

IGNITION OF METHANE-AIR MIXTURES
BY HOT NITROGEN JETS

By

Ming Biu TUNG
Heat Transfer Section
Department of Mechanical Engineering
Imperial College
London University

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ABSTRACT

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The deduction of overall chemical reaction rate from a hot gas ignition system has several advantages over using other systems, notably the good repeatability of the ignition temperature. In this study a parallel investigation was carried out to determine the overall reaction rate for a methane-air mixture. Experimentally the methane air mixture was made to ignite by an axisymmetric hot turbulent nitrogen jet. The ignition temperature was found to occur at a well defined value and was repeatable to within $\pm 5^\circ\text{C}$.

Theoretically, a prediction method was developed to calculate the ignition temperature. The method is based on the characteristic differences in the axial temperature profiles of the hot gases across a critical jet temperature which separates ignition from no ignition. The governing heat, mass and momentum equations are written in parabolic form. The effect of turbulent mixing is modelled by two turbulent quantities, namely the turbulent kinetic energy and its dissipation rate. The chemical reaction rate of a stoichiometric mixture is represented by a global expression given by:-

$$- K \cdot m_{\text{CH}_4} \cdot m_{\text{O}_2} \cdot p^2 \cdot T^{-3/2} \cdot \exp(-E/RT)$$

where m is the mass fraction, p and T are pressure and temperature respectively and K , E and R are constants.

The governing equations are solved by the finite difference numerical scheme in conjunction with Spalding and Partankar's method.

Then by matching the measured and the predicted ignition temperatures under a given set of flow conditions, the deduced kinetic constants were found to be:-

$$K = 7.88 \times 10^6 \text{ (s}^{-3} \cdot \text{K}^{3/2}/\text{kg-m)}; E = 2.15 \times 10^8 \text{ (J/kg-mole)}$$

Incorporating these constants into the prediction method, the calculated ignition temperatures were in good agreement with the measurements in so far as the changes of flow conditions did not significantly alter the turbulence intensity and the chemical compositions.

During the course of this study a high temperature electric heater was developed for heating the nitrogen jet to the temperature required for ignition. The heater was capable of heating the nitrogen jet up to 1580°C at a flow rate of 3.2 g/s. Construction of this heater requires careful design to prevent overheating due to voltage breakdown of the insulators, porosity changes of the ceramic tube and other causes, which are recorded in detail to provide a design guidance.

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CHAPTER 1

INTRODUCTION

1.1. THE SUBJECT OF THE PRESENT STUDY

1.1.1. Ignition by a Hot Gas

The phenomena studied in this thesis take place when a hot turbulent nitrogen jet is injected into a stream of methane-air mixture as shown in Figure 1. The two gas flows, which are co-axial and symmetric about the centre line, will gradually mix in the downstream region of the flow. Under favourable conditions a flame will be formed in the mixing layer, propagate and ignite the unburnt mixture of the methane-air gases in the outer (secondary) flow. Such phenomena are known as "ignition by hot gas" or simply as "hot gas ignition"¹⁴⁻²⁸.

1.1.2. The Minimum Ignition Temperature

The condition leading to the ignition of the combustible mixture is determined primarily by the temperature of the hot nitrogen jet. Ignition was found to occur at a clearly defined temperature of the nitrogen jet at the nozzle exit. This may be illustrated by the axial temperature profile shown in Figure 1A.

The gas temperatures at the centre line will initially decrease near the potential core region where no methane gas is present to provide chemical reaction, and heat is lost in the presence of a steep radialwise temperature gradient. If the temperature of the nitrogen jet were sufficiently high, as in the case of the upper curve, the rate of chemical reaction would reach a level at which the released heat would exceed the heat loss. As a result the temperature of the hot gases will increase, thereby increasing the rate of the reaction until the accelerated reaction produces a flame in the mixing layer.

If, on the other hand, as in the case of the lower curve, the

temperature of the hot nitrogen jet were below a critical value, then the heat loss would exceed the heat release. In this case, the axial temperature will continue to decrease in the downstream direction and no flame will be observed in the flow.

The change from the case of no ignition (lower curve) to the case of ignition (upper curve) is separated by a small temperature difference of the hot nitrogen jet at the nozzle exit. The temperature of the hot nitrogen jet, at which ignition is just observed, is defined in this thesis as the minimum ignition temperature (M.I.T., see Figure 1A). This ignition temperature is affected by the velocity, temperature, chemical composition and the geometry of the flow. The measurement and the calculation of this ignition temperature form the main subject of this study.

1.2. THE IMPORTANCE OF THE IGNITION TEMPERATURE

1.2.1. Relevance to Engineering Problems

Fatal explosions in the coal mining industry have been caused by hot gas ignition. Combustible mixtures (mainly methane-air) in the coal mines may be ignited by a hot stream of gases issuing from an enclosure⁹, (e.g. an electric machinery) or from the process of blasting. Similar explosion hazards also exist in other industrial environments, such as flour mills, chocolate factories, etc., in which the atmosphere is fuel laden. On the other hand, a pilot flame may fail, partially or completely, to ignite the gases in a combustor. This may give rise to a potential explosion hazard in the case of a complete failure to ignite the gas or as in the case of a gas turbine some of the fuel may leave the combustor unburnt due to the ignition delay^{12,13}. The unburnt gases represent not only a combustion loss but the incomplete combustion also generates undesirable pollutants. Hot gas ignition also plays an important part in the design of fuel injection of rocket engine; flame stabilisation of burner by retention flame ; pilot flame ignition of ram jet and other domestic and industrial gas appliances.

In order to prevent an explosion or to improve the performance of a combustor, it is necessary to quantify accurately the ignition

temperature and the factors which affect this temperature. This data may be obtained empirically, but full scale experiments are, in general, expensive, inconvenient and possibly very difficult to conduct.

1.2.2. Relevance to Chemical Kinetic Studies

Alternatively, it may be possible to calculate the ignition temperature based on data obtained from relevant small-scale experiments. If, for instance, the axial temperature profile could be calculated, the ignition temperature would be readily deduced from graph such as Figure 1A. Calculation of the temperature profile requires the solution of governing heat, mass and momentum equations and, above all, a known chemical reaction rate. This knowledge is at present not readily available due partly to the insufficient understanding in the field of chemical kinetics.

Amongst the hydrocarbons methane is chemically the simplest molecule. But despite several studies, e.g. 3,94,96 and 130, the detailed kinetics of methane-air combustion is not yet fully understood (see paragraph 1.5). Alternatively the chemical reaction is treated by some combustion technologists as a single step reaction with an "overall" reaction rate e.g. 5,6,119,120,123. The reaction rate, $\dot{m}_f'''$, contains an Arrhenius type temperature dependence:-

$$\dot{m}_f''' = -K \cdot m_f \cdot m_{O_2} \cdot \exp(-E/RT) \cdot p^2 \cdot T^{-3/2}$$

where m_f and m_{O_2} are mass fractions of fuel and oxygen, T and p are temperature and pressure respectively, R is the gas constant and K and E are two kinetic constants.

The overall kinetics concept has been studied by various techniques including the shock tube⁶, batch reactor⁷ and flow reactor⁸ systems. This work has contributed to the overall kinetic reaction rate measurements, but have suffered several defects, notably the effect of the walls of the apparatus on the reaction rate^{26,122}.

The hot gas ignition system may also be used to deduce the overall kinetic constants. The technique is to calculate the ignition

temperature with presumed kinetic constants. The correct kinetic constants are obtained by comparing the calculated and measured ignition temperatures until the two are matched. Such a method is superior to other systems for two principle reasons:-

- (i) the energy for the initiation of ignition is provided by the hot gas jet which is heated independently of the combustion process. The temperature of the hot gas can be maintained at a very steady value and this allows the ignition temperature to be measured accurately prior to the ignition (see Chapter 2).
- (ii) the processes leading to ignition take place entirely in the gas phase and are free from the effect of a solid surface.

1.2.3. Relevance to the Turbulent Flame Calculations

The hot gas ignition system was applied by Vanpée and Fink²⁶ to deduce the overall reaction rate for laminar flows. For most practical engineering problems, the flows are likely to be turbulent and frequently associated with methane gas. Recently large amounts of natural gas have been found. Since methane gas constitutes over 80% of the natural gas, the physical properties of these two gases are very similar. Thus, the need to provide a reaction rate for the calculation of a turbulent flame involving methane gas is indeed a prime task of today's combustion technologists.

1.3. THE OBJECTIVE OF THE PRESENT STUDY

The objective and the main theme of this thesis is therefore the deduction of the overall kinetic constants for methane gas from the study of a turbulent hot gas ignition system. This objective was achieved through a parallel study of experimental and theoretical work. Experimentally, the task was to construct a test rig so as to measure the minimum ignition temperature and to quantify the factors which influence its magnitude. Theoretically, the task was to develop a calculation method so as to predict the ignition temperature. From this parallel study, the overall kinetic constants for methane gas in a turbulent flame were then obtained by the process of iteration to match the calculated and the measured ignition temperatures.

We shall now proceed to review previous work on hot gas ignition. The phenomenon of hot gas ignition was treated largely in the past either as a theoretical or experimental subject. It may therefore be convenient to review this subject in two separate sections.

1.4. REVIEW OF PREVIOUS EXPERIMENTAL WORK

In this section the concept of "ignition temperature" as a parameter to determine the occurrence of hot gas ignition will be described through the historical developments. The background leading to the demand for the present experimental work will then be clearly seen.

1.4.1. Work on Safety in Mines

It was observed at the turn of this century that an explosion inside an enclosure would not necessarily induce the surrounding methane-air gases to explode, even though apertures were cut open in the surfaces of the enclosure (see Beyling (1906), quoted in Reference 9). This observation prompted many experimental investigations and produced various flame trap devices. One such flameproof enclosure has a pair of flanges which have a narrow passage between them. Smith⁹ and Titman¹⁰ found that a gap of 1 mm between two 13 mm breadth flanges would prevent external explosion. The cooling effect of the flanges was at first accepted as a prime factor causing the quenching of the flame. But visible flames ejected from holes and perforated plates could be seen outside the enclosure and yet failed to ignite the external mixture. Further work by Staples (1945, quoted in Reference 9), also observed that preheating the flanges and replacing the flanges with better conductive materials did not have a significant effect on the quenching distance between the flanges. Although the "safe gap" was used as a parameter to safeguard mining equipment (B.S. 229, 1946) the mechanism leading to the ignition of the outside combustible mixture remained largely unknown.

1.4.2. Work on Gas Turbines

The unsolved problem was later looked at from a different view. Lloyd¹¹ observed that in the combustion chamber of a gas turbine, a fraction of fuel may pass through the primary combustion zone unburnt.

The combustion loss was linked to an "ignition delay time" by Mullins^{12,13}. If the ignition delay time was longer than the residence time of the fuel in the hot gas stream then ignition could not possibly occur. However, these two time scales are not properties of the fuel alone, but are also affected by the local heat generation and dissipation rates of the gases.

Nevertheless, Mullins was able to demonstrate that the "ignition delay time" could be measured as a dependent variable which was affected by several independent parameters. For instance, the fuel/air ratio was found to have little effect on the ignition delay time, but the oxygen index of the hot gases was inversely proportional to the square of the delay time. At 750°C the ignition delay time of methane gas was found to be 600 times longer than that of hydrogen gas. Jackson and Brokaw (quoted in Reference 51) deduced different results but Mullins' findings were reinforced by the work of Miller⁵¹.

1.4.3. Ignition by Hot Product Gases

In the late 1950's Wolfhard and Bruszak^{14,15,16,17} started a long series of experiments on hot gas ignition. They devised an apparatus to study the quenching of the ejected flame. A short burst of flame was discharged from a jet nozzle into a stream of combustible mixture flowing co-axially in the same direction. The ejected flame would or would not ignite the combustible mixture depending not only on the diameter of the jet, but also on the fuel/air ratio of the flame and other factors such as the type of fuel.

This investigation cast doubt on whether the flame, if quenched, was extinguished before entering or after leaving the jet nozzle. It was particularly interesting to note that the hot product gases of a methane-air mixture could ignite a cold mixture after it had apparently been extinguished. This phenomenon suggested that the cold mixture was not ignited by the "flame" as such, but merely by the thermal energy of the hot product gases.

To prove the point, Wolfhard and Burgess¹⁸ employed another set of apparatus in which a flame was continuously discharged and stabilised at the jet nozzle while a cold combustible mixture was discharged

momentarily from a cylinder which enclosed the jet nozzle. This eliminated the unknown of the quenching location as the flame must be extinguished outside the nozzle. The thermal energy needed to ignite the cold mixture was measured and from the "thermodynamic charts for combustion processes" (Hottel, H. C., et al, Willey, 1949) the corresponding adiabatic flame temperature was calculated.

Wolfhard and Burgess went on to show that the adiabatic flame temperature (the adiabatic flame temperature at which the cold mixture could just be ignited) was a function of the flow rate, dimensions of nozzle, etc. and thus confirmed the fact that the ignition of a combustible mixture was a result of heating by the hot gases and the temperature of the hot gas could be used as a dependent parameter.

The term "hot gas ignition temperature" (which is referred to in this thesis as the "minimum ignition temperature") was suggested and subsequent hot gas ignition experiments carried out by the other workers also employed this parameter. Non-combustible hot gases (e.g. nitrogen, air, etc.) were used in place of the combustion product gases since a flame was no longer a necessary condition for ignition.

1.4.4. Ignition by Hot Non-Combustible Gases

Wright and Becker⁵² were among the first to use non-combustible hot gas in the investigation of bluff body flame stabilisation. The cases of hot gas ignition of a combustible mixture by a hot laminar jet were thoroughly studied by Wolfhard^{19,20,21}, Vanpee²², Kuchta²³, Singer^{24,25} and Fink²⁶. The case of hot gas ignition of a propane-air mixture by a hot turbulent jet was studied by Goh and Ma²⁷. Because of the rapid development in rocket engines experimental work on hot gas ignition was extended into the field of supersonic flow. Slutsky, et al⁴⁴ and Cohen, et al⁵³ both studied the hot gas ignition of a supersonic free jet flow while the case of duct flow was investigated by Peter, et al²⁸ and Bray, et al⁴¹.

Most of these experiments employed similar apparatus. The non-combustible hot gas was heated by a platinum rhodium resistance heater. Attempts to extend the measurement of ignition temperature to the case of methane-air mixture by a hot turbulent non-combustible

gas failed, because the platinum-rhodium heater could not provide the high temperature of the hot gas needed to ignite the mixture, and there were no suitable and convenient methods to replace the platinum-rhodium resistance heater (see Chapter 5 for detailed discussion).

The present experimental investigation is an attempt to tackle an important part of this long series of experimental work on hot gas ignition. (Important because of the methane gas and the turbulent flow, see paragraph 1.2).

1.5. REVIEW OF PREVIOUS THEORETICAL WORK

It may be recalled (paragraph 1.3) that part of the present study is to calculate the ignition temperature and it has been stated (paragraph 1.2.2) that this task requires the solution of the governing equations which may be written in general form as²⁷ (see also Figure 18):-

$$\rho u \frac{\partial \phi}{\partial x} + \rho v \frac{\partial \phi}{\partial r} = \frac{1}{r} \frac{\partial}{\partial r} (\Gamma_{\phi} \cdot r \cdot \frac{\partial \phi}{\partial r}) + S_{\phi} \quad - \quad (2)$$

where ϕ is the dependent variable including the velocity, enthalpy (and hence temperature) and mass fraction of various chemical species, etc.; x and r are axial and radial co-ordinates; u and v are velocities; ρ is the density; Γ_{ϕ} is the diffusion coefficient and S_{ϕ} is a source term of ϕ .

The solution of the above equation involves four major aspects of combustion research. These are:-

- (i) the mathematical solution of the equation,
- (ii) the physics of the turbulent mixing,
- (iii) the chemistry of the reaction, and
- (iv) the interaction between the turbulent mixing and the chemical reaction.

Large volumes of work have been and are still being done in each of these areas. In this section the relevant work will be examined separately before a summary remark is made in paragraph 1.5.5.

1.5.1. Numerical Solutions to the Non-Linear Equation

The governing equations are two dimensional parabolics. They are non-linear in nature and the variables are interdependent. It requires the simultaneous solution of all the equations. Before the computer had widespread usage, attempts to treat hot gas ignition were confined to laminar flows.

The general mathematical approach was to assume the product of the laminar viscosity and the density of the gases to be independent of the temperature, by Howarth's Transformation⁵⁸. The transformed momentum equation, which was uncoupled from the energy and species equations, could be readily reduced to Blasius's equation, the solution of which has been well tabulated⁵⁹. Then, by neglecting the kinetic heating term in the energy equation and by assuming the source terms of the energy and species equations to take the Arrhenius' exponential form, similarity between the energy and species equations could be established.

Marble and Adamson²⁹ were amongst the first to employ this technique. The ignition of a cold combustible mixture by a parallel hot product stream was studied. The "similar" equations were solved by a perturbation method up to the onset of ignition. Beyond the flame front the flow field was solved by the integral method developed by Von Karman⁶⁰. Dooley³⁰ continued the parallel flow problem while Cheung and Kavity³¹ found that the ignition distance in the wake behind a flat plate was shortened due to non-uniform initial velocity distribution, which was assumed uniform in Marble and Dooley's studies. If the non-uniform temperature distribution was taken into consideration, Cheung and Chiu³² found that by lowering the temperature of the hot gas stream the overall temperature of the flow did not necessarily decrease, since the heat loss to the cold gas was reduced at the same time.

For the ignition of a combustible mixture by a hot surface Toong³³ concluded that the incipient ignition occurred at the same ratio of the wall temperature to the flow velocity. Hot plate ignition was also investigated by Dooley³⁴ using the iteration method up to the formation of a flame. A similar numerical method was also employed

by Tsuji³⁵, who found that a minimum width of hot gas jet must be exceeded for the ignition of a parallel stream of cold combustible mixture. Casaccio³⁶ applied the same treatment to a parallel flow with strong pressure gradients.

The technique described above is severely restricted in its applications. Since the momentum equation must be uncoupled from the others, the technique is applicable only to laminar flows. The need to establish similarity between the energy and species equations has prevented these equations from assuming their exact forms and hence induces errors. Furthermore, the mathematical method such as perturbation, iteration, integral methods, etc. are approximate. Libby⁶¹ applied the integral method proposed by Oseen⁶² to the treatment of a co-axial reacting flow and found that errors were incurred in predicting the initial mixing region. Zeiberg and Bleick⁴² also reported that the integral method was in serious error in calculating a supersonic wake behind a bluff body. Although a large number of small strips could be employed in conjunction with the integral strip method⁶³ such elaboration would then approach the same exactness offered by the finite difference method^{37,38}.

The finite difference method removes the restrictions by the exactness of its approach in reducing the differential equations to the corresponding finite difference equations. Although numerical approximations are made, the physical structure of the equations are retained. The finite difference method was first applied to non-reacting flows by Kramer and Lieberstein³⁷, Howe³⁸, Wo⁶⁵ and others. Mixing with chemical reactions was discussed by Pai⁶⁶. Later Visiliu⁴⁰ applied the six-nodes Crank-Nicolson method⁶⁷ in the mixing of two turbulent supersonic streams.

The six nodes implicit method was also employed by Spalding and Partankar³⁹. The general boundary layer parabolic flow with or without chemical reaction was written into a computer program which was used by a number of workers investigating the hot gas ignition phenomenon. These include Bray and Fletcher⁴¹, who treated the ignition of a turbulent supersonic pre-mixed ethylene-air mixture by a hot co-axial jets Fink and Vanpee²⁶, who studied the ignition of a laminar pre-mixed combustible mixture of various fuels and Goh and Ma²⁷

who investigated the ignition of a propane-air mixture by a hot turbulent jet.

The arrival of the computer age has not only improved numerical accuracy, but has also enabled complicated turbulent mixing to be mathematically modelled as described below.

1.5.2. Mathematical Modelling of Turbulent Flows

Hot gas ignition problems with a turbulent flow were treated by such workers as Ting and Libby⁶⁹, Libby⁶¹, Bray and Fletcher⁴¹ and Goh and Ma²⁷. All these workers employed the Prandtl's (1925) mixing length hypothesis, in which the "turbulent viscosity" was proportional to the square of a length scale. The weakness of this model is that the length scale must be prescribed by the properties of the time mean values which are not turbulent quantities. Prandtl's (1945) later hypothesis of linking the turbulent viscosity to the turbulent kinetic energy was a step forward, but this model also contained a length scale which must again be prescribed.

Other workers suggested that the "length scale" (l) could be combined with the "turbulent kinetic energy" (k) to form a second turbulent quantity, and hence eliminated the need to prescribe it algebraically. Various k and l combinations were tried. Chou⁷¹ used $k^{3/2}/l$ (also known as the turbulent energy dissipation rate ϵ) while Spalding⁷⁰ proposed the k/l^2 combination. Others, such as $k^{1/2}/l$ and $k-l$, have also been tried.

The turbulent viscosity, μ_t , as calculated from these two turbulent quantities (k and $k-l$ combination) was added to the laminar viscosity to form, mathematically, an "effective" viscosity. An alternative to the "effective viscosity" concept is to compute the Reynold's stress $\overline{\rho u'v'}^{1,2}$ (where u' , v' are fluctuating velocities) so that the diffusion effect caused by the turbulent fluctuations may be calculated directly.

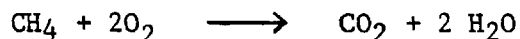
Launder¹¹⁸ et al. tested these three different approaches, namely the mixing length hypothesis, the $k - \epsilon$ model and the Reynold's stress model. The $k - \epsilon$ model was found to be slightly superior to

the mixing length hypothesis and was comparable to the Reynold's stress model, but it has simpler mathematical structure. Rodi⁷², however, found that if the $k - \epsilon$ model is applied to a round jet, some of the "universal-constants" embodied in the model must be treated as a function of the axial velocity gradient. Launder and Jones⁷³ also suggested modification to a low Reynold's number flow, but the model was made for the region near a wall and was not immediately applicable to a free-jet flow.

1.5.3. Chemical Kinetics of Methane-Air Mixtures

The classical explanations of the ignition of a combustion system are approached by two different theories. The thermal explosion theory⁸² explains the ignition of a combustible mixture as a result of the energy released by the chemical reaction exceeding the heat lost by the system. The branching chain explosion theory⁹¹ describes ignition through a material balance on the intermediate active centres that are necessary to maintain the branching chain. Recent attempts^{92,93} have tried to unify the two theories by taking into account the parameters of temperature, pressure, and concentrations simultaneously.

If the branching chain theory is ignored, the methane-oxygen oxidation may be expressed by a single step overall reaction:-



with a reaction rate $\dot{m}_{\text{CH}_4}$ expressed by:-

$$\dot{m}_{\text{CH}_4} = -K \dot{m}_{\text{CH}_4} \cdot \dot{m}_{\text{O}_2} \cdot p^2 \cdot T^{-3/2} \cdot \exp(-E/RT)$$

(symbols have been explained in paragraph 1.2.2.).

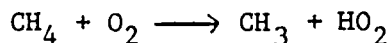
Various techniques have been established to measure the kinetic constants. Kydd and Foss¹²³ injected burnt gases of different aeration into a well stirred adiabatic reactor and measured the delay time (t) to reach the equilibrium temperature (T). The activation energy (E) was then calculated from the graph of $\ln t$ vs $1/T$. In a similar manner, Nemeth and Sawyer⁸ injected a pre-heated $\text{CH}_4\text{-O}_2\text{-Ar}$

mixture into a quartz duct and measured the reaction time from which E was again deduced. Williams et al¹²⁰ also obtained overall kinetic data from an adiabatic flow reactor. The data obtained from these reactor studies are subject to the effect of the wall where active centres may be initiated or terminated. The heat losses at the wall in these studies were also not adequately accounted for.

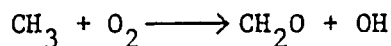
The burning velocity of a flame was related to the reaction rate by Vandenabele et al⁵, but the measurement of the burning velocity by the Schlieren method produced an activation energy which was very different to other measurements (see Table 16). Low temperature reaction at high pressure (> 100 atmosphere) was studied by Melvin⁷. The reaction time, which was found to be a few seconds to several minutes, was correlated with flame temperature to calculate the activation energy.

Other techniques include shock tube measurement. Sharp pressure, temperature and species concentration changes behind a reflected shock wave are measured^{6, 119}. This technique requires the measurement of rapid changes in the flow properties for the duration of a few micro-seconds. Accuracy of the deduced ignition delay time, which is related to the reaction rate, is limited by the accuracy of interpretation of the measured curves and the approximation in the temperature calculation across the shock wave. The hot gas ignition system is superior to other systems for reasons which have already been discussed (paragraph 1.2). Fink and Vanpee²⁶ use a photographic technique to measure the flame length and plot it against $1/T$ (T is the temperature of the hot gas) to deduce the activation energy. Optical measurement of the flame length is, however, approximate because of the difficulties in deciding the exact location of the flame front.

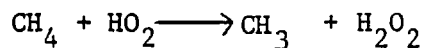
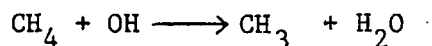
The overall kinetic concept is, of course, a simplified version of the actual reaction mechanism. The detailed chemical kinetics of methane gas has been a subject of active research. In the 50's various oxidation mechanisms were proposed. For instance, Enikolopyan⁹⁴ suggested, from his low temperature studies, that the methane was initially attacked by O₂:-



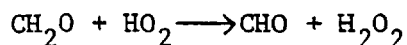
subsequently, methyl is also attacked by O_2 to form formaldehyde:-



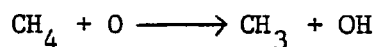
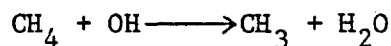
and CH_4 is further attacked by:-



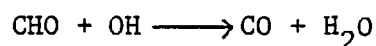
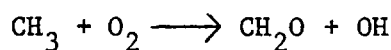
formaldehyde is converted to formyl by the active hydroxyl and HO_2 , O_2 :-



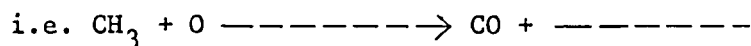
Westernberg and Fristrom³ argued that the $\text{CH}_4 + \text{O}_2$ reaction is endothermic. The initial attack on methane is more likely to be initiated by hydroxyl and the O and H radicals:-



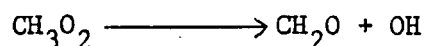
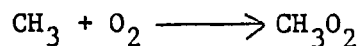
This view was shared by Dixon-Lewis et al⁹⁵ and Blundell et al⁴, but Glassman¹²¹ and Bradley⁹¹ believed O_2 was the initial attacking agent. Westernberg and Fristrom³ also suggested the decomposition of methyl into CO by way of:-



but according to Fenimore and Jone¹²⁶ CH_3 was attacked by O radical through unspecified steps:-



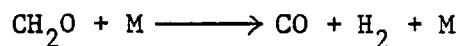
Bradley⁹¹ also suggested that oxidation of methyl firstly formed the methylperoxy which was then decomposed:-



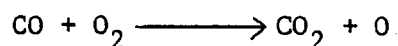
The measurement of Peters and Machmen⁹⁶ confirmed the finding of Fenimore and Jone¹²⁶ that methyl was mainly removed by O radicals:-



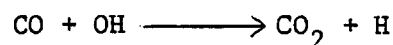
They also found that the collision with a third particle could produce CO:-



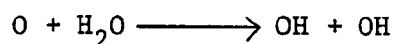
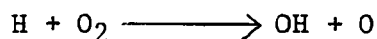
The final combustion product of CO_2 is suggested by Westernberg³ to be:-



But again, Peters et al⁹⁶ believed the CO to be combined by OH,



There was little argument about the branching reactions because of the studies in the $\text{H}_2\text{-O}_2$ systems:-



The chain propagation and termination were believed^{3,96} to be those shown in Table 8. But, added to this list, other reactions may also be found in the literature^{129,130}, etc.

Methane oxidation in air will inevitably produce nitrogen oxides. These oxides are minor species but are classified as pollutants. If the reactions leading to the formation of nitrogen oxides are included, the oxidation mechanism will become even more complicated^{127,128} and disputable⁹⁸. (Reference 98 employs 134 reactions).

1.5.4. Modelling of Turbulent Reacting Flow

It may be expected that in a turbulent reacting flow the turbulent mixing and the chemical reaction will interact on each other. For instance, turbulence produces fluctuation of the species concentration which will alter the reaction rate. Instability of the combustion will in turn increase the turbulent transportation.

Bray¹³¹ argued that the buoyancy effect on turbulent kinetic energy (k) is well established experimentally, but the effect is not explicitly reflected in the k equation. He suggested that this effect may be introduced through the pressure term in the k equation.

The effect of turbulence on combustion has been treated by four different approaches. In the case where the dominating time scale is the reaction time (i.e. the turbulent mixing is so fast that the reaction rate depends primarily on the reaction time) the effect of turbulence may be treated by an "overall kinetic" reaction constant¹³³. In the other extreme, the fuel and oxidant may be engulfed in large eddies. These large eddies must be "stretched" so that they can be broken into smaller eddies until molecular reaction can take place. The mixing time in this case is much greater than the reaction time and hence the reaction rate depends primarily on the rate of stretching. Spalding^{80,81} suggests that the stretching rate may be proportional to the mean velocity gradient in his "eddy break up" model.

In between, the reaction time and the mixing time may be of a similar order of magnitude. In this case, the reaction rate depends

on the probability of the fuel and oxidant existing at the same place and the same time.

The time mean reaction rate $\overline{\dot{m}_f''''}$ is then modelled by a "presumed" probability density function (P)¹³¹:-

$$\overline{\dot{m}_f''''} = \int_0^1 \rho \cdot \dot{m}_f'''' P dm_j$$

where m_j are the mass fractions of species 'j'. Various probability density functions (pdf) have been assumed, depending on the type of flow, e.g. 99,131,134,135,136,etc.

This approach is deficient in two areas: (a) the pdf must be prescribed, possibly backed by experience or experimental measurements; (b) it takes no account of the laminar diffusion effect.

Spalding and his co-workers, in their ESCIMO theory^{124,132}, suggested that the pdf may be constituted in two parts which are each determined by equations based on exact physical laws. In the first part, the population density distribution in a system is calculated by Eulerian fixed co-ordinates. The small eddies are then observed with Lagrangian moving co-ordinates, so that the flow becomes laminar to the moving observer. Since the reaction rate in a laminar flow may be calculated, the need to prescribe the pdf is eliminated. But although the population density distribution of the large eddies is known in a few special cases, e.g. a fully stirred reactor, it is still largely unknown for most types of fluid flow.

1.5.5. Concluding Remarks

From the above examination of the current status in the four aspects of turbulent reacting flow calculation, it may be seen that the numerical and turbulent mixing of non-reacting flows are fairly well established. There remains, however, a large gap in our knowledge of the other two aspects, namely the chemical kinetics of methane-air oxidation and the effect of turbulent mixing on the reaction rate. In time, better understanding will be found to resolve these problems, but until then a simplified approach is needed to bridge the gap.

1.6. THE APPROACHES OF THE PRESENT STUDIES

1.6.1. Measurement of M.I.T.

Figure 1B illustrates the scheme by which the minimum ignition temperature (M.I.T.) was measured under a given set of conditions. The mass flow rate, temperature and concentration of the gases, which may affect the M.I.T., were preset by the gas valves and the heaters to reach steady values. Afterwards, the nitrogen jet was gradually heated until ignition was just observed through the glass cylinder which enclosed the flows. A platinum-rhodium thermocouple attached to a traversing table was used to measure the temperature of the hot nitrogen jet prior to and after the ignition had occurred. It was found that the measured M.I.T. was repeatable to within $\pm 5^{\circ}\text{C}$ approximately.

In this study the following variables of the flows (see Figure 1) were changed, one at a time, to determine their effects on the M.I.T.:-

- (i) the mass flow rate of the primary flow,
- (ii) the diameter of the jet nozzle from which the hot nitrogen jet emerges,
- (iii) the temperature of the secondary flow,
- (iv) the air/fuel ratio of the combustible mixture,
- (v) the oxygen concentration of the secondary flow.

From the previous experimental works on hot gas ignition^{e.g. 6,19, 22,27,etc.} the M.I.T. of a methane-air mixture by a hot turbulent nitrogen jet was estimated in the region between $1300-1500^{\circ}\text{C}$. To heat a turbulent flow to this temperature, a heater of unconventional design was required. Several heater designs were considered and tried (see Chapter 5). At the end a molybdenum-alumina heater was used after no less than twenty prototypes had been built.

Basically, the heater consisted of an electrically heated

molybdenum tube wrapped round an alumina tube. Heat generated by the molybdenum element was conducted through the alumina tube to the nitrogen jet which was flowing inside the alumina tube. The detailed structure of this heater is shown in Figures 7,8 and 9. The fundamental features of the heater were its low voltage supply and the elaborate protecting chamber. It was found that unless extreme care was taken to protect the molybdenum from oxidation by the ambient air, and to reduce the risk of electrical insulation breakdown, the heater could easily be destroyed during test.

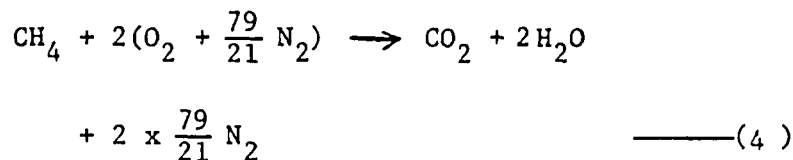
Development of this heater has been accompanied by extreme difficulties during the course of this study. A detailed account of the heater design and the causes of failure of the prototype heaters will be discussed in Chapter 5.

1.6.2. Calculation of M.I.T.

The governing equation (equation 2, see paragraph 1.5) was solved by the six nodes implicit method, in a computer program which was based on Spalding and Partankar's method³⁹. The domain of calculation was restricted to the region where changes of flow properties were significant, i.e. in the mixing layer only.

The search for the M.I.T. was started by an initial 'guessed' temperature of the nitrogen jet. A "marching integration" swept the calculation of the flow from the nozzle exit gradually towards the downstream region to detect any sign of axial temperature increase after the initial fall near the potential core region (see Figure 1A). The initial guessed temperature of the nitrogen jet was then updated with a zig-zag searching technique until the two temperatures, one of which produced an increased axial temperature profile and the other which did not, were separated by a very small amount. In this manner, the M.I.T. was found to be predictable to within $\pm 1^{\circ}\text{C}$.

Embodied in the calculation was a single step global chemical reaction:-



with the reaction rate expressed by the Arrhenius type temperature dependence as follows:-

$$\frac{d}{dt} \text{CH}_4 = -K \text{CH}_4^m \text{O}_2^m P^2 T^{-3/2} \exp(-E/RT) \left(\frac{2}{1+\eta}\right)^a \quad \text{---(5)}$$

where η is the equivalence ratio defined in Chapter 2 and a , E and K are overall kinetic constants which were obtained by matching the predicted and a set of measured M.I.T. The best-fit constants were then used to predict the other measured M.I.T. in order to check the validity of the deduced constants.

The effect of the turbulent mixing was expressed by two turbulent time mean properties, namely the turbulent kinetic energy, k , and the dissipation rate, ϵ . These two quantities were expressed in the same form as equation 2 (paragraph 1.5), i.e. with $\Phi = k$ and $\Phi = \epsilon$ respectively.

1.6.3. Results of the Present Studies

The present study has achieved results in the following areas:-

- (i) a high temperature heater was successfully built. The heater raised the temperature of turbulent nitrogen jet with a mass flow rate of 3.2×10^{-3} kg/s to a maximum of 1580°C . This has never before been obtained,
- (ii) the M.I.T. of methane-air by a hot turbulent nitrogen jet was measured under several different flow conditions with repeatability to within $\pm 5^\circ\text{C}$,
- (iii) an ignition temperature calculation method was developed with an accuracy to within $\pm 1^\circ\text{C}$,
- (iv) a set of overall kinetic constants for the methane-air reaction rate was extracted from the turbulent hot gas ignition system.

1.7. SUMMARY OF THE REMAINING THESIS

This thesis consists of six chapters of which the general background and the scheme of the present studies are introduced in this first Chapter. Chapter 2 describes the experimental work. The details of the rig are explained with particular reference to the design of the high temperature heaters. This is followed by a description of the experimental procedures before the result of the M.I.T. measurement at the stoichiometric ratio is given. Special cases of rich and lean mixtures are presented separately. The repeatability of the measurements is thoroughly checked.

