in Fig.6.

6. Calculation of Stagnation Point Heat Flux

A binary gas model is used to represent the flame gases. The model assumes that only hydrogen atoms diffuse through the gas because the Lewis numbers for all of the species, except hydrogen atoms, are approximately unity. The Lewis number required in either equation (12) or (13) is given by

$$Le_f = \frac{D_{H,N_2} \rho C_{p,f}}{\lambda_f} \quad \text{at } T$$

where the binary diffusivity is available⁽¹³⁾ and the properties ρ , $C_{p,f}$ and λ_f are evaluated for hydrogen atoms. The Prandtl number was considered to be constant at $Pr_f = 0.71$.

The heat of recombination for hydrogen and the enthalpy of each of the species in the gas are also available⁽¹⁴⁾. The Wilke approximation⁽¹⁵⁾ was used to calculate the viscosity and thermal conductivity of the gas from values available for H and H₂⁽¹⁶⁾ and O and N₂⁽¹⁷⁾, the OH radicals being included as O atoms and all molecular species being included as N₂ molecules. An approximate value for the stagnation point velocity gradient $(\frac{du}{dr})_s$ can be obtained if we consider the flame to be a submerged turbulent jet. In our experiments the heat flux meter was positioned at a distance of 0.4 nozzle diameters from the nozzle exit and is therefore within the potential core of the jet according to the observations of Poreh and Cermak⁽¹⁸⁾. In this case, the gas velocity on the centre-line of the jet is approximately equal to the mean jet velocity and can be evaluated from Q, the volumetric flow rate at STP, i.e.

$$\begin{aligned} u_{CL} \approx \bar{u} &= \frac{4Q}{\pi d^2} \cdot \frac{T_s}{298} \cdot \frac{28.8}{M_s} \\ &= 1.12 \frac{T_s}{M_s} \end{aligned}$$

According to Comfort et al⁽¹⁹⁾

$$\left(\frac{du}{dr}\right)_s \approx \frac{u_{CL}}{r'}$$

in the fully developed region of the jet. Extrapolation of their results to a point which corresponds to the position of

our heat flux meter gives

$$\left(\frac{du}{dr}\right)_s \approx \frac{u_{CL}}{d} = 86 \frac{T_s}{M_s} \quad (15)$$

The values of the properties $(\rho \mu)$, Le_f , $\frac{m_{H,e} \Delta H}{h_s}$, h and M are plotted against temperature T in Fig.5 and can be used to evaluate the heat flux q_s from equations (12) and (13) provided that the boundary layer condition is established. For an equilibrium boundary layer, the local temperature fixes the composition of the flame according to Fig.1(a). Therefore appropriate values of the required properties can be obtained from Fig.5 at temperatures T_s and T_w . However, the composition throughout a frozen boundary layer is fixed by the stagnation temperature T_s , only. The required properties must then be evaluated at temperatures T_s and T_w for this composition.

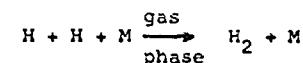
The stagnation flux q_s has been calculated for an equilibrium boundary layer using both equations (12) and (13) at values of T_s between 2200K and 3000K. As the two values agree to within 4 per cent, further calculations have been carried out using equation (13) only and the curves of heat flux q_s against surface temperature T_w at boost ratios from 0 to 1.2 are shown in Fig.6. The calculations were repeated for a frozen boundary layer assuming a perfectly catalytic surface and the heat fluxes were found to exceed the equilibrium fluxes by a maximum of 5 per cent. The frozen fluxes are therefore not shown in Fig.6.

7. Approach to Equilibrium in the Boundary Layer

Just how closely thermochemical equilibrium is approached in the boundary layer can be established using the following criterion:

$$\frac{\tau_R}{\tau_D} = \frac{\text{time for homogeneous recombination}}{\text{time for diffusion through the boundary layer}}$$

For the homogeneous recombination



$$\frac{dn_H}{dt} = -k_R n_H^2 n_M \quad (16)$$

where the rate constant is given by⁽²⁰⁾

$$k_R = \frac{3 \times 10^{-41}}{T}$$

T is the temperature in the boundary layer. Integrating equation

(16) gives

$$\tau_R = \frac{1}{k_R n_H n_M}$$

where

$$n = \frac{x P}{k T}$$

Hence,

$$\tau_R = \frac{k^2 T^3}{3 \times 10^{-41} (x_H \cdot x_M)}$$

The time for diffusion, τ_D is given by⁽¹⁰⁾

$$\tau_D = \frac{du}{dr} \Big|_s^{-1} = \frac{86 T_s^{-1}}{M_s}$$

The criterion τ_R / τ_D now becomes

$$\frac{\tau_R}{\tau_D} = \frac{54 \times 10^{-15} T^3 T_s}{x_H (1 - x_H) M_s}$$

12(a)

where P has been taken as atmospheric pressure.