Chapter 3 describes the theoretical work. The basis of M.I.T. prediction is firstly introduced and this leads to the simplifications of the governing equations. Treatment of the chemical reaction rate and the turbulent mixing are specified before the numerical solution procedure is presented. The solution procedure is handled by a computer program, code-named "METHANE". The validity of the calculation method is tested against non-reacting flows. This is then followed by the prediction of the M.I.T. Comparison between the predicted and the measured M.I.T. values provides a set of best-fit overall kinetic constants. Finally, the computer program is used to predict M.I.T. outside the range of the experiments.

Chapter 5 describes the general background of the heater design. The main causes of failure of the prototype heaters are discussed in view of the possible usefulness of the present design and to prevent repeated failure elsewhere.

The thesis ends with a discussion of the experimental and theoretical work in Chapter 4. The main findings are presented in Chapter 6.

CHAPTER 2

EXPERIMENTAL INVESTIGATIONS

2.1. SCOPE OF THE PRESENT EXPERIMENTAL WORK

The task of the present experimental work was to measure the minimum ignition temperature (M.I.T.) of methane-air mixture by a hot turbulent nitrogen jet with the scheme as shown in Figure 1B. This task was carried out in three stages:-

Stage I : Construction and development of the test rig,

Stage II : Measurement of the M.I.T., and

Stage III : Measurement of the velocity profiles at ambient temperature.

2.1.1. Stage I: Development of the Test Rig

The scheme illustrated in Figure 1B was translated into a test rig which is shown in Figure 2 and Plates 1 to 3. Essentially, the test rig consisted of a test section (in the main body), several electrical and flow circuits and five heaters. The heaters apart, construction of the rig demanded no more than systematic planning and laborious manufacturing and fitting. Most development work was spent on the design of a high temperature heater.

The ignition temperature of the methane-air mixture by hot turbulent nitrogen was estimated in the region between 1300-1500°C. This estimation was based on previous work on hot gas ignition. The ignition temperature of methane-air by a hot laminar nitrogen jet (emerged from a 15 mm diameter nozzle) was found to be in the region of 1300°C²⁶. Meanwhile, the ignition temperature of a propane-air mixture by hot laminar and turbulent jets were measured by Wolfhard et al.²⁰ and Ma et al.²⁷. The measured values were approximately 1000°C and 1250°C respectively for a 10 mm diameter nozzle.

No laboratory heater could heat a turbulent jet to the required ignition temperature of methane-air mixture. Wolfhard,¹⁷ Goh²⁷, etc.

wound platinum-rhodium (Pt-Rh) resistance heating elements (melting points: Pt = 1772°C ; Rh = 1963°C) on the outside wall of a recrystallised alumina tube (maximum working temperature = 1950°C). The maximum gas temperature obtained by these heaters depended on the gas flow rate. Vanpee and Fink²⁶ reported a maximum gas temperature of 1436°C at a flow rate of $0.07 \times 10^{-3} \text{ Kg/s}$. Goh and Ma²⁷ found that the Pt-Rh heater would burn out at about 1300°C with a $3.0 \times 10^{-3} \text{ Kg/s}$ nitrogen jet.

At the start of the present study the author employed a similar Pt-Rh heater, but it failed to ignite the methane-air mixture. Subsequently the Pt-Rh resistance wire was replaced by iridium-rhodium (Ir-Rh) resistance heating elements (melting point of Ir = 2447°C) but again the methane gas failed to ignite, due to reasons discussed in Chapter 5. It was then decided that other heating elements must be used. Molybdenum metal was employed and after numerous modifications to the original design (see Chapter 5) a heater was successfully used to heat the nitrogen jet to a maximum of 1580°C at a flow rate of $3.2 \times 10^{-3} \text{ Kg/s}$.

2.1.2. Stage II: Measurement of M.I.T.

Since ignition by hot gas is determined by the balance between the heat released by chemical reactions and the heat transfer between the hot and cold gases, it may be expected that those factors which affect this balance may also affect the M.I.T. These factors may include (a) the temperature and chemical compositions of the combustible gases of the secondary flow, (b) the diameter of the nozzle and the mass flow rate of the flows, and (c) the flow pressure.

The number of factors and the range of variations to be investigated were determined by two considerations. They must on the one hand reflect fully the effect of these factors on M.I.T., but they must also be practically attainable. For instance, it might be desirable to investigate high mass flow rate, but a high velocity nitrogen jet would imply a short residence time of hot gas in the test section in relation to the ignition delay time of the combustible mixture. As a result the temperature of the hot nitrogen jet required for ignition would be extremely high and difficult to obtain.

The effect of flow pressure was not investigated because safety precautions could not be provided in the laboratory. In practice, one may find a hot jet being discharged into a stagnant combustible mixture. It would therefore be unrealistic to vary or impose a high velocity on the secondary flow. Furthermore, only nitrogen was used as the hot gas jet. This was because in the calculation of the ignition temperature the hot gas was assumed to take no part in the chemical reaction (see Chapter 3). This assumption ruled out air as the hot gas and there was no need to consider other inert gases (e.g. helium, argon etc.) since the effect would be the same as the nitrogen gas. Apart from these restrictions, the following factors were investigated:-

- (i) The diameter of the nozzle, d_p . Two diameters were tested. These were 15.00 mm and 19.35 mm,
- (ii) Mass flow rate of the primary flow, $\dot{m}_p$. The range tested was between 1.4 and 3.6×10^{-3} Kg/s. The corresponding velocity of the hot nitrogen jet at the nozzle exit was between 24 and 115 m/s,
- (iii) Temperature of the secondary flow, T_s . This was tested between 18°C to 187°C .
- (iv) Equivalence ratio of the secondary flow, η , which is defined as

$$\eta = \frac{\frac{m_{\text{CH}_4}}{m_{\text{O}_2}}}{\left(\frac{m_{\text{CH}_4}}{m_{\text{O}_2}}\right) \text{ at stoichiometric ratio}}$$

- where m_{CH_4} and m_{O_2} are mass fractions of methane and oxygen respectively, η was tested between 0.56 and 1.36, and

- (v) Oxygen index of the secondary flow, ξ , which is defined as

$$\xi = \frac{m_{\text{O}_2}}{m_{\text{O}_2} + m_{\text{N}_2}}$$

The normal air oxygen index is 0.233. Lowest index tested was 0.188.

The diameter of the glass cylinder which enclosed the flows and the mass flow rate of the secondary flow were maintained constantly at 290 mm and 50×10^{-3} Kg/s respectively. The corresponding velocity of the secondary flow was 0.6 to 1.1 m/s depending on its temperature.

2.1.3. Stage III: Measurement of the Velocity Profiles

In addition to the ignition temperature measurements the axial velocity profile in (a) a free round air jet and (b) an air to air co-axial flow at ambient temperature having the same geometry as Figure 1, were measured. The velocity profiles were measured by a three-hole probe (Ref. 57, see also Figure 17). The purpose of these measurements was to provide a computational check against the cold flow calculations obtained from a computer program which was subsequently used to predict the M.I.T. (see Chapter 3).

2.1.4. Summary of the Remaining Part of the Chapter

In the remaining pages of this chapter the experimental work will be described in three sections, each of which covers one of the three stages of work. The detailed construction of the test rig is described in paragraphs 2.2. to 2.6. Measurement of the M.I.T. is presented in paragraphs 2.7. to 2.8. and finally, the measurement of the velocity profile is given in paragraph 2.9.

2.2. GENERAL LAYOUT OF THE RIG

The general layout of the rig is shown in Figure 2 and plates 1 to 3. For description purposes, it may be convenient to divide the rig into four sections:-

- I: the main body in which the ignition was observed,
- II: the heater from which the gas flows were raised to the required temperatures,
- III: the electrical and fluid flow circuits by which the temperatures and the flow rates of the gas flows were controlled, and

IV: the instrumentation on which the various flow properties were measured.

2.3. THE RIG. I: THE MAIN BODY - FIGURE 3

The main body of the test rig consisted of a test section (Figure 3, W), two gas ducts, a cooling water jacket (Figure 3, C) and a fuel injector (Figure 3, G).

2.3.1. The Test Section - Figure 3, W

The test section was enclosed by a transparent heat resistant glass cylinder (Figure 3, A). The upper end of the cylinder was open. Burnt or unburnt gases were allowed to be discharged freely out of the open end of the cylinder. A vented hood (not shown) was placed 1200 cm above the glass cylinder to remove the discharged gases from the building. The working section occupied a space of 500 mm length measured from the nozzle of the primary flow to the top of the glass cylinder and had a circular cross-section of 290 mm diameter. Seven 6 mm holes were drilled along a vertical line on the glass cylinder (Figure 3, B) for the insertion of measuring probes (thermocouple and pressure tube). Ignition could be visibly observed through the glass cylinder.

2.3.2. The Primary Flow

The primary flow (nitrogen gas) was heated by three heaters. These were, in the order of the direction of the flow, the pre-heater (Figure 3, S), the connector heater (Figure 3, Y) and the main heater (Figure 3, D). The heated nitrogen gas was discharged vertically upwards from an alumina tube which was a part of the main heater (Figure 3, D and Figure 4). A converging flow reducer* (Figure 5) could be cemented on the top of the alumina tube to form a smaller nozzle. The original internal diameter of the alumina tube and the reduced nozzle were 19.35 mm and 15.0 mm respectively at ambient temperature. (Corrections for thermal expansion were made during the calculation of M.I.T.).

* Machined out of machinable block, supplied by Anderman, London.

2.3.3. The Secondary Flow

The secondary flow was composed of a mixture of air, diluting nitrogen and methane gases. Air and nitrogen gases were mixed in the first of the two secondary flow heaters (Figure 2) before entering the settling chamber (Figure 3, X) via two 76.2 mm diameter circular ducts (Figure 3, L). Further heating took place inside the settling chamber. The gases then entered vertically upwards into the mixing duct (Figure 3, Z) where methane gas was injected downwards from the fuel injector ring (Figure 3, G). Further mixing of the gases was enforced as the gases passed through a layer of glass beads (Figure 3, F). A honeycomb section (Figure 3, E, 50 mm long) was used to straighten the flow before the mixture entered the test section.

2.3.4. The Cooling Water Jacket - Figure 3, C

In order to avoid the possibility of ignition by a hot surface, the secondary flow was separated from the main heater (Figure 3, D) by a cooling water jacket (Figure 3, C). The jacket was a 1085 mm long, triple walled brass cylinder with a 140 mm long conical stainless steel cap (Figure 3, C). (Diameters of the cylinders: 70 mm I.D., 111 mm O.D.; diameters of the cone: 111 mm O.D. base, 35 mm O.D. top. Surface of the cone was inclined at 15° to the vertical, see Figure 4).

2.3.5. The Fuel Injector - Figure 6

The injector ring was a 25 mm square sectioned duct which was fixed to the wall of the mixing duct (Figure 3, Z) by two rods and a 13 mm diameter copper tube. This copper tube was also the gas inlet. Forty-eight Amal injectors were equally spaced around the underside of the ring. On each head of the Amal injector seven 0.5 mm holes were drilled in such an arrangement as to maximise the spray of the gases and hence the mixing with the air-nitrogen gases (Figure 6). Pressure drop between the inlet and the injectors (i.e. the pressure drop inside the ring) was expected to be far smaller than the pressure drop across the injectors. Therefore the amount of methane gas discharged through each of the forty-eight injectors should be approximately the same.

2.4. THE RIG. II: THE HEATERS

A total of five heaters were built. Three of these heaters were used for the heating of the primary flow (the nitrogen gas) and the other two for the heating of the secondary flow (the combustible mixture).

2.4.1. The Main Heater - Figure 7

(a) The heating element

A molybdenum metal sheet*, 0.5 mm thick, 76 mm wide and approximately 1150 mm long was rolled and pressed into a split tube of 25.5 mm I.D. (Figure 9). On the opposite side of this split, which was 4 mm wide, a 4 mm gap was cut longitudinally from the lower end of the tube to a distance of 38 mm from the top end so that the molybdenum tube was almost separated longitudinally into two equal halves by the two 4 mm gaps, except at the top end.

Each half of the lower end of the molybdenum tube was again split longitudinally into three identical strips (134 mm long and 12 mm wide). These strips were then bent outwardly through approximately 75°. The molybdenum tube was then slid over a purox recrystallised alumina tube⁺ (25.0 mm O.D., 1220 mm long and 6 mm thick). A 38 mm gap was left between the top ends of the molybdenum and the alumina tubes. At the lower end, the molybdenum tube was clamped to the ceramic tube by a device shown in Figure 8, Section A-A.

The entire surface of the molybdenum metal, except the "fork strips" (Figure 9) was covered by several layers of alumina cement^x. The cement coating took a total of three days, in order to allow the drying of the inner layer before an outer layer was applied.

* Supplied by Amax Speciality Metals, USA

+ Supplied by Morgan Refractories, UK

x Supplied by Morgan Refractories, UK

These processes were necessary to keep the two halves of the molybdenum tube at a distance apart, because the di-electric strength (or breakdown voltage, as it is also called) of alumina cement falls exponentially beyond 1000°C ⁵⁴. If the gap were smaller than a critical value, short circuit would develop and damage the heater (see Chapter 5 for further discussion). Presence of water in the cement could also decrease the di-electric strength, thus the coated molybdenum tube was dried in a large oven at 110°C for at least twenty-four hours. The electrical resistance of this heating element was 0.007 ohms at 20°C , but increased to about 0.07 ohms at 1900°C . The heating element was supplied by high current (up to 350 amperes) but at low voltage (maximum 14 volts) to reduce the risk of voltage breakdown.

(b) The protecting chamber

Molybdenum oxidises readily above 400°C and rapidly above 1000°C and may not be used in oxidising atmospheres. For this reason the heating element was housed inside a protecting chamber.

The inner wall of this chamber was the alumina tube (Figure 7, A, this wall caused serious oxidation problems, see Chapter 5 for details). The outer wall was made up of a mild steel tube (Figure 7, L, dimensions 68 mm O.D., 3 mm thick and 870 mm long), an alumina tube (Figure 7, J, dimensions 40 mm O.D., 34 mm I.D., 140 mm long), two alumina caps (Figure 7, B and C) which were cast from 1800 castable alumina cement*, and a mild steel box (Figure 7, M: dimensions 216 mm O.D., 89 mm high).

The walls of the chamber were jointed together by various methods in order to prevent leakage. B (referring to Figure 7, and also applying to the rest of this paragraph) was jointed to J by alumina cement; C and J were cast in one piece; C and L and L and M were compressed between a layer of gasket; M and A were sealed by a special sealing unit (Figure 7, D) which was a pair of male to female caps (cast from 1800 cement) with a layer of compressed Suffil⁺ (a ceramic fibre, working temperature 1600°C) between them. M and A

* Supplied by Morgan Refractories, UK

+ Supplied by Morgan Refractories, UK

were further sealed by a layer of Autostik and alumina cement on the outside (Figure 7, P and T). The gap between A and B was filled with a layer of Suffil (Figure 7, E).

Even with above sealings a certain amount of air was found to enter the chamber due possibly to (a) the gradual formation of thermal cracks in the alumina cement, (b) change of porosity of the alumina tube at elevated temperature and (c) diffusion through the Suffil packing.

Subsequently, the chamber was pressurised to create a positive pressure difference with respect to the surrounding air and hence prevent the outside air from entering the chamber. Protecting gases, either argon or forming gas (25% H₂ - 75% N₂) were injected into the chamber under pressure (approximately 2-3 p.s.i.) and allowed to leak out of the chamber through the gaps (e.g. between A and B, A and D, of Figure 7). To reduce the flow rate of the protecting gas, the inside of the chamber was filled with alumina insulating powder*, Kaowool⁺ and Suffil (Figure 7, E, K and R).

(c) Electrical connections

The two ends of the molybdenum heating element (i.e. the "fork" strips, see Figure 9) were connected to the copper terminal bars (see Figure 7, V, Figure 8, Section B-B). Each copper terminal bar was connected to a pair of brass connectors (Figure 8, Section B-B) which were extended through the mild steel box (Figure 7, M) for external electrical connections. The brass connectors were electrically insulated with asbestos sockets.

A water cooling coil was inserted inside the mild steel box (Figure 7, S) to reduce the temperature in the vicinity of the copper terminals. This was necessary because any small amount of oxidation of the molybdenum heating element, even a thin film, could create a high electrical resistance at the contact surfaces between the molybdenum and the copper bars. At low temperature the intensity of oxidation would be greatly reduced.

*+ Supplied by Morgan Refractories, UK

(d) The ceramic fragments

The alumina tube (Figure 7, A) is not a good heat conductor. To improve the heat transfer to the gas flow, two thirds of the lower part of the alumina tube was fitted with segments of alumina. These segments were arranged three in a set, each 100 mm long and back to back, to form a delta section (Figure 9, Section B-B). Each set was then placed above and across the other so that maximum turbulence was created as the nitrogen gas passed through these ceramic fragments.

The maximum temperature of the hot gas attained by this heater alone was 1085°C at a flow rate of 3.0×10^{-3} Kg/s. Clearly this temperature was not high enough to ignite the methane gas and a pre-heater was needed.

2.4.2. The Pre-Heater (Figure 10)

(a) The heating matrix

The pre-heater was made up of thirty-four heating matrices. Each matrix (Figure 11) was constructed by coiling a heating element, either in the form of a coil or tape, on an alumina frame. The frame was formed by joining two alumina rods and two square columns together in the manner shown in Figure 12.

For economic reasons three different heating elements were used. The Nichrome V* tape provided the first sixteen heating matrices and raised the gas flow temperature to a maximum of 870°C. The tape was 0.2 mm thick, 1.3 mm wide and was wound between the two alumina rods at a pitch of ten strips per inch (25.4 mm). Each Nichrome V heating element was approximately 24 ohms.

Kenthal-Al⁺ wire was used in the next five heating matrices. The wires were 1.0 mm diameter and were coiled into a helical section of 4.0 mm diameter before being wound around the alumina rods at a pitch of 2.5 coils per inch. These heating matrices were about 12 ohms each and were capable of raising the gas temperature by a further

* Supplied by British Driver Harris, UK

+ Supplied by Hall & Pickles Ltd., UK.

170°C to a maximum of 1030°C.

The final thirteen heating matrices were made by 80% Platinum-20% Rhodium* alloy. The diameter of the Pt-Rh wire was 0.5 mm and was coiled into a 2.0 mm helix before being stretched between the rods at four coils per inch. Each heating matrix was 12 ohms approximately. The thirteen Pt-Rh matrices raised the gas temperature to a final maximum of 1320°C.

(b) The gas duct

The thirty-four heating matrices were inserted inside a gas duct which was formed by forty alumina blocks sandwiched between forty-one mild steel plates (Figure 10). The alumina block was cast from the 1800 castable alumina cement. (Overall dimensions 300 mm square and 38 mm thick, Figure 13). In the middle of each block was a 102 mm square opening. The heating matrices were placed on the recesses cast out in each block except the first and the last three blocks, which did not have a heating matrix, but were used to provide passages for the gas flow from a 25 mm diameter circular tube to the 102 mm square duct and vice versa. The electrical terminals of the heating elements were led out of the block through the grooves on one side of the blocks (Figure 13).

The adjacent alumina blocks were firmly pressed between a layer of Kaowool (a ceramic fibre in the form of blanket, maximum working temperature is 1250°C) by the compression of the steel plates (Figure 14). These steel plates were "chained" together at alternative sections. A pair of rollers were attached to every four steel plates.

The assembled heater sat on two rails so that the bulk of the heater could move freely during the thermal expansion (or contraction), except at the exit end of the heater which was anchored to the floor by two triangular posts (Figure 3, S). This anchorage was needed to prevent the pre-heater from breaking the alumina tube of the main heater during thermal expansion.

* Supplied by Johnson Mattheys, UK.

On the outside of the alumina block and between the steel plates a sealing compound made up of calcium flouride and sodium silicate was applied to reinforce the sealing provided by the Kaowool gasket. Originally, the pre-heater was linked to the main heater by an alumina tube which was insulated by several layers of Kaowool blankets. The gas flow temperature was found to drop by as much as 200°C between the exit of the pre-heater and the entrance of the main heater. To reduce this temperature drop a connector heater was built.

2.4.3. The Connector Heater - Figure 15

(a) The heating blocks

The connector heater was made up of five heating blocks. These heating blocks were cast from 1800 alumina castable cement*. Immersed inside the blocks were Kanthal-Al heating coils arranged in a closely packed zig-zag fashion. The heating elements were made from 1.0 mm wire and were placed nearer to one surface of the block so that this surface could be readily heated to just under 1000°C.

(b) The steel container box

The steel box (Figure 15) was 356 mm long, 127 mm high and 203 mm wide. One end of the box was cut open for the "docking" to the last steel plate of the pre-heater (see Figure 3). Four of the heating blocks were placed against the inside walls of the steel box, as shown in Figure 15. The pre-heater and the main heater were then linked together by an alumina tube (25 mm diameter) and a connector block which was cast from alumina cement. Space inside the steel box was filled with alumina insulating powder. Finally, the top of the box was covered by the fifth heating block (Figure 15).

With this arrangement the temperature drop of the gas flow between the pre-heater exit and the main heater entrance was reduced to less than 70°C.

* Supplied by Morgan Refractories, UK.

2.4.4. The Secondary Flow Heaters

Since the maximum design temperature for the secondary flow was only 200°C heating could be adequately provided by commercial heaters. There were two secondary flow heaters (Figure 2).

The first heater was a 3 kW Secomark Industrial Heater*. This cylindrical heater has six heating elements arranged in two sections in the direction of the flow. The second heater consisted of sixteen $\frac{1}{2}$ kW domestic electric heating bars equally spaced inside the settling chamber (Figure 2).

* Supplied by Service Electric Co. Ltd., U.K.

2.5. THE RIG. III: FLUID FLOWS AND ELECTRICAL CIRCUITS

In the design of the present test rig "supply" and "control" were two important factors. The experiments were conducted continuously day and night for up to a week in order to avoid frequent heating and cooling, which could cause damage to the heaters. Thus, it was necessary to plan and ensure continuous supplies of all fluid flows and to regulate the electrical power loading to the heaters as accurately and smoothly as possible. A schematic diagram of the supply and control system is given in Figure 2.

2.5.1. Fluid Flows - (See Also Plate 2)

(a) Primary flow - Figure 2, top right

Nitrogen was the only gas in the primary flow but air was temporarily used in place of the nitrogen during the heating up and cooling down periods to reduce the cost. Air was supplied from the laboratory "shop-air" but nitrogen was fed from bottles of compressed "oxygen-free nitrogen" gas*. The bottle nitrogen gases were arranged in two sets of six bottles. Each set supplied approximately six hours of continuous running. A three-way valve provided the change over to replace the empty bottles. The mass flow rate of the primary flow was adjusted by a coarse 25.4 mm diaphragm valve and a parallel fine 6.35 mm needle valve.

(b) Secondary flow - Figure 2, top left.

The secondary flow was a mixture of air, nitrogen and methane gases. Clean air was obtained from the department's Howden compressor while nitrogen was fed from bottles of compressed gas as before. During the ignition test methane was injected only when the ignition was thought to be approaching. Thus, a solenoid valve was inserted in the supply line to provide a quick cut-off on completion of the ignition test. The methane gas was supplied from a bottle of commercial graded compressed gas (purity of methane was over 99.6%)[†]. Adjustment to the mass

* Supplied by British Oxygen Corporation, UK.

† Figure supplied by British Oxygen Corporation, UK.

flow rate was by a 76.2 mm globe valve in parallel with a 25.4 mm needle valve for air and a 25.4 mm diaphragm valve in parallel with a 6.35 mm needle valve for nitrogen and methane gases.

(c) Protecting gases

Ideally, forming gas (75% N₂-25% H₂) should be used to protect the molybdenum metal from oxidation because the presence of hydrogen could remove any traces of oxygen. But hydrogen gas could leak into the test section and take an active part in the combustion. As a result, ignition temperature could be affected by the presence of the hydrogen gas. Therefore, during the ignition test forming gas was replaced by argon, which is, of course, an inert gas. Both of these gases were supplied from bottles of compressed gas and were pre-dried by concentrated sulphuric acid. The typical flow rate of the argon gas was 0.006×10^{-3} Kg/s (i.e. 0.2 ml/min) as compared to the flow rate of 2.05×10^{-3} Kg/s for the hot nitrogen gas. Thus, even if all the argon gas had diffused into the primary flow its presence should not have any significant effect on the result of the ignition temperature measurements.

2.5.2. Electrical Circuits - Figure 2, bottom, and Plate 3

The total current demanded by the five heaters was high and this was supplied from a 400 amp rated power sub-station in the laboratory. Currents applied to the heaters were regulated by twenty-four variacs in order that the temperature of the gas flow could be increased gradually.

(a) Main heater

The 415 volt main was stepped down by a heavy duty transformer at a ratio of 11½:1. Output from the transformer was regulated by an inbuilt variac to a maximum of 350 amperes at 14 volts giving a maximum power supply of about 5 kW to the main heater. In addition a small transformer and a variac were inserted in the primary circuit of the heavy duty transformer

to provide fine control on the temperature of hot nitrogen jet. On average, these controls were able to adjust the nitrogen gas temperature to within 1°C of the desired value.

(b) Pre-heater

The thirty-four heating matrices of the pre-heater were divided into ten groups. Each group was supplied individually by a 240 volts main. All the heating matrices were connected in parallel so that a failure of one individual heater would not fail the heater as a whole and hence disrupt the proceedings of the experiment. (An early version of the pre-heater was less versatile and frequently disrupted the experiment, see Chapter 5). Nichrome and Kanthal heating elements were controlled in groups of three or four by a 20 amp rated variac, but the Pt-Rh heating elements were each controlled by an 8 amp rated variac.

(c) Connector heater

The heating elements of the five heating blocks were divided into three groups of the same electrical resistances. These were then supplied by 240 volt three-phase main (live to neutral) via a 13 amp rated three-phase variac (also connected live to neutral).

(d) Secondary heaters

The six heating elements in the first of the two secondary flow heaters (i.e. the Secamak Industrial Heater) could each be switched on to give six discrete changes of gas flow temperature. The sixteen heating elements in the settling chamber (Figure 3, K) were, however, connected in parallel and jointly regulated by a 30 amp rated three-phase variac (240 volts, live to neutral). This variac was able to control the secondary flow temperature to within 2°C of the prescribed value.

2.6. THE RIG. IV: INSTRUMENTATION

2.6.1. Temperature Measurements

(a) Minimum ignition temperature - Figure 16

The temperature of the hot nitrogen jet which was the minimum ignition temperature when an ignition was just observed, was

measured by a platinum-platinum 13% rhodium thermocouple made from 0.5 mm diameter wires. The bead of the hot junction was approximately 1.5 mm diameter. The leading wires of this thermocouple were sleeved inside a twin bored 2.5 mm diameter alumina insulating tube which was in turn inserted into a stainless steel tube, as shown in Figure 16. The steel tube was bent downward to face the hot nitrogen jet. A length of 107 mm of alumina tube was exposed outside the steel tube to prevent overheating of the metal in the high temperature zone and to reduce heat conduction by the steel tube. Furthermore, the hot junction of the thermocouple was at a distance of 6.35 mm from the alumina insulator so that disturbance to gas flow in the space near the hot junction was as little as possible.

This thermocouple probe was inserted into the working section through an opening in the glass cylinder. The steel tube was attached to a traversing table. Normally the hot junction of the probe was located at the near side of the glass cylinder and only moved to the centre line of the primary flow for measurement. Two stoppers at the sliding handle of the traversing table provided quick movements between these two positions.

The hot junction was paired with a cold junction which was immersed inside an ice box. This thermocouple was then connected to a Solartron digital volt meter (readable to ± 0.001 mV) via a DISA (52B30) integrator. Conversion to temperature was provided by a pre-calibrated table*. Heat loss due to radiation is estimated and values are presented in Chapter 4.

(b) Secondary flow - Figure 3

The secondary flow temperature was measured by a copper-constantan thermocouple located at the base of the working section mid-way between the glass cylinder and the cooling water jacket (Figure 3,T). The thermocouple wires were insulated by glass fibre and supported by a stainless steel tube. This thermocouple was also paired with a cold junction (at 0°C) and connected directly to an "advanced" digital volt meter (readable to ± 0.01 mV). Conversion to temperature was made using BS 1828 (1961) tables.

* Supplied by Johnson Matthey Metals Ltd., London.

In addition, another fifteen thermocouples of various types were inserted at important locations such as inside the pre-heater. Details of these thermocouples are given in Table 1.

2.6.2. Mass Flow Rate Measurements

Both the primary and the secondary flow rates were measured by orifice meter with D-D/2 tappings. An orifice plate of appropriate throat diameter was inserted inside a straight pipe at a location of at least 30 diameters downstream of the flow entry. Upstream pressure and the pressure difference across the D-D/2 tappings were measured in U-tube glass manometers filled with appropriate fluids (with mercury or paraffin of S.G. = 1.58 and 0.784). The temperature of the upstream of the orifice plate was measured by a copper-constantan thermocouple. This temperature was later used to correct the gas flow properties in the calculation of the mass flow rate based on the procedure laid down in B.S. 1042, part 4 (1964). The detail of pipe size, orifice plate throat diameter, etc. is given in Table 2.

2.6.3. Velocity Measurements

The measurement of axial and radial velocities of a free round jet and an air to air co-axial flow at ambient temperature (see paragraph 2.1.3 for reasons of measurement) was provided by a three hole pressure probe.

(a) The probe - Figure 17

The pressure probe was constructed based on the design of Heitt and Powell⁵⁷. It has three pressure holes of 0.725 mm diameter drilled in a V groove on a solid stainless steel cylindrical head (Figure 17) of 6.35 mm diameter. These holes were linked to three hypodermic tubes enclosed inside a 6.35 mm O.D. stainless tube which was silver soldered into the cylindrical head.

The V groove was 1.75 mm wide with an inclination angle of 120°. Two of the pressure holes (hereafter called holes No. 1 and 2) were drilled in one of the inclined surfaces of the V groove at a radial angle of 72° (see Figure 17, section X-X). A third hole (hole No. 3) was drilled in the other inclined surface of

the groove opposing hole No. 1.

(b) Calibration

The probe was calibrated in a low speed wind tunnel. It was assumed that the mean velocity profile in the working section of the wind tunnel was uniform and that the flow was parallel to the walls. The time mean velocity was measured by a conventional two-hole pitot static tube, (i.e. the three-hole probe was calibrated against the pitot static tube).

Calibration was carried out in two steps. In the first stage, the ratio of $(p_1 - p_2)/V.H.$ was measured as a function of the yaw angle (i.e. rotation angle about the longitudinal axis of the probe, see Figure 19, lower graph), where:-

p_1 and p_2 were the pressures in hole Nos. 1 and 2,
 $V.H.$ was the velocity head of the flow defined by
 $V.H. = \frac{1}{2} \rho . Q^2$, where Q and ρ were mean velocity (see Figure 18) and density of the flow respectively.

Secondly, $(p_1 - p_3)/(p_1 - p_2)$ was also calibrated against the yaw angle (p_3 was the pressure of hole No. 3, see Figure 19, upper graph).

To calculate velocities the pressure ratio $(p_1 - p_3)/(p_1 - p_2)$ was used to find the yaw angle and from this $V.H.$ was found using the lower graph of Figure 19. The two component velocities were then calculated from (see Figure 18):-

$$U = Q \sin \theta \text{ and } V = Q \cos \theta$$

where U and V were axial and radial velocities and
 θ was the yaw angle.

Measurements of the pressure differences (i.e. $p_1 - p_3$ and $p_1 - p_2$) were taken on a Furness micromanometer, which was connected to a Solartron digital voltmeter (± 0.001 mV) via a DISA (52B30) integrator.

2.7. THE EXPERIMENT. I: IGNITION TESTS

2.7.1. Procedures for Operating the Heaters

At least ten hours before the heaters were switched on, forming gas was injected into the protecting chamber (Figure 4) in order to repel the residue air. The presence of forming gas inside the protecting chamber was checked by passing a combustible gas (e.g. methane) in place of the forming gas for a short period of time. Formation of a flame above the jet nozzle (Figure 3) would indicate that the chamber was filled with the passing gas.

At the start of the heating (usually in the morning of the first day) air was used in the primary flow. The electricity supplied to the heaters was gradually increased, twice an hour, but later stepped up to three or four times an hour. A typical rate of temperature increase of the hot gas jet at this stage was about 100°C per hour.

About ten hours later (first day, evening) the hot gas jet would reach a temperature of about 1000°C . This flow temperature was then kept constant overnight without further adjustment to the power supply. At this stage, air in the primary flow was replaced by the nitrogen gas. (This is a very important procedure, see Chapter 5 for discussion).

Another twelve hours later (second day, morning) a further increase of hot gas temperature was made, but at a slower rate of about $40\text{--}70^{\circ}\text{C}$ per hour. The secondary flow (excluding methane gas) and its heaters were also switched on at this stage. When the primary flow temperature was approaching the estimated ignition temperature (usually on the second day, mid-day) forming gas was replaced by argon in order to avoid possible effects of the presence of hydrogen (in the forming gas) on the ignition temperature measurement as discussed in paragraph 2.5.1.

2.7.2. Procedure of Searching Minimum Ignition Temperature

As the estimated ignition temperature was approached the primary flow temperature just above the nozzle (at $x = 5\text{ mm}$, $y = 0$, see Figure 18) was measured by the Pt-Rh thermocouple (Figure 16). The thermocouple

was then quickly withdrawn from the hot gas zone before methane gas was injected into the secondary flow. Injection of methane gas lasted for not more than fifteen seconds (except for rich mixtures see paragraph 2.8.4). If, during this time, the primary flow temperature was high enough, a flame could be seen to form in the mixing layer and then quickly propagated into the unburnt combustible mixture in the secondary flow. At this moment the methane gas was quickly cut off.

The temperature of hot gas jet was measured again, before it was reduced by a small amount. The ignition test was then repeated and depending on whether the ignition had taken place or not the temperature of hot nitrogen jet was either further decreased or increased. Such processes were repeated several times until two successive tests, which produced one with ignition and one without ignition, were separated by a smallest temperature difference of the hot nitrogen jet (up to $\pm 5^{\circ}\text{C}$). The temperature of hot nitrogen jet which just managed to produce an ignition was, by definition, the minimum ignition temperature.

2.7.3. Reproducibility of the M.I.T.

Two types of tests were carried out to check the reproducibility of the measured M.I.T. These were:-

- (a) Test under a given set of flow conditions (referred to as reference flow conditions, see Table 3), but measured at different dates, Figure 20.
- (b) Test under variable secondary flow temperature, measured at the beginning and the end of one continuous experiment, Figure 21.

From these tests the M.I.T. was found to be repeatable within $\pm 5^{\circ}\text{C}$. The lowest and the highest measured M.I.T. under the reference flow conditions were as follows:-

for $d_p = 19.35 \text{ mm}$
 $1279^{\circ}\text{C} < \text{M.I.T.} < 1288^{\circ}\text{C}$

for $d_p = 15.00 \text{ mm}$
 $1372^{\circ}\text{C} < \text{M.I.T.} < 1379^{\circ}\text{C}$

where d_p is the nozzle diameter of the primary flow.

2.8. THE EXPERIMENT. II: IGNITION TEMPERATURE MEASUREMENT

2.8.1. Test Range and Result

After the first ignition was found the test was continued to carry out ignition temperature measurements for various flow conditions. The variables and test ranges were as follows:-

$$(i) 1.4 \times 10^{-3} \leq \dot{m}_p \leq 3.6 \times 10^{-3} \text{ Kg/s}$$

where $\dot{m}_p$ is the mass flow rate of the primary flow,

$$(ii) 18^\circ\text{C} \leq T_s \leq 187^\circ\text{C}$$

where T_s is the temperature of the secondary flow,

$$(iii) 0.56 \leq \eta \leq 1.36$$

where η is the equivalence ratio of the secondary flow as defined in paragraph 2.1.,

$$(iv) 0.188 \leq \xi \leq 0.233$$

where ξ is the oxygen ratio of the secondary flow, again as defined in paragraph 2.1.

These variables were tested at first for a jet nozzle of the hot nitrogen gas of 19.35 mm diameter (d_p). They were then repeated for a second diameter of 15.00 mm. At the start and sometimes at the end of a given set of experiments, the ignition temperature was checked under the reference conditions given in Table 3 to ensure that the rig had not developed faults, such as gas leakage, which could alter the ignition temperature.

Results of the ignition temperature measurements are tabulated in Tables 4 to 7 and plotted in Figures 22 to 25.

Prior to an ignition test, the mass flow rates and flow temperatures were stabilised and measured. Since the methane gas was injected after the flow temperatures were measured the temperature of the secondary flow was that of the flow which excluded the methane gas. As a result the measured temperature was higher than the actual secondary flow

temperature. Thus, adjustments were made to correct the measured temperature.