Values of x_H can be obtained from Fig.1(a); for an equilibrium boundary layer x_H is evaluated at temperature T whilst in the frozen case, x_H must be determined at temperature T_s . We will determine τ_R/τ_D for both of these conditions. If τ_R/τ_D exceeds unity then the boundary layer will be frozen whilst a value of τ_R/τ_D which is less than unity indicates that the boundary layer is in equilibrium. There will be a transition region between these two extremes at values of τ_R/τ_D from about 0.1 to 10. The results of calculations carried out for our flames are shown in Fig.4. Calculations which assumed equilibrium gave $\tau_R/\tau_D > 1$, indicating that the boundary layer was never completely in equilibrium. The two curves shown in Fig.4 were plotted assuming a frozen boundary layer both at stagnation temperatures between 2000K and 5000K and at film temperatures 1000K below these stagnation temperatures. The boundary layer was therefore mainly frozen under these conditions. No conclusions can be drawn at other temperatures.

8. Comparison between Experimental and Predicted Heat Fluxes

For an augmented flame the extent by which the experimentally determined heat flux exceeds the predicted heat flux can be obtained from the ratio

$$\phi = \frac{(q_s - q_{s, BE=0})_{\text{experimental}}}{(q_s - q_{s, BE=0})_{\text{predicted}}}$$

Values of ϕ at various boost ratios and surface temperatures have been obtained from Fig.6 and are given in Table II

B_E	ϕ at T_w		
	750	900	1000
0.27	3.9	4.8	4.8
0.62	4.3	4.8	4.8
0.81	4.0	4.4	4.5
1.20	5.0	5.8	5.8

Table II Values of ϕ

It can be seen from Table II that the experimental values of the heat flux due to electrical augmentation exceed the predicted values by an approximately constant factor of between

4 and 6. Agreement is reasonable between the predicted and experimental values of heat flux for the flame without augmentation.

The assumptions that have been made in deriving equations (12) and (13) and in applying these equations to predict stagnation point heat fluxes from electrically augmented flames are given in Table III. The only assumptions that are likely to influence the predicted values sufficiently to account for $\phi = 4$ to 6 are assumptions B1 and B2.

The validity of assumption B1 is difficult to assess but it is likely that a large proportion of the flame gases at the periphery of the combustion chamber could bypass the arc⁽²⁾. This would give rise to an increase in both the enthalpy h_s and the stagnation point heat flux. Thermal diffusion could then become significant because the flame would contain a larger proportion of H atoms. Assumption B5 in Table III would also be invalidated. The flame temperature T_s which must be used to give accurate prediction of the stagnation point heat flux at $B_p = 1.2$ has been calculated to be 3700K, compared to a uniform temperature of 3000K used to obtain the corresponding predicted heat flux in Fig.6. This calculation shows that the temperature distribution in the flame must be well-defined because a relatively small increase in temperature T_s corresponds to a large increase in enthalpy h_s and heat flux q_s .

The validity of assumption B2, that thermal radiation from the arc is negligible can be assessed as follows: The arc is located on the tip of an electrode situated 65mm below the nozzle and co-axial with it. The other electrode is an annulus below the nozzle. The path of the arc and the point

of attachment of the arc to this annular electrode are both ill-defined. We will consider that the heat flux meter sees the arc as an opaque strip of thickness b and of length equal to half the nozzle diameter. The radiation heat flux is given by

$$q_r = \frac{bd}{2} \cdot F_{aw} \sigma a_w \frac{T_a^4}{A_w}$$

Taking $a_w = 0.5$, $T_a = 6000K$, $b = 1mm$ and relevant values of the view factor F_{aw} ⁽²¹⁾, q_r was calculated for two extreme cases

(a) Arc exists at nozzle exit gives $q_r = 10^4 \text{ kWm}^{-2}$

(b) Arc exists 65mm below nozzle exit gives $q_r = 10 \text{ kWm}^{-2}$

Comparing these values with the convective fluxes q_s given in Fig.6 indicates that arc radiation is highly significant if case (a) occurs.