2.8.2. Ignition at or Near Stoichiometric Mixture

At or near the stoichiometric ratio of the combustible mixture, the formation of the visible flame in the primary flow was accompanied by a loud low pitch "bang" (which sounded like "foom"). As soon as it was formed, the flame could be seen to propagate into the unentrained combustible mixture in the secondary flow. In a fraction of a second the flame quickly moved down the test section in the opposite direction to the flows by the phenomenon known as "flash-back". If methane gas was not quickly cut off the flame could be seen to be stabilised at the top of the honeycomb section (Figure 3, E).

2.8.3. Ignition of a Lean Mixture

As the fuel/air ratio decreased to a lean value (approximately $\eta < 0.75$) the "loud bang" which accompanied the formation of flame was absent. Instead a pale bluish haze was seen to form in an inversed conical shell at a height of about 0.1 to 0.3 metres above the jet nozzle. The bluish haze was accompanied by whistling noises and persisted for a short time (a couple of seconds, but longer as η decreased) after the injection of methane gas. Finally, a flame was seen to propagate into the secondary flow followed by the flash back into the mixing duct. The noise observed during this period sounded like "sz.....sz.....sz.....zoom" (at this moment the flame was formed). As the equivalence ratio was further decreased the bluish haze was seen to form at a distance further away from the jet nozzle. The brightness of the haze was also gradually decreased until it could no longer be seen at an equivalence ratio of about 0.56.

2.8.4. Flame Formation of a Rich Mixture

The following phenomenon was observed, for a rich mixture ($\eta > 1.1$ approximately), when the hot nitrogen jet temperature was just below (about 10-20°C) the measured ignition temperature:-

As the ignition temperature was approached, fuel was injected for

a maximum period of about 15 seconds. Since no ignition was observed the methane gas was cut off. But, a few seconds after the fuel was cut off, it was a surprise to see that a flame had formed above the level of the top of the glass cylinder (Figure 3, i.e. outside the test section). Almost at once a very "loud bang" (which sounded like "bom") was heard. The flame lifted upwards and disappeared. However, it was not clear whether the "bang" was heard before or after the flame vanished. The whole phenomenon occurred in a fraction of a second.

At first it was thought that ignition had occurred, so the fuel was again injected. No ignition was, however, observed after two minutes of fuel injection, but as soon as the fuel was cut off the same phenomenon was observed again.

If the primary flow temperature was increased (by about 10 to 20°C) the normal ignition phenomenon as described in paragraph 2.8.2. was observed. On the other hand, if the temperature was lowered further (more than 20°C approximately below the measured ignition temperature) no ignition of either kind was observed.

The ignition phenomena of lean and rich mixtures will be further discussed in Chapter 4.

2.9. THE EXPERIMENT. III: VELOCITY MEASUREMENTS

For reasons already explained in paragraph 2.1.3., the axial and radialwise axial velocity profiles were measured for (a) a round air-free jet and (b) a confined air to air co-axial flow. Both flows were under ambient temperature and pressure. The Reynolds' number of these flows was in the order of 1.0×10^4 and was similar to that in the ignition experiment.

2.9.1. Measurement of Free Jet Flow

The glass cylinder (Figure 3,A) was removed from the main body so that an air jet could be discharged freely from the 15 mm diameter flow reducer nozzle (Figure 5). The air flow rate was set at a constant 2.25×10^{-3} Kg/s under an average ambient temperature of 20°C approximately (varied between 17°C to 25°C). Velocities were measured by

the following procedures.

(a) Locating the 3-hole probe

With the probe mounted on the sleeving ring (Figure 16) the position of the traversing table was adjusted until the probe crossed the centre line of the jet nozzle. The probe was then moved horizontally to match the centre of the V-groove of the probe (Figure 17) with the centre of the nozzle. To ensure the probe traversed in the vertical plane containing the centre line of the nozzle, two more sleeving rings were fixed on the vertical bar of the traversing table. Vertical traversing of the mobile sleeving ring, which was between the two fixed rings, was then guided by a vertical rod linking the three rings.

The probe was raised 15 mm above the nozzle and rotated about its axis until the pressure difference of $p_1 - p_2$ was zero. The direction of the flow was then mid-way between the pressure holes Nos. 1 and 2. The probe was again rotated by 36° so that Nos. 1 and 3 pressure holes were both facing the direction of the air flow.

(b) Measurement of axial velocity profile

Vertical traversing of the probe along the centre line of the jet nozzle was taken at intervals of 15 mm, up to a height of 300 mm above the nozzle (i.e. 20 diameters downstream). The results are given in Table 9 and Figure 26. Symbols used in these tables and graphs are given in Figure 18.

(c) Measurement of radialwise axial velocity profiles

Radial traversing (i.e. horizontally) was taken at distances of 60, 120, 180, 240 and 300 mm (i.e. 4, 8, 12, 16 and 20 diameters) above the jet nozzle. Results of the measurements are given in Table 9 and Figure 28.

2.9.2. Measurement of Confined Co-axial Flow

Measurements of the confined co-axial flow were similar to those of the free jet flow except for the following changes:-

- (a) The glass cylinder was put back to its original position (Figure 3),
- (b) Primary and secondary flow rates were 2.0×10^{-3} and 50×10^{-3} Kg/s respectively,
- (c) Radial traversing was taken at distances of 63,161,228,285 and 345 mm above the jet nozzle (i.e. at 4.2,10.7,15.2,19 and 23 diameters).

The results of measurements are given in Table 10 and Figures 27 and 29.

2.10. CLOSURE

In this chapter the detailed construction of the rig, particularly the heaters, is given in full before the experimental procedures, observations and results are presented. The implications of the experimental results will be discussed in Chapter 4.

The present experimental work took an estimated total time of about three and a half years to complete. It was expensive, difficult, painful but finally successful. This proved the point that experimental work, though valuable as it is, could be costly, both in terms of time and cash.

It is then inevitable to ask this question: could the phenomenon of hot gas ignition be investigated by means of theoretical analysis in so far as it were possible? The next chapter will look into this question by a parallel theoretical investigation of the same problem, i.e. the prediction of the M.I.T.

CHAPTER 3

THEORETICAL INVESTIGATIONS

3.1. SCOPE OF PRESENT THEORETICAL WORK

The task of the present theoretical study was to develop a mathematical method so that the minimum ignition temperature (M.I.T.) could be calculated. This task was carried out in three stages:-

Stage I: Formulation of the equations governing the hot gas ignition phenomenon and solution of these equations,

Stage II: Testing of the solution method against a non-reacting flow before combustion was introduced into the calculation and, finally,

Stage III: Prediction of the M.I.T. based on an assumed overall reaction rate and deduction of correct reaction rate by comparison with the measured M.I.T.

3.2. THEORY I: THE ASSUMPTIONS

3.2.1. Basis for M.I.T. Prediction

It may be recalled (see Chapter 1) that the axial temperature profiles between the cases of ignition and no ignition are remarkably different (see Figure 1,A). If the axial temperature could be found for different initial temperatures of the hot nitrogen jet then the M.I.T. could be readily deduced. Thus, the task of calculating the M.I.T. was to find a solution to the equation which determined the temperature distribution in the flow field.

The flow field, as illustrated in Figure 1, is governed by conservation equations. These equations may be written in cylindrical co-ordinates ($x - r$, see Figure 18) as²⁷:-

continuity equation:

$$\frac{\partial}{\partial x}(\rho u r) + \frac{\partial}{\partial r}(\rho v r) = 0 \quad (1)$$

other conservation equations:

$$\rho u \frac{\partial \Phi}{\partial x} + \rho v \frac{\partial \Phi}{\partial r} = \frac{1}{r} \frac{\partial}{\partial r} \left(\Gamma_{\Phi} r \frac{\partial \Phi}{\partial r} \right) + S_{\Phi} \quad (2)$$

where Φ stands for the dependent variables which include velocity (u), total enthalpy ($\bar{h}$), mass fraction of various chemical species (m_j) and turbulent transport quantities (k, ϵ). Γ_{Φ} is an effective exchange coefficient and S_{Φ} is a source term of Φ . As for the temperature, T , it is expressed indirectly in the enthalpy equation by the following definition:-

$$\bar{h} = C_p T + m_{CH_4} H + \left(\frac{1}{2} u^2 + k \right) \quad (3)$$

where m_{CH_4} is the mass fraction of methane
 H is the heat of reaction of methane
and k is the turbulent kinetic energy.

3.2.2. Boundary Layer Assumption

In writing equations 1 and 2, it is assumed that the flow is two-dimensional parabolic, steady and axisymmetrical. These assumptions are generally correct because mixing between the fast moving hot nitrogen jet (typically 60 m/s) and the slow moving combustible mixture (typically 1 m/s) produces a large radial change of velocity, temperature and concentration as compared to the small changes in the axial direction (i.e. $\frac{\partial \Phi}{\partial r} \gg \frac{\partial \Phi}{\partial x}$). Thus, the flow field as shown in Figure 1 can be treated using boundary layer approximations, except at the lip of the jet nozzle.

As the primary and the secondary flows meet at the exit of the main heater (Figure 31), they form a small annular recirculation zone which is not parabolic but elliptic. The entire flow field could of course be rewritten in elliptical form so as to account for this recirculation zone, but in doing so one would invite two difficulties:-

- (i) numerical solution of an elliptical equation required far more computing time than the parabolic equation,

- (ii) the boundary conditions in the recirculation zone required elaborate experimental measurements.

In the present study this small recirculation zone was ignored and this decision was supported by the close agreement between the measured and the calculated results (Figures 26 to 29).

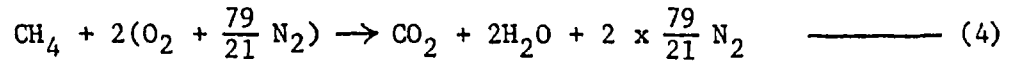
3.2.3. Steady Flow Assumption

For a non-reacting system, for example before methane is injected into the mixing duct, the flow as shown in Figure 1 is steady (i.e. independent of time and hence two-dimensional (x and r)). Ignition of a hot gas is, however, not a steady, but a transient phenomenon. After the flame is formed at a height of about 5 to 10 diameters above the jet nozzle, it will propagate into the secondary flow. Flame propagation is time dependent. The only time the flow might remain steady would be with a stabilised flame, which could occur if the burning velocity of the flame was equal and opposite to the velocity of the flow. This would, however, be a special case which would be unlikely to occur.

However, the objective of the present study is in the prediction of the occurrence of an ignition and not in the calculation of flame propagation after the ignition. It is valid to assume a steady flow up to and including the flame front during the initial stages of the formation of the flame. Within this region (i.e. from $x = 0$ to the position where flame is first formed) the axial temperature profile will develop sufficiently to indicate whether a flame has been formed or not (Figure 1,A). It is automatically assumed without further calculation that this flame will propagate into the secondary flow and cause the methane-air mixture to burn. This assumption is, of course, based on the experimental observations.

3.2.4. Single Step Overall Chemical Reaction Assumption

The chain reaction of methane-air oxidation has been discussed in some detail in Chapter 1 and it is concluded that we have yet to determine the exact oxidation mechanism. In this study the methane-air oxidation is assumed to take place by a single step overall reaction:-



with a reaction rate given by:-

$$\frac{d}{dt} \text{CH}_4 = - K \text{CH}_4^m \text{O}_2^m p^2 T^{-3/2} \exp(-E/RT) \left(\frac{2}{1+\eta}\right)^a \quad \text{————— (5)}$$

where η is the equivalence ratio defined in Chapter 2 (see paragraph 2.1.2.), we have also concluded that the current knowledge of the relationship between chemical reaction rate and the turbulence of the flow is still in its exploratory state. Thus, in this study the effect of turbulence on the reaction rate is solely reflected by the overall kinetic constant, K , of equation 5. This assumption will be further discussed in Chapter 4.

3.3. THEORY II: THE EQUATIONS

3.3.1. Momentum Equations

Axial velocity, u Substituting $\Phi = u$, $\Gamma_\Phi = \mu_{\text{eff}}$ which is the effective viscosity, and taking into account the buoyancy and pressure forces, equation 2 becomes:-

$$\rho u \frac{\partial u}{\partial x} + \rho v \frac{\partial u}{\partial r} = \frac{1}{r} \frac{\partial}{\partial r} (\mu_{\text{eff}} \cdot r \cdot \frac{\partial u}{\partial r}) + ((\rho_E - \rho)g - \frac{dp}{dx}) \quad \text{————— (6)}$$

where ρ_E is the free stream gas density at the same downstream distance as ρ . The effective viscosity, μ_{eff} , is a sum of the laminar viscosity (μ_l) and the turbulent viscosity (μ_t):-

$$\text{i.e.} \quad \mu_{\text{eff}} = \mu_l + \mu_t \quad \text{————— (7)}$$

Laminar viscosity For a mixture which consists of n species, the laminar viscosity may be written as:-

$$\mu_l = \sum_{j=1}^n m_j \cdot \mu_{l,j} \quad \text{————— (8)}$$

where m_j is the mass fraction of species j . and $\mu_{l,j}$ is the corresponding laminar viscosity, which may be assumed to obey

Sutherland's law²⁹:-

$$\mu_{1,j} = (\mu_{1,j})_{\text{ref}} \left(\frac{T}{T_{\text{ref}}} \right)^{\frac{1}{2}} \left(\frac{1.505}{1 + 0.505 \frac{T_{\text{ref}}}{T}} \right) \quad (9)$$

The reference temperature, T_{ref} , is set at 500°C and the corresponding reference viscosity $(\mu_{1,j})_{\text{ref}}$, for gas at 500°C is taken from Kaye and Laby⁶⁸. These reference viscosities are shown in Table 11.

Turbulent viscosity and the transport equations The turbulent viscosity is calculated from two turbulent transport quantities, namely the turbulent kinetic energy, k , and its dissipation rate, ϵ .

$$\text{i.e.} \quad \mu_t = C_\mu C_d \cdot \rho \frac{k^2}{\epsilon} \quad (10)$$

C_μ and C_d are functions of axial distance, x . Equation 10 was introduced by Launder and Spalding⁶⁴ and the two turbulent transport quantities may also be written in the form of equation 2:-

$$\rho u \frac{\partial k}{\partial x} + \rho v \frac{\partial k}{\partial r} = \frac{1}{r} \frac{\partial}{\partial r} \left(r \cdot \frac{\mu_{\text{eff}}}{\sigma_k} \cdot \frac{\partial k}{\partial r} \right) + \left(\mu_t \left(\frac{\partial u}{\partial r} \right)^2 - \rho \epsilon \right) \quad (11)$$

$$\text{and } \rho u \frac{\partial \epsilon}{\partial x} + \rho v \frac{\partial \epsilon}{\partial r} = \frac{1}{r} \frac{\partial}{\partial r} \left(r \cdot \frac{\mu_{\text{eff}}}{\sigma_\epsilon} \cdot \frac{\partial \epsilon}{\partial r} \right) + \frac{\epsilon}{k} \left(C_1 \mu_t \left(\frac{\partial u}{\partial r} \right)^2 - C_2 \rho \epsilon \right) \quad (12)$$

where σ_ϵ , σ_k , C_1 and C_2 are constants. Derivation of these equations may be found in Reference 64. k and ϵ are related to each other by a length scale, l :-

$$\epsilon = C_d \frac{k^{3/2}}{l} \quad (13)$$

The "constants" The values of C_μ , C_d , σ_k , σ_ϵ , C_1 and C_2 in equations 10 to 13 were believed⁶⁴ to be universal constants. But Rodi⁷² and Jones et al⁷³ found that some of these constants needed to be modified when applied to a low Reynold's number round jet flow.

In the present study C_μ and C_d values are deduced from the experimental measurements of Rodi⁷² and Bradshaw et al.⁷⁴ (see Appendix A). The value deduced from the measurements at a distance less than five

diameters downstream is different from those deduced at a distance beyond twenty diameters downstream (Figure 32). This is possibly due to the preponderance of the turbulent energy generation rate over its dissipation rate, in the region near the nozzle. The values of C_μ and C_d are assumed to be linear functions of x (streamwise distance) as shown in Figure 33. The other three constants have exactly the same values as those recommended by Launder et al.⁶⁴,

$$\text{i.e. } C_2 = 1.92; \sigma_K = 1.0; \sigma_\epsilon = 1.34$$

but it is necessary to change the value of C_1 from the recommended 1.56 to 1.6 in order to obtain better agreement between the predicted and measured velocity profiles.

3.3.2. Energy Equation

Total enthalpy, $\bar{h}$ Substituting $\Phi = \bar{h}$, which is defined as:-

$$\bar{h} = C_p T + m_{CH_4} H + \left(\frac{1}{2} u^2 + k \right) \quad \text{--- (3)}$$

equation 2 becomes:-

$$\begin{aligned} \rho u \frac{\partial \bar{h}}{\partial x} + \rho v \frac{\partial \bar{h}}{\partial r} = \frac{1}{r} \frac{\partial}{\partial r} \left(\frac{\mu_{eff}}{6h} \cdot r \cdot \frac{\partial \bar{h}}{\partial r} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left(r \mu_{eff} \cdot \left(1 - \frac{1}{\sigma_h} \right) \frac{\partial \left(\frac{u^2}{2} \right)}{\partial r} \right. \\ \left. + \left(\frac{1}{\sigma_k} - \frac{1}{\sigma_h} \right) \frac{\partial k}{\partial r} \right) \quad \text{--- (14)} \end{aligned}$$

where σ_h is the Prandtl number and is equal to 0.7 for axisymmetric jets⁷⁵. The source term includes effects due to kinetic heating by the mean velocity and fluctuating velocity gradients.

Specific heat, C_p Again, for a mixture which consists of n species, the specific heat may be calculated from:-

$$C_p = \sum_{j=1}^n \frac{m_j}{W_j} C_{p,j} \quad \text{--- (15)}$$

where $C_{p,j}$ is the specific heat of species j . Values of $C_{p,j}$ are

obtained from Spier⁷⁶ and are assumed to be polynomial functions of second order:-

$$C_{p,j} = a_j + b_j T + c_j T^2 \quad \text{--- (16)}$$

The coefficients of these second order polynomial are given in Table 12. W_j of equation 15 is the molecular weight of species j .

Density ρ Density is calculated from the known temperature and pressure:-

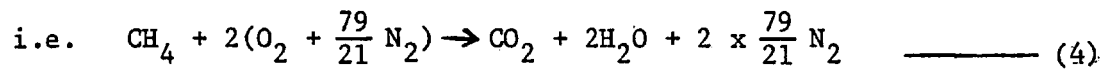
$$\rho = P/RT \quad \text{--- (17)}$$

where $R = \mathcal{R} \cdot \sum_{j=1}^n \frac{m_j}{W_j}$ --- (18)

and $\mathcal{R}$ is the universal gas constant.

3.3.3. Mass Fraction Equations

The single step overall chemical reaction as expressed in Equation 4,



contains five species, namely CH_4 , O_2 , CO_2 , H_2O and N_2 . The distribution of mass fraction, m_j , of each of these five species is also governed by Equation 2.

Thus, with $\Phi = m_j$;

$$\rho u \frac{\partial m_{\text{CH}_4}}{\partial x} + \rho v \frac{\partial m_{\text{CH}_4}}{\partial r} = \frac{1}{r} \frac{\partial}{\partial r} \left(r \cdot \frac{\mu_{\text{eff}}}{\sigma_s} \frac{\partial m_{\text{CH}_4}}{\partial r} \right) + \dot{m}_{\text{CH}_4} \quad \text{--- (19a)}$$

$$\rho u \frac{\partial m_{\text{O}_2}}{\partial x} + \rho v \frac{\partial m_{\text{O}_2}}{\partial r} = \frac{1}{r} \frac{\partial}{\partial r} \left(r \cdot \frac{\mu_{\text{eff}}}{\sigma_s} \frac{\partial m_{\text{O}_2}}{\partial r} \right) + \dot{m}_{\text{O}_2} \quad \text{--- (19b)}$$

$$\rho u \frac{\partial m_{\text{H}_2\text{O}}}{\partial x} + \rho v \frac{\partial m_{\text{H}_2\text{O}}}{\partial r} = \frac{1}{r} \frac{\partial}{\partial r} \left(r \cdot \frac{\mu_{\text{eff}}}{\sigma_s} \frac{\partial m_{\text{H}_2\text{O}}}{\partial r} \right) + \dot{m}_{\text{H}_2\text{O}} \quad \text{--- (19c)}$$

$$\rho u \frac{\partial m_{CO_2}}{\partial x} + \rho v \frac{\partial m_{CO_2}}{\partial r} = \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\mu_{eff}}{\sigma_s} \frac{\partial m_{CO_2}}{\partial r} \right) + \dot{m}'''_{CO_2} \quad (19d)$$

$$\rho u \frac{\partial m_{N_2}}{\partial x} + \rho v \frac{\partial m_{N_2}}{\partial r} = \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\mu_{eff}}{\sigma_s} \frac{\partial m_{N_2}}{\partial r} \right) \quad (19e)$$

where σ_s is the Schmidt number which is also equal to 0.7 and is the reaction rate per unit volume of species j.

By the assumption of the single step overall chemical reaction (paragraph 3.2.3.), generation and consumption of four of the five species (i.e. CH_4 , O_2 , CO_2 and H_2O) must be fixed at relative rates. Thus, if α and β are defined by:-

$$\alpha = m_{CO_2} + S_2 m_{CH_4} \quad (20)$$

$$\text{and } \beta = m_{O_2} - S_1 m_{CH_4} \quad (21)$$

where S_1 and S_2 are stoichiometric ratios, equations 19a, 19b and 19d may be combined to yield:-

$$\rho u \frac{\partial \alpha}{\partial x} + \rho v \frac{\partial \alpha}{\partial r} = \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\mu_{eff}}{\sigma_s} \frac{\partial \alpha}{\partial r} \right) \quad (22)$$

$$\text{and } \rho u \frac{\partial \beta}{\partial x} + \rho v \frac{\partial \beta}{\partial r} = \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\mu_{eff}}{\sigma_s} \frac{\partial \beta}{\partial r} \right) \quad (23)$$

Similarity between equations 22 and 23 suggests that α and β are linearly related:-

$$\text{i.e. } \frac{\alpha - \alpha_I}{\alpha_E - \alpha_I} = \frac{\beta - \beta_I}{\beta_E - \beta_I} \quad (24)$$

where I and E denote the boundary values. Furthermore, the following two algebraic equations may also be established:-

$$m_{H_2O} = S_3 m_{CO_2} \quad (25)$$

$$\text{and } m_{N_2} = 1 - m_{CH_4} - m_{O_2} - m_{CO_2} - m_{H_2O} \quad (26)$$

Thus the five species equations (equations 19a to 19e) can be reduced to two differential equations (equations 19a and 22, or 23) plus three algebraic equations (equations 24, 25 and 26). The stoichiometric ratios, S_1 , S_2 and S_3 are 4.0; 2.75; $9/11$ respectively.

It appears in the first instance that either equation 22 or 23 may be equally used as the second differential equation. Consideration of initial conditions shows that only $\mathcal{L}$ may be used. This is because the initial value of β could be zero for all r if the fuel/air ratio were stoichiometric. It would remain zero because the equation does not contain a source term.

3.3.4. Summary of the Governing Equations

(a) Primary dependent variables

Continuity equation:-

$$\frac{\partial}{\partial x} (\rho u r) + \frac{\partial}{\partial y} (\rho v r) = 0 \quad \text{--- (1)}$$

Other conservation equations:-

$$\rho u \frac{\partial \Phi}{\partial x} + \rho v \frac{\partial \Phi}{\partial y} = \frac{1}{r} \frac{\partial}{\partial y} \left(\Gamma_{\Phi} r \frac{\partial \Phi}{\partial r} \right) + S_{\Phi} \quad \text{--- (2)}$$

where Φ stands for the six primary dependent variables, namely u , k , ε , $\bar{h}$, m_{CH_4} and $\mathcal{L}$ and may be expanded fully into the following equations:-

$$\rho u \frac{\partial u}{\partial x} + \rho v \frac{\partial u}{\partial y} = \frac{1}{r} \frac{\partial}{\partial r} \left(\mu_{eff} r \frac{\partial u}{\partial r} \right) + \left((\rho_E - \rho) g - \frac{dp}{dx} \right) \quad \text{--- (6)}$$

$$\rho u \frac{\partial k}{\partial x} + \rho v \frac{\partial k}{\partial r} = \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\mu_{eff}}{\sigma_k} \frac{\partial k}{\partial r} \right) + \left(\mu_t \left(\frac{\partial u}{\partial r} \right)^2 - \rho \varepsilon \right) \quad \text{--- (11)}$$

$$\rho u \frac{\partial \varepsilon}{\partial x} + \rho v \frac{\partial \varepsilon}{\partial r} = \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\mu_{eff}}{\sigma_{\varepsilon}} \frac{\partial \varepsilon}{\partial r} \right) + \frac{\varepsilon}{k} \left(C_1 \mu_t \left(\frac{\partial u}{\partial r} \right)^2 - C_2 \rho \varepsilon \right) \quad \text{--- (12)}$$

$$\rho u \frac{\partial \bar{h}}{\partial x} + \rho v \frac{\partial \bar{h}}{\partial r} = \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\mu_{eff}}{\sigma_h} \frac{\partial \bar{h}}{\partial r} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left\{ r \mu_{eff} \left[\left(1 - \frac{1}{\sigma_h} \right) \frac{\partial \left(\frac{u^2}{2} \right)}{\partial r} + \left(\frac{1}{\sigma_k} - \frac{1}{\sigma_h} \right) \frac{\partial k}{\partial r} \right] \right\} \quad \text{--- (14)}$$

$$\rho u \frac{\partial m_{CH_4}}{\partial x} + \rho v \frac{\partial m_{CH_4}}{\partial r} = \frac{1}{r} \frac{\partial}{\partial r} \left(r \cdot \frac{\mu_{eff}}{\sigma_s} \cdot \frac{\partial m_{CH_4}}{\partial r} \right) + K \cdot m_{CH_4} \cdot m_{O_2} \cdot p^2 \cdot T^{-3/2} \cdot \exp(-E/RT) \left(\frac{2}{1+\eta} \right)^a \quad (19a)$$

$$\rho u \frac{\partial \alpha}{\partial x} + \rho v \frac{\partial \alpha}{\partial r} = \frac{1}{r} \frac{\partial}{\partial r} \left(r \cdot \frac{\mu_{eff}}{\sigma_s} \frac{\partial \alpha}{\partial r} \right) \quad (22)$$

(b) Secondary dependent variables

$$\mu_{eff} = \mu_l + \mu_t \quad (7)$$

$$\mu_t = C_\mu C_d \rho \frac{k^2}{\varepsilon} \quad (10)$$

$$1 = C_d \frac{k^{3/2}}{\varepsilon} \quad (13)$$

$$T = (\bar{h} - m_{CH_4} \cdot H - \frac{1}{2} u^2 - k) \quad (3)$$

$$\rho = P/RT \quad (17)$$

$$m_{CO_2} = \alpha - S_2 m_{CH_4} \quad (20)$$

$$\beta = (\beta_E - \beta_I) \left(\frac{\alpha - \alpha_I}{\alpha_E - \alpha_I} \right) + \beta_I \quad (24)$$

$$m_{O_2} = \beta + S_1 m_{CH_4} \quad (21)$$

$$m_{H_2O} = S_3 m_{CO_2}$$

$$m_{N_2} = 1 - m_{CH_4} - m_{O_2} - m_{CO_2} - m_{H_2O} \quad (26)$$

(c) Constants

Prandtl numbers:-

$$\sigma_h = 0.7; \sigma_s = 0.7; \sigma_k = 1.0; \sigma_\varepsilon = 1.3$$

Stoichiometric ratios:-

$$S_1 = 4.0; S_2 = 2.75; S_3 = 9/11$$

Turbulent constants:-

$$C_1 = 1.60; \quad C_2 = 1.92$$

	C_μ	C_d
$\frac{x}{dp} < 5$	0.6	0.228
$\frac{x}{dp} > 20$	0.45	0.095
$5 \leq \frac{x}{dp} \leq 20$	$-0.01(\frac{x}{dp}) + 0.65$	$-0.00867(\frac{x}{dp}) + 0.2723$

where dp is the diameter of the primary flow jet nozzle.

3.4. THEORY III: CO-ORDINATE TRANSFORMATIONS

3.4.1. Transformation from Cylindrical to Von Mises Coordinates

By applying boundary layer assumptions with the approximation of $d\psi \approx \rho u r dr$, where ψ is a stream function defined by:-

$$\frac{\partial \psi}{\partial r} = \rho u r; \quad \frac{\partial \psi}{\partial x} = -\rho v r \quad \text{————— (27)}$$

equations 1 and 2 can be combined into one equation expressed in Von Mises coordinates $(x - \psi)$ as:-

$$\rho u \frac{\partial \phi}{\partial x} = \rho u \frac{\partial}{\partial \psi} (\rho u r^2 \Gamma_\phi \frac{\partial \phi}{\partial \psi}) + S_\phi \quad \text{————— (29)}$$

The advantage of this coordinate transformation is that the radial velocity, v , is eliminated from the calculation. This approximation produces no severe error, but see the discussion in paragraph 3.7.1.

In general, the domain of calculation is bounded by constant x and ψ lines. One obvious boundary of ψ is at $r = 0$. Another boundary of constant stream function may be found in the secondary flow away from the mixing zone, for example at the wall of the glass cylinder.

Such a calculation domain is numerically uneconomical because unnecessary calculations are included in regions of insignificant radialwise changes of flow properties, (i.e. $\frac{\partial \phi}{\partial \psi} \approx 0$), while relatively few numerical calculations are carried out in the region of steep radial profile, (e.g. in the mixing layer).

3.4.2. Transformation from Von Mises to Spalding - Pantankar's Coordinates

By using a non-dimensional coordinate, ω , which is defined as:-

$$\omega = \frac{\psi - \psi_I}{\psi_E - \psi_I} \quad \text{————— (28)}$$

it is possible to confine the domain of calculation to that bound by $\psi = \psi_I$ (i.e. $\omega = 0$) and $\psi = \psi_E$ (i.e. $\omega = 1$). Neither ψ_I nor ψ_E is necessarily a constant with respect to x . This method was originated by Spalding and Pantankar³⁹. The subscripts I and E denote the chosen inner and outer boundaries. Since the flow is axisymmetric about the centre-line the inner boundary is conveniently chosen at $r = 0$ and $\psi_I = 0$ for all x .

The bulk of the secondary flow (Figure 1) is unaffected by the mixing in the primary flow. It would be numerically more accurate to exclude the secondary flow from the domain of calculation. Therefore, the outer boundary of the mixing layer, that is the boundary between the primary and the secondary flows, is chosen as the 'E' boundary.

Applying the definition of ω in equation 28, equation 2a can be transformed into $x - \omega$ coordinates as:-

$$\frac{\partial \phi}{\partial x} + (a + b\omega) \frac{\partial \phi}{\partial \omega} = \frac{\partial}{\partial \omega} \left(c \frac{\partial \phi}{\partial \omega} \right) + d \quad \text{————— (2b)}$$

where:

$$\left. \begin{aligned} a &= \frac{-d\psi_I}{\psi_E - \psi_I} , \\ b &= \frac{-d(\psi_E - \psi_I)}{\psi_E - \psi_I} , \\ c &= \frac{\rho u r^2 \mu_{eff}}{(\psi_E - \psi_I)^2} \end{aligned} \right\} \quad \text{————— (29)}$$

$$\text{and} \quad d = \frac{S\Phi}{\rho u}$$

3.4.3. Entrainment Rate Calculation

Equation 29 contains terms of entrainment rate at the 'I' and 'E' boundaries, i.e. $\frac{d\psi_I}{dx}$ and $\frac{d\psi_E}{dx}$ respectively. Obviously, $\frac{d\psi_I}{dx} = 0$ since $\psi_I = 0$ for all x . It would also be an easy task to calculate the entrainment rate at the 'E' boundary from the definition of the stream function, namely:-

$$\left(\frac{\partial \psi}{\partial x}\right)_E = -(\rho v r)_E \quad \text{————— (27)}$$

but for the elimination of the 'v' component velocity from the calculation. An alternative approximate formulation may be derived from the following considerations:-

At the 'E' boundary it can be assumed that the cross stream gradients are zero from the definition of "free boundary", (i.e.

$\left(\frac{\partial \Phi}{\partial \omega}\right)_E = 0$). Hence, equation 26 becomes:-

$$\begin{aligned} (a + b) \frac{\partial \Phi}{\partial \omega} &= \frac{\partial}{\partial \omega} \left(c \frac{\partial \Phi}{\partial \omega} \right) \\ \text{or} \quad a + b &= \frac{\frac{\partial}{\partial \omega} \left(c \frac{\partial \Phi}{\partial \omega} \right)}{\frac{\partial \Phi}{\partial \omega}} \quad \text{————— (30)} \end{aligned}$$

Also, from equation 29, the entrainment rate at the E boundary may be written as:-

$$\frac{d\psi_E}{dx} = (a + b) (\psi_E - \psi_I) \quad \text{————— (31)}$$

Combining equations 30 and 31 it can be readily shown that the entrainment rate at the E boundary is given approximately by:-

$$\frac{d\psi_E}{dx} \approx \frac{-2 (r_{eff}^{\mu})_E}{(\delta r)_E} \quad \text{————— (32)}$$

This formulation provides a convenient method of calculating the entrainment rate and hence of determining the outer boundary of the mixing layer. However, the entrainment rate calculation depends critically on the evaluation of $(\delta r)_E$. In the numerical solution of equation 26, which will be presented in the next section, the downstream value of r is calculated from the upstream flow properties (i.e. from $d\psi = \rho u r dr$). The value of r cannot be obtained until the entrainment rate is evaluated. Thus, the step size between the upstream and downstream "grid points" must be small enough to prevent error caused by abrupt axial changes in the flow properties. The optimum size of the forward step will be examined later in this chapter.

3.4.4. Boundary Conditions

The domain of calculation is bounded by $x = 0$, $\omega = 0$ and $\omega = 1$ lines (Figure 34). At each of these three lines the boundary conditions are as follows:-

(a) Initial boundary, (i.e. at $x = 0$)

(i) Velocity (u): the velocity profile in a pipe flow at low Reynolds number (4×10^3) was measured by Nikurade⁷⁹ and was found to be:-

$$u = \left(\frac{r}{r_E}\right)^{1/6} (u_I - u_E) + u_E \quad \text{————— (27)}$$

This empirical formulation is used to generate the initial velocity profile at $x = 0$. The boundary velocities u_E and u_I are calculated from the mass flow rate measurements.

(ii) Turbulent transport quantities (k and ϵ): it is impractical to measure the initial values of k and ϵ for each flow condition. Instead, the "length scale, l " (equation 13) is generated by the turbulent mixing length hypothesis⁶⁴. The calculated length scale is then used to evaluate the initial values of k and ϵ from the following equations (see Appendix A):-

$$k = \frac{C}{C_d} \mu \left(\frac{\partial u}{\partial y} x_1 \right)^2 \quad \text{-----} \quad (28)$$

$$\text{and } \varepsilon = C_d \frac{k^{3/2}}{1} \quad \text{-----} \quad (13)$$

(iii) Temperature (T): the initial temperature profile is calculated from the $\frac{1}{7}$ power law:-

$$\text{i.e. } \frac{T - T_E}{T_I - T_E} = \left(1 - \frac{r}{r_E} \right)^{\frac{1}{7}} \quad \text{-----} \quad (29)$$

(iv) Mass Fractions (m_j):

$$m_{CO_2} = m_{H_2O} = 0 \quad \text{for all } r$$

$$m_{CH_4} = m_{O_2} = 0 \quad \text{for all } r \text{ except at } r = r_E \left(r_E = \frac{dp}{2} \right) \text{ where they take the values of the secondary flow}$$

$$m_{N_2} = 1.0 \quad \text{for all } r \text{ except at } r = r_E \text{ where } m_{N_2} = (m_{N_2})_{E, x=0}$$

(b) Inner boundary (i.e. at $\omega = 0$)

$$\frac{\partial \phi}{\partial r} = 0 \quad \text{for all } \phi \text{ and } x$$

(c) Outer boundary (i.e. at $\omega = 1$)

$$\begin{aligned} \phi &= (\phi)_E \quad \text{for all } \phi \text{ and } x \\ &= (\phi)_{E, x=0} \end{aligned}$$

where $(\phi)_{E, x=0}$ are calculated from the secondary flow

3.5. THEORY IV: FINITE DIFFERENCE EQUATIONS

3.5.1. Transformation into Finite Difference Equations

The flow field may be divided into large numbers of small elements bounded by constant x and ω lines, as shown in Figure 34.

Each ω line is given a number which starts from 1 ($\omega = 0$), 2 $i-1$, i , $i+1$, ... to n ($\omega = 1$). The adjacent constant x lines are also denoted by symbols U (upstream) and D (downstream). Consider an element bounded by $i+\frac{1}{2}$, $i-\frac{1}{2}$, U and D lines (the shadowed area, see Figure 31) and integrate equation 2b over this element:-

$$\int_{i-\frac{1}{2}}^{i+\frac{1}{2}} \int_D^U \left\{ \frac{\partial \phi}{\partial x} + (a + b) \frac{\partial \phi}{\partial \omega} \right\} dx d\omega =$$

$$\int_{i-\frac{1}{2}}^{i+\frac{1}{2}} \int_D^U \left\{ \frac{\partial}{\partial \omega} \left(c \frac{\partial \phi}{\partial \omega} \right) + d \right\} dx d\omega$$

The resultant finite difference equation was found⁴⁷ to be as follows:-

$$D_i \phi_{i,D} = A_i \phi_{i+1,D} + B_i \phi_{i-1,D} + C_i \quad \text{--- (2c)}$$

where A_i , B_i , C_i and D_i are "coefficients" of the finite difference equation given by:-

$$\left. \begin{aligned} A_i &= (G - \frac{1}{2} \dot{m}')_{i+\frac{1}{2}} \\ B_i &= (G + \frac{1}{2} \dot{m}')_{i-\frac{1}{2}} \\ C_i &= \phi_{i,u} \gamma (\omega_{i+\frac{1}{2}} - \omega_{i-\frac{1}{2}}) + S_i \\ D_i &= A_i + B_i + (\omega_{i+\frac{1}{2}} - \omega_{i-\frac{1}{2}}) - S_i \\ G_{i+\frac{1}{2}} &= \frac{(r_{eff}^\mu, \phi)_{i+\frac{1}{2}}}{(y_{i+1} - y_i)_U} \\ G_{i-\frac{1}{2}} &= \frac{(r_{eff}^\mu, \phi)_{i-\frac{1}{2}}}{(y_i - y_{i-1})_U} \\ \gamma &= \frac{\psi_E - \psi_I}{\delta x} \end{aligned} \right\} \quad \text{--- (33)}$$

(x = forward step size)

$$\dot{m}'_{i+\frac{1}{2}} = (a + b\omega)_{i+\frac{1}{2}} (\psi_E - \psi_I)_U$$

$$\dot{m}'_{i-\frac{1}{2}} = (a + b\omega)_{i-\frac{1}{2}} (\psi_E - \psi_I)_U$$

S_i and S_i' are two linearised components of the source term defined by:-

$$d_{i,U} = \frac{S_i}{\psi_{i+\frac{1}{2}} - \psi_{i-\frac{1}{2}}} + \frac{S_i'}{\psi_{i+\frac{1}{2}} - \psi_{i-\frac{1}{2}}} \cdot \phi_{i,U} \quad (34)$$

3.5.2. Marching Integration

Equation 2c contains three "downstream" values, i.e. $\phi_{i,D}$, $\phi_{i+1,D}$ and $\phi_{i-1,D}$ while the upstream values are embodied in the "coefficients" (i.e. A_i , etc.) of the finite difference equation. If the numerical calculation were started at $x = 0$ where the initial conditions of the flow properties were known, the adjacent downstream values (i.e. $\phi_{i,D}$ etc) might be calculated, and on completion of the calculation the downstream values could be updated as "upstream" values for the calculation of the next adjacent grid line.

For each constant x grid line the n simultaneous equations (i.e. equation 2c with $i = 1, 2, \dots, n-1, n$) may be solved by the tri-diagonal matrix algorithm technique. Equation 2c is converted into an alternative form which contains only two downstream values:-

$$\phi_{i,D} = P_i \phi_{i+1,D} + Q_i \quad (2d)$$

$$\text{where } P_i = A_i / (D_i - B_i P_{i-1})$$

$$Q_i = (B_i Q_{i-1} + C_i) / (D_i - B_i P_{i-1}) \quad (35)$$

The upstream values of A_i , B_i , C_i and D_i are calculated thus enabling P_i and Q_i to be evaluated. $\phi_{i,D}$ may then be calculated in the reverse order of i from $i = n-1$ to $i = 2$. In this manner the flow properties including the temperature may be calculated point by point in a given constant x grid line then line by line from $x = 0$ to a designated downstream grid line. Such a process is known as "marching integration"⁴⁷.

3.5.3. Grid Distribution

(a) Radialwise grid distribution

It is obvious that in the region of large gradients of flow properties a larger number of grid points is required than in the regions where the gradient is relatively small. Near the 'E' boundary (i.e. outer boundary of the mixing layer) large gradients in the flow properties may be expected, particularly in the regions close to the jet nozzle exit. In the present study thirty grid points are used (i.e. thirty ω points, $n = 30$). At $x = 0$, ten of these grid points are assigned in the region between $r = r_p$ and $r = 0.9 r_p$, where r_p is the radius of the jet nozzle. The other twenty points are distributed in the region between $r = 0$ and $r = 0.9 r_p$. In both regions the grid points are evenly distributed with respect to the radial distance (r). Non-uniform distribution of the grid points, such as sinusoidal and polynomial function of second and third orders, were tried but did not give better results than the linear distribution.

(b) Axialwise grid distribution

The forward step size, δx , (i.e. distance between the upstream and downstream lines, see Figure 34) is determined by:-

$$\delta x = FRA \cdot r_p \quad \text{————— (36)}$$

where FRA is a scaling factor and has a normal value of 0.05 except in the first twenty steps of calculation for which the forward step size is modified by:-

$$\delta x = FRA \cdot r_p \cdot \left(\frac{1 + ISTEP}{20} \right) \quad \text{————— (36a)}$$

where ISTEP is the number of steps counted from $x = 0$.

3.5.4. Effect of Grid Size on M.I.T. Calculation

Clearly the more grid points that could be allocated to the domain of calculation the better the numerical accuracy would be but it would also increase the number of calculation steps and hence

the computing time. It is necessary to compromise between the numerical accuracy and the computing time consumption.

It was found that the predicted M.I.T. was affected by the size of the grid element. Figure 35 and Figure 36 show that the predicted M.I.T. converges into a finite value as the number of grid points in the ω direction (i.e. n) is increased, while the forward step size ($\delta x = \text{FRA} \cdot \text{dp}$) is decreased.

The predicted M.I.T. with $n = 30$ and $n = 60$ are 1283°C and 1279°C respectively. (Figure 35). The difference is 4°C but to increase n from 30 to 60 will double the computing time. Similarly, the predicted M.I.T. with $\text{FRA} = 0.05$ is 1297°C and is 1307°C if $\text{FRA} = 0.005$ (Figure 36). The difference is 10°C but reducing FRA from 0.05 to 0.005 will increase the computing time by ten times. To reduce the computing time the grid size used in this study is defined by $n = 30$ and $\text{FRA} = 0.05$.

3.5.5. Summary of Finite Difference Equations

$$\Phi_{i,D} = P_i \Phi_{i+1,D} + Q_i \quad \text{-----} \quad (2d)$$

$$\left. \begin{aligned} P_i &= A_i / (D_i - B_i P_{i-1}) \\ Q_i &= (B_i Q_{i-1} + C_i) / (D_i - B_i P_{i-1}) \end{aligned} \right\} \text{-----} \quad (35)$$

$$\left. \begin{aligned} A_i &= (G - \frac{1}{2} \dot{m}')_{i+\frac{1}{2}} \\ B_i &= (G + \frac{1}{2} \dot{m}')_{i-\frac{1}{2}} \\ C_i &= \Phi_{i,u} \gamma (\omega_{i+\frac{1}{2}} - \omega_{i-\frac{1}{2}}) + S_i \\ D_i &= A_i + B_i + \gamma (\omega_{i+\frac{1}{2}} - \omega_{i-\frac{1}{2}}) - S_i \\ G_{i+\frac{1}{2}} &= \frac{(r^\mu_{\text{eff},\Phi})_{i+\frac{1}{2}}}{(y_{i+\frac{1}{2}} - y_i)_u} \\ G_{i-\frac{1}{2}} &= \frac{(r^\mu_{\text{eff},\Phi})_{i-\frac{1}{2}}}{(y_i - y_{i-1})_u} \end{aligned} \right\} \text{-----} \quad (33)$$

$$\gamma = \frac{(\psi_E - \psi_I)_U}{\delta x}$$

$$\dot{m}_{i\pm\frac{1}{2}} = (a + b\omega)_{i\pm\frac{1}{2}} (\psi_E - \psi_I)_U$$

$$\frac{S_i}{\psi_{i+\frac{1}{2}} - \psi_{i-\frac{1}{2}}} + \frac{S_i'}{\psi_{i+\frac{1}{2}} - \psi_{i-\frac{1}{2}}} \phi_{i,u} \equiv d_{i,u} \quad (34)$$

$$a = \frac{\frac{d\psi_I}{dx}}{\psi_E - \psi_I}$$

$$b = \frac{\frac{d(\psi_E - \psi_I)}{dx}}{\psi_E - \psi_I}$$

$$c = \frac{\rho u r^2 \mu_{eff}}{(\psi_E - \psi_I)^2}$$

$$d = \frac{S \phi}{\rho u}$$

$$\omega = \frac{\psi_E - \psi_I}{\psi_E - \psi_I} \quad (28)$$

$$\frac{d\psi}{dr} \approx \rho u r \quad (27)$$

subscript 'E' denotes outer boundary
 " 'I' " inner "
 " 'i' " grid number

$$\left(\frac{d\psi}{dx}\right)_I = 0$$

$$\left(\frac{d\psi}{dx}\right)_E = \frac{-2 (r \mu_{eff})_E}{(\delta r)_E} \quad (32)$$

subscript 'U' denotes upstream
 " 'D' " downstream

$$\delta x = FRA \cdot dp \cdot \left(\frac{1 + ISTEP}{20} \right) \quad ISTEP \leq 20 \quad \text{--- (36)}$$

$$\delta x = FRA \cdot dp \cdot \quad ISTEP > 20$$

$$FRA = 0.05$$

Boundary conditions

(a) At $x = 0$

$$u = \left(\frac{r}{r_E} \right)^{1/6} (U_I - U_E) + U_E \quad \text{--- (27)}$$

$$k = \frac{C_\mu}{C_d} \left(\frac{\partial u}{\partial y} \cdot l \right)^2 \quad \text{--- (28)}$$

$$\epsilon = C_d \frac{k^{3/2}}{l} \quad \text{--- (13)}$$

$$T = \left(1 - \frac{r}{r_E} \right)^{1/7} (T_I - T_E) + T_E \quad \text{--- (29)}$$

$$m_{CO_2} \text{ and } m_{H_2O} = 0$$

$$m_{CH_4} \text{ and } m_{O_2} = 0 \quad \text{for all } r \text{ except at } r = r_E, \quad m_{CH_4} \text{ and } m_{O_2} =$$

$$(m_{CH_4})_E \text{ and } (m_{O_2})_E, \quad m_{N_2} = 1.0 \text{ for all } r \text{ except at } r = r_E,$$

$$m_{N_2} = (m_{N_2})_E$$

(b) At $\omega = 0$ (i.e. I boundary)

$$\frac{\partial \Phi}{\partial r} = 0$$

(c) At $\omega = 1$ (i.e. E boundary)

$$\Phi = \Phi_E = \Phi_{E, x=0}$$

3.6. THE COMPUTER PROGRAM

The finite difference equations summarised in paragraph 3.5.5. are solved by a computer program code named METHANE. This program was developed from the GENMIX program, which was written by Spalding and Partankar³⁹. In this study GENMIX is thoroughly modified and reorganised to the extent that only part of the original program is retained. This is necessary not only because GENMIX can then be adapted to the present flow geometry but also because the length of the original program may be greatly reduced to cut the computing time. For example, in finding the M.I.T. the program is required to loop several times and each loop requires about twenty seconds of computing time on a CDC 6400 machine.

Program METHANE consists of four sub-routines, namely START, MARCH, COMP and PHYS. The flow chart for this program is given in Figure 37 and the listing is given in Appendix C. A sample of the computer output showing the prediction of M.I.T. is also included in Appendix D. The overall structure of the program and some of the main features are briefly described in the following pages, but a detailed description of the program may be found in Appendix B.

3.6.1. Function of Sub-Routine START

Sub-routine START has two main functions: (i) it computes the grid point distributions and generates the initial flow conditions, (ii) it searches for the M.I.T. and terminates the program by deciding whether the predicted M.I.T. has reached the required accuracy.

The iteration procedure for finding the M.I.T. is illustrated in Figure 38. It starts by guessing an M.I.T., T_0 . The domain of calculation is then swept in a streamwise direction to about twenty-five diameters downstream. Sub-routine MARCH is called in to carry out the marching integration and to test for ignition. Depending on whether ignition has been found, or not, the guessed M.I.T. is either subtracted or added to a preset trial temperature ΔT . This new guessed M.I.T. (i.e. $T_0 \pm \Delta T$) is again tested for ignition by the same procedure starting from $x = 0$. The process is repeated

several times, each time with a halved ΔT (i.e. $(\Delta T)_{\text{new}} = \frac{1}{2} (\Delta T)_{\text{old}}$) until the final ΔT is less than a pre-set error temperature, T_{error} .

It is possible to predict the M.I.T. such that $T_{\text{error}} < 1^\circ\text{C}$, but since the measured M.I.T. cannot be produced to the same degree of accuracy, the value of T_{error} is set at 1°C .

3.6.2. Function of Sub-Routine MARCH

Sub-routine MARCH has two main functions, (i) it organises the marching integration and calculates the secondary dependent variables, (ii) it detects the occurrence of ignition.

Before the finite difference equation (equation 2d, see paragraph 3.5.5.) can be solved by the tri-diagonal matrix method at a given constant x grid line, the size of the forward step (i.e. δx), the location of the boundaries (which are determined by the entrainment rates) and the flow conditions at these boundaries must first be determined. Sub-routine COMP is then called in to compute the six primary dependent variables, (see paragraph 3.3.4.) before the secondary dependent variables, such as T , ρ , m_{O_2} , m_{CO_2} , $m_{\text{H}_2\text{O}}$ and m_{N_2} can be calculated from the algebraic relationships given in paragraph 3.3.4.

The only variable which is not solved either by a differential or an algebraic equation is the pressure, p . Since the flow field is assumed to be a boundary layer it follows that $\frac{\partial p}{\partial r} = 0$ and $\frac{\partial p}{\partial x} = \frac{dp}{dx}$. This pressure gradient may be found in the u equation, (equation 6, see paragraph 3.3.4.). For a free jet, $\frac{dp}{dx} = 0$. But for a confined flow the pressure gradient is affected by the presence of the glass cylinder and may be approximated using mass continuity and momentum conservation considerations⁴⁷ (see Appendix E).

The occurrence of ignition is detected by comparing the axial temperature, T , with an "ignition temperature, T_{CRIC} ". T_{CRIC} is defined as a temperature which is just higher than the temperature of the hot nitrogen jet at $x = 0$, $r = 0$. This detection method is based on the fact that if ignition does occur then the axial temperature of the primary flow will increase to above the initial

temperature at the nozzle exit (see Figure 1a).

3.6.3. Functions of Sub-Routines COMP and PHYS

Sub-routine COMP has two main functions: (i) it calculates the radial distance, r , from equations 27 and 28 (see paragraph 3.5.5.) which are combined to form:-

$$r = \int_0^{\omega} \left(\frac{1}{\rho u} \right) (\psi_E - \psi_I) d\omega \quad \text{————— (41)}$$

(ii) it solves the finite difference equations (equation 2d, see paragraph 3.5.5.).

Sub-routine COMP handles all the numerical aspects of the calculations, such as A_i , B_i , C_i , D_i , G , Y , m , etc. (see paragraph 3.5.5.), but not the computations of the effective exchange coefficients (μ_{eff}) and the source terms (S_ϕ) which are governed by physical laws and are handled in sub-routine PHYS.

3.7. THE PREDICTION. I: NON-REACTING FLOWS

The computer program described above is checked for its validity and accuracy by comparing the calculated velocity and temperature profiles with the measurements in non-reacting flows. Since the Prandtl number and the Schmidt number are assumed to be the same (i.e. $\sigma_h = \sigma_s = 0.7$) there is no need to predict the concentration profiles.

3.7.1. Prediction of Isothermal Free Jet Flow

The calculation starts with the simplest case study of a free-air round jet flow at ambient temperature. This exercise eliminates the effect of heat and mass transfer and thus allows the predicted hydrodynamic properties of the flow to be examined alone, without the effect of an axial pressure gradient (i.e. $\frac{dp'}{dx} = 0$).

The prediction is tested against the measurements of the present study (see paragraph 2.9.1., Figure 26 and 28, Table 9) under the

following initial conditions:-

diameter of jet: $d_p = 15.0 \text{ mm}$
 mass flow rate: $\dot{m}_p = 2.25 \times 10^{-3} \text{ kg/s}$
 ambient temperature: $T_s = T_p \approx 20^\circ\text{C}$

The computed axial profile of the u component velocity is in good agreement with the measurement (Figure 26), but this cannot be viewed as an accuracy test of the calculation method since some of the constants and the initial profiles described in paragraph 3.3 and 3.4 have been so chosen to fit the experimental measurements.

The computed radial profile of the u component velocity is also in good agreement with the measured value although discrepancy begins to enlarge away from the axis of symmetry (i.e. $r = 0$, Figure 28). Various computational changes have been made in an attempt to narrow the discrepancy. These include changes in the forward step size, number of grid points and grid distributions, initial values of k , ϵ and the initial profile of velocity as well as the turbulent constants (C_d , C_μ , etc.). None of these changes could, if not enlarge, narrow the discrepancy.

We have discussed the assumptions introduced in the continuity equation (i.e. $\frac{\partial \psi}{\partial r} \approx \frac{d\psi}{dr}$, see paragraph 3.4.1.) and the entrainment formulation, (i.e. $\frac{d\psi_E}{dx} \approx \frac{-2(r\mu_{eff})_E}{(\delta r)_E}$, see paragraph 3.4.3.). Both

these assumptions may induce approximations in the calculation of the stream function with respect to the true radial distance and hence the velocity with respect to the radial distance. In other words, the approximations made during the transformation from the x - r cylindrical coordinates to the x - ψ Van Mises coordinates have affected the calculation of u velocity in the radial direction. The discrepancy is between 5 and 15% approximately, but the advantage gained in eliminating the v component velocity from the calculation has overriding importance in the simplification of the numerical scheme.

3.7.2. Prediction of Isothermal Confined Flow

The next test includes the effect of axial pressure gradient in an isothermal confined flow under the following conditions:-

diameter of the jet:	$d_p = 15.0 \text{ mm}$
diameter of the duct:	$d_s = 290 \text{ mm}$
mass flow rate of primary flow:	$\dot{m}_p = 2.0 \times 10^{-3} \text{ kg/s}$
mass flow rate of secondary flow:	$\dot{m}_s = 50 \times 10^{-3} \text{ kg/s}$
ambient temperature:	$T_p = T_s \approx 20^\circ\text{C}$

The results are shown in Figures 27 and 29. It can be seen that the axial velocity profile agrees closely with the measurement up to about fifteen diameters downstream (Figure 27). Beyond this region significant discrepancy begins to emerge and at 23 diameters downstream the difference is about 13%. If the turbulent constants C_μ and C_d were adjusted the discrepancy could be reduced to less than 10% but alteration of these values, which were deduced from measurements quoted in references 72 and 74, was without experimental support. Prediction of the radial profile of the u component velocity (Figure 29) encounters similar difficulties as in the case of the free jet flow.

3.7.3. Prediction of Non-Isothermal Confined Flow

A further test for the calculation method includes the effect of buoyancy force created by a temperature gradient. Prediction is made to compare with the measurements of Goh and Ma²⁷ for a confined flow under the following conditions:-

diameter of jet:	$d_p = 19.5 \text{ mm}$	
mass flow rates:	$\dot{m}_p = 3 \times 10^{-3} \text{ kg/s}$	
	$\dot{m}_s = 50 \times 10^{-3} \text{ kg/s}$	
initial temperatures:	<u>primary flow</u>	<u>secondary flow</u>
	(T_p)	(T_s)
I:	300°C	30°C
II:	1100°C	36°C

The prediction is shown in Figure 30. Close agreement is obtained in two regions: (i) $0 \leq \frac{x}{d_p} < 3$; (ii) $7 < \frac{x}{d_p} < 20$. Between

3 and 7 diameters the discrepancy is about 5 to 15%. If the Prandtl number were reduced from 0.7 to 0.6, the discrepancy could be reduced in this region, but at the same time the difference between the predicted and measured values would be enlarged in the downstream area, i.e. $\frac{x}{dp} > 7$.

3.8. THE PREDICTION.II: REACTING FLOWS - CALCULATION OF M.I.T.

3.8.1. Deduction of the Overall Kinetic Constants (K & E)

For reacting flows the overall kinetic constants, namely K, E and a, of equation 19a (see paragraph 3.3.4.) must be determined first in order to evaluate the source term of this mass fraction equation. This is obtained by comparing the measured M.I.T. with the corresponding calculated M.I.T. The comparison is carried out under the reference flow conditions (see Table 3). At these conditions, $\eta = 1$, (i.e. a stoichiometric fuel to air ratio). Consequently, $(\frac{2}{1+\eta})^a$ (see equation 19a, paragraph 3.3.4.) is also equal to unity and thus the need to presume a value for 'a' may be temporarily absent from the calculations.

Furthermore, whether the flow is turbulent or laminar, the activation energy 'E' has the same physical meaning. The activation energy of methane obtained by other methods of measurements (see Table 13) is used as a guide during a trial and error process which produces a set of K and E values for which the calculated M.I.T. is closest to the measured M.I.T.

The measured mean M.I.T. under the reference flow conditions (Table 3) is 1283°C for the 19.35 mm diameter nozzle and 1376°C for the 15.0 mm diameter nozzle. The best-fit overall kinetic constants were found to be:-

$$\begin{array}{ll} K = 7.88 \times 10^6 & S^3 - K^{3/2} / \text{kg-m} \\ E = 2.15 \times 10^8 & \text{J/Kg-mole} \end{array}$$

which produce M.I.T.'s of 1283°C and 1369°C for the large and small nozzles under the same reference flow conditions.

3.8.2. Differences Between Ignition and No Ignition

Using these deduced values of K and E the differences of flow properties between the cases of ignition and no ignition may be examined. The reference flow condition (Table 3) with the 15.0 mm diameter nozzle is used as a case study. Under these flow conditions ignition was detected (by calculation) if the initial hot nitrogen jet temperature was 1642°K and no ignition could be detected if the jet temperature was 1641°K . The calculated velocity, temperature and concentration profiles under these two initial jet temperatures are shown in Figures 39 to 46.

Temperature profiles (Figures 39 and 40) The difference in the temperature profiles between the cases of ignition and no ignition are noticeable. These characteristic differences have already been repeatedly stressed. For the case of no ignition, both the axial and radial profiles decrease monotonically and gradually. But for the case with ignition the axial profile (Figure 39) shows a minimum at about seven diameters downstream and the radial profile (Figure 40) exhibits a maximum at a radial distance of approximately 10 mm from the centre line (at $10\frac{1}{2}$ diameters downstream). These minimum and maximum values shown on the curves would denote the positions of a flame front of the newly formed flame if the flame could be stabilised after the ignition.

Experimental observations (see Chapter 2) have indicated that the flame would propagate into the secondary flow after it had been formed in the primary flow. The propagating flame would invalidate further calculations from the moment when the flame began to propagate. Flame propagation is, however, beyond the scope of this study.

Concentration profiles (Figures 41 to 44) In the axial direction methane concentration is zero up to about three diameters downstream (Figures 41 and 42). This indicates the existence of a potential core in the concentration profile. Beyond this point the

methane concentration rises steadily until about seven diameters downstream. Whether ignition has occurred or not, slow methane oxidation has taken place as indicated by the release of H_2O and CO_2 species.

From seven diameters onwards methane concentration started to fall if ignition had occurred, and the fuel was completely burnt at about nine diameters downstream. In the case of no ignition the methane concentration continues to increase as the diffusion rate exceeds the consumption rate of the fuel.

In the radial direction slow oxidation of methane can again be observed near the centre line (Figure 43) but if ignition has occurred (Figure 44) the methane is completely consumed in the region near the centre line (i.e. $y \approx 12$ mm). Beyond this "completely burnt region" slow oxidation may also be observed as far out as 35 mm from the centre line.

Velocity profiles (Figures 45 and 46) There is little difference in the velocity profiles between the cases of ignition and no ignition. Up to about seven diameters downstream the axial velocity profiles are exactly the same (Figure 45). With ignition the axial decay rate is slightly reduced beyond this distance. The reduced decay rate may be explained by the thermal expansion of the gas which produces a higher buoyancy force (i.e. $(\rho_E - \rho)g$ of equation 6, see paragraph 3.3.4.). This buoyancy effect may also be seen in the radial profile (Figure 46).

3.8.3. Prediction of M.I.T. Inside The Experimental Range

During the ignition measurements the M.I.T. was found to be affected by various flow conditions (see paragraph 2.8.). The M.I.T. calculation method developed above may now be used to see whether similar effects can be predicted. The effect of primary flow, mass flow and the secondary flow temperature and oxygen index were tested within the ranges shown below:-

$$1.4 \times 10^{-3} \leq \dot{m}_p \leq 3.6 \times 10^{-3} \text{ kg/s}$$

$$18^\circ\text{C} \leq T_s \leq 190^\circ\text{C}$$

$$0.185 \leq \xi \leq 0.235$$

These calculations are based on the ignition of a stoichiometric mixture ($\eta = 1$) with a reaction rate which is calculated from the deduced overall kinetic constants, namely,

$$K = 7.88 \times 10^6 ; E = 2.15 \times 10^8 \text{ (in S.I. units)}$$

The results are shown by the solid lines in Figures 22 to 24. For a non stoichiometric ratio the power factor 'a' in the reaction rate, $\dot{m}_{CH_4}'''$,

$$\text{i.e. } \dot{m}_{CH_4}''' = -K p^2 m_{CH_4} m_{O_2} \left(\frac{2}{1+\eta}\right)^a T^{-3/2} \exp(-E/RT)$$

is determined by changing the value of 'a' so that the calculated M.I.T. is as close as possible to the measured M.I.T. (with $dp = 15.0 \text{ mm}$). It was found that no single value of the power factor 'a' could be fitted to both the rich and lean mixtures (see Figure 25). The closest fit values were found to be:-

$$a = 4.1 \quad \text{for } \eta < 1 \text{ and}$$

$$a = 3.3 \quad \text{for } \eta > 1$$

These values were incorporated into the reaction rate formula to calculate the M.I.T. for the 19.35 mm diameter jet nozzle. The predicted result is again shown by solid lines in Figure 25.

3.8.4. Prediction of M.I.T. Outside Experimental Range

The M.I.T. measurements were tested within the range given by:-

$$3.2 \times 10^3 \leq R_e \leq 8.3 \times 10^3$$

where R_e is the Reynolds' number. If the measurements were extended to a higher Reynolds number flow, either a higher mass flow

or a larger nozzle would be required. In either case, it would require a heater of high power loading. Such a heater would be difficult to construct. Instead, the present computer program may be used to predict the M.I.T. for flow conditions outside the measured range. The present study has extended the M.I.T. prediction to the range limited only by the following three factors:-

- (i) $Re < 8 \times 10^4$
- (ii) $dp < 80 \text{ mm}$
- (iii) $M < 0.3$

where M is the Mach number of the flow. The last limit is necessary to avoid the effect of compressibility which may change the governing equations. The predicted M.I.T. is drawn in Figure 47 with constant dp, Re and M lines. Two features can be observed and are summarised below:-

- (a) Any three constant lines of dp, Re and M form a triangular area. The significance of this triangle may be found in two of the three apices. Below the lower apex (i.e. intersection between Re and M lines) ignition is not possible, but above the top apex (i.e. intersection between dp and Re lines) ignition always occurs. Thus, knowing the values of these three variables (i.e. dp, Re and M) this chart may be used to find the minimum and maximum ignition temperatures for the prevention or the assurance of ignition.
- (b) Both the Re and dp lines are almost straight in the chart. This suggests that the M.I.T. is an exponential function of the mass flow rate ($\dot{m}_p$) if either dp or Re is kept constant.

3.9. CLOSURE

In this chapter the assumptions, formulation and the computer program used to predict the M.I.T. are described in some detail before the predicted M.I.T. are presented. This theoretical study took just over one year to complete as compared with three and a half years spent in the experimental investigation. The difference is

chiefly due to the fact that the numerical solution and the mathematical modelling of turbulence were well established prior to the present study and also due to the fact that considerable time was spent in the development of the heaters, almost from scratch without prior knowledge or expertise. It has nevertheless stressed the point that the analytical approach may be transmitted readily through literature and may be carried out at a lower cost while experimental work needs first-hand experience and often is expensive to carry out. The need to provide experimental measurements for the validation of the prediction method must, however, be noted.

It must also be pointed out that the present prediction method is based on assumptions which are simplified descriptions of a complex phenomenon, such as the chemical reaction mechanism. The deduced overall kinetic constants are obtained by comparison with measured data and their validations needed to be carefully assessed. This task will now be carried out in the next chapter.

CHAPTER 4

DISCUSSION

4.1. OUTLINE OF THE CHAPTER

The objective of the present study is to deduce the overall kinetic constants for methane gas using a turbulent hot gas ignition system (see Chapter 1, paragraph 1.3.). The results of the experimental and theoretical work, which led to the deduction of these kinetic constants, must be examined in order to assess the validity of the deduced constants. Since the deduction of the kinetic constants is based on the measurements it is logical to discuss the accuracy and the implications of the measured M.I.T. first. Any errors accumulated in the measurements are likely to be carried over and added to the calculation procedures, because the kinetic constants are adjusted until the predicted M.I.T. is matched with the measured values (under the reference flow conditions, see Table 3 and paragraph 3.8.1.).

It is not easy to assess the accuracy of the prediction method, but a general discussion on the employed method and a comparison of the predicted M.I.T. with the present measurements and with those obtained by other workers will help to determine the validity of the deduced kinetic constants. This Chapter will end by proposing future work to advance the present prediction method.

4.2. THE EXPERIMENTAL RESULTS. I: ESTIMATED ACCURACY

The ignition temperature is treated in the present study as the dependent variable while the other flow parameters, such as mass flow rates of the primary and secondary flows, are regarded as independent variables. For clarity, the accuracy of these two types of measurement will be assessed separately.

4.2.1. M.I.T. Measurements

It may be recalled that the M.I.T. was measured by a platinum-platinum/13% rhodium thermocouple, (see paragraph 2.6.1.). The common errors in measuring a gas flow temperature by such thermocouples are the radiation and conduction losses of the hot junction, and further

error may be induced by the calibration of the thermocouple. Error due to ambient temperature changes is negligible since the thermocouple is compensated by an ice-point cold junction.

Radiation loss is by far the largest source of error. The magnitude of the error depends on the temperature and the velocity of the hot nitrogen jet. An estimated radiation loss is calculated, based on the procedure recommended by Fristrom and Westenberg¹¹⁴. Details of the calculation are shown in Appendix F and the results plotted in Figure 48.

There is, however, no significant error induced by conduction loss of the hot junction. This is because the hot junction is immersed in the potential core of the nitrogen jet where the axial temperature varies very little for at least two diameters downstream (see Figure 30). Sufficient time was always allowed for the thermocouple to stabilise before the temperature reading was taken.

The thermocouple wire was supplied by Johnson Mathey (U.K.). A calibration table was provided by the manufacturer. It was claimed that the accuracy of the calibration was $\pm 4^{\circ}\text{C}$ at temperatures above 1200°C . No further check was carried out on this claim.

Under the reference flow conditions (see Table 3) the measured M.I.T. was repeatable to within $\pm 5^{\circ}\text{C}$ (see Chapter 2, paragraph 2.7.3.). It appears that the radiation loss of the thermocouple at a given temperature of the hot gases induces an error of similar magnitude for each of the individual tests.

4.2.2. Other Measurements

Mass flow rate as measured by the orifice meter is accurate to $\pm 1\%$ according to B.S. 1042, part 4. In addition to this there is the instrumentation error in reading the pressure difference in a U-tube manometer. On average the pressure difference across the orifice plate is equivalent to about 400 mm parafin (S.G. = 0.78). The height of the manometer fluid was readable to 1 mm. Thus, on average, a further error of $\pm 1\%$ may be induced by the two pressure readings on the orifice meter, resulting in a net error of $\pm 2\%$ for the mass flow rate measurement.

The nozzle diameter (i.e. the diameter of the primary flow, d_p , see Figure 1) was measured by a venier gauge. The small nozzle ($d_p = 15.0$ mm) was machined from an alumina block to a tolerance of ± 0.05 mm. The large nozzle has a maximum diameter of 19.65 mm and a minimum diameter of 19.05 mm. Thus, the roundness deviation of this nozzle is about 2.6%.

4.2.3. Estimated Errors

To sum up, the measurements presented in this study may incur errors of the following magnitude:-

(a) Ignition temperature measurements:

Typical radiation loss: -20°C

(see Figure 48)

Calibration error = $\pm 4^{\circ}\text{C}$

Repeatability of the measured M.I.T. = $\pm 5^{\circ}\text{C}$

(b) Other measurements:

Mass flow rates: $\pm 2\%$

Nozzle diameter roundness: 2.6%

Secondary flow temperature: $\pm 1^{\circ}\text{C}$.

4.3. THE EXPERIMENTAL RESULTS. II: INTERPRETATIONS

Ignition of methane-air mixture by a hot gas jet is a result of balance between heat generation by the chemical reaction and heat loss due to the temperature difference between the hot nitrogen gas and the surrounding cold mixture. It is therefore no surprise to find that the M.I.T. is affected by flow conditions in the primary and secondary flows, since heat generation and dissipation are both affected by these flow conditions. Some parameters have a stronger influence on the M.I.T. than others. Consideration of the mixing processes may help in understanding this behaviour.

4.3.1. Effect of the Mass Flow Rate and Nozzle Diameter of the Primary Flow

It may be seen from Figure 23 that to reduce the nozzle diameter and increase the mass flow rate of the primary flow will increase the M.I.T. Other conditions being the same, the small nozzle (15.0 mm

diameter) requires the nitrogen gas to be hotter by approximately 100°C to ignite the combustible mixture than the large nozzle (19.35 mm diameter). This effect may be interpreted in terms of the jet velocity and a residence time.

Consider a hot nitrogen jet having a constant enthalpy. The product of the jet velocity and the cross-sectional area of the nozzle is approximately constant*. Thus, the velocity of a small nozzle is higher than that of a large nozzle. A high speed jet will entrain more cold methane-air mixture from the secondary flow than a low velocity jet because the entrainment rate is approximately proportional to the turbulent viscosity (see equation 32, paragraph 3.4.3.) and turbulent viscosity is proportional to the square of turbulent kinetic energy (paragraph 3.3.1.) which is in turn roughly related linearly to the mean velocity. As a result, the hot gases discharged from a small nozzle are highly diluted by the entrained cold mixture and the resultant temperature of the mixture is lower than for hot gases discharged from a large nozzle. If the temperature of the mixture is to be restored to the level required for ignition of the same combustible mixture, the enthalpy of the hot nitrogen jet must be increased correspondingly. An increase of enthalpy for the same mass flow rate will increase the temperature of the nitrogen jet and this explains the fact that the M.I.T. is higher for a small nozzle than a larger nozzle. By the same reasoning, a high mass flow jet will require a higher temperature to ignite a methane-air mixture than a low mass flow jet of the same nozzle size.

It may also be possible to interpret these effects in terms of a residence time of the combustible mixture in the hot gas zone. The residence time is short in a high velocity flow and in order to maintain the reaction rate required for ignition, the enthalpy of the hot nitrogen gas must be increased to extend the high temperature zone into a region further downstream.

These interpretations are two aspects of the same mechanism, which leads to the occurrence of ignition. The first interpretation is

$$\begin{aligned} * \quad \rho \cdot A \cdot U \cdot C_p \cdot T &= \text{constant} \\ &= \frac{p}{RT} \cdot A \cdot U \cdot C_p \cdot T \\ &= \text{constant} \cdot A \cdot U \end{aligned}$$

based on the heat loss of the hot gas while the second is based on the heat generation of the chemical reaction. It has been repeatedly stressed that the hot gas ignition is a result of balance between heat generation and dissipation rates.

The result shown in Figure 23 gives an impression of a linear correlation between the M.I.T. and the mass flow rate. This is in fact a distortion due to the small range of flow rate tested. On an enlarged scale, based on calculations, M.I.T. is shown to be an exponential function of the mass flow rate for a given size of jet nozzle (see Figure 47).