9. Effect of Surface Temperature on Heat Flux

For the range of wavelengths of arc radiation, the surface absorptivity a_w decreases only slightly as the surface temperature T_w increases. Therefore, over the range of surface temperatures shown in Fig.6, the radiation flux q_r will be approximately constant. This is in contrast to the experimentally determined heat fluxes shown in Fig.6 which exhibit a marked dependence on surface temperature. Arc radiation is therefore unlikely to be primarily responsible for the large difference between the experimental and predicted values of heat flux.

The heat fluxes determined by experiment were calculated using equation (14). This equation assumes that the heat flux q is independent of both surface temperature T_w and time τ .

As this is not the case, the dependence of heat flux on surface temperature shown in Fig.6 will be modified, although the trend is expected to remain the same. In Fig.3, the rate of increase of surface temperature can be seen to decrease during the experiment, confirming this trend.

In Fig.6 the decrease in heat flux with increasing surface temperature becomes more rapid as the boost ratio B_E is increased. This can be explained by referring to Fig.4.

The boundary layer can be considered to be largely frozen. The magnitude of the heat flux from a frozen boundary layer is dependent upon the heterogeneous recombination coefficient γ . For metals at room temperature γ is high as shown in Table I. At surface temperatures above 1000K desorption of atoms from the surface occurs before recombination, accompanied by a decrease in the heat flux⁽⁵⁾. Consequently the heat flux will exhibit a greater dependence on surface temperature than can be expected by consideration of the enthalpy driving force $(h_g - h_w)$ alone.

10. Conclusions

1. The heat flux from an augmented flame to a steel surface decreases as the surface temperature increases. This effect becomes more marked as the boost ratio is increased.
2. The stagnation point heat flux is increased by a factor of 8 if the flame is augmented with a boost ratio of unity.
3. The heat fluxes determined by experiment exceed predicted values based on a uniform enthalpy distribution in the flame by a factor of between 4 and 6.

4. The enthalpy distribution in the augmented flame is non-uniform, the highest enthalpies occurring in the centre of the flame.
5. Correlations in the form of equations (12) and (13) can only be used to predict heat fluxes from electrically augmented flames if the distribution of either gas temperature or enthalpy in the flame is well-defined.

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SYMBOLS

a_w	absorptivity of surface
A_w	area of heat flux meter (m^2)
B	boost ratio
C_p	specific heat ($kJ kg^{-1} K^{-1}$)
D_{AB}	binary diffusivity ($m^2 s^{-1}$)
d	diameter of burner nozzle (m)
h'	heat transfer coefficient ($kW m^{-2} K^{-1}$)
ΔH	heat of recombination ($kJ kg^{-1}$)
k	Boltzmann constant ($kJ molecule^{-1} K^{-1}$)
k_R	homogeneous recombination rate constant ($m^6 s^{-1} molecule^{-2}$)
m	mass fraction
Le	Lewis number ($D_{AB} \rho C_p / \lambda$)
M	molecular weight
n	number density ($molecule m^{-3}$)
P	total pressure (kNm^{-2})
Pr	Prandtl number ($u C_p / \lambda$)
q	heat flux ($kW m^{-2}$)
Q	volumetric flow rate at STP ($m^3 s^{-1}$)
r	radial distance (m)
r'	radius at $u = \frac{u_{CL}}{2}$ (m)
R	universal gas constant ($kJ k mole^{-1} K^{-1}$)
St	Stanton number ($h' / \rho u C_p$)
T	temperature (K)
u	gas velocity (ms^{-1})
x	mole fraction
y	exponent of Le
α	thermal diffusivity ($m^2 s^{-1}$)
δ	heterogeneous recombination coefficient

λ	thermal conductivity ($kW m^{-1} K^{-1}$)
μ	viscosity ($kg m^{-1} s^{-1}$)
ρ	density ($kg m^{-3}$)
τ	time (s)
ϕ	ratio of experimental to predicted heat fluxes