4.3.2. Effect of the Secondary Flow Temperature

An increase in the temperature of the secondary flow will produce two effects; it will increase the thermal energy of the entrained methane-air mixture and it will also reduce the temperature difference between the hot and cold gases. The first will reduce the energy needed by the methane-air mixture to produce an accelerating reaction and the second will reduce the heat lost by the hot nitrogen gas. In both cases the net result is a reduction of enthalpy of the hot nitrogen gas required to ignite the combustible mixture. These effects are reflected by the decreasing M.I.T. as the secondary flow temperature increases (see Figure 22).

The increase of thermal energy of the methane-air mixture and the reduction of heat loss of the primary flow are both linearly dependent on the size of the increased secondary flow temperature, T_s . It may therefore be expected that the M.I.T. will be linearly reduced by T_s and this has been confirmed by the measurements (Figure 22). The reductions in M.I.T. are approximately 0.54°C and 0.48°C per degree Celsius increase in T_s for the small ($d_p = 15.0 \text{ mm}$) and large ($d_p = 19.35 \text{ mm}$) nozzles respectively.

4.3.3. Effect of the Oxygen Index

Varying the oxygen concentration of the secondary flow affects the M.I.T. in the manner shown in Figure 24. It may be noted that the methane/oxygen ratio is always stoichiometric and the mass flow rate of secondary flow has been maintained at the same rate throughout

these tests (i.e. 50 g/s). The effect of oxygen index on the M.I.T. may be interpreted in terms of heat generation rate as follows:-

The concentration of methane and oxygen gases is reduced as the secondary flow is diluted by the nitrogen gas. The entrainment rate is, however, almost unaffected by these concentration changes since the same velocities of primary and secondary flow are maintained. Therefore, for each volume of the cold mixture entrained into the hot nitrogen gas, there will be less methane-oxygen gases available to provide the chemical reaction and hence less heat will be generated. To restore the heat balance it is necessary to increase the enthalpy of the hot nitrogen jet.

Based on this argument, the effect of increasing the nitrogen additive but without a reduction in the mass flow rate of methane-oxygen mixture will produce a similar result. This is because the methane-oxygen concentrations are effectively reduced as the total mass flow rate of the secondary flow, $\dot{m}_s$, is increased by the dilution of the nitrogen gas. Assuming the entrainment rate is not affected by the small increase of $\dot{m}_s$ (because of the large velocity difference, i.e. 1 m/s to 40 m/s), the actual masses of methane-oxygen gases entrained into the hot nitrogen gas is again reduced by the increase of $\dot{m}_s$.

Correlation between M.I.T. and the oxygen index is not linear (see Figure 24), although the curvature of the curve is very small. Mullin¹³ found that the square of the ignition delay time is inversely proportional to the oxygen index. It may also be possible to fit the present data by the inverse square formulation as shown in Figure 49.

4.3.4. Effect of the Equivalence Ratio

The measured M.I.T. with equivalence ratio, η , as a variable is shown in Figure 25. M.I.T. is at the lowest point for an equivalence of about 0.95 and it varies very little (about 5°C) in the range between $\eta = 0.85$ and $\eta = 1.15$. The curvature of the curves is steeper in the lean mixture region than in the rich mixture region, but again the total variation of M.I.T. is less than 30°C which indicates that the effect of equivalence ratio on the M.I.T. is small compared to the influence produced by other parameters. This behaviour is similar to

the observations obtained in the ignition of methane-air mixtures by laminar hot jets²².

It may be recalled (see paragraph 2.8.3.) that the ignition of a lean mixture is preceded by a bluish haze which lasts for a few seconds before the secondary flow is ignited. A possible interpretation of this phenomenon may be found in terms of the burning velocity. It is well known that burning velocity varies with flame temperature and in general it is smaller at lower flame temperature (see, for example, reference 115). When the equivalence ratio is reduced to a level at which the burning velocity of the flame is equal to the entrainment velocity of the unburnt mixture, the flame may be temporarily stabilised in the boundary between the primary and secondary flows. This temporarily stabilised flame can, however, exist only for a short time before the instability of the flow affects the balance between the two velocities.

It may also be recalled that the ignition of a rich mixture is preceded by a flame formed above the enclosing glass cylinder (see paragraph 2.8.4.). This phenomenon may again be explained in terms of fuel/air ratio changes as follows:-

As the temperature of hot nitrogen gas approaches, but is still below the M.I.T. no ignition will be observed when methane is injected into the secondary flow. But as the fuel is cut off the mixture will gradually be diluted such that the equivalence ratio of the mixture is lowered. Since a mixture of lower equivalence ratio requires a lower temperature to ignite, a flame may be formed in the primary flow as the fuel is diluted to the corresponding ignition temperature. This flame will then move into the secondary flow but propagation of the flame is restricted. It cannot move towards the upstream region since the fuel has already been cut, nor can it move towards the downstream region because the flame velocity (in the order of 0.3 m/s) is smaller than the flow velocity (about 1 m/s). As a result the flame is blown off and is accompanied by a loud bang.

4.4. THE EXPERIMENTAL RESULTS. III: COMPARISON WITH OTHER WORK

The present M.I.T. measurements of methane-air mixture by a turbulent hot nitrogen jet are tabulated alongside the M.I.T. measurements of the

same mixture but by laminar jets^{17,21,22,26} (see Table 13). Direct comparison between these measurements is not valid because the ignition temperature is affected by the heat transfer between the hot gases and the combustible mixture. The mechanism of heat transfer in a turbulent flow is very different to that of a laminar flow. Furthermore, the M.I.T. is affected by the conditions of the secondary and primary flows. A comparison would be valid only if the flow conditions were identical.

It is, however, possible to make indirect comparisons. Firstly, the present M.I.T. measurements are adjusted for the effects of secondary flow temperature by using the result obtained and shown in Figure 22. Secondly, the effects of flow rate and diameter of jet nozzle are grouped together by the term $\frac{\dot{m}_p}{d_p^2} \cdot T$, where T is the temperature of the hot gas jet. The magnitude of this term is proportional to the mean velocity of the hot gas jet and if the M.I.T. is plotted against this term, as shown in Figure 50, the following features become apparent:-

- (i) Whether the hot gas jet is laminar or turbulent, the M.I.T. is a logarithmic function of the jet velocity, U

$$\text{i.e. M.I.T.} \propto \ln U$$

furthermore, the rate of M.I.T. increment with respect to $\ln U$ is approximately the same for all three cases considered. Since the residence time of methane-air mixture is proportional to the jet velocity, it becomes clear that the residence time is a prime factor in the determination of the hot gas ignition. This behaviour has already been discussed in paragraph 4.3.1.

- (ii) A turbulent jet is more effective in the promotion of mixing between the energy carrying hot gas and the combustible cold mixture, than is a laminar jet. Therefore, it requires a lower ignition temperature than a laminar jet (deduced from observation of curves I and III, Figure 50). In other words, the turbulent mixing has increased the effective residence time of the combustible mixture for a given jet velocity.
- (iii) It appears that curves II and III (Figure 50) may form one single line. Although such deduction is speculative it has nevertheless indicated that the effect of substituting a nitrogen jet with an air jet is equivalent to the effect produced when the flow is changed from laminar to turbulent.

The above indirect comparison has indicated that the measurements obtained by the present study agree with the general trend observed by other workers. It now remains to see how accurately the M.I.T. can be predicted.

4.5. THE THEORETICAL PREDICTION. I: ACCURACY OF THE PREDICTION METHOD

Prediction of the M.I.T. depends on the ability to calculate the axial temperature profile accurately since the M.I.T. is deduced from the change of the axial temperature profile from one form to another (see Figure 1A). It may be recalled that the temperature of the primary flow is deduced from equation 3, i.e.:

$$\bar{h} = C_p \cdot T + m_{CH_4} \cdot H + (\frac{1}{2}u^2 + k) \quad (3)$$

the last term on the RHS is of the order of 10^4 while the term on the LHS and the second term on the RHS are both of the order of 10^6 . The temperature, T, may therefore be written approximately as:-

$$T \approx \frac{1}{C_p} (\bar{h} - m_{CH_4} \cdot H) \quad (3a)$$

Furthermore, for a non-reacting flow, $m_{CH_4} = 0$. Thus,

$$T \approx \frac{1}{C_p} \cdot \bar{h}$$

It has been demonstrated that the computed axial temperature profile for a non-reacting flow is in good agreement with experimental measurements (see Figure 30 and paragraph 3.7.3.). This evidence has formed a secure base on which the hydrodynamic model is built. It then remains to be seen what the effect is on the temperature calculation when combustion is introduced.

Initially, at the nozzle exit (i.e. $t=0$, $x=0$) there is no methane gas in the primary flow. Methane gas enters the primary flow by the mechanism of entrainment and once in the primary flow it is moved to a higher temperature region by the mechanism of diffusion. Finally, it is wholly or partly consumed by the chemical reactions. The rates of these three mechanisms, namely entrainment, diffusion and chemical reaction, thus determine the methane concentration distribution in the

flow field and hence the axial temperature as expressed by equation 3a.

4.5.1. Entrainment and Diffusion Rate Calculations

The entrainment rate is calculated by an approximate formula (equation 32, see paragraph 3.4.3.). If the calculated entrainment rate were higher than the actual rate, the boundary of the primary flow would expand further out into the secondary flow and vice versa if the rate were under calculated. From the results of isothermal non-reacting flow studies in free and confined jets (see paragraph 3.7.), the average jet expansion angles are as follows:-

	<u>Measured Angle</u>	<u>Calculated Angle</u>
Free jet	10.6°	12.2°
Confined jet	9.9°	11.1°

Both results indicate that the calculated entrainment rate is higher than the actual rate, however the difference is moderately small (about 12%). An over-calculated entrainment rate does not immediately imply that the calculated methane concentration is higher than the actual concentration. The value would be incorrectly predicted if the rate of diffusion were also affected by the calculation.

The diffusion rate depends largely on the turbulent viscosity, μ_t . The magnitude of μ_t is of the order of 10^{-2} as compared to the laminar viscosity which is of the order of 10^{-5} . The value of μ_t as defined by the two turbulent quantities k and ϵ (see equation 10, paragraph 3.3.1.) is calculated from the deduced constants measured by Rodi⁷² and Bradshaw⁷⁴ (i.e. C_μ , C_ϵ , etc., see paragraph 3.3.1.). Using these constants the predicted radial velocity profiles are in good agreement with the measured profiles (see Figure 28 and Figure 29). The predicted profile for a confined jet (Figure 29) is slightly better than for a free jet (Figure 28), particularly in the region near the jet nozzle (i.e. within 15 diameters downstream).

A well predicted radial profile near the nozzle is important to the calculation of M.I.T. This is because the predicted ignition is detected mostly in the region between 5 to 10 diameters downstream. A calculation error beyond the 10 diameters region will not affect the predicted M.I.T., but the development of velocity and temperature

profiles near the jet nozzle will bear direct consequence to the calculation of the M.I.T. The calculated radial velocity profile (Figure 29) and the axial temperature profile (Figure 30) are both very close to the measured profiles. Discrepancies between them are less than 10% in the region where the ignitions were detected.

4.5.2. Reaction Rate Calculations

The third factor which affects the methane concentration is the reaction rate, $\dot{m}_{CH_4}$. In the present study, the time mean value of the reaction rate is written as:-

$$- K \cdot m_{CH_4} \cdot m_{O_2} \cdot p^2 \cdot T^{-3/2} \cdot \exp(-E/RT) \cdot \left(\frac{1+\eta}{2}\right)^a$$

It has been pointed out (see Chapter 1, paragraph 1.5.3. and 1.5.4.) that this treatment is a global representation of complicated mixing and reaction mechanisms. In this global model the overall activation energy, E, represents the net effect of the combined activities of all intermediate reactions under a given mixing process, i.e.

$$\text{Constant} \times \exp(-E/RT) = \sum_{j=1}^n K_j \exp(-E_j/RT)$$

where K_j and E_j are constants for each intermediate reaction. Such a conception is valid mathematically in so far as the same reaction mechanism can be precisely repeated for all temperatures so that:-

$$\text{Constant} \times \exp(-E) = \sum_{j=1}^n K_j \exp(-E_j)$$

It is reasonable to expect that this is the case for a mixture of gases of the same chemical composition. Deviation will be likely to occur when the compositions are altered, since exactly the same reactions are unlikely to be repeated when the initial compositions of the gases are altered. It may be possible to argue that the prime species will react at the same rate as before and only the minor reactions will be affected. There is, however, no evidence to support such a hypothesis.

For a stoichiometric mixture the mixing process, that is, the probability of two reactants existing at the same location, is represented by the global reaction rate constant, K. This value for turbulent flow will clearly be significantly different from the value for a

laminar flow and above all, it is likely to be different at different turbulent levels. It has been suggested^{80,81} that the reaction rate be linked to the mean velocity gradient of the flow so that it is correlated to the intensity of the turbulence. Such a theory has met with only limited success. The current view,^{e.g. 99,124,130,132, etc.,} is that the probability distribution of the reactants brought together by the mixing must be taken into consideration (see paragraph 1.5.4.). Such an approach is, however, beyond the scope of the present study.

4.6. THE THEORETICAL PREDICTION. II: COMPARISON WITH MEASUREMENTS

4.6.1. Comparison with the Present Studies

The predicted and measured M.I.T. are given in Figures 22 to 25. Overall, the predicted M.I.T. (denoted by the solid lines) are in good agreement with the measured values, although the predictions of M.I.T. as a function of oxygen index and temperature of the secondary flow are much better than the predictions of the M.I.T. as a function of primary flow rate and secondary flow equivalence ratio. This difference may be interpreted in the following manner.

Changing the secondary flow temperature will affect mainly the heat loss of the hot nitrogen gas and the thermal energy of the combustible gas. It does not affect the concentration distribution of methane gas nor significantly affect the turbulence level of the flows. Similarly changing the oxygen index affects only the relative concentration of methane gas. Everywhere the initial ratio of m_{CH_4}/m_{O_2} is maintained. It does not affect the entrainment rate of cold combustible mixture nor the diffusion rate and chemical composition of methane-oxygen mixture. It has been argued (see paragraph 4.5.) that the mechanisms which are likely to affect the reaction rate and hence the axial temperature of the hot gases are entrainment, diffusion and the chemical reaction. These mechanisms have not been significantly affected by the changing temperature and oxygen index of the secondary flow.

On the other hand a change in the primary flow and the mass flow rate will alter the entrainment rate and the turbulent intensity of the hot gases. The predicted M.I.T. (Figure 23) is seen to become pro-

gressively lower than the measured values as the mass flow rate is increased from the reference point at $\dot{m}_p = 2.05 \times 10^{-3}$ kg/s. At $\dot{m}_p = 3.4 \times 10^{-3}$ kg/s, the discrepancy is about 35°C (equivalent to 35%; increase in M.I.T. from $\dot{m}_p = 2.0 \times 10^{-3}$ to 3.4×10^{-3} kg/s is about 100°C).

When the equivalence ratio changes, the relative composition of methane to oxygen is altered. The lower curve of Figure 25 is obtained by adjusting the "constant" 'a' in the $\dot{m}_{CH_4}$ equation (equation 17b) with different 'a' values for the rich and lean mixtures. Using the same 'a' values, the predicted M.I.T. shows large discrepancies with the measured M.I.T. (upper curve of Figure 25). The justification to provide different 'a' value for lean and rich mixtures is physically weak although some workers (e.g. Ref. 26) also suggest that the 'a' value (which is called the total order) should be different for the lean and rich mixtures. If a single value of 'a' is used the predicted curves have poor correlation with the measured values.

4.6.2. Comparison with Other Work

The time mean reaction rate, $\dot{m}_{CH_4}$, is written in the present study as:-

$$\dot{m}_{CH_4} = -K \dot{m}_{CH_4} \cdot \dot{m}_{O_2} \cdot p^2 \cdot T^{-3/2} \cdot \exp(-E/RT) \cdot \left(\frac{2}{1+\eta}\right)^a \quad \text{----- (5)}$$

Using the present prediction method, the deduced kinetic constants are:-

$K = 7.88 \times 10^6$	$S^3 - ^\circ K^{3/2} / \text{kg/m}$
$E = 2.15 \times 10^8$	J/kg - mole
$a = 4.1$	$\eta < 1$
$a = 3.3$	$\eta < 1$

These constants are obtained by matching the predicted M.I.T. with measured values under the reference flow conditions (see paragraph 3.8.1.), but the measured M.I.T. have not been corrected for the radiation loss of the thermocouple. If radiation loss is accounted for, the kinetic constants will become:-

$$K = 7.97 \times 10^6 \text{ } S^3 - ^\circ K^{3/2} / \text{kg/m}$$

$$E = 2.15 \times 10^8 \text{ J/Kg - mole}$$

The reaction rate has been expressed in general form²⁶ as follows:-

$$\dot{m}_{CH_4} \equiv A \cdot (P/T)^{C+D} \cdot m_{O_2}^D \cdot m_{CH_4}^C \exp (-E/RT) \quad \text{--- (5a)}$$

where C+D is called the total order

C = the fuel power

D = the oxygen power

and A is a frequency factor.

The activation energy, E, obtained by the present study is tabulated alongside the values obtained by different experimental methods⁶, 26,119,120,121,123 (Table 16). The present value is about 10% lower than those obtained from flow reactor and fully stirred reactor systems but is very close to the value measured by the shock tube system.

Equations 5 and 5a are written in slightly different form. Direct comparison of the reaction rate constant, K, with its corresponding value in equation 5a is not valid. The constants are adjusted and tabulated for indirect comparison as shown in Table 17.

4.7. CONCLUDING REMARKS

A special feature of hot gas ignition experiments is the good repeatability of ignition temperature measurement, e.g. ²⁶. This feature was observed in the present experiments which showed that the ignition temperature could be reproduced to within $\pm 5^\circ\text{C}$ (see paragraph 2.7.3.). Although there is no existing data available for direct comparison, an indirect comparison with M.I.T. measurements obtained in laminar flows has demonstrated that the present measurements are in line with the work done elsewhere (see Figure 50). Thus, the deduction of the kinetic constants is based on a set of reliable experimental data.

There is less confidence in the accuracy of the prediction method. In a non-reacting flow the present method has accurately predicted the axial velocity and temperature profiles (see Figures 26, 27 and 30) but discrepancies of up to 15% exist in the calculation of jet expansion angle and the radial-wise velocity profiles (Figures 28, 29). The predicted M.I.T. as a function of secondary flow temperature and oxygen index follow the measurement very closely, indicating that the prediction method is valid for these two variables which do not affect the calcul-

ation of methane concentration (Figures 22 and 24). Alternating this pattern, either by way of changing the primary flow rate which alters the turbulence intensity, or by way of changing the fuel/air ratio which alters the reaction rate, the prediction method is shown to be deficient in accounting for the complex mechanisms of intermediate chemical reaction and the effect of turbulent mixing on the reaction rates. This has pointed to the inadequacy of the overall kinetic reaction rate conception and clearly there is scope for improvement in these areas.

It must, however, not be interpreted that the present prediction procedure cannot be used in practical applications. Engineers have, for a long time, used simplified descriptions for complicated phenomenon. The present prediction method has demonstrated its good accuracy in the prediction of certain variables, but to a lesser extent for other variables. In applying the present method, its limitations must be noted.

CHAPTER 5

DESIGN OF A HIGH TEMPERATURE HEATER WITH FLOW

5.1. INTRODUCTION

5.1.1. The Conventional Heater Construction and Its Shortcomings

Since Wolfard¹⁷ revived hot gas ignition work in 1958, progress on ignition of methane-air mixture experiments has been hindered by the lack of a suitable high temperature heater. A typical construction of heater used in many hot gas ignition experiments, e.g. 17,19,22,26, 27, etc. is illustrated in Figure 51. The heater consists essentially of a platinum-rhodium alloy wire wound on the outside of a recrystallised alumina tube. Heat generated by the heating element is conducted through the ceramic walls into the gas flowing inside the tube. This type of heater is easy to construct but it bears several shortcomings:-

- (i) although the recrystallised alumina tube can withstand temperatures up to 1950°C ⁸⁹ before it loses its mechanical strength in a prolonged experiment the maximum working temperature of platinum-rhodium alloy is only 1750°C approximately. Thus the limit of this heater is dictated by the maximum working temperature of the platinum-rhodium alloy.
- (ii) the thermal conductivity of alumina is poor⁹⁰, (pure alumina: $19.5 \text{ W/m}^{\circ}\text{C}$ at 20°C ; copper: $377 \text{ W/m}^{\circ}\text{C}$ at 100°C). This high thermal resistance produces a larger temperature drop across the ceramic wall. The magnitude of the temperature drop depends on the effectiveness of heat transfer at the inside surfaces of the alumina tube. To give some idea of the temperature drop, a heater could fail when the gas flow temperature was still under 1200°C while the heating element had been heated to over 1500°C *.
- (iii) the heat transfer rate from a smooth inner surface of a circular tube is low⁺.

* Mean temperature of the heating element, measured by temperature-resistance correlation method.

+ For a laminar flow $Nu = 4.4$ and for a turbulent flow $Nu = 0.023 Re^{0.8} Pr^{0.4}$.
 $Nu = 12.1$ if $Re = 3000$, $Pr = 0.7$.

- (iv) in practice it is difficult to ensure a uniform electrical power loading over the entire length of the heating element. As a result hot spots may develop at the locations at which there are defects and non-uniform cross-sections, etc. Hot spots often destroy a heater long before limitations imposed by other factors are reached. For this reason the average temperature of the heating element is usually kept well below the maximum working temperature of the element.

- (v) ideally the primary and the secondary flows should be parallel (see Figure 52). The heater, which is located between the two flows, distorts the parallelity and in order that this distortion be as small as possible, the space available to house the heater is greatly restricted. Furthermore, all the terminal connections must leave the bottom end of the heater since the top end is occupied by the gas flows. These space limitations restrict the freedom of the heater design and will be further discussed later in this Chapter.

The heater illustrated in Figure 51 was first applied by Wolfhard¹⁷ to hot gas ignition experiments and was widely used by combustion technologists. For convenience this type of heater will subsequently be referred to as the "conventional heater". The maximum gas temperature produced by the conventional heater varies according to the mass flow rate of the gas (see Chapter 2). It is not possible to apply this heater in its original form for the present study. The maximum gas temperature and mass flow rate required are beyond the limits of the conventional heater.

5.1.2. The Purpose of This Chapter

A considerable amount of effort and resources have been devoted to the development of a high temperature heater during the course of the present study. The experiences were painful and the costs were high, but the accumulated knowledge of heater design is valuable. The purpose of this Chapter is to record the causes of failure of the heaters in the hope that the same faults would not be repeated elsewhere. It is also believed that a brief review of various heater designs will help towards an understanding of the problems encountered in high temperature heater construction. In the following section the various options of

heater design which may overcome the shortcomings of the conventional heater will be discussed first. This will then be followed by a presentation of the causes of failure of the prototype heaters.

5.2. DESIGN OF HIGH TEMPERATURE HEATER WITH FLOW

A heater may be constructed using different methods, materials and forms. The use of alternative heating elements will be examined first.

5.2.1. Alternative Heating Elements

One of the principal shortcomings of the conventional heater is the low working temperature of platinum-rhodium alloy. It is obvious that the first option for a new heater design is to replace the platinum-rhodium alloy by a heating element which has higher working temperatures. Heating elements may be classified into four groups:-

- (a) Low temperature metals: these are mainly nickel, chromium, aluminium and ferric alloys branded usually under trade names, such as Nichrome, Kanthal. The maximum operating temperature (of the heating element and not the gas flow) of these alloys is less than 1300°C although Kanthal-super is said to be capable of reaching 1400°C .
- (b) Non-Metals: silicon carbide and molybdenum disilicide are the two most useful compounds amongst the non-metal heating elements which can be operated in oxidising atmospheres*. Again, they are branded under trade names, such as Crystolon, Crusilite, and may be used up to 1600°C .
- (c) Noble metals: osmium has the highest melting point (3050°C) in this group but the formation in air of poisonous tetroxide prohibits its application as a heating element. The next best metals are iridium (melting point 2447°C), rhodium (1963°C) and platinum (1772°C). Alloys of these three metals form useful heating elements which may be exposed to air, but they are expensive.
- (d) Refractory metals: all metals in this group have high melting points but are readily oxidised, even at low temperature. These metals

* Other non-metals such as graphite are attacked by air although they have high melting points.

include tungsten (melting point 3410°C), tantalum (2996°C), molybdenum (2610°C) and niobium (2415°C).

From the above classifications it may be seen that only iridium-rhodium alloys and the refractory metals can be used as substitutes for the platinum-rhodium alloy. Iridium-rhodium alloy was reported to be extremely fragile on exposure to air at 1700°C and it lost mass at high temperature. This alloy was used in the second heater built in the present study. The heater was damaged prematurely at a gas temperature of about 1150°C . Of the 104 grams of metal used, only 98 grams was recovered. Several traces of hot spots were found at the junctions of coil sections (the heating element was divided into three sections and supplied by a three-phase main). The metal was fused with the alumina cement at these locations. Development and causes of the hot spots will be discussed later in this Chapter.

Iridium-rhodium alloy was about three times as expensive as the platinum-rhodium alloy. The resources of this study were inadequate to pursue further development based on this alloy. This left refractory metals as the only other possible substitute. The refractory metals cannot be used unless they are protected from oxidation. One of the metals, namely molybdenum, was used successfully in conjunction with the recrystallised alumina tube, by the metallurgists^{e.g. 56.86.87}, as the heating element for the furnaces used in their research work.

The furnace consists of a molybdenum tape (or wire) wound on to an alumina tube (see Figure 53). A metal case filled with forming gas (or hydrogen) encloses the molybdenum metal and thus protects it from oxidation. Both ends of the alumina tube are normally closed and there is no gas flowing through the inside of the alumina tube. The hottest zone of this furnace is at the centre of the tube where a specimen is normally placed. Temperature of the alumina tube gradually decreases towards the ends due to conduction and convection losses. The space between the alumina tube and the metal case is sealed by rubber 'O' rings which are compressed by a pair of flanges. Copper coils carrying cooling water surround the vicinity of the 'O' rings to prevent it from overheating.

The furnace described above is capable of heating the air inside the alumina tube up to 1700°C and even up to 1800°C for a short duration.

This construction method thus provides a well tried technique for the design of a high temperature heater for the present study. But a heater with gas flowing inside the ceramic tube presents several serious problems unseen in the metallurgist's furnace in which the air is static inside the alumina tube. Amongst them is the problem of sealing between the metal case and the alumina tube.

In the case of the heater with flow (see Figure 51), the top end of the alumina tube, where the hot gas emerges, is extremely hot. The lower end of the tube could also be hot if pre-heating were used. In these circumstances it is not possible to seal the gaps by rubber 'O' rings because a drastic reduction of the surface temperature by cooling water will certainly crack the ceramic tube due to excessive thermal stress. Apart from this obvious sealing problem, there are others which will be discussed later.

The combination of molybdenum with alumina has, however, a big advantage. The thermal expansion of these two materials is very similar (see Figure 62). At high temperature, thermal stress between the heating element and the ceramic is considerably less with this combination.

5.2.2. Alternative Heating Methods

Another option of the heater design is to seek a totally different heating method in place of the electrical resistance heating method. Several means of obtaining high temperature⁸⁹ have been examined. These include combustion heating, induction heating, direct heating and others.

Figure 54 illustrates a possible counter flow gas-to-gas heat exchanger using exhaust gases or miniature flames as the heat sources. This system could produce a very high temperature gas flow if, for instance, a pre-mixed oxygen-acetylene flame were impinging directly on the ceramic tube. But this system has several difficulties which cannot readily be solved:-

- (i) it is difficult to control the heating rate so that the temperature of the primary flow can be changed with the precision required for the present ignition experiment (e.g. 1 to 2°C)

- (ii) space limitation and difficulty of sealing the concentric tubes will cause flueing problems. If the exhaust gases were leaked into the main gas stream, contamination of the hot nitrogen would affect the experimental results
- (iii) it is doubtful whether a ceramic tube can withstand the thermal shock produced by the sudden heating and cooling of the gases.

Alternatively, heating may be provided by the induction method. The cooling water jacket could be replaced by a water-cooled induction copper coil and the alumina tube could also be replaced by a graphite susceptor, as illustrated in Figure 55. High frequency alternating current in the induction coil will induce a current in the graphite susceptor, which will in turn heat the gas flowing inside it. The main deficiency of this heating method is the need to protect the graphite susceptor from oxidation. Taking into account the cost of a high frequency generator, there is no advantage of this system over the resistance heating method employing the molybdenum metal.

There are electrically conductive high temperature materials which will not oxidise in air. For instance, metallic oxides such as zirconia and thoria with a small amount of additives, such as yttria and lanthania, can substantially increase their electrical conductiveness when heated to an elevated temperature ($>1000^{\circ}\text{C}$). These oxides are chemically far more stable than molybdenum and graphite, and oxidation protection is not required. It is even possible to use these oxides in the form of a tube which becomes a heating element itself (Figure 56).

Such a direct heating system is easy to construct and operate but the deficiencies are (i) it is necessary to pre-heat the oxide tube, (ii) these special oxides are excessively expensive. Coupling with the cost of the platinum-rhodium coil this heating system is beyond a moderately budgeted project.

Alternatively, the alumina tube of a conventional heater could be replaced by a metallic tube made from iridium-rhodium alloy. Gas flowing inside the tube could again be directly heated. The main opposition to this scheme would be the cost of the iridium-rhodium alloy and furthermore, the alloy has no mechanical strength to retain its shape at elevated temperatures. One possible solution is to support

the metallic tube by a ceramic tube as shown in Figure 57.

Other systems such as electric arc heating, electric bombardment heating and dielectric heating, etc., are unsuitable for hot gas ignition experiments.

5.2.3. Alternative Ceramic Tube

It may be recalled that the thermal conductivity of alumina is poor in comparison with metals. Consequently, it causes a large temperature drop across the walls of the ceramic tube. Most ceramic materials are poor thermal conductors. In fact, the thermal conductivity of alumina is better than most ceramics (see Table 15). It is difficult to reduce the temperature drop so long as a ceramic tube is used. If, however, the working temperature of the ceramic tube can be increased (by using material other than alumina) to the level which is compatible with the working temperature of the heating element (say, molybdenum) then the temperature drop may be compensated by the increase in working temperatures of the metal and ceramic.

The search for an alternative ceramic has been extended to the non-oxides such as boron-nitride, but in general non-oxides are chemically less stable than the oxides. Within the oxide group there are several would-be substitutes: thoria can be used up to 2700°C but it is radioactive; beryllia can withstand temperatures up to 2100°C but the beryllia powder is poisonous to handle (beryllia cement would be needed to anchor the heating element). The most promising oxide is zirconia (melting point is about 2700°C) but this ceramic is not commercially available in the form of a long tube (about 1.2 metres). Zirconia is also slightly more porous than alumina - an important point to bear in mind when it is used with a refractory metal (see paragraph 5.3 for details). The compound of alumina and magnesia ($\text{Al}_2\text{O}_3 \cdot \text{MgO}$) is slightly better than the pure alumina (operation temperature is about 100° higher) but its thermal conductivity is three times less (6.3 and $19.5 \text{ W/m}^{\circ}\text{C}$ respectively at 20°C). Porosity of pure magnesia is comparably high (about 30%, DIN 1065) although the melting point of magnesia is greater than 2500°C .

5.2.4. Alternative Winding Methods

Assuming the electric resistance heating method must be used, what other construction methods are better than the conventional heater construction in order that the gas flow temperature may be maximised? Two aspects of construction may be considered. These are, the method by which the heating element is wound on to the ceramic tube since it affects the power loading of the heating element, and the shape of surfaces of the ceramic tube since it affects the heat transfer rate at the surfaces.

The resistance of most metallic heating elements varies with the temperature of the element. For instance, the resistance of molybdenum metal at 1900°C is about ten times as large as the resistance at 20°C . Since the electrical power loading of a heating element depends on the resistance of the element, the power loading will also depend on the temperature of the element. In a conventional heater (Figure 51) the temperature of heating element is much cooler near the gas entry than in the vicinity of the gas exit. Thus, the power loading is higher at the hot end than the cool end and this imbalance of power loading along the direction of the tube is likely to damage the heater.

A heating element may be wound on to the ceramic tube by methods demonstrated in Figure 58. Arrangement 'a' is the one length winding adopted in the conventional heater. The heater is normally wound in a lathe and thus the pitch of the coil is uniform along the tube. It may be possible to reduce the number of coils per unit length towards the hot end (top end as seen from Figure 58). This is, however, difficult to arrange and it is also difficult to calculate the coil reduction accurately.

Arrangement 'b' assumes a uniform winding but the entire length is divided into three equal sections which are connected to a three-phase supply. Since the voltage applied to each section is the same, any increase of resistance will decrease the current supply. This in turn reduces the power loading in a hot zone and lessens the possibility of damage due to overheating. On the other hand, arrangement 'b' requires four terminal wires instead of the two in arrangement 'a'. In a tight space, separation of these terminal wires and prevention of short circuits could be a problem as the number of terminal wires is

increased. The number of terminal wires could be six if the adjacent sections could not be joined to the same terminal.

Arrangement 'c' avoids any terminal wires running alongside the heating element but the power loading imbalance of this arrangement is as bad as arrangement 'a'.

All the above three arrangements require long lengths of wire or tape, typically 20 to 30 metres. A long wire is likely to have non-uniform cross-sectional areas and other non-uniformities, such as bursts, kinks, etc. These non-uniformities often produce local hot spots. Arrangement 'd' is superior to the others because the ratio of length to cross-sectional width is considerably less.

5.2.5. Alternative Heat Transfer Surface

The contact surface area of a circular tube between the gas and the ceramic is $2 \pi r L$, where r and L are radius and length of the tube. This area may be increased several fold by a finned tube such as the one shown in Figure 59 'b'. Such a tube is not commercially available and must be prepared specially.

An alternative method of increasing the heat transfer rate is illustrated in Figure 58 'c'. Arrangement of the ceramic segments has already been described in paragraph 2.4.1. It has been demonstrated that this arrangement can increase the gas flow temperature by about 115°C .

5.2.6. Concluding Remarks

The above discussions list various options to overcome the shortcomings of the conventional heater. There are few promising but untried heating methods and materials. Amongst them the direct heating method employing an iridium-rhodium tube is perhaps the most feasible method. (see paragraph 5.2.2.). The choice of electric resistance heating methods employing molybdenum-alumina combinations for the present study was determined largely by cost considerations and the commercial availability of certain materials. In other words, the present choice is not necessarily the best, but is governed by non-technical problems. Alternative methods of heater construction should therefore not be ruled

out if the non-technical considerations are not constraining factors.

5.3. CAUSES OF THE FAILURE OF THE PROTOTYPE HEATERS

During the course of the present study over twenty prototype heaters were built, some with minor changes to their predecessors and others with major modifications. They failed for various reasons and in some cases for reasons which are still not clear to the author. It was very difficult to detect the causes of failure because the heater was totally enclosed inside the cooling water jacket and could not be seen nor access gained to it when in operation. When it failed the heater was often reduced to lumps of molten metal mixed with ceramic cement and insulating powder.

Tracing the causes was limited to a few clues such as the long shining yellow needles of molybdenum oxide crystal which suggested that the metal was seriously attacked by air entering the protection chamber; the blackened and molten ceramic cement which suggested that an electrical short circuit had induced an electric spark. To make the matter worse a symptom, such as oxidation of the metal, could result from more than a single cause. It could be attacked by air before the heater failed or after a hot spot had developed and burnt through the alumina tube through which air entered subsequently.

The following section is a record of the principal causes of failure in the heaters. It must, however, be pointed out that even a minor defect in the construction stage could lead to a total failure of the heater. For instance, molybdenum metal is extremely fragile. A hair crack during the cutting process could develop into a hot spot which might eventually destroy the heater. Thus, it is recommended that every care be taken during the construction of such a heater.

5.3.1. Failure Due to Voltage Breakdown

It may be recalled (see paragraph 5.1.1.) that the space available to house the heater in a conventional structure is small. If the heating element is wound to the alumina tube in one of the four arrangements shown in Figure 58, the distance between the terminal wires and the heating element is small (or between the two halves of the heating elements as in the case of arrangements 'c' and 'd'). The terminal

wires could be at a high voltage with respect to the heating element and the metal case. It could be as high as 415 volts if it were supplied by a three-phase main.

To prevent a voltage breakdown between two current - carrying conductors, the terminal wires were separated by alumina cement, powder and sleeving tubes. The breakdown voltage, or dielectric strength as it is also called, is usually quoted in volts/mm and is found to be a function of the temperature. Miyazawa and Okada⁵⁴ found that the dielectric strength of alumina cement was approximately 1500 volts/mm at all temperatures up to 1000°C. Beyond this temperature the dielectric strength decreased exponentially with the temperature, and at 1700°C it was reduced to about 25 volts/mm.

At this value the alumina cement presents no danger of a voltage breakdown in the metallurgist's furnace even at very high temperature. The voltage drop between two successive coils of the metallurgist's furnace is small. For instance, if 240 volts is applied to 240 coils, the voltage drop between adjacent coils is only one volt. It may also be noted that the two terminal wires (see Figure 53) between which there is a high voltage drop, are far apart from each other.

In the case of the present heater the terminal wires were at the best 10 mm from the heating element and the metal case (see Figure 60) but more likely they were at a shorter distance apart because it was very difficult to keep the terminal wires exactly mid-way between the coils and the case. If the cement were heated to 1700°C or above, the breakdown voltage would be 250 volts for a 10 mm distance according to Miyazawa and Okada's findings. This voltage had certainly been exceeded in the early prototypes in which the wires were wound in the arrangements shown in Figure 58'b'.

When the breakdown voltage was exceeded local hot spots developed but the power supply had not been cut off immediately. Instead, the temperature of the hot spots grew until the alumina tube was burnt through and air was let in to oxidise the molybdenum metal giving the impression that the heater had failed due to oxidation. The real cause of failure was not discovered until systematic inspection of the failed heaters revealed the fact that the hot spots were always associated with the maximum voltage drop between the conductors.

The solution to this problem was, therefore, to reduce the voltage supply to a level well below the breakdown voltage. But difficulties arose because the value of dielectric strength of alumina cement at the temperature of fusion was quoted quite differently by various workers, due possibly to different compositions of the cements tested. Table 14 gives the dielectric strength of alumina cement measured at different laboratories.

In the later prototypes the heating element was wound on to the alumina tube in the arrangement shown in Figure 58 'd'. The "tube form" heating element allowed the resistance to be reduced to 0.007 ohms at 20°C so that the voltage applied to the heater at no time exceeded 15 volts. With a 4 mm gap between the two halves of the circular tube the maximum voltage drop is 3.75 volts/mm which is well below the dielectric strength quoted in the literature.

5.3.2. Failure Due To Porosity Changes of Alumina Tube

At low temperatures the recrystallised alumina tube was quoted by the manufacturers* to be impermeable. But this non-porosity property changes at high temperature according to Williams¹¹². He found that a tracer could diffuse through the ceramic wall at temperatures above 1300°C and the diffusion rate increased with the temperature of the ceramic wall. It may also be expected that the diffusion rate will increase if the pressure difference across the wall were increased.

In the case of the metallurgist's furnace the protecting chamber is pressurised to ensure that it is filled with a protecting gas (e.g. hydrogen, see Figure 53). The air inside the alumina tube is static. Thus, the pressure inside the chamber is positive with respect to the inside of the alumina tube. As the porosity of the alumina tube changes at high temperature the protecting gas, rather than air, will be forced through the ceramic wall under pressure.

In the case of the heater with flow (see Figure 51) the total pressure head of the gas flow is greater than the pressure inside the protecting chamber. Air will readily diffuse into the protecting chamber and as the rate of diffusion increases, serious oxidation

* Morgan Refractories, U.K., and Degussit of Germany.

of the metal can take place depending on the type of protecting gas.

It was noted that most early prototypes failed at about the same time of day. The heater was usually started in the morning at a rate of about 100°C per hour. By the evening the gas flow temperature would reach the 1000°C mark and was usually left unchanged overnight. During this period most heaters failed when the temperature of the alumina tube was, as could be reasonably expected, a few hundred degrees higher than the gas flow temperature*. At this temperature the alumina tube will permit gaseous diffusion. The work of William was not known in the early stages of the present study. Air was used as the primary flow during the heating up period for economic reasons. In these heaters traces of molybdenum oxides, which could be easily distinguished by their yellow needle shaped crystals, were found.

Formation of molybdenum oxide did not immediately cause the heater to fail. Instead the oxide altered the electrical resistance of the insulating materials, (i.e. alumina cement and powder). Electrical leakage then allowed hot spots to form in the weakest locations until a short circuit was made or, as in some cases, the hot spot grew to the extent that the alumina tube was burnt through and allowed large amounts of air to enter the chamber and cause extensive oxidation.

The solution to this problem is to substitute the air by nitrogen in the primary flow after the gas flow temperature has reached about 1000°C .

5.3.3. Failure Due To Bad Electrical Contact

Molybdenum metal is readily oxidised in air even at low temperatures. The terminal wires of the heating elements cannot therefore be taken out of the protecting chamber and exposed to air without protection. (An early prototype with the terminal wire led out to a supposed "safe low temperature" region failed due to oxidation problems). For this reason the terminal wires of the early prototypes (arranged in the

* Although the temperature of alumina tube could not be measured, the heating element was in the region of $1300-1400^{\circ}\text{C}$. This was measured by temperature-resistance correlation methods.

form shown in Figure 58, arrangement 'b') were joined to Pt-Rh wires which were then taken out of the chamber.

Molybdenum and Pt-Rh alloy have very different thermal expansivities and melting points. Several methods of joining these two dissimilar metals have been tried, but failed. These include the following methods:-

- (a) Twisting the two wires together: compared with Pt-Rh alloy, molybdenum is a very brittle metal. It is not possible to twist the two wires together without breaking the molybdenum metal. Thus the multi-stranded Pt-Rh alloy was wrapped around the molybdenum wire in a manner similar to the screen wire wrapping round an electrical cable. This method failed due to differential thermal expansion rates of the two metals. Contact between the two wires became loose at high temperature since Pt-Rh alloy expanded more than the molybdenum metal and the noble metal was on the outside of the joint. The loosen contact surface created a high resistance and caused hot spots to form in these joints.
- (b) Argon arc welding: after failing to twist the two wires together, the metals were welded unsuccessfully under the argon arc. The failure was due to two reasons. Firstly, the Pt-Rh alloy melted long before the molybdenum metal. Similar difficulties were experienced when rhodium was welded to iridium in the making of a thermocouple. Correct current rating must be adjusted to obtain a successful joint. Even then the molybdenum metal became extremely brittle after it had been heat-treated to its melting point. The welded molybdenum wire was so brittle that it could not withstand a gentle bending.
- (c) Cold welding: it was suggested that the ductibility of the molybdenum might be retained if the two wires were cold welded. Cold welding requires a compression of approximately 100 tons/in^2 . This was tried but the molybdenum split when the compression force was only 4 tons/in^2 .
- (d) Clamping the two metals together: a terminal block was machined from a molybdenum rod. The two wires were connected together by molybdenum screws in a manner similar to an ordinary electrical terminal block connection. This method failed due possibly to

the formation of a thin film of impurity on the contact surfaces. The substance of the impurity is not known. It may have been molybdenum oxide, but its appearance was not the same as the yellow needle crystals found elsewhere. The molybdenum terminal blocks were inside high temperature zones and in these cases the chamber was filled with argon gas rather than forming gas.

The solution to this problem has already been described in paragraph 2.4.1. (see also Figure 7). The lower end of the protection chamber was enlarged (see Figure 7, M) so that the molybdenum terminals could be taken to a cooler region which was further cooled by a water cooling coil (Figure 7, S).

5.3.4. Failure Due To The Type of Protecting Gas

In principle, so long as the air inside the protecting chamber was displaced and replaced by an inert gas, molybdenum metal should not oxidise. Thus, either helium, argon or even nitrogen gases could be used as the protecting gas. Nitrogen will, however, react with molybdenum to form molybdenum nitrides. Argon was preferred to helium on the grounds of cost. In practice, although argon has been used in a molybdenum furnace⁵⁶, forming gas or hydrogen gas are more commonly used^{e.g. 86,87}. But hydrogen is an explosive gas and if it were allowed to leak freely into the laboratory it could be a potential hazard.

In the case of the metallurgist's furnace (see Figure 53) the protecting gas is collected and ducted away. Thus, even if pure hydrogen is used, there is no danger of the hydrogen gas being accumulated in the laboratory. In the case of the heater with a flow, the protecting chamber could not be sealed properly (see paragraph 2.4.1.), and the protecting gas was allowed to discharge into the surrounding space. On the grounds of safety, the use of forming gas was not permitted in the early prototype heaters.

Kitchener and Bockris⁵⁶ found "blackened" cements in the furnace if argon was used during the entire experiment. These blackened cements were also found in the early prototypes. X-rays of these blackened cements revealed that they were carbon based compounds used as a binding ingredient in the cement.

Park* also found a similar compound segregated at high temperature but subsequently recombined with the cement. The cements were made by the same manufacturer[†].

The resistivity of the blackened area was found to be 100-300 ohms over a length of 0.2 to 0.5 metres as compared to 10^6 ohms in an unblackened area over a similar length. Traces of molten cement caused by sparks were found in the blackened area. It was not known how the presence of the hydrogen gas could prevent the formation of the blackened cement, but no such blackened area was found when forming gas was used.

Forming gas was used after the college authority had been convinced that it was necessary to use it. The flow rate of the forming gas was typically 0.2 to 1.0 ml/min. Ventilation of the laboratory was operated at full load as soon as the forming gas was used. No incident happened in connection with the use of the forming gas in the laboratory.

5.3.5. Failure Of The Pre-Heater

The pre-heater used in the early development was very different from that described in paragraph 2.4.2. (see also Figure 10). It consisted of three to five heaters connected in series (Figure 61). Each heater was 1.2 m long with a three-section heating coil. The heating coils were connected in parallel to reduce uneven heat loading. Kanthal A-1 and Pt-Rh alloy were used at the low and high temperature ends, although at one stage molybdenum was also used at the high temperature end.

The biggest problem of these heaters was the probability of failure. When one heater failed, it lost not only a large proportion of heating power but also created a heat sink due to the length of each heater. Assuming the failure probability of each heater was equal, the system failure was three to five times greater when the heaters were connected in series.

*Dr. Park, research assistant, chemical engineering department, Imperial College.

[†]Morgan Refractories, U.K.

At first only three heaters were used but it was necessary to apply a large power loading to each heater. Subsequently two further heaters were added. This reduced the heat loading of each heater but also increased the probability of system failure. As a result, tests in the main heater design were frequently disrupted in order to repair a failed pre-heater.

At first glance the later design of the pre-heater as shown in Figure 10, seems bulky and clumsy. Only detailed consideration can reveal its advantages:-

- (i) The multi-heating matrices render part of the system redundant. This enables the experiment to continue even if one or a few of the heating matrices fail. By the end of the present study, four of the thirty-four heating matrices had failed, but no repair was necessary. The remaining thirty heating matrices were capable of pre-heating the primary flow.
- (ii) Should a number of heating matrices fail, only those heating matrices needed to be replaced. This could be done readily. (Some spare heating matrices were kept).
- (iii) By exposing the heating elements directly to the gas flow, the heat transfer rate was greatly increased. This helped to reduce the power loading and hence reduce the failure rate.
- (iv) The "sandwich" design with soft Kaowool packings between the alumina blocks allowed the individual heating matrice to expand freely since the complete heater was fitted with rollers resting on rails.

5.3.6. Concluding Remarks

The causes of failure recorded in this Chapter are deduced from the observations gathered during the course of the present study. It is not possible to say, for instance, that a heater failure was caused by voltage break-down or a change of porosity or both, or even a combination of other factors known and unknown to the author. The heater design has never been a prime target of the present study but only a means to achieve the ignition temperature experiments. Thus, no attempts have

been made to conduct controlled experiments in order to testify the exact causes of failure of the heaters. It can, however, be positively concluded that if care is taken to eliminate all the known causes of failure, it will work.

The heater described in paragraph 2.4.1. has raised the primary flow temperature (about 3.2×10^{-3} kg/s) to a maximum of 1580°C for a short duration. If a higher temperature or a bigger mass flow rate is required in the future, the author believes a combination of molybdenum with zirconia may push the maximum temperature to about 1800°C . Beyond this level either a new material or a different heating method must be considered.

CHAPTER 6

CONCLUSIONS

Main Findings

- (i) The present study has confirmed the view that hot gas ignition is an accurate system for the deduction of kinetic constants, due mainly to its good repeatability of the ignition temperature. It has been shown that a cold mixture of methane-air could be ignited by a co-axial (Figure 1) hot nitrogen turbulent round jet if the hot gas had reached a minimum temperature which is referred to as the minimum ignition temperature (M.I.T.). This ignition temperature was found to be repeatable to within $\pm 5^{\circ}\text{C}$.
- (ii) The M.I.T. was found to be between 1242°C and 1452°C within the tested range of :-
- $$\begin{array}{rclcl} 15.0 & \leq & d_p & \leq & 19.35 \text{ mm} \\ 1.41 \times 10^{-3} & \leq & \dot{m}_p & \leq & 3.59 \times 10^{-3} \text{ Kg/s} \\ 18 & \leq & T_s & \leq & 187^{\circ}\text{C} \\ 0.56 & \leq & \eta & \leq & 1.36 \\ 0.188 & \leq & \xi & \leq & 0.233 \end{array}$$
- (see Tables 4 to 8).
- (iii) The magnitude of M.I.T. is influenced by all five quantities listed above, namely the diameter of the jet nozzle, d_p , the mass flow rate of the primary flow, $\dot{m}_p$, the temperature of the secondary flow, T_s , the equivalence ratio η and the oxygen index in the secondary flow, ξ (Figures 22 to 25). Indirect comparison with data obtained elsewhere shows that the present measurements are in line with measurements obtained in laminar flows (Figure 50).
- (iv) It is possible to predict the M.I.T. based on the characteristic changes of the axial temperature profiles between the cases of ignition and no ignition (Figure 1A). The axial temperature distribution can be calculated with good accuracy by a numerical scheme which adapts the implicit finite difference method and incorporates the Spalding-Partankar technique³⁹ (Figure 30).

(v) Overall, the predicted M.I.T. matches fairly well with the present measurements (Figures 22 to 25). The predicted M.I.T. with T_g and ξ as variables agree extremely well with the measured values (Figures 22 and 24), but evidence has emerged to suggest that the prediction method is inadequate in accounting for the complex chemical reactions and the effect of turbulent mixing on the reaction rates.

(vi) This is due possibly to the adaption of the overall kinetic reaction rate which is expressed as:-

$$= K \cdot p^2 \cdot T^{3/2} \cdot m_{CH_4} \cdot m_{O_2} \cdot \exp(-E/RT) \cdot \left(\frac{2}{1+\eta}\right)^a$$

where K, E and a are the overall kinetic constants which are found to be*

$$K = 7.88 \times 10^6 \quad s^3 \cdot K^{3/2} / Kg/m$$

$$E = 2.15 \times 10^8 \quad J/Kg\text{-mole}$$

$$a = 4.1 \quad \text{for } \eta < 1$$

$$a = 3.3 \quad \text{for } \eta > 1$$

by matching the measured and calculated M.I.T. under the reference folow conditions (Table 3).

Other Findings

(vii) A heater employing a combination of molybdenum heating element and alumina tube is capable of heating a nitrogen gas to a maximum temperature of 1580°C at a flow rate of 3.2×10^{-3} Kg/s (Figure 7).

(viii) Construction of this heater requires careful design to prevent failure due to oxidation of the metal, voltage breakdown of the ceramic insulating cement and the development of hot spots caused by bad surface contacts.

Recommendations

(i) The present prediction method can be used for calculations of engineering problems provided that the limitation imposed by the

* Measurement uncorrected for radiation loss, see Chapter 4, paragraph 4.6.2.

inadequacy to account for the effects of intermediate chemical reactions and large variations in turbulence intensity are noted.

- (ii) Further work is required to improve the present method, in the areas of chemical kinetics and its interaction with turbulent mixing.

NOMENCLATURE

A	= area
A	= frequency factor (equation 5a)
Al	= alumina
a	= constant in equation 5
a,b,c,d	= coefficients in equation 2b
a _j ,b _j ,c _j	= coefficients in equation 16
A _i ,B _i ,C _i ,D _i	= coefficients in equation 2c
C _μ , Cd	= constants in equation 10
Cp	= specific heat (equation 15)
d	= diameter
E	= activation energy (equation 5)
FRA	= forward step factor (equation 36)
g	= gravity acceleration
G	= diffusion rate (equation 33)
h	= heat transfer coefficient (Appendix F)
$\bar{h}$	= enthalpy
h	= total enthalpy (equation 3)
H	= heat of reaction (equation 3)
i	= grid point
I'	= an integral (Appendix E)
I''	= an integral (Appendix B)
Ir	= iradium
j	= species j
k	= turbulent kinetic energy (equation 11)
k	= thermal conductivity (Appendix F)
K	= rate constant of reaction rate (equation 5)
l	= length scale (equation 13)
m	= mass fraction
$\dot{m}'$	= proportion of entrainment rate (equation 33)
$\dot{m}''$	= entrainment rate
$\dot{m}'''$	= chemical reaction rate
M	= Mach number
M.I.T.	= minimum ignition temperature
Mo	= molybdenum
n, N	= number of grid points
Nu	= Nussult's number
p	= pressure

P	= probability density function
Pt	= platinum
P, Q	= coefficients in equation 2d
Q	= resultant velocity
r	= radius; radial distance
R	= gas constant
$\bar{R}$	= universal gas constant
Rh	= rhodium
s	= stoichiometric ratio (equations 20,21,25)
S	= source term (equation 2)
St	= Stanton's number
t	= time
T	= temperature
u	= streamwise component velocity
v	= radialwise component velocity
u', v'	= fluctuating velocities in x and y directions
W	= molecular weight
x	= streamwise distance
y	= radialwise distance
α	= mass fraction (equation 20)
β	= mass fraction (equation 21)
Π	= exchange coefficient (equation 2)
δx	= forward step size (equation 36)
ε	= dissipation rate of k (equation 12)
ϵ	= emissivity (Appendix F)
η	= equivalence
θ	= yaw angle
λ	= a scaling factor in mixing length hypothesis
μ	= viscosity
ξ	= oxygen index
ρ	= density
σ	= Prandtl's number
σ	= Stefan-Boltzman's constant
τ	= shear stress (Appendix A)
Φ	= dependent variable (equation 2)
ψ	= stream function (equation 27)
ω	= dimensionless quantity (equation 28)

Subscripts

a	= ambient
c	= convective
CL	= centre line
D	= downstream
E	= outer boundary
eff	= effective
f	= fuel
g	= gaseous
i	= grid number
I	= inner boundary
j	= species j
l	= laminar
n	= grid size
o	= at $x = 0$
P	= primary flow
R	= radiative
ref	= reference
S	= secondary flow
S	= surface
t	= turbulent
W	= wall

Chemical Species

CHO	= formyl
CH ₂ O	= formaldehyde
CH ₃	= methyl
CH ₃ O ₂	= methylperoxy
CH ₄	= methane
CO	= carbon monoxide
CO ₂	= carbon dioxide
H	= hydrogen
H ₂	= hydrogen gas
H ₂ O	= water
HO ₂	= hydroperoxy
H ₂ O ₂	= hydrogen peroxide
N ₂	= nitrogen gas

OH	=	hydroxyl
O	=	oxygen
O ₂	=	oxygen gas
M	=	third body

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APPENDIX A

DERIVATION OF C_μ and C_d

From the mixing length hypothesis (see reference 64):

$$\mu_t = \rho \left(\frac{\partial u}{\partial r} \right) l^2 \quad \text{————— (1)}$$

Also, from dimensional argument, the turbulent viscosity may be written in terms of turbulent kinetic energy with a scaling factor, C_μ , which is defined as:-

$$\left(\frac{\partial U}{\partial r} \right) \cdot l = C_\mu \cdot k^{\frac{1}{2}} \quad \text{————— (2)}$$

and hence

$$\mu_t = \rho \cdot C_\mu \cdot k^{\frac{1}{2}} \cdot l \quad \text{————— (3)}$$

From equations 1 and 3:-

$$k = \frac{1}{C_\mu} 2 \left(\frac{\partial U}{\partial r} \cdot l \right)^2 \quad \text{————— (4)}$$

Also, from the definition of shear stress,

$$\tau = \mu_t \left(\frac{\partial U}{\partial r} \right) \quad \text{————— (5)}$$

equations 1 and 5 yield:-

$$\tau = \rho \left(\frac{\partial U}{\partial r} \cdot l \right)^2 \quad \text{————— (6)}$$

therefore, from equations 4 and 6:-

$$C_\mu^2 = \frac{\tau}{\rho k} \quad \text{————— (7)}$$

Furthermore, in the region where the generation and dissipation of both the turbulent kinetic energy and its dissipation rate are roughly equal, the source term of k and ϵ is approximately zero:-

$$\text{i.e.} \quad \mu_t \left(\frac{\lambda U}{\delta r} \right)^2 - \rho \varepsilon = 0 \quad \text{-----} \quad (8)$$

and from the definition of ε

$$\text{i.e.} \quad \varepsilon = C_d \cdot \frac{k^{3/2}}{l} \quad \text{-----} \quad (9)$$

It can be seen from equations 8 and 9 that:-

$$\frac{C_d}{C_\mu} = \frac{\tau}{\rho k} \quad \text{-----} \quad (10)$$

and from equations 7 and 10:

$$C_d = C_\mu^3 \quad \text{-----} \quad (11)$$

$$\text{Thus, } C_\mu \cdot C_d = \left(\frac{\tau}{\rho k} \right)^2 \quad \text{-----} \quad (12)$$

Therefore, from the measurements of τ and k , the values of C_d and C_μ may be deduced from equations 11 and 12.

APPENDIX B

PROGRAM METHANE

Program METHANE has four sub-routines. The flow chart of this program is given in Figure 37.

B.1. Sub-Routine START

There are two functions of this sub-routine: (i) to sort out the control indices, data input and initial conditions, etc. so as to prepare the start of the computation, (ii) to terminate the program by deciding whether the predicted M.I.T. has reached the required accuracy. This sub-routine has nine chapters:-

Chapter 0. Data block. The physical constants, such as laminar viscosities, Prantl's numbers, etc. are inputted in the form of the data block.

Chapter 1. Index Selection. Control indices are selected according to whether the flow jets are free or confined (JFREE); reacting or non-reacting (INERT), etc.

Chapter 2. Data Input. The inlet flow properties such as temperature, flow rate, equivalence, etc. are prescribed.

Chapter 3. Searching for M.I.T. The M.I.T. iteration searching procedure starts from statement 30, which is also the starting point to the outer loop. The "span" of the temperature search (DTEMP) and the tolerated accuracy of prediction (TERROR) are preset. The initial guessed temperature (TPRIFL) is adjusted by $\pm$ DTEMP which in turn is reduced by half at each of the iteration loops. Some initial flow properties are reset to prevent carrying over after the previous iteration.

Chapter 4. Geometry. The radius of the jet nozzle (R(I)) is compensated for thermal expansion. R(I) is evenly distributed with respect to I, the grid point, in the two regions separated by NRDIV (= 20).

Chapter 5. Initial Profiles. The initial profiles (i.e. $x = 0$) of all the flow properties are prescribed in this Chapter except the laminar

viscosity (EMU) and the two turbulent quantities, k and ϵ , which are computed in Chapters 1 and 3 respectively of the sub-routine PHYS.

Chapter 6. Grid Distribution. ω_i (OM(I)) is calculated from the known ρ (RHO(I)), U (U(I)), r (R(I)) and $\psi_E - \psi_I$ (PEI) which have been previously evaluated in Chapters 4 and 5. Three other ω values are also computed for later uses from the following definitions.

$$\begin{aligned}\omega_{\text{mean}} \text{ (OMINT (I))} &= \frac{1}{2} (\omega_i + \omega_{i+1}) \\ \delta \omega_{\text{mean}} \text{ (BOM(I))} &= \frac{1}{2} (\omega_{i+1} - \omega_{i-1}) \\ \delta \omega \text{ (OMDIF (I))} &= \omega_i - \omega_{i-1}\end{aligned}$$

Chapter 7. Marching Integration. Having set the initial preparation of boundary conditions, grid distributions, etc. the sub-routine MARCH is called to perform the marching integration from $x = 0$ (ISTEP = 0) to a defined distance $x = XULAST$ (e.g. $XULAST = 25 \times dp$). Whether the mixing process produces ignition or no ignition is indicated by the return of the index ICON (ICON = 2 for ignition and = 1 for no ignition).

Chapter 8. Termination. The searching of M.I.T. is terminated in this Chapter. If the predicted M.I.T. is within the prescribed accuracy (i.e. $DTEMP < ERROR$) the program will stop, otherwise it will return to statement 30 and the procedure is repeated until $DTEMP < ERROR$ or the searching loop has run over more than ILAST times (ILAST: the maximum RUN permitted).

B.2. Sub-Routine MARCH

The functions of sub-routine MARCH are twofold: (i) to detect the occurrences of ignition, (ii) to detect the occurrence of ignition. This sub-routine has ten chapters.

Chapter 1. Forward Step and Entrainment. Each forward step starts at Chapter 1 and finishes at Chapter 10. The size of the forward step (DX) is basically computed from equation 36, but its size is also restricted by a length scale obtained from Reynold's number (DXRE) and/or entrainment rate calculation (DXPSI). Entrainment rate calculation is fundamentally based on equation 33, but because the formulation is an approximation the rate of entrainment is adjusted by multiplying equation 33 by a factor given by⁴⁷:-

$$C_1 \times \frac{f}{1+f} \times f^{C_2}$$

where
$$f = \frac{|\delta U|_{\text{E}}}{C_3 (\delta U)_{\text{max}}}$$

where C_1 (FACE), C_2 (FACEXP)

and C_3 (ULIM) are constants obtained empirically⁴⁷.

Chapter 2. Boundary Conditions. The bulk of the secondary flow has, in practical terms, remained unchanged. Thus, the outer boundary condition is assigned with the initial upstream value, i.e. at $x = 0$.

Chapter 3. Adjustment of Turbulent Constants. The product of C_μ and C_D (CMUCD) is a function of x given by:-

$$\frac{x}{dp} < 5$$

$$C_\mu C_D = 0.137$$

$$5 \leq \frac{x}{dp} \leq 20$$

$$C_\mu C_D = 0.00163 \left(\frac{x}{dp}\right) + 0.167$$

$$\frac{x}{dp} > 20$$

$$C_\mu C_D = 0.045$$

Chapters 4 and 8. Pressure Gradient. The initial guessed pressure gradient (DP) is evaluated in Chapter 4 based on the erroneous area (DA) and this is readjusted in Chapter 8 with the downstream values (see Appendix E).

Chapter 5. Solution Procedure. The sub-routine COMP is called to solve the finite difference equation. The six dependent variables, u , $\bar{R}$, k , ε , $\dot{m}_{CH_4}$, and $\dot{m}_{CO_2} + S_2 \dot{m}_{CH_4}$ are computed in the "SOLVE" section of the COMP sub-routine.

Chapter 6. The Secondary Variables. The flow properties such as temperature, density, etc. are dependent variables, but which can be evaluated from algebraic relationships. These are calculated after the prime dependent variables are known.

Chapter 7. Test for Ignition. At each forward step the radial temperature distribution (F(I,JTE)) is tested against an "ignition temperature" (TCRIC) which is a temperature a few degrees higher than the jet temperature at $x = 0$. If F(I,JTE) is greater than TCRIC, ignition is assumed and the

ignition index ICON is put at 2.

Chapter 9. Output Prints. Computed values of all variables are printed out at regular intervals, the length of which is decided by the index NSTA. An example of the M.I.T. prediction listing is given in Appendix D.

Chapter 10. Decise. The marching integration is terminated if XU is greater than XULAST. It can also be terminated if ignition has been detected before XU reaches XULAST by the conditional transfer in Chapter 7 to statement 102, in Chapter 9B.

B.3. Sub-routine COMP

The functions of this sub-routine are twofold: (i) to compute the radial distance, R(I); (ii) to deal with the solution procedure of the finite difference equations. This sub-routine has eight chapters.

Chapter 1. Calculation of $r^2/2$. The square of radial distance is calculated from the integral I :-

$$\frac{r^2}{2} = I'' = \int_0^{\omega} \frac{\psi_E - \psi_I}{\rho u} d\omega$$

At the E boundary the integral is modified by⁴⁷:-

$$I_E'' = I_E'' \times \frac{6 (r_n + r_{n-1})}{\left(\frac{\rho_{n-1} u_{n-1}}{\rho_n u_n} \right) (5r_{n-1} + 3r_n) + (r_{n-1} + 3r_n)}$$

This modification is based on the assumption that u is parabolic in r within the half-interval near the boundary.

Chapter 2. Calculation of r. $r = \sqrt{2 \times I''}$

Chapter 3. $1/R$, G and $\dot{m}'$. For convenience, the terms G and $\dot{m}'$ are multiplied by the factor of $\delta x / (\psi_E - \psi_I)$:-

$$HCON(I):(\text{relate to } \dot{m}') = \left(\dot{m}_I'' + (\dot{m}_E'' - \dot{m}_I'') \omega \frac{\delta x}{\psi_E - \psi_I} \right)$$

$$DIFU(I):(\text{relate to } G) = \left(\frac{r \mu_{eff}}{r} \cdot \frac{\delta x}{\psi_E - \psi_I} \right)$$

$$\text{DXDPEI: (relate to } 1/R) = \frac{\delta x}{\psi_E - \psi_I}$$

Chapter 4. A,B,C,D for U-velocity. Again, for convenience, the coefficients in the U equation are multiplied by $x/(\psi_E - \psi_I)$:

$$A(I) = \frac{\delta x}{(\psi_E - \psi_I)} \left\{ \frac{r_{\mu\text{eff}}}{r_{i+1} - r_i} - \frac{1}{2} \left[\ddot{m}_I + (\ddot{m}_E - \ddot{m}_I) \right] \omega \right\}$$

$$B(I) = \frac{\delta x}{(\psi_E - \psi_I)} \left\{ \frac{r_{\mu\text{eff}}}{r_i - r_{i-1}} + \frac{1}{2} \left[\ddot{m}_I + (\ddot{m}_E - \ddot{m}_I) \right] \omega \right\}$$

$$C(I) = \phi_{i,u} (\omega_{i+\frac{1}{2}} - \omega_{i-\frac{1}{2}}) + \frac{\delta x}{\psi_E - \psi_I} - S_i$$

$$D(I) = A_i + B_i + (\omega_{i+\frac{1}{2}} - \omega_{i-\frac{1}{2}}) - \frac{\delta x}{\psi_E - \psi_I} \cdot S_i'$$

A_i and B_i are further evaluated in conjunction with the hybrid formulae⁴⁷.

$$A_i = \max \left[0, (T - \frac{1}{2} \dot{m})_{i+\frac{1}{2}}, -\dot{m}_{i+\frac{1}{2}}' \right]$$

$$B_i = \max \left[0, (T + \frac{1}{2} \dot{m})_{i+\frac{1}{2}} \right]$$

The source terms are evaluated in sub-routine PHYS with the following notations:-

$$SI(I) = \frac{\delta x}{\psi_E - \psi_I} \cdot S_i = \frac{\delta x}{-\rho u} \cdot (\omega_{i+\frac{1}{2}} - \omega_{i-\frac{1}{2}}) \cdot S_\phi$$

where S_ϕ is the source term in equation 2.

Chapter 5. The u-velocity. $C(I)$ and $D(I)$ array are used temporarily to store Q_i and P_i and from which the velocity u_i is computed in reverse order of i :-

$$u_{i,D} = P_i \cdot u_{i+1,D} + Q_i$$

Chapter 6. A,B,C,D for ϕ (F(I,J)). The five other dependent variables (hence $NF = 5$) are computed in the DO loop (DO 480). The coefficients are evaluated by the same procedures as before except for $\sigma_\phi = 1$ for which the diffusion term is exactly the same as the velocity equation. The source terms are treated in three different manners. For these variables which have no source term (i.e. $S_i' = S_i = 0$), $KSOURC = 3$. For these variables whose source terms are not treated as functions of ϕ (i.e. $S_i = 0$), $KSOURC = 2$ and the rest are given the value of $KSOURC = 1$.

Chapter 7. The Dependent Variables. The five dependent variables $F(I,J)$ are evaluated by the same manner as the u-velocity:-

$$\text{i.e. } \phi_{i,D} = P_i \cdot \phi_{i+1,D} + Q_i$$

in the reverse order of i.

Chapter 8. Updating the Step. Finally, the downstream functions are updated to become the upstream value in preparation for the next marching step.

B.4. Sub-Routine PHYS

The functions of this sub-routine are twofold: (i) to calculate the exchange coefficients, (ii) to calculate the source terms. This sub-routine has nine chapters:-

Chapter 1. Laminar Viscosity. The laminar viscosity is calculated according to Sutherland's law³⁹:

$$\text{EMU (I)} = (\mu_{1,j})_{\text{Ref}} \cdot \left(\frac{T}{T_{\text{Ref}}}\right)^{\frac{1}{2}} \left(\frac{1.505}{1+0.505 \frac{T_{\text{Ref}}}{T}}\right)$$

Chapter 2. Turbulent Length Scale. The initial (at $x = 0$) turbulent length scale, $F(I,JEL)$, is derived from the Prandtl's mixing length hypothesis⁴⁷:

$$F(I,JEL) = \lambda \cdot (r_{I.} - r_{II})$$

where λ is a constant ($\lambda = 0.09$, ALMG) and r_I and r_{II} are edges⁴⁷ at which the velocity gradient changes from above to below a prescribed minimum gradient. ($\text{DUDYMN} = \text{FR} \cdot (U_{\text{max}} - U_{\text{min}})/r_p$, where $\text{FR} = 0.033$, r_p is the radius of the jet nozzle).