Subscripts

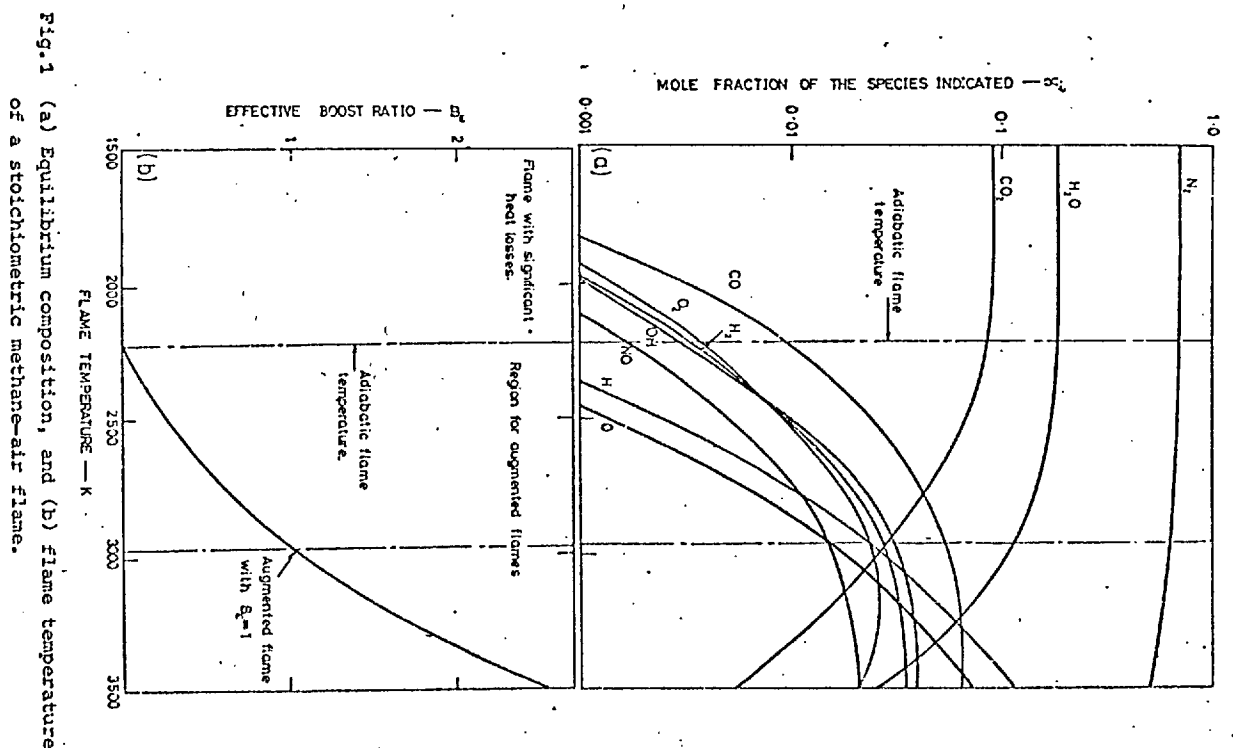
a	arc
A	atomic species A
B	molecular species B
CL	centre line
e	free stream
eq	equilibrium
E	effective
f	frozen
H	hydrogen atoms
o	initial value
r	radiation
R	recombination
s	stagnation
w	wall or surface

A In deriving equations (12) and (13)			B In applying equations (12) and (13)		
1	No bulk flow	-	1	Uniform distribution of electrical energy across flame	i
2	No thermal diffusion	i	2	No radiation from arc	i
3	No radiation from gas	i	3	No entrainment in jet	d
4	Binary gas model of atoms and molecules	-	4	No turbulence induced by arc	i
5	Laminar boundary layer	i	5	Centre-line velocity = mean jet velocity at nozzle exit	-
6	Either equilibrium or frozen boundary layer	-	6	Adiabatic flame	d
7	Perfect catalytic surface in frozen case	d	7	Only H atoms have $Le_f > 1$	i

i = increase in value of q_s if assumption is invalid

d = decrease in value of q_s if assumption is invalid

Table III List of assumptions made in deriving equations (12) and (13) and in applying these equations to electrically augmented flames.