Chapter 3. Initial k and ε values. Initial k and ε (at $x = 0$) are calculated from:-

$$k = 2 \cdot \frac{C_\mu}{C_D} \cdot \left(1 \cdot \frac{\partial u}{\partial r}\right)^2$$

$$\text{and } \varepsilon = \frac{1}{2} \sqrt{C_\mu \cdot C_D} \cdot \frac{\partial u}{\partial r} \cdot k$$

Chapter 4. Turbulent Viscosity.

$$EMUT = C_{\mu} \cdot Cd \cdot \rho \frac{k^2}{\varepsilon}$$

Chapter 5. Momentum Source Term. For momentum equation, KSOURC = 2, (i.e. $S_i = 0$). Thus:

$$SI(I) = \frac{\delta x}{\rho u} (\omega_{i+\frac{1}{2}} - \omega_{i-\frac{1}{2}}) \left[g(\rho_E - \rho) - \frac{dp}{dx} \right]$$

Chapter 6. Exchange Coefficients. The exchange coefficient $\Gamma_{eff, \phi}$ ($= \frac{\mu_{eff}}{\sigma_{eff}}$) is distinguished between $\Gamma_{eff, \phi} = 1$ (NEWPR = 1) or otherwise (NEWPR = 2). For NEWPR = 1 the $\Gamma_{eff, \phi} = \mu_{eff}$. The two diffusion terms are:-

$$\begin{aligned} DIFU(I) &= \frac{\delta x}{\psi_E - \psi_I} \cdot \frac{r \cdot \mu_{eff}}{\delta r} \quad (NEWPR = 1) \\ DIF(I) &= \frac{\delta x}{\psi_E - \psi_I} \cdot \frac{r \cdot \mu_{eff}}{\delta r \cdot \sigma_{eff}} \quad (NEWPR = 2) \end{aligned}$$

Chapter 7. Source Term for h. KSOURC = 2, thus $S_i = 0$, thus

$$SI(I) = \frac{\delta x}{\psi_E - \psi_I} \cdot \delta \left\{ r \cdot \mu_{eff} \left[\left(1 - \frac{1}{\sigma_h} \frac{\partial \left(\frac{u^2}{2} \right)}{\partial r} + \left(\frac{1}{\sigma_k} - \frac{1}{\sigma_h} \right) \frac{\partial k}{\partial r} \right) \right] \right\}$$

Chapter 8. Source Term for m_{CH_4} . The source term of m_{CH_4} is based on up-stream values. This could induce a large errors in areas where there was a step change, such as in the region near the flame front. To prevent this from happening, a term m'_{CH_4} is devised and defined as⁴⁷:-

$$m'_{CH_4} = \frac{1}{S_1} \left[|m_{O_2} - S_1 m_{CH_4}| - (m_{O_2} - S_1 m_{CH_4}) \right]$$

so that:

$$\text{lean mixture: } (m_{O_2} - S_1 m_{CH_4}) > 0 \quad m'_{CH_4} = 0$$

$$\text{rich mixture: } (m_{O_2} - S_1 m_{CH_4}) \leq 0 \quad m'_{CH_4} = m_{CH_4} - \frac{m_{O_2}}{S_1}$$

Thus, the source term is linearised as:-

$$d = \frac{-S_i}{\delta \psi} \left(1 - \frac{m_{CH_4}}{m_{CH_4}} \right) + \frac{S_i}{\delta \psi} \left(1 - \frac{m_{CH_4}}{m_{CH_4}} \right) \frac{m_{CH_4}}{m_{CH_4}}$$

$$\text{where } S_i = \frac{\delta \psi}{\rho u} \cdot S_{\phi} = S_i'$$

$$\text{and } S_{\phi} = -K m_{CH_4} \cdot m_{O_2} \cdot p^2 \cdot T^{-3/2} \cdot \exp(-E/RT) \cdot \left(\frac{2}{1+\eta}\right)^a$$

Chapter 9. Source Term for k and ε. The generation and dissipation terms in the source term of k and ε are each calculated as follows:-

$$GENK(I) = \frac{\delta x \cdot \omega}{\rho u} \cdot \mu_t \cdot \left(\frac{\partial u}{\partial r}\right)^2$$

$$DISSK(I) = \frac{\delta x \cdot \delta \omega}{\rho \cdot u} \cdot \rho \cdot \varepsilon$$

These terms are then linearised as:-

For k

$$S_i = \frac{\delta x \cdot \delta \omega}{\rho \cdot u} \cdot \left[1.5 \mu_t \left(\frac{u}{r}\right)^2 + 0.92 \rho \varepsilon \right]$$

$$\text{and } S_i' = \frac{\delta x \cdot \delta \omega}{\rho \cdot u} \left[-0.5 \mu_t \left(\frac{u}{r}\right)^2 - 1.92 \rho \varepsilon \right]$$

For ε

$$S_i = \frac{\delta x \cdot \delta \omega}{\rho u} \left[1.6 \mu_t \left(\frac{\partial u}{\partial r}\right)^2 + 0.92 \rho \varepsilon \right]$$

$$\text{and } S_i' = \frac{\delta x \cdot \delta \omega}{\rho \cdot u} \left[-2.84 \rho \varepsilon \right] \cdot \frac{1}{k}$$

APPENDIX C

Listing of Program METHANE

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בס"ד

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6

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C

C

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C	-----PRANTAL AND SCHMIDT NUMBERS	START	114
	DO 20 J=1,NF	START	115
	RECPRL(J)=1./PRLAM	START	116
20	RECPRT(J)=1./PRTURB	START	117
	RECPRT(JK)=1./SIGK	START	118
	RECPRT(J2)=1./SIG2	START	119
C	-----	START	120
C	2B 2B FLOW PROPERTIES 2B 2B	START	121
C	-----TEMPERATURE AND PRESSURE	START	122
	PRESS=1.013E+5	START	123
	TSECFL=423.0	START	124
	TPRIFL=1745.0	START	125
C	-----FLOWRATE	START	126
	PRIFLO=0.0115	START	127
	SECFL0=0.05	START	128
	FLOPR1=PRIFLO	START	129
	FLOSEC=SECFL0	START	130
	PRIFLO=PRIFLO/(2.*3.142)	START	131
	SECFL0=SECFL0/(2.*3.142)	START	132
C	-----FUEL /AIR RATIO	START	133
	OXIND=0.23285	START	134
	FUIND=1.0	START	135
	IF(INERT.NE.1) GO TO 21	START	136
	OXIND=0.233	START	137
	FUIND=0.0	START	138
21	CONTINUE	START	139
C	-----RADIUS	START	140
	RPRIFL=0.009675	START	141
	ROUT=0.145	START	142
C	-----COMBUSTION MODEL CONSTANTS	START	143
	CEBUA=4.0	START	144
	CEBUB=1.47	START	145
	PREEXP=7.88E6	START	146
	ARRCON=2.15E8	START	147
	TT=4.1	START	148
	IF(FUIND.GT.1.0) TT=3.3	START	149
C	-----	START	150

CHAPTER	3333333333333333	SEARCH FOR IGNITION TEMP	3333333333333333	START	151
	INDEX=1			START	152
	ICON=1			START	153
	ILAST=10			START	154
	IF(INERT.EQ.1) ILAST=1			START	155
	IRUN=1			START	156
	TERROR=1.0			START	157
	DTEMP=32.0			START	158
	IF(IRUN.EQ.1) GO TO 33			START	159
30	INDEX=INDEX*2			START	160
	GO TO (31,32),ICON			START	161
31	TPRIFL=TPRIFL+2.0*DTEMP/FLOAT(INDEX)			START	162
	GO TO 33			START	163
32	TPRIFL=TPRIFL-2.0*DTEMP/FLOAT(INDEX)			START	164
33	CONTINUE			START	165
	ICON=1			START	166
	TDELTA=2.0*DTEMP/FLOAT(INDEX)			START	167
	TCRIC=TPRIFL+100.0			START	168
	-----RESET INITIAL VALUES			START	169
	XD=XU			START	170
	DP=DX=0.0			START	171
	ISTEP=0			START	172
	IFIN=1			START	173
	CMUCD=0.137			START	174
	XU=0.0			START	175
	DX=DXLAST=0.16			START	176
	QPI=QPE=1.0			START	177
	FACE=1.0			START	178
	PRESS=1.013E5			START	179
	DO 34 I=1,N			START	180
	U(I)=0.0			START	181
	EMU(I)=0.0			START	182
	DISSK(I)=0.0			START	183
	GENK(I)=0.0			START	184
	DO 34 J=1,12			START	185
34	F(I,J)=0.0			START	186
	-----			START	187


```

      F(I,JBE)=F(1,JBE)
509 F(I,JOX)=F(1,JOX)
506 CONTINUE
C -----CARBON DIOXIDE AND WATER VAPOUR AND NITROGEN
DO 511 I=1,N
F(I,JCO2)=F(1,JH2O)=0.
511 F(I,JN2)=1.-F(1,JF)-F(1,JOX)-F(1,JCO2)-F(1,JH2O)
C ----- ALFA AND BETA
IF (INERT.NE.2) GO TO 513
DO 512 I=1,N
512 F(I,JBE)=F(1,JOX)-OXDFJ*F(1,JF)
513 CONTINUE

DO 514 I=1,N
514 F(I,JAL)=F(1,JCO2)+CO2DFU*F(1,JF)
C -----TEMPERATURE
F(1,JTE)=TPRIFL
F(N,JTE)=TSECFL
DF=F(1,JTE)-F(N,JTE)
DO 515 I=1,N
515 F(I,JTE)=F(N,JTE)+DF*(1.-R(I)/R(N))**(1./TTEMP)
C -----DENSITY
PDGSCN=PRESS/GASCON
DO 516 I=1,N
516 RHO(I)=PDGSCN/F(I,JTE)
RHOCON=PDGSCN/F(1,JTE)
VMIX(I)=F(1,JF)*RECWFJ+F(1,JOX)*RECWOX+F(1,JCO2)*RECWCO
+ F(1,JH2O)*RECWHO+F(1,JN2)*RECWN2
1 RHO(I)=RHOCON/VMIX(I)
C -----VELOCITY
U(N)=2.*SECFLU/(RHO(N)*(ROUT-R(N))*(ROUT+R(N)))
AINT1=AINT2=0.
DO 517 I=1,NH1
517 RHOI=RHO(I)*R(I)
RHOI=RHOI*(1.-0.5*(R(I)+R(I+1))/R(N))**(1./TVEL)
DELR=R(I+1)-R(I)
AINT1=AINT1+RHOI*DELR
AINT2=AINT2+RHOI*DELR
U(1)=(PRIFLU+U(N)*(AINT2-AINT1))/AINT2

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START 261

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208 FORMAT(3H I,4X,13HTHIS IS AFTER,5(1H-),6HSTEP=,14,2X,3HAT XU=,
1 1PE9.3,2X,11HAFTER IRUN=,12,2X,12HWITH TDELTA=,1PE9.3,2X,
2 11HAND TERROR=,1PE9.3,7X,1HI)
DO 209 I=1,3
209 WRITE(6,205)
WRITE(6,206)
IF(IRUN.GE.ILAST.OR.TDELTA.LE.TERROR) GO TO 120
IRUN=IRUN+1
GO TO 30
120 CONTINUE
STOP
END

```

```

START 335
START 337
START 338
START 339
START 340
START 341
START 342
START 343
START 344
START 345
START 346
START 347

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SUBROUTINE MARCH

Line	Code	Statement	Event	Time
1	COMMON/COMA/		MARCH	3
2	ADPEL(50),BIG,BOM(50),CSALFA,DIF(50),DIFU(50),DP,DX,DXLAST,		MARCH	4
3	EMU(50),F(50,12),HOMDFE,HOMDF1,1DIMF,IFIN,ISTEP,ITEST,KEX,KIN,J,		MARCH	5
4	KRAD,KSOURC,MOMSOJ,N,NEWPR,NF,NM1,NM2,NM3,OM(50),OMDIF(50),OM1,		MARCH	6
5	OME,PEI,PSIE,PSI1,R(50),RECRU(50),RECYDF(50),RHO(50),RME,RMI,		MARCH	7
6	SI(50),SIP(50),TINY,J(50),XD,XU,Y(50),YE,Y1,OMINT(50)		MARCH	8
7	COMMON/COMB/		MARCH	9
8	AGRAV,ALNG,ANSTA,ARRCON,CEBUA,CEBUB,C02DFU,CD,CMU,CMUCD,C1MOD4,		MARCH	10
9	C1MOD5,C2MOD4,C2MOD5,CMIX(50),DISSK(50),DUOY(50),DPOX,OTEMP,		MARCH	11
10	DXMAX,FR,FRA,FACE,FACEXP,FJ2D,FJKD,FLOPR1,FLOSEC,FLOTOT,FUIND,		MARCH	12
11	GASCON,GENK(50),HFU,H2UC02,IPASS,ICONBT,INERT,ICON,IRUN,JFREE,		MARCH	13
12	JAL,JLE,JCO2,JEL,JF,JH,JH20,JK,J2,JN2,JOX,JTE,KUDIF,NSTA,OXIND,		MARCH	14
13	OXDFU,PREEXP,PRESS,PRIFLU,PEILIM,RECPRL(5),RECPRT(5),REYNOS,		MARCH	15
14	KPRIFL,RECWFU,RECWOX,RECWCO,RELWHO,RECWN2,ROUT,S1GK,S1G2,DXRAT,		MARCH	16
15	TGRIC,TPRIFL,TSEOFI,TERROR,TTEMP,TVEL,TAUDK,TT,TREFV,UOIF,UFAC,		MARCH	17
16	ULIN,VISCO2,VISFU,VISH20,VISN2,VISOX,VN1X(50),XULAST,XOUT		MARCH	18
17	CHAPTER 111111111111 STEP CONTROL AND ENTRAINMENT 11111111111111111111		MARCH	19
18	GO TO 700		MARCH	20
19	600 DXY=FRA*RPRIFL		MARCH	21
20	IF(ISTEP.LT.20) DXY=FRA*RPRIFL*((1.+FLOAT(ISTEP))/20.)		MARCH	22
21	DXRE=DXY*PEI/(.5*(R(1)+R(N))*EMU(1)+TINY)		MARCH	23
22	----- ENTRAINMENT RATES		MARCH	24
23	KUDIF=ISTEP		MARCH	25
24	UMAX=U(1)		MARCH	26
25	UMIN=U(1)		MARCH	27
26	DO 615 I=2,N		MARCH	28
27	UMAX=AMAX1(UMAX,U(I))		MARCH	29
28	615 UMIN=AMIN1(UMIN,U(I))		MARCH	30
29	UDIF=UMAX-UMIN		MARCH	31
30	RATE=ABS((U(NM1)-U(N))/(UDIF*ULIM+TINY))		MARCH	32
31	RME=-(R(NM2)+R(NM1))*(EMU(NM2)+EMU(NM1))*RECYDF(NM2)*RATE/		MARCH	33
32	(1.+RATE)		MARCH	34
33	FACE=FACE*RATE**FACEXP		MARCH	35
34	FACE=AMAX1(.01,AMIN1(FACE,10.))		MARCH	36
35	RME=RME*FACE		MARCH	37

	U(1)=U(2)	MARCH	77
	DO 737 J=1,NF	MARCH	78
737	F(1,J)=F(2,J)	MARCH	79
	IF(ISTEP.EQ.0) GO TO 71	MARCH	80
C	----- E BOUNDARY	MARCH	81
	U(N)=UD	MARCH	82
	F(N,JH)=ENTHD	MARCH	83
	F(N,JTE)=TD	MARCH	84
	F(N,JF)=FUD	MARCH	85
	F(N,JOX)=OXD	MARCH	86
	F(N,JCO2)=CO2D	MARCH	87
	F(N,JH2O)=H2OD	MARCH	88
	F(N,JN2)=N2D	MARCH	89
	F(N,JAL)=ALD	MARCH	90
	F(N,JBE)=BED	MARCH	91
	RHO(N)=RHOD	MARCH	92
	CMIX(N)=CMIXD	MARCH	93
	RECRU(N)=1./(RHO(N)*J(N)+TINY)	MARCH	94
	F(N,JK)=F(NM1,JK)	MARCH	95
	F(N,J2)=F(NM1,J2)	MARCH	96
71	CONTINUE	MARCH	97
C	-----	MARCH	98
	CHAPTER 3333 TURBULENT CONSTANTS ADJUSTMENT 333333333333333333333333	MARCH	99
	IF(ISTEP.EQ.0) GO TO 752	MARCH	100
	XDDIA=XU/(2.0*RPRIFL)	MARCH	101
	CMUCD=-0.00613*XDDIA+0.137	MARCH	102
	IF(XDDIA.LT.5.0) CMUCD=0.137	MARCH	103
	IF(XDDIA.GT.20.0) CMUCD=0.045	MARCH	104
752	CONTINUE	MARCH	105
	GO TO ISTART, (751,800)	MARCH	106
751	ASSIGN 800 TO ISTART	MARCH	107
	GO TO 900	MARCH	108
C	-----	MARCH	109
	CHAPTER 444444444444 PRESSURE GRADIENT (A) 444444444444444444444444	MARCH	110
800	IF(JFREE.EQ.1) GO TO 801	MARCH	111
	AFLOWU=AFLOWD	MARCH	112
	AUCTD=0.5*ROUT*ROUT	MARCH	113


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1 7HTSECFL=,1PE9.3,34X,1HI)
WRITE(6,1015) FUIND,OXIND
1015 FORMAT(3H 1,4X,17HEQUIVALENT RATIO=,F5.3,31X,13HOXYGEN INDEX=,
1 F5.3,41X,1HI)
WRITE(6,1016) REYNDS,AMACH
1016 FORMAT(3H 1,4X,16HREYNOLDS NUMBER=,1PE9.3,26X,12HAMACH NUMBER=,
1 1PE9.3,38X,1HI)
WRITE(6,1017) N,FRA,XULAST
1017 FORMAT(3H 1,4X,9HGRID SIZE,5(1H-),26X,2HN=,12,18X,4HFRA=,F6.,
1 12X,7HXULAST=,F5.3,16X,1HI)
WRITE(6,1018) ARCON,PREEXP,TT
1018 FORMAT(3H 1,4X,26HCOMBUSTION CONSTANTS,5(1H-),15X,7HARCON=,

1 1PE9.3,6X,7HPREEXP=,1PE9.3,6X,3HTT=,F4.2,21X,1HI)
WRITE(6,1019)
1019 FORMAT(3H 1,4X,17HGRID DISTRIBUTION,5(1H-),74UN(1),S,5(1H-),7cX,
1 1HI)
WRITE(6,1020) OM(I),I=1,N)
1020 FORMAT(3H 1,4X,1P10E10.3,12X,1HI)
WRITE(6,1021)
1021 FORMAT(3H 1,4X,10(1H+),18HINITIAL CONDITIONS,10(1H+),74X,1HI)
GO TO 1022
1026 FORMAT(2X,118(1HT))
106 CONTINUE
-----
9B 9B 9B.....STATION OUTPUT.....9B 9B 9B
1100 CONTINUE
IF(FLOAT(ISTEP/NSTA).EQ.FLOAT(ISTEP)/ANSTA) GO TO 102
GO TO 105
102 CONTINUE
XOD1A=XU/D1ANET
WRITE(6,1024)
DO 107 I=1,5
107 WRITE(6,1027)
WRITE(6,104) IRUN,ISTEP,XU,XOD1A
104 FORMAT(3H 1,4X,10(1H*),11HSTEP OUTPUT,10(1H*),10X,5HIRUN=,12,6X,
1 6HISTEP=,14,6X,34XU=,1PE9.3,6X,4HX/D=,1PE9.3,11X,1HI)
WRITE(6,1027)

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RETURN
END

MARCH 299
MARCH 300

SUBROUTINE COMP

C	----- COMMON BLOCK -----	COMP	3
	COMMON/CONA/	COMP	4
	1 AUPEI(50),BIG,BOM(50),CSALFA,DIF(50),DIFU(50),DP,DX,DXLAST,	COMP	5
	2 EMU(50),F(600),HOMDFE,HOMDFI,IDIMF,IFIN,ISTEP,IT=ST,KEX,KIN,J,	COMP	6
	3 KRAO,KSOURCE,HOMSOJ,N,NEWPR,NF,NM1,NM2,NM3,OM(50),OMDIF(50),O=1,	COMP	7
	4 OME,PEI,PSIE,PSII,R(50),RECRU(50),RECYDF(50),RHO(50),RME,RMI,	COMP	8
	5 SI(50),SIP(50),TINY,J(50),XD,XU,Y(50),YE,YI,OMINT(50)	COMP	9
	DIMENSION A(50),B(50),C(50),CON(50),D(50),HCON(50)	COMP	10
	EQUIVALENCE (A(1),DIF(1)),(C(1),SI(1)),(D(1),SIP(1))	COMP	11
C	DISTAN ----- DISTAN ----- DISTAN ----- DISTAN	COMP	12
	ENTRY DISTAN	COMP	13
C	DISTAN ----- DISTAN ----- DISTAN ----- DISTAN	COMP	14
C	-----	COMP	15
C	CHAPTER 11111111111111 CALAULATION OF Y(I)**2/2 11111111111111111111	COMP	16
C	----- RECIPROCAL OF RHO(I)*U(I) -----	COMP	17
	DO 221 I=1,N	COMP	18
	RECRU(I)=1./(RHO(I)*U(I)+TINY)	COMP	19
	IF(I.EQ.1.OR.I.EQ.N) GO TO 221	COMP	20
	ADPEI(I)=BOM(I)*RECRU(I)	COMP	21
	IF(RECRU(I).GT.0.) GO TO 221	COMP	22
	IFIN=2	COMP	23
	WRITE(6,223) RECRU(I),I,ISTEP	COMP	24
	223 FORMAT(14H *** RECRU(I)=,1PE10.3,6H AT I=,14,11H AND ISTEP=,15,	COMP	25
	1 16H *** COMP.DISTAN)	COMP	26
	221 CONTINUE	COMP	27
C	----- THE BOUNDARY MODIFICATION -----	COMP	28
	RAT=RECRU(2)*RHO(1)*U(1)	COMP	29
	BPI=(R(1)+(.833333*RAT+.16667)+.5*R(2)*(RAT+1.))/(R(1)+R(2))	COMP	30
	RAT=RECRU(NM1)*RHO(N)*J(N)	COMP	31
	BPE=(R(N)+(.833333*RAT+.16667)+.5*R(NM1)*(RAT+1.))/(R(N)+R(NM1))	COMP	32
	STORE=OM(2)/BPI	COMP	33
	ADPEI(2)=(HOMDFI+STORE)*RECRU(2)	COMP	34
	Y(2)=PEI*RECRU(2)*STORE	COMP	35
	HPEI=.5*PEI	COMP	36
C	----- TEMPORARY USE OF Y(1) ARRAY -----	COMP	37
	DO 231 I=3,NM1	COMP	38
	231 Y(I)=Y(I-1)+HPEI*UMDIF(I)*(RECRU(1)+RECRU(I-1))	COMP	39

ENT=ABS(RM1)+ABS(RME)	COMP	77
IF(ENT.LE.TINY) GO TO 310	COMP	78
HCON1=RM1*CONST1	COMP	79
HCONDF=(RME-RM1)*CONST1	COMP	80
DO 412 I=2,NH1	COMP	81
HCON(I)=HCON1+HCONDF*DMINT(I)	COMP	82
412 CON(I)=HCON(I)+HCON(I)	COMP	83
310 J=0	COMP	84
C ----- CALL SUBROUTINE PHYS AT ENTRY PHYSU	COMP	85
CALL PHYSU	COMP	86
CONST2=.5*CONST1	COMP	87
DO 416 I=2,NM2	COMP	88
416 DIFU(I)=CONST2*(R(I+1)+R(I))*(EMU(I)+EMU(I+1))*RCYDF(I)	COMP	89
C -----	COMP	90
CHAPTER 444444444444444444444444 A,B,C,D FOR U VELOCITY 4444444444444444444444	COMP	91
IF(ENT.LE.TINY) GO TO 312	COMP	92
DO 417 I=2,NH2	COMP	93
A(I)=AMAX1(0.,DIFU(I)-HCON(I),-CON(I))	COMP	94
417 B(I+1)=A(I)+CON(I)	COMP	95
GO TO 314	COMP	96
312 DO 315 I=2,NH2	COMP	97
A(I)=DIFU(I)	COMP	98
315 B(I+1)=A(I)	COMP	99
314 TI=0.	COMP	100
TE=0.	COMP	101
B(2)=AMAX1((TI+RM1)*DXDPEI,0.)	COMP	102
A(NH1)=AMAX1((TE-RME)*DXDPEI,0.)	COMP	103
IF(MUMSQU.EQ.0) GO TO 431	COMP	104
DO 418 I=2,NH1	COMP	105
C(I)=U(I)*BOM(I)+SI(I)	COMP	106
418 D(I)=A(I)+B(I)+BOM(I)	COMP	107
GO TO 432	COMP	108
431 DO 433 I=2,NH1	COMP	109
C(I)=U(I)*BOM(I)	COMP	110
433 D(I)=A(I)+B(I)+BOM(I)	COMP	111
432 CONTINUE	COMP	112
IF(ITEST.EQ.1) GO TO 404	COMP	113


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TIF=0.
TEF=0.
IF (ITEST.EQ.1) GO TO 450
WRITE(6,451) J,(DIF(I),I=2,NM1)
451 FORMAT(24H COMP SOLVE TESTS FOR J=,13/8H DIF(I)=/(3X,1P5E11.3))
450 IF (NEWPR.EQ.1) GO TO 337
IF (ENT.LE.TINY) GO TO 335
DO 484 I=2,NM2
A(I)=AMAX1(0.,DIF(I)-4CON(I),-CON(I))
484 B(I+1)=A(I)+CON(I)
GO TO 337
335 DO 338 I=2,NM2
A(I)=DIF(I)
338 B(I+1)=A(I)
337 CONTINUE
B(2)=AMAX1((TIF+RMI)*DXDPEI,0.)
A(NM1)=AMAX1((TEF-RME)*DXDPEI,0.)
GO TO (501,502,503), KSOURC
----- KSOURC=1, GENERAL
C
501 DO 485 I=2,NM1
IJ=I+IDJ
D(I)=A(I)+B(I)+BOM(I)-SIP(I)
485 C(I)=F(IJ)*BOM(I)+SI(I)
GO TO 504
----- KSOURC=2, NO SIP
C
502 DO 505 I=2,NM1
IJ=I+IDJ
D(I)=A(I)+B(I)+BOM(I)
505 C(I)=F(IJ)*BOM(I)+SI(I)
GO TO 504
----- KSOURC=3, NO SIP OR SI
C
503 DO 506 I=2,NM1
IJ=I+IDJ
D(I)=A(I)+B(I)+BOM(I)
506 C(I)=F(IJ)*BOM(I)
504 CONTINUE
C
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COMP	187

IF (ITEST.EQ.1) GO TO 464	COMP	188
WRITE(6,405) (A(I),I=2,NM1)	COMP	189
WRITE(6,406) (B(I),I=2,NM1)	COMP	190
WRITE(6,407) (C(I),I=2,NM1)	COMP	191
WRITE(6,408) (D(I),I=2,NM1)	COMP	192

C	COMP	193
CHAPTER 7777777777777777 THE OTHER DEPENDING VARIABLES 777777777777	COMP	194
464 C(2)=(B(2)*F(I1J)+C(2))/D(2)	COMP	195
D(2)=A(2)/D(2)	COMP	196
DO 465 I=3,NM1	COMP	197
T=1./(D(I)-B(I)*D(I-1))	COMP	198
D(I)=A(I)*T	COMP	199
465 C(I)=(B(I)*C(I-1)+C(I))*T	COMP	200
DO 466 IDASH=1,NM2	COMP	201
I=N-IDASH	COMP	202
IJ=I+IDJ	COMP	203
466 F(IJ)=D(I)*F(IJ+1)+C(I)	COMP	204
F(I1J)=F(I2J)	COMP	205
IF (ITEST.EQ.1) GO TO 480	COMP	206
WRITE(6,476) J, (F(I+IDJ),I=1,N)	COMP	207
476 FORMAT(6H F(I,,I2,1H)/(3X,1P6E11.3))	COMP	208
480 CONTINUE	COMP	209

C	COMP	210
CHAPTER 8888888888888888 UPDATE THE STEP 8888888888888888888888888888888888	COMP	211
481 XU=XD	COMP	212
PSII=PSII-RMI*DX	COMP	213
PSIE=PSIE-RNE*DX	COMP	214
PEI=PSIE-PSII	COMP	215
ISTEP=ISTEP+1	COMP	216
RETURN	COMP	217
END	COMP	218

SUBROUTINE PHYS

C	COMMON BLOCK	PHYS	3
	COMMON/CONA/	PHYS	4
	1 ADPEI(50),BIG,60N(50),CSALFA,DIF(50),DIFU(50),DP,DX,DXLAST,	PHYS	5
	2 EMU(50),F(50,12),HOMDFE,HOMDF1,1DIMF,IF1N,1STEP,1TEST,KEX,KIN,J,	PHYS	6
	3 KRAD,KSOURCE,MOMSOU,N,NEWPR,NF,NM1,NM2,NM3,OM(50),OMDIF(50),OMI,	PHYS	7
	4 OME,PEI,PSIE,PSII,R(50),RECRU(50),RECYDF(50),RHU(50),RME,XMI,	PHYS	8
	5 SI(50),SIP(50),TINY,J(50),XD,XU,Y(50),YE,YI,UMINT(50)	PHYS	9
	COMMON/COMB/	PHYS	10
	1 AGRAV,ALMG,ANSTA,ARRCON,CEBUA,CEBUB,C02DFU,CD,CMU,CMUCD,C1MOD4,	PHYS	11
	2 C1MOD5,C2MOD4,C2MOD5,CMIX(50),DISSK(50),DUDY(50),DPDX,DIEMP,	PHYS	12
	3 DXMAX,FR,FRA,FACE,FADEXP,FJ2D,FJKD,FLUPRI,FLOSEC,FLOTOT,FJIND,	PHYS	13
	4 GASCON,GENK(50),HFU,H2O2,IPASS,ICOMBT,INERT,ICUN,IRUN,JFREE,	PHYS	14
	5 JAL,JBE,JC02,JEL,JF,JH,JH20,JK,J2,JN2,JOX,JTE,KUDIF,NSIA,OXIND,	PHYS	15
	6 OXDFU,PREEXP,PRESS,PRIFLO,PEILM,RECPRL(5),RECPRT(5),REYNDS,	PHYS	16
	7 RPRIFL,RECWFU,RECWX,RECWC0,RECWHU,RECWN2,ROUT,SIGK,SIG2,DXRAT,	PHYS	17
	8 TCRI,TPRIFL,TSECFL,TERROR,TTEMP,TVEL,TAUDK,TT,TREFV,UDIF,UFAC,	PHYS	18
	9 JLIH,VISCO2,VISFJ,VISH20,VISN2,VISOX,VNIX(50),XULAST,XOUT	PHYS	19
	DIMENSION YEDGE(6)	PHYS	20
	DATA KUDIF/-1/	PHYS	21
C	PHYSU	PHYS	22
C	PHYSU	PHYS	23
C	PHYSU	PHYS	24
C	PHYSU	PHYS	25
C	PHYSU	PHYS	26
C	PHYSU	PHYS	27
	CHAPTER 11111111111111111111111111111111 LAMINAR VISICUSITY 11111111111111111111	PHYS	28
	DO 110 I=1,N	PHYS	29
	TR2=F(I,JTE)/TREFV	PHYS	30
	TR1=1.505*SQRT(TR2)/(1.0+0.505*TR2)	PHYS	31
	VFU=VISFU*TR1	PHYS	32
	VOX=VISOX*TR1	PHYS	33
	VC02=VISCO2*TR1	PHYS	34
	VH20=VISH20*TR1	PHYS	35
	VN2=VISN2*TR1	PHYS	36
	110 EMU(1)=VFU*F(1,JF)+VN2*F(1,JN2)+VOX*F(1,JOX)+VC02*F(1,JC02)	PHYS	37
	1 +VH20*F(1,JH20)	PHYS	38
C	REYNOLDS NUMBER	PHYS	39
	IF(1PASS.NE.L) GO TO 111	PHYS	39

113	AVEMU=0.	PHYS	41
	DO 113 I=1,N	PHYS	41
	113 AVE4U=AVE4U+EMU(I)	PHYS	41
	AVEMU=AVE4U/FLOAT(N)	PHYS	43
	REYNDS=4.*PRIFLO/(RPRIFL*AVEMU)	PHYS	44
111	CONTINUE	PHYS	45
00	-----	PHYS	45
00	CHAPTER 222222222222222 TJR3ULENT LENGTH SCALE 22222222222222222222	PHYS	47
00	----- VELOCITY GRADIENTS	PHYS	48
	DO 114 I=2,NM1	PHYS	49
114	DUDY(I)=ABS(U(I+1)-U(I-1))/(Y(I+1)-Y(I-1))	PHYS	50
	IF(IPASS.NE.0) GO TO 184	PHYS	51
	IF(KUDIF.EQ.1STEP) GO TO 102	PHYS	52
	UMAX=U(1)	PHYS	53
	UMIN=U(1)	PHYS	54
	DO 101 I=2,N	PHYS	55
	UMAX=AMAX1(UMAX,U(I))	PHYS	56
101	UMIN=AMIN1(UMIN,U(I))	PHYS	57
	UDIF=UMAX-UMIN	PHYS	58
102	HUOIF=.5*UDIF	PHYS	59
	DUDYMN=FR*UDIF/RPRIFL	PHYS	60
	K=1	PHYS	61
	EX=DUDY(2)-DUDYMN	PHYS	62
	IF(EX.LT.0.) GO TO 103	PHYS	63
	YEDGE(K)=0.	PHYS	64
	K=2	PHYS	65
103	DO 104 I=3,NM1	PHYS	66
	EXL=EX	PHYS	67
	EX=DUDY(I)-DUDYMN	PHYS	68
	IF(EX*EXL.GE.0.) GO TO 104	PHYS	69
	YEDGE(K)=.5*(Y(I)+Y(I-1))	PHYS	70
	IF(K.EQ.6) GO TO 107	PHYS	71
	K=K+1	PHYS	72
104	CONTINUE	PHYS	73
	IF(EX.LT.0.) GO TO 105	PHYS	74
	YEDGE(K)=Y(N)	PHYS	75
	IF(K.EQ.6) GO TO 107	PHYS	76

```

      K=K+1
108  CONTINUE
      DO 106 KAY=K,6
106  YEDGE(KAY)=Y(N)
107  CONTINUE
      EL12=(YEDGE(2)-YEDGE(1))*ALMG
      EL34=(YEDGE(4)-YEDGE(3))*ALMG
      EL56=(YEDGE(6)-YEDGE(5))*ALMG
      EL23=.5*(EL12+EL34)
      EL45=.5*(EL34+EL56)
      ASSIGN 119 TO K
      DO 130 I=2,NN1
      YVALUE=Y(I)
      GO TO K, (119,121,123,125,127,129)
119  IF(YVALUE.LT.YEDGE(1)) GO TO 120
      ASSIGN 121 TO K
121  IF(YVALUE.LT.YEDGE(2)) GO TO 122
      ASSIGN 123 TO K
123  IF(YVALUE.LT.YEDGE(3)) GO TO 124
      ASSIGN 125 TO K
125  IF(YVALUE.LT.YEDGE(4)) GO TO 126
      ASSIGN 127 TO K

```

```

127  IF(YVALUE.LT.YEDGE(5)) GO TO 128
      ASSIGN 129 TO K
      GO TO 129
120  F(I,JEL)=0.
      GO TO 130
122  F(I,JEL)=EL12
      GO TO 130
124  F(I,JEL)=EL23
      GO TO 130
126  F(I,JEL)=EL34
      GO TO 130
128  F(I,JEL)=EL45
      GO TO 130
129  F(I,JEL)=EL56

```

3

----- JPPER LIMITS TO MIXING LENGTH

PHYS	77
PHYS	78
PHYS	79
PHYS	80
PHYS	81
PHYS	82
PHYS	83
PHYS	84
PHYS	85
PHYS	86
PHYS	87
PHYS	88
PHYS	89
PHYS	90
PHYS	91
PHYS	92
PHYS	93
PHYS	94
PHYS	95
PHYS	96
PHYS	97
PHYS	98
PHYS	99
PHYS	100
PHYS	101
PHYS	102
PHYS	103
PHYS	104
PHYS	105
PHYS	106
PHYS	107
PHYS	108
PHYS	109
PHYS	110
PHYS	111
PHYS	112
PHYS	113


```

CONST4=C2MOD5
DO 3010 I=2,NM1
SI(1)=CONST1*GENK(1)+CONST2*DISSK(I)
3010 SIP(I)=- (CONST3*GENK(I)+CONST4*DISSK(I)) / (F(I,JK)+TINY)
GO TO 9000
6000 IF(J.NE.J2) GO TO 9000
KSOURC=1
CONST1=C1MOD5
CONST2=C2MOD5-1.
CONST3=0.
CONST4=2.*C2MOD5-1.
DO 4003 I=2,NM1