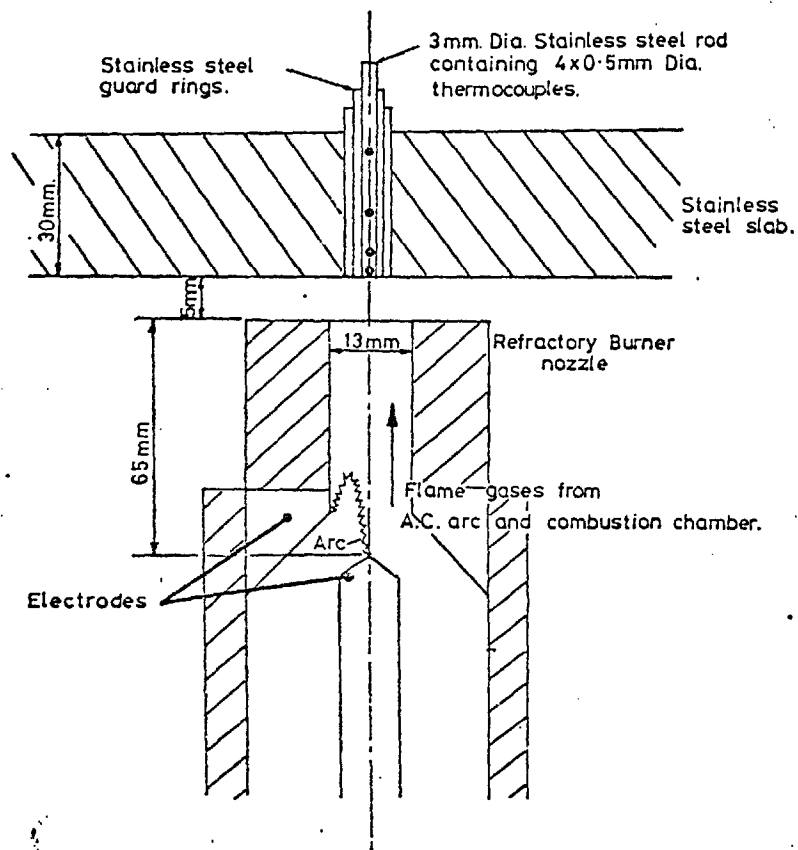


Fig.2 Cross-section through experimental apparatus.

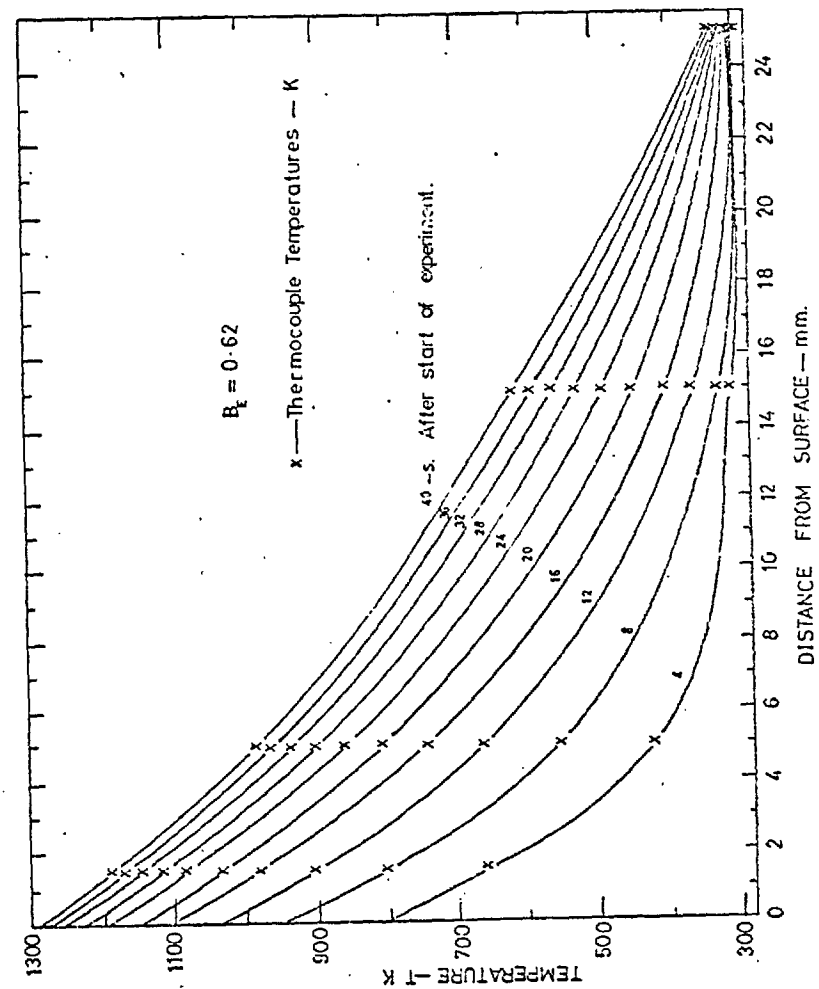


Fig.3 Typical temperature profiles in heat flux meter.

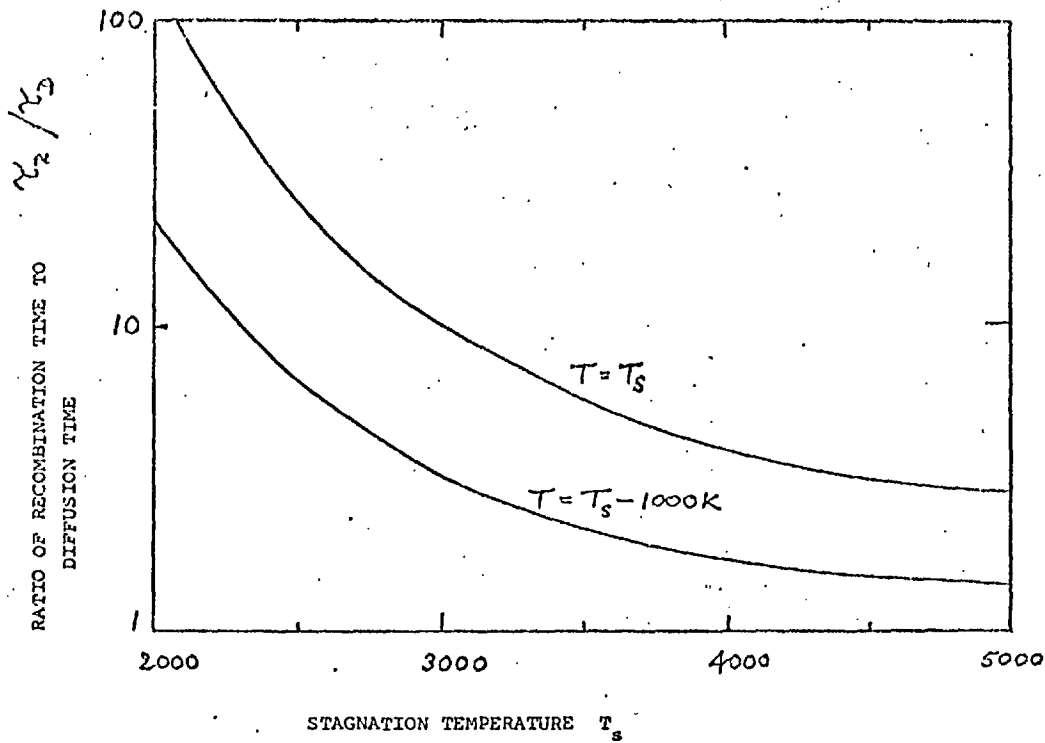


Fig.4 Effect of temperature on non-equilibrium in the boundary layer for hydrogen atoms.

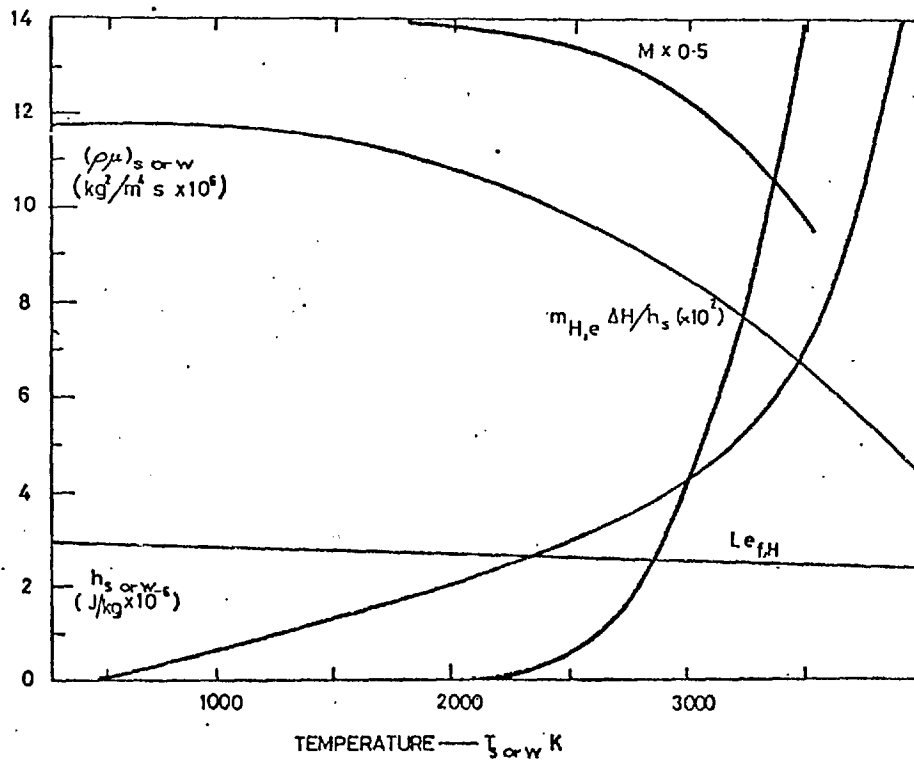


Fig.5 Property values required by evaluate equations (12) and (13).

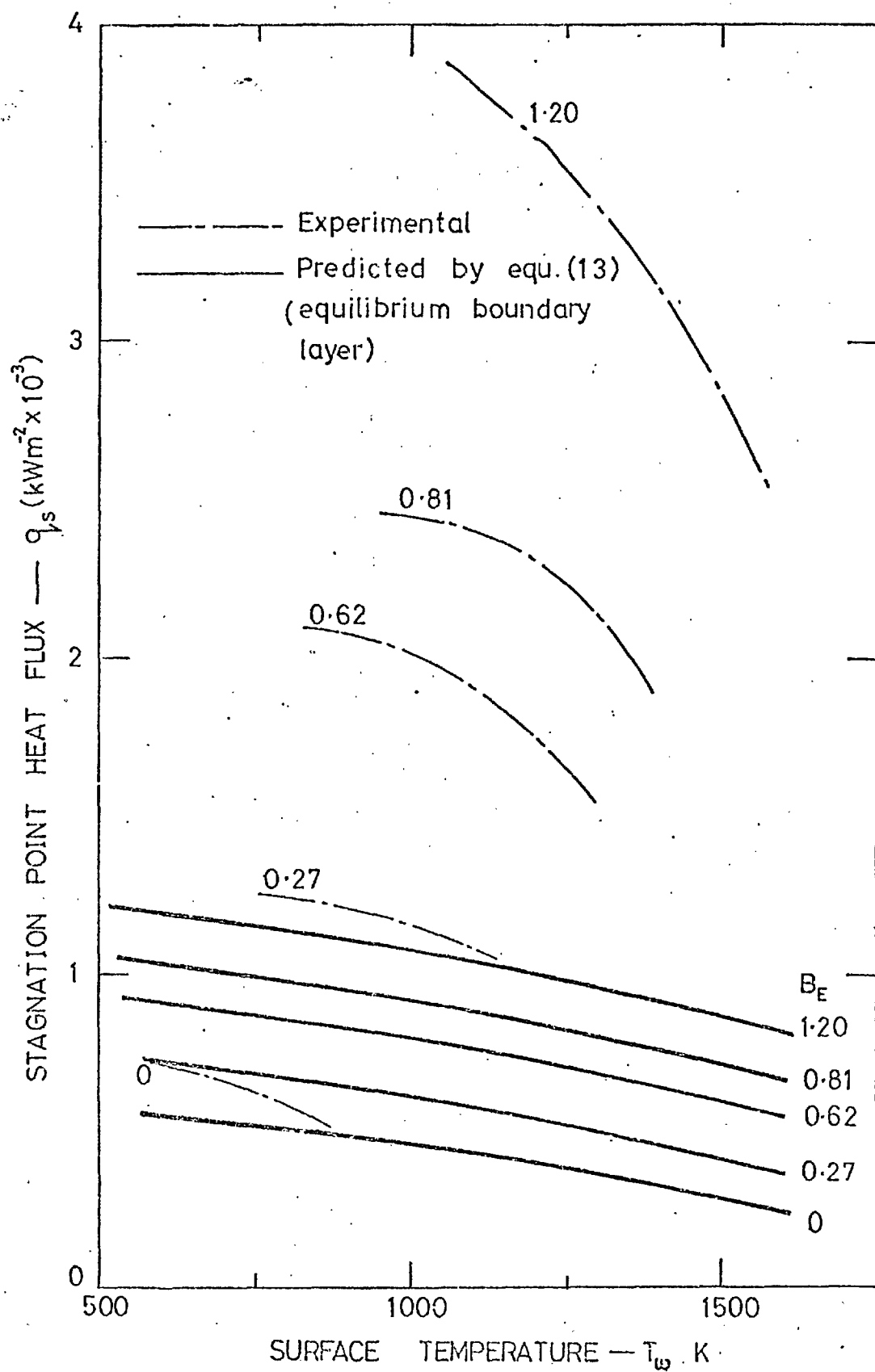


Fig.6 Experimental and predicted values of stagnation point heat flux.

Appendix D

Temperature °C	Mean Specific heat $\bar{C}$ -cal/gr deg C	Temperature °C	Conductivity k-cal/sec.Cm.deg C
20 to 100	0.121	0	0.038
20 to 200	0.125	20	0.038
20 to 300	0.126	100	0.039
20 to 400	0.128	200	0.041
20 to 500	0.131	300	0.044
20 to 600	0.135	400	0.048
20 to 700	0.137	500	0.052
20 to 800	0.139	600	0.057
20 to 900	0.141	700	0.061
20 to 1000	0.142	800	0.064
		900	0.064
		1000	0.067

Table Ap.D. Mean specific heat and thermal conductivity of En 58A stainless steel.

Woolman, J. A. and Mottram, R. A., Properties of
British Standard En Steels, Vol.3, Pergamon Press,
Oxford (1969).

Symbols

B	boost ratio
b	spread of heat flux distribution
C	specific heat
C_1	time for recombination/time for diffusion
cl	centre line
D_{AB}	binary diffusivity
d	electrode gap
d_1	nozzle diameter
$\frac{du_e}{dr}$	velocity gradient
e	stoichiometric factor = $\frac{\text{moles of air in the mixture}}{\text{moles of air required for stoichiometric combustion}}$
e'	electron charge
F	Moles of product formed per moles of CH_4 burnt
H	enthalpy
h	distance between burner and heat flux meter
h'	heat transfer coefficient or depth of charge
I	current
I, J	integer
i, j	species in multi component mixture
K	equilibrium constant
K_1	Boltzman constant
k	thermal conductivity of solid
L	latent heat
Le	Lewis number
M	molecular weight
n	number of gram atoms
P	total pressure
Pr	Prandtle number
Q	volumetric flow rate

q	heat flux
q'	overall heat flux
q_0	constant heat flux at the surface
R, r	Radial distance
R'	resistance
R_1	universal gas constant
r'	radius at $u = \frac{u_{cl}}{d_1}$
St	Stanton number
T	temperature degree Kelvin
t	temperature degree centigrade
u	gas velocity
V	potential
X	mole fraction
x	distance from the surface of slab
y	exponent of Le

Greek symbols

α	thermal diffusivity
β	$\frac{u_{cl}}{r'}$
ω	angular velocity
ρ	density
λ	thermal conductivity of gas
τ	time
θ	phase lag
ϕ	work function
μ	viscosity
ψ	heat flux potential
γ	heterogeneous recombination coefficient
η	ratio of experimental to predicted
Ω	ohm

Subscripts

A	atomic species e
a	annode
B	molecular species B
c	cathode
cl	<i>centre line</i>
E	effective
e ₁	electron
e	<i>free stream</i>
F	film
f	frozen
g	gas
I	input
m	melting
o	initial value
p	product
r	reactant
s	stagnation
s [•]	initiation
W	wall or probe temperature
Af.Aug	adiabatic augmented flame
Af.Unaug	adiabatic unaugmented flame
chem	chemical
elec	electrical
R.M.S.	root mean square
$\frac{\Delta H_{\text{chem}}}{\Delta H}$	fraction of total enthalpy due to recombination of H atoms

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