REFCJJK=1. / (F(I,JK)+TINY)
FJ2DJJK=F(I,J2)*REFCJJK
SI(1)=FJ2DJJK* (CONST1*GENK(1)+CONST2*DISSK(I))
4003 SIP(I)=-REFCJJK* (CONST3*GENK(I)+CONST4*DISSK(I))
C
9000 IF(ITEST.EQ.1) RETURN
WRITE(6,9001) J, (SI(I),I=2,NM1)
WRITE(6,9002) (SIP(I),I=2,NM1)
RETURN
9001 FORMAT(18H PHYS TESTS FOR J=,I3/7H SI(1)=/(3X,1P6E11.3))
9002 FORMAT(8H SIP(1)=/(3X,1P6E11.3))
END

```

PHYS	220
PHYS	220
PHYS	227
PHYS	223
PHYS	229
PHYS	230
PHYS	231
PHYS	232
PHYS	233
PHYS	234
PHYS	235
PHYS	235
PHYS	237
PHYS	238
PHYS	239
PHYS	240
PHYS	241
PHYS	242
PHYS	243
PHYS	244
PHYS	245
PHYS	246
PHYS	247
PHYS	248

APPENDIX D

Example of Computer Output

***** OUTPUT *****

RADI--
 FLOW RATES--
 TEMPERATURES--
 EQUIVALENT RATIO=1.000
 REYNOLDS NUMBER=2.063E+04
 GRID SIZE--
 COMBUSTION CONSTANTS--
 GRID DISTRIBUTION--OM(I),S--
 RPRIFL=.009675 ROUT=.145
 PRIFLO=1.150E-02 SECFL0=5.000E-02
 TPRIFL=1.745E+03 TSECFL=4.230E+02
 OXYGEN INDEX=.233
 MACH NUMBER=2.786E-01
 N=30 FRA=.0500 XULAST=.350
 ARRC0N=2.150E+08 PREEXP=7.880E+06 IT=*

0 2.467E-03 9.854E-03 2.213E-02 3.926E-02 6.122E-02 8.795E-02 1.194E-01 1.556E-01 1.964E-01
 2.418E-01 2.916E-01 3.459E-01 4.046E-01 4.674E-01 5.343E-01 6.051E-01 6.795E-01 7.572E-01 8.375E-01
 8.548E-01 8.721E-01 8.894E-01 9.068E-01 9.241E-01 9.414E-01 9.585E-01 9.754E-01 9.918E-01 1.000E+00

+++++INITIAL CONDITIONS+++++

I	Y	TEMP	DENSITY	ENTHALPY	JF	JOX	JCO2	JN2	/K	J2	
1	.000	2.243E+02	1.745E+03	1.955E-01	2.260E+06	0	0	0	1.000E+00	6.463E+01	4.779E+04
2	.005	2.243E+02	1.736E+03	1.965E-01	2.280E+06	0	0	0	1.000E+00	6.463E+01	4.779E+04
3	.010	2.224E+02	1.726E+03	1.976E-01	2.264E+06	0	0	0	1.000E+00	7.037E+01	5.430E+04
4	.014	2.205E+02	1.716E+03	1.988E-01	2.248E+06	0	0	0	1.000E+00	7.698E+01	6.212E+04
5	.019	2.184E+02	1.706E+03	2.000E-01	2.231E+06	0	0	0	1.000E+00	8.464E+01	7.162E+04
6	.023	2.162E+02	1.695E+03	2.013E-01	2.212E+06	0	0	0	1.000E+00	9.359E+01	8.328E+04
7	.028	2.139E+02	1.683E+03	2.027E-01	2.193E+06	0	0	0	1.000E+00	1.042E+02	9.779E+04
8	.032	2.115E+02	1.671E+03	2.041E-01	2.173E+06	0	0	0	1.000E+00	1.168E+02	1.161E+05
9	.037	2.090E+02	1.658E+03	2.058E-01	2.152E+06	0	0	0	1.000E+00	1.321E+02	1.396E+05
10	.042	2.062E+02	1.644E+03	2.075E-01	2.129E+06	0	0	0	1.000E+00	1.508E+02	1.704E+05
11	.046	2.033E+02	1.629E+03	2.094E-01	2.105E+06	0	0	0	1.000E+00	1.742E+02	2.115E+05
12	.051	2.001E+02	1.613E+03	2.115E-01	2.079E+06	0	0	0	1.000E+00	2.041E+02	2.681E+05
13	.056	1.967E+02	1.595E+03	2.138E-01	2.051E+06	0	0	0	1.000E+00	2.430E+02	3.485E+05
14	.060	1.930E+02	1.576E+03	2.164E-01	2.020E+06	0	0	0	1.000E+00	2.955E+02	4.672E+05
15	.065	1.890E+02	1.555E+03	2.194E-01	1.985E+06	0	0	0	1.000E+00	3.688E+02	6.314E+05
16	.070	1.841E+02	1.530E+03	2.229E-01	1.947E+06	0	0	0	1.000E+00	4.765E+02	9.567E+05
17	.074	1.787E+02	1.503E+03	2.270E-01	1.903E+06	0	0	0	1.000E+00	6.457E+02	1.509E+06
18	.079	1.724E+02	1.469E+03	2.322E-01	1.852E+06	0	0	0	1.000E+00	9.385E+02	2.644E+06
19	.083	1.646E+02	1.429E+03	2.388E-01	1.789E+06	0	0	0	1.000E+00	1.530E+03	5.504E+06
20	.088	1.544E+02	1.374E+03	2.482E-01	1.707E+06	0	0	0	1.000E+00	2.141E+03	9.114E+06
21	.089	1.517E+02	1.360E+03	2.508E-01	1.687E+06	0	0	0	1.000E+00	3.314E+03	1.755E+07
22	.090	1.488E+02	1.345E+03	2.537E-01	1.664E+06	0	0	0	1.000E+00	4.340E+03	2.362E+07
23	.091	1.455E+02	1.327E+03	2.571E-01	1.639E+06	0	0	0	1.000E+00	5.060E+03	3.310E+07
24	.092	1.419E+02	1.307E+03	2.609E-01	1.611E+06	0	0	0	1.000E+00	6.567E+03	4.895E+07
25	.093	1.376E+02	1.285E+03	2.655E-01	1.579E+06	0	0	0	1.000E+00	8.956E+03	7.796E+07
26	.094	1.326E+02	1.258E+03	2.712E-01	1.544E+06	0	0	0	1.000E+00	1.315E+04	1.387E+08
27	.095	1.265E+02	1.224E+03	2.787E-01	1.503E+06	0	0	0	1.000E+00	2.181E+04	2.963E+08
28	.096	1.183E+02	1.179E+03	2.894E-01	1.463E+06	0	0	0	1.000E+00	4.661E+04	9.254E+08
29	.097	1.055E+02	1.108E+03	3.080E-01	1.381E+06	0	0	0	1.000E+00	8.615E+04	7.337E+09
30	.098	9.557E-01	4.230E+02	7.956E-01	3.293E+06	5.501E-02	2.200E-01	0	7.249E-01	6.615E+04	7.337E+09

*****STEP OUTPUT*****

IRUN= 1

ISTEP= 352

XU=1.655E-01

X/D=8.502E+00

	Y	U	TEMP	DENSITY	ENTHALPY	JF	JOX	JCO2	JN2	/K	J2
1		1.097E+02	1.846E+03	1.834E-01	2.709E+06	1.499E-03	5.998E-03	7.915E-02	8.486E-01	4.486E+02	8.134E+05
2	.018	1.097E+02	1.846E+03	1.834E-01	2.709E+06	1.499E-03	5.998E-03	7.915E-02	8.486E-01	4.486E+02	8.134E+05
3	.035	1.041E+02	1.800E+03	1.861E-01	2.729E+06	3.432E-03	1.373E-02	7.639E-02	8.446E-01	4.735E+02	8.984E+05
4	.053	9.632E+01	1.585E+03	2.135E-01	2.756E+06	1.122E-02	4.488E-02	5.833E-02	8.378E-01	4.388E+02	9.472E+05
5	.069	8.957E+01	1.278E+03	2.348E-01	2.784E+06	2.169E-02	8.677E-02	3.300E-02	8.315E-01	4.914E+02	9.507E+05
6	.084	8.232E+01	1.109E+03	3.049E-01	2.811E+06	2.746E-02	1.098E-01	2.061E-02	8.252E-01	4.832E+02	9.177E+05
7	.099	7.493E+01	1.003E+03	3.370E-01	2.841E+06	3.124E-02	1.249E-01	1.383E-02	8.187E-01	4.646E+02	8.517E+05
8	.114	6.743E+01	9.263E+02	3.648E-01	2.872E+06	3.411E-02	1.365E-01	9.691E-03	8.118E-01	4.359E+02	7.582E+05
9	.130	5.991E+01	8.653E+02	3.904E-01	2.904E+06	3.652E-02	1.461E-01	6.972E-03	8.047E-01	3.986E+02	6.462E+05
10	.146	5.248E+01	8.136E+02	4.151E-01	2.937E+06	3.867E-02	1.547E-01	5.091E-03	7.974E-01	3.547E+02	5.265E+05
11	.164	4.523E+01	7.679E+02	4.396E-01	2.972E+06	4.065E-02	1.626E-01	3.740E-03	7.900E-01	3.067E+02	4.088E+05
12	.184	3.825E+01	7.263E+02	4.647E-01	3.007E+06	4.251E-02	1.700E-01	2.742E-03	7.825E-01	2.570E+02	3.009E+05
13	.205	3.150E+01	6.877E+02	4.906E-01	3.043E+06	4.429E-02	1.772E-01	1.959E-03	7.749E-01	2.078E+02	2.082E+05
14	.229	2.537E+01	6.515E+02	5.176E-01	3.079E+06	4.600E-02	1.840E-01	1.415E-03	7.674E-01	1.615E+02	1.336E+05
15	.257	1.969E+01	6.178E+02	5.457E-01	3.115E+06	4.763E-02	1.905E-01	9.776E-04	7.601E-01	1.202E+02	7.827E+04
16	.290	1.474E+01	5.871E+02	5.740E-01	3.149E+06	4.914E-02	1.965E-01	6.521E-04	7.531E-01	8.653E+01	4.151E+04
17	.329	1.077E+01	5.610E+02	6.000E-01	3.179E+06	5.044E-02	2.018E-01	4.247E-04	7.470E-01	6.265E+01	2.665E+04
18	.377	7.929E+00	5.409E+02	6.227E-01	3.203E+06	5.146E-02	2.058E-01	2.803E-04	7.422E-01	4.862E+01	1.675E+04
19	.433	6.019E+00	5.265E+02	6.396E-01	3.221E+06	5.220E-02	2.088E-01	1.944E-04	7.386E-01	4.198E+01	6.731E+03
20	.497	4.711E+00	5.160E+02	6.526E-01	3.235E+06	5.275E-02	2.110E-01	1.426E-04	7.360E-01	4.012E+01	5.463E+03
21	.512	4.492E+00	5.141E+02	6.549E-01	3.237E+06	5.284E-02	2.114E-01	1.344E-04	7.355E-01	4.021E+01	5.413E+03
22	.527	4.284E+00	5.123E+02	6.571E-01	3.240E+06	5.294E-02	2.117E-01	1.269E-04	7.351E-01	4.047E+01	5.427E+03
23	.542	4.088E+00	5.107E+02	6.593E-01	3.242E+06	5.303E-02	2.121E-01	1.201E-04	7.347E-01	4.090E+01	5.503E+03
24	.557	3.903E+00	5.091E+02	6.614E-01	3.244E+06	5.311E-02	2.124E-01	1.138E-04	7.342E-01	4.151E+01	5.640E+03
25	.572	3.728E+00	5.075E+02	6.633E-01	3.246E+06	5.319E-02	2.128E-01	1.080E-04	7.338E-01	4.229E+01	5.843E+03
26	.588	3.564E+00	5.061E+02	6.652E-01	3.248E+06	5.327E-02	2.131E-01	1.027E-04	7.335E-01	4.328E+01	6.113E+03
27	.604	3.409E+00	5.047E+02	6.671E-01	3.250E+06	5.334E-02	2.134E-01	9.782E-05	7.331E-01	4.447E+01	6.456E+03
28	.619	3.264E+00	5.034E+02	6.688E-01	3.252E+06	5.341E-02	2.136E-01	9.340E-05	7.328E-01	4.587E+01	6.876E+03
29	.635	3.131E+00	5.021E+02	6.704E-01	3.253E+06	5.348E-02	2.139E-01	8.943E-05	7.324E-01	4.748E+01	7.374E+03
30	.640	9.556E-01	4.230E+02	7.956E-01	3.293E+06	5.501E-02	2.200E-01	0	7.249E-01	4.770E+01	7.446E+03

RMI= 0 RM=-5.778E-02 PSII= 0 PSIE=1.270E-02 PEI=1.270E-02
 CUMOD= .115 CMU= .600 CD= .230 CUMOD5=1.600 C2MOD5,1.920
 VISCOSITY-----
 3.628E-05 5.241E-03 5.428E-03 6.266E-03 7.780E-03 8.945E-03 9.834E-03 1.052E-02 1.104E-02 1.141E-02
 1.163E-02 1.172E-02 1.170E-02 1.161E-02 1.158E-02 1.190E-02 1.313E-02 1.574E-02 1.924E-02 2.208E-02
 2.246E-02 2.278E-02 2.302E-02 2.319E-02 2.332E-02 2.340E-02 2.346E-02 2.350E-02 2.353E-02 9.045E-06

*****IGNITION HAS BEEN DETECTED-----IGNITION TEMPERATURE=1.745E+03
 DETECTED AT-----XU=1.655E-01 ISTEP= 352 IRUN= 1 WITH TDELTA=6.400E+01 AND TERROR=1.000E+00

*****STEP OUTPUT*****

IRUN= 2

ISTEP= 600

XU=2.854E-01

X/D=1.475E+01

I	Y	U	TEMP	DENSITY	ENTHALPY	JF	JOX	JCO2	JN2	/K	J2
1	.019	6.258E+01	7.787E+02	4.337E-01	2.927E+06	3.947E-02	1.579E-01	2.750E-03	7.976E-01	1.686E+02	9.879E+04
2	.037	6.116E+01	7.736E+02	4.365E-01	2.932E+06	3.972E-02	1.589E-01	2.686E-03	7.965E-01	1.722E+02	1.529E+05
3	.056	5.921E+01	7.659E+02	4.409E-01	2.941E+06	4.011E-02	1.604E-01	2.590E-03	7.947E-01	1.761E+02	1.078E+05
4	.075	5.621E+01	7.556E+02	4.469E-01	2.952E+06	4.062E-02	1.625E-01	2.465E-03	7.924E-01	1.793E+02	1.113E+05
5	.095	5.286E+01	7.431E+02	4.543E-01	2.966E+06	4.123E-02	1.649E-01	2.316E-03	7.896E-01	1.804E+02	1.126E+05
6	.115	4.907E+01	7.287E+02	4.632E-01	2.982E+06	4.195E-02	1.678E-01	2.147E-03	7.864E-01	1.783E+02	1.104E+05
7	.137	4.496E+01	7.127E+02	4.735E-01	2.999E+06	4.274E-02	1.710E-01	1.965E-03	7.827E-01	1.725E+02	1.043E+05
8	.159	4.063E+01	6.954E+02	4.852E-01	3.019E+06	4.361E-02	1.744E-01	1.773E-03	7.787E-01	1.628E+02	9.452E+04
9	.183	3.617E+01	6.770E+02	4.983E-01	3.040E+06	4.453E-02	1.781E-01	1.576E-03	7.745E-01	1.496E+02	8.186E+04
10	.209	3.166E+01	6.577E+02	5.128E-01	3.062E+06	4.550E-02	1.820E-01	1.378E-03	7.700E-01	1.334E+02	6.744E+04
11	.236	2.715E+01	6.375E+02	5.289E-01	3.085E+06	4.651E-02	1.860E-01	1.180E-03	7.653E-01	1.150E+02	5.252E+04
12	.267	2.273E+01	6.168E+02	5.466E-01	3.109E+06	4.755E-02	1.902E-01	9.868E-04	7.605E-01	9.536E+01	3.827E+04
13	.301	1.845E+01	5.955E+02	5.659E-01	3.134E+06	4.863E-02	1.945E-01	7.995E-04	7.554E-01	7.544E+01	2.568E+04
14	.340	1.440E+01	5.743E+02	5.870E-01	3.160E+06	4.972E-02	1.989E-01	6.217E-04	7.503E-01	5.645E+01	1.551E+04
15	.387	1.073E+01	5.523E+02	6.093E-01	3.186E+06	5.080E-02	2.032E-01	4.588E-04	7.452E-01	3.984E+01	8.217E+03
16	.445	7.678E+00	5.334E+02	6.314E-01	3.210E+06	5.179E-02	2.072E-01	3.206E-04	7.405E-01	2.727E+01	3.843E+03
17	.516	5.470E+00	5.177E+02	6.504E-01	3.230E+06	5.260E-02	2.104E-01	2.194E-04	7.366E-01	1.967E+01	1.773E+03
18	.601	4.063E+00	5.066E+02	6.646E-01	3.244E+06	5.317E-02	2.127E-01	1.546E-04	7.339E-01	1.612E+01	9.817E+02
19	.698	3.176E+00	4.989E+02	6.747E-01	3.254E+06	5.357E-02	2.143E-01	1.145E-04	7.319E-01	1.502E+01	7.378E+02
20	.720	3.033E+00	4.976E+02	6.765E-01	3.255E+06	5.364E-02	2.146E-01	1.080E-04	7.316E-01	1.500E+01	7.229E+02
21	.742	2.900E+00	4.964E+02	6.782E-01	3.257E+06	5.371E-02	2.148E-01	1.022E-04	7.313E-01	1.505E+01	7.179E+02
22	.765	2.776E+00	4.952E+02	6.797E-01	3.259E+06	5.377E-02	2.151E-01	9.672E-05	7.310E-01	1.517E+01	7.221E+02
23	.787	2.660E+00	4.941E+02	6.812E-01	3.260E+06	5.382E-02	2.153E-01	9.170E-05	7.307E-01	1.536E+01	7.351E+02
24	.810	2.552E+00	4.931E+02	6.827E-01	3.261E+06	5.388E-02	2.155E-01	8.706E-05	7.304E-01	1.562E+01	7.569E+02
25	.833	2.451E+00	4.921E+02	6.840E-01	3.263E+06	5.393E-02	2.157E-01	8.275E-05	7.302E-01	1.594E+01	7.876E+02
26	.857	2.357E+00	4.912E+02	6.853E-01	3.264E+06	5.398E-02	2.159E-01	7.877E-05	7.300E-01	1.635E+01	8.275E+02
27	.880	2.269E+00	4.903E+02	6.865E-01	3.265E+06	5.403E-02	2.161E-01	7.519E-05	7.297E-01	1.682E+01	8.771E+02
28	.902	2.189E+00	4.895E+02	6.876E-01	3.266E+06	5.407E-02	2.163E-01	7.177E-05	7.295E-01	1.737E+01	9.360E+02
29	.919	9.558E-01	4.230E+02	7.956E-01	3.290E+06	5.501E-02	2.200E-01	0	7.249E-01	1.742E+01	9.416E+02

RMI= C FME=-4.358E-02 PSII= C PSI=1.881E-02 PEI=1.861E-02
 CMUCD=.877 CMU=.600 CD=.230 CUMOD5=1.600 C2MOD5=1.920
 VISCOSITY-----
 3.548E-05 9.599E-03 9.671E-03 9.786E-03 9.935E-03 1.010E-02 1.026E-02 1.039E-02 1.047E-02 1.048E-02
 1.041E-02 1.025E-02 9.992E-03 9.649E-03 9.279E-03 9.057E-03 9.403E-03 1.009E-02 1.353E-02 1.586E-02
 1.619E-02 1.645E-02 1.665E-02 1.680E-02 1.690E-02 1.697E-02 1.701E-02 1.703E-02 1.704E-02 9.045E-06
 SPECIFIC HEAT-----
 1.220E+03 1.220E+03 1.219E+03 1.217E+03 1.215E+03 1.213E+03 1.210E+03 1.206E+03 1.202E+03 1.198E+03
 1.194E+03 1.189E+03 1.183E+03 1.178E+03 1.172E+03 1.166E+03 1.160E+03 1.155E+03 1.152E+03 1.150E+03
 1.149E+03 1.149E+03 1.148E+03 1.148E+03 1.148E+03 1.147E+03 1.147E+03 1.147E+03 1.147E+03 1.121E+03

-----NO IGNITION HAS BEEN DETECTED,-----JET TEMPERATURE=1.713E+03
 THIS IS AFTER-----1STLP= 734 AT XU=3.500E-01 AFTER IRUN= 2 WITH TDELTA=3.200E+01 AND TERROR=1.000E+00

*****STEP OUTPUT*****

IPUN= 3

ISTEP= 600

XU=2.854E-01

X/D=1.475E+01

I	Y	U	TEMP	DENSITY	ENTHALPY	JE	JOX	JCO2	JN2	/K	J2
1	.019	6.338E+01	8.000E+02	4.222E-01	2.933E+06	3.897E-02	1.559E-01	4.053E-03	7.978E-01	1.723E+02	1.024E+05
2	.037	6.189E+01	7.942E+02	4.252E-01	2.938E+06	3.924E-02	1.570E-01	3.951E-03	7.966E-01	1.760E+02	1.066E+05
3	.056	5.967E+01	7.855E+02	4.299E-01	2.947E+06	3.965E-02	1.586E-01	3.798E-03	7.948E-01	1.801E+02	1.116E+05
4	.076	5.677E+01	7.740E+02	4.362E-01	2.958E+06	4.020E-02	1.608E-01	3.609E-03	7.925E-01	1.833E+02	1.154E+05
5	.096	5.332E+01	7.602E+02	4.441E-01	2.972E+06	4.086E-02	1.634E-01	3.366E-03	7.896E-01	1.842E+02	1.165E+05
6	.117	4.943E+01	7.443E+02	4.535E-01	2.988E+06	4.162E-02	1.665E-01	3.103E-03	7.863E-01	1.817E+02	1.138E+05
7	.138	4.522E+01	7.267E+02	4.644E-01	3.005E+06	4.246E-02	1.698E-01	2.822E-03	7.826E-01	1.754E+02	1.071E+05
8	.161	4.081E+01	7.078E+02	4.767E-01	3.025E+06	4.337E-02	1.735E-01	2.530E-03	7.786E-01	1.651E+02	9.656E+04
9	.185	3.626E+01	6.877E+02	4.905E-01	3.045E+06	4.433E-02	1.773E-01	2.232E-03	7.743E-01	1.513E+02	8.319E+04
10	.210	3.170E+01	6.669E+02	5.057E-01	3.067E+06	4.534E-02	1.814E-01	1.936E-03	7.698E-01	1.345E+02	6.819E+04
11	.238	2.716E+01	6.453E+02	5.225E-01	3.090E+06	4.639E-02	1.856E-01	1.645E-03	7.651E-01	1.156E+02	5.284E+04
12	.269	2.271E+01	6.232E+02	5.409E-01	3.114E+06	4.747E-02	1.899E-01	1.363E-03	7.602E-01	9.562E+01	3.832E+04
13	.304	1.841E+01	6.007E+02	5.610E-01	3.139E+06	4.857E-02	1.943E-01	1.094E-03	7.552E-01	7.550E+01	2.562E+04
14	.343	1.437E+01	5.781E+02	5.828E-01	3.164E+06	4.968E-02	1.987E-01	8.419E-04	7.501E-01	5.645E+01	1.543E+04
15	.390	1.072E+01	5.561E+02	6.058E-01	3.189E+06	5.077E-02	2.031E-01	6.148E-04	7.450E-01	3.989E+01	8.176E+03
16	.448	7.683E+00	5.359E+02	6.264E-01	3.213E+06	5.178E-02	2.071E-01	4.259E-04	7.403E-01	2.749E+01	3.846E+03
17	.519	5.494E+00	5.198E+02	6.477E-01	3.232E+06	5.258E-02	2.103E-01	2.890E-04	7.366E-01	1.993E+01	1.795E+03
18	.604	4.092E+00	5.084E+02	6.622E-01	3.246E+06	5.316E-02	2.126E-01	2.024E-04	7.338E-01	1.641E+01	1.005E+03
19	.701	3.202E+00	5.006E+02	6.725E-01	3.255E+06	5.356E-02	2.142E-01	1.491E-04	7.319E-01	1.532E+01	7.604E+02
20	.723	3.058E+00	4.992E+02	6.743E-01	3.257E+06	5.363E-02	2.145E-01	1.407E-04	7.316E-01	1.531E+01	7.457E+02
21	.745	2.923E+00	4.980E+02	6.760E-01	3.259E+06	5.369E-02	2.148E-01	1.329E-04	7.313E-01	1.536E+01	7.411E+02
22	.767	2.798E+00	4.968E+02	6.776E-01	3.260E+06	5.375E-02	2.150E-01	1.258E-04	7.310E-01	1.549E+01	7.457E+02
23	.790	2.682E+00	4.956E+02	6.792E-01	3.262E+06	5.381E-02	2.153E-01	1.192E-04	7.307E-01	1.568E+01	7.595E+02
24	.813	2.572E+00	4.946E+02	6.806E-01	3.263E+06	5.387E-02	2.155E-01	1.131E-04	7.305E-01	1.594E+01	7.822E+02
25	.836	2.470E+00	4.936E+02	6.820E-01	3.264E+06	5.392E-02	2.157E-01	1.074E-04	7.302E-01	1.628E+01	8.141E+02
26	.859	2.375E+00	4.926E+02	6.833E-01	3.265E+06	5.397E-02	2.159E-01	1.022E-04	7.300E-01	1.666E+01	8.557E+02
27	.882	2.286E+00	4.917E+02	6.846E-01	3.267E+06	5.402E-02	2.161E-01	9.744E-05	7.297E-01	1.718E+01	9.071E+02
28	.904	2.205E+00	4.909E+02	6.857E-01	3.268E+06	5.406E-02	2.162E-01	9.310E-05	7.295E-01	1.774E+01	9.683E+02
29	.921	9.558E-01	4.230E+02	7.956E-01	3.291E+06	5.501E-02	2.200E-01	0	7.249E-01	1.779E+01	9.741E+02

RMI= 0
CNUCD= .677
VISCOSITY-----

RMI=-4.398E-02
CNU= .600

PSII= 0
CD= .230

PSII=1.889E-02
CUMOD5=1.600

PEI=1.889E-02
C2MOD5,1.920

3.562E-05	9.416E-03	9.493E-03	9.615E-03	9.773E-03	9.949E-03	1.012E-02	1.026E-02	1.035E-02	1.038E-02
1.032E-02	1.017E-02	9.928E-03	9.605E-03	9.262E-03	9.077E-03	9.473E-03	1.103E-02	1.365E-02	1.596E-02
1.629E-02	1.655E-02	1.675E-02	1.690E-02	1.700E-02	1.706E-02	1.710E-02	1.712E-02	1.713E-02	9.045E-06

SPECIFIC HEAT-----

1.226E+03	1.226E+03	1.225E+03	1.223E+03	1.221E+03	1.218E+03	1.215E+03	1.211E+03	1.207E+03	1.202E+03
1.197E+03	1.191E+03	1.186E+03	1.180E+03	1.173E+03	1.167E+03	1.161E+03	1.156E+03	1.153E+03	1.150E+03
1.150E+03	1.149E+03	1.149E+03	1.149E+03	1.148E+03	1.148E+03	1.148E+03	1.147E+03	1.147E+03	1.121E+03

-----NO IGNITION HAS BEEN DETECTED,-----JET TEMPERATURE=1.729E+03
THIS IS AFTER-----ISTEP= 734 AT XU=3.500E-01 AFTER IPUN= 3 WITH TDelta=1.600E+01 AND TERROR=1.000E+00

*****STEP OUTPUT*****

IRUN= 4

ISTEP= 600

XU=2.854E-01

X/D=1.475E+01

I	Y	U	TEMP	DENSITY	ENTHALPY	JF	JOX	JCO2	JN2	/K	J2
1	.019	6.395E+01	8.231E+02	4.103E-01	2.935E+06	3.833E-02	1.533E-01	5.674E-03	7.980E-01	1.745E+02	1.046E+05
2	.038	6.395E+01	8.231E+02	4.103E-01	2.935E+06	3.833E-02	1.533E-01	5.674E-03	7.980E-01	1.745E+02	1.046E+05
3	.057	6.010E+01	8.065E+02	4.103E-01	2.941E+06	3.863E-02	1.545E-01	5.516E-03	7.968E-01	1.784E+02	1.092E+05
4	.077	5.711E+01	7.935E+02	4.255E-01	2.961E+06	3.968E-02	1.587E-01	4.978E-03	7.925E-01	1.857E+02	1.179E+05
5	.097	5.357E+01	7.779E+02	4.340E-01	2.975E+06	4.040E-02	1.616E-01	4.623E-03	7.896E-01	1.863E+02	1.187E+05
6	.116	4.959E+01	7.601E+02	4.441E-01	2.991E+06	4.122E-02	1.649E-01	4.230E-03	7.862E-01	1.834E+02	1.156E+05
7	.139	4.531E+01	7.406E+02	4.557E-01	3.009E+06	4.212E-02	1.685E-01	3.814E-03	7.825E-01	1.766E+02	1.083E+05
8	.162	4.084E+01	7.197E+02	4.688E-01	3.028E+06	4.309E-02	1.724E-01	3.388E-03	7.784E-01	1.659E+02	9.719E+04
9	.187	3.626E+01	6.979E+02	4.833E-01	3.049E+06	4.411E-02	1.764E-01	2.961E-03	7.741E-01	1.516E+02	8.336E+04
10	.212	3.166E+01	6.753E+02	4.994E-01	3.071E+06	4.516E-02	1.807E-01	2.542E-03	7.696E-01	1.345E+02	6.505E+04
11	.241	2.711E+01	6.522E+02	5.170E-01	3.093E+06	4.625E-02	1.850E-01	2.137E-03	7.648E-01	1.154E+02	5.256E+04
12	.271	2.265E+01	6.288E+02	5.361E-01	3.117E+06	4.737E-02	1.895E-01	1.751E-03	7.600E-01	9.531E+01	3.803E+04
13	.306	1.837E+01	6.051E+02	5.570E-01	3.141E+06	4.850E-02	1.940E-01	1.389E-03	7.550E-01	7.523E+01	2.539E+04
14	.346	1.434E+01	5.814E+02	5.795E-01	3.166E+06	4.963E-02	1.985E-01	1.057E-03	7.499E-01	5.630E+01	1.530E+04
15	.393	1.071E+01	5.586E+02	6.031E-01	3.191E+06	5.074E-02	2.030E-01	7.628E-04	7.449E-01	3.990E+01	8.137E+03
16	.451	7.698E+00	5.378E+02	6.261E-01	3.214E+06	5.175E-02	2.070E-01	5.222E-04	7.403E-01	2.759E+01	3.857E+03
17	.521	5.519E+00	5.213E+02	6.459E-01	3.233E+06	5.256E-02	2.102E-01	3.507E-04	7.366E-01	2.014E+01	1.818E+03
18	.606	4.118E+00	5.097E+02	6.605E-01	3.246E+06	5.314E-02	2.126E-01	2.434E-04	7.339E-01	1.663E+01	1.026E+03
19	.703	3.223E+00	5.016E+02	6.711E-01	3.256E+06	5.355E-02	2.142E-01	1.780E-04	7.319E-01	1.554E+01	7.784E+02
20	.724	3.077E+00	5.002E+02	6.729E-01	3.258E+06	5.362E-02	2.145E-01	1.677E-04	7.316E-01	1.553E+01	7.636E+02
21	.746	2.942E+00	4.989E+02	6.747E-01	3.259E+06	5.368E-02	2.147E-01	1.583E-04	7.313E-01	1.558E+01	7.590E+02
22	.768	2.816E+00	4.977E+02	6.763E-01	3.261E+06	5.374E-02	2.150E-01	1.496E-04	7.310E-01	1.571E+01	7.639E+02
23	.791	2.698E+00	4.966E+02	6.779E-01	3.262E+06	5.380E-02	2.152E-01	1.416E-04	7.307E-01	1.591E+01	7.781E+02
24	.814	2.586E+00	4.955E+02	6.794E-01	3.264E+06	5.386E-02	2.154E-01	1.343E-04	7.305E-01	1.617E+01	8.015E+02
25	.837	2.484E+00	4.944E+02	6.808E-01	3.265E+06	5.391E-02	2.156E-01	1.275E-04	7.302E-01	1.652E+01	8.343E+02
26	.866	2.388E+00	4.933E+02	6.821E-01	3.266E+06	5.396E-02	2.158E-01	1.213E-04	7.300E-01	1.694E+01	8.769E+02
27	.883	2.298E+00	4.925E+02	6.834E-01	3.267E+06	5.401E-02	2.160E-01	1.155E-04	7.298E-01	1.743E+01	9.298E+02
28	.905	2.216E+00	4.917E+02	6.846E-01	3.268E+06	5.405E-02	2.162E-01	1.104E-04	7.295E-01	1.800E+01	9.927E+02
29	.922	2.155E+00	4.910E+02	6.856E-01	3.269E+06	5.409E-02	2.164E-01	0	7.293E-01	1.856E+01	1.067E+03

RMI= 0
CMUCD= .077
VISCOSITY-----

RME=-4.430E-02
CMU= .600

PSII= 0
CD= .230

PSIE=1.894E-02
CUMOD5=1.600

PEI=1.894E-02
C2MCO5,1.920

3.575E-05	9.185E-03	9.269E-03	9.402E-03	9.572E-03	9.761E-03	9.945E-03	1.010E-02	1.021E-02	1.025E-02
1.021E-02	1.008E-02	9.853E-03	9.553E-03	9.236E-03	9.084E-03	9.513E-03	1.109E-02	1.370E-02	1.601E-02
1.633E-02	1.659E-02	1.679E-02	1.694E-02	1.704E-02	1.711E-02	1.715E-02	1.717E-02	1.718E-02	9.045E-06
1.233E+03	1.233E+03	1.232E+03	1.230E+03	1.227E+03	1.224E+03	1.220E+03	1.215E+03	1.211E+03	1.205E+03
1.200E+03	1.194E+03	1.188E+03	1.181E+03	1.175E+03	1.168E+03	1.162E+03	1.157E+03	1.153E+03	1.151E+03
1.150E+03	1.150E+03	1.149E+03	1.149E+03	1.149E+03	1.148E+03	1.148E+03	1.148E+03	1.147E+03	1.121E+03

-----NO IGNITION HAS BEEN DETECTED,-----JET TEMPERATURE=1.737E+03
THIS IS AFTER-----ISTEP= 73+ AT XU=3.506E-01 AFTER IRUN= 4 WITH TDELTA=8.000E+00 AND TERROR=1.000E+00

*****STEP OUTPUT*****

IRUN= 5

ISTEP= 377

XU=1.776E-01

X/D=9.177E+00

	Y	U	TEMP	DENSITY	ENTHALPY	JF	JOX	JCO2	JN2	/K	J2
1		1.011E+02	1.842E+03	1.837E-01	2.748E+06	2.215E-03	8.859E-03	8.239E-02	8.391E-01	4.011E+02	6.311E+05
2	.019	1.011E+02	1.842E+03	1.837E-01	2.748E+06	2.215E-03	8.859E-03	8.239E-02	8.391E-01	4.011E+02	6.311E+05
3	.038	9.618E+01	1.726E+03	1.961E-01	2.766E+06	6.585E-03	2.634E-02	7.258E-02	8.351E-01	4.203E+02	6.831E+05
4	.055	9.033E+01	1.347E+03	2.511E-01	2.788E+06	1.952E-02	7.806E-02	3.970E-02	8.302E-01	4.324E+02	7.228E+05
5	.070	8.427E+01	1.148E+03	2.945E-01	2.810E+06	2.621E-02	1.048E-01	2.408E-02	8.252E-01	4.360E+02	7.316E+05
6	.085	7.781E+01	1.033E+03	3.273E-01	2.835E+06	3.022E-02	1.209E-01	1.609E-02	8.196E-01	4.307E+02	7.133E+05
7	.101	7.101E+01	9.533E+02	3.545E-01	2.862E+06	3.312E-02	1.325E-01	1.139E-02	8.137E-01	4.156E+02	6.673E+05
8	.116	6.401E+01	8.916E+02	3.790E-01	2.891E+06	3.550E-02	1.420E-01	8.341E-03	8.073E-01	3.910E+02	5.978E+05
9	.133	5.695E+01	8.399E+02	4.022E-01	2.921E+06	3.769E-02	1.504E-01	6.223E-03	8.007E-01	3.584E+02	5.124E+05
10	.150	4.995E+01	7.943E+02	4.251E-01	2.953E+06	3.953E-02	1.581E-01	4.682E-03	7.939E-01	3.197E+02	4.197E+05
11	.169	4.310E+01	7.528E+02	4.484E-01	2.986E+06	4.134E-02	1.654E-01	3.525E-03	7.869E-01	2.771E+02	3.276E+05
12	.190	3.648E+01	7.143E+02	4.724E-01	3.019E+06	4.308E-02	1.723E-01	2.637E-03	7.798E-01	2.326E+02	2.424E+05
13	.212	3.016E+01	6.781E+02	4.974E-01	3.054E+06	4.476E-02	1.791E-01	1.944E-03	7.726E-01	1.884E+02	1.684E+05
14	.238	2.423E+01	6.438E+02	5.237E-01	3.088E+06	4.639E-02	1.856E-01	1.401E-03	7.655E-01	1.464E+02	1.084E+05
15	.267	1.879E+01	6.116E+02	5.511E-01	3.122E+06	4.795E-02	1.918E-01	9.776E-04	7.585E-01	1.089E+02	6.353E+04
16	.302	1.404E+01	5.821E+02	5.789E-01	3.155E+06	4.940E-02	1.976E-01	6.563E-04	7.518E-01	7.809E+01	3.359E+04
17	.343	1.023E+01	5.568E+02	6.050E-01	3.184E+06	5.066E-02	2.026E-01	4.284E-04	7.459E-01	5.616E+01	1.655E+04
18	.394	7.499E+00	5.373E+02	6.268E-01	3.208E+06	5.165E-02	2.066E-01	2.824E-04	7.413E-01	4.326E+01	6.502E+03
19	.454	5.676E+00	5.233E+02	6.434E-01	3.225E+06	5.236E-02	2.094E-01	1.954E-04	7.378E-01	3.715E+01	5.251E+03
20	.522	4.440E+00	5.132E+02	6.560E-01	3.238E+06	5.289E-02	2.115E-01	1.430E-04	7.353E-01	3.538E+01	4.218E+03
21	.537	4.231E+00	5.115E+02	6.583E-01	3.241E+06	5.298E-02	2.119E-01	1.343E-04	7.349E-01	3.544E+01	4.172E+03
22	.553	4.036E+00	5.098E+02	6.604E-01	3.243E+06	5.307E-02	2.123E-01	1.272E-04	7.344E-01	3.564E+01	4.174E+03
23	.569	3.851E+00	5.082E+02	6.625E-01	3.245E+06	5.315E-02	2.126E-01	1.203E-04	7.340E-01	3.600E+01	4.225E+03
24	.585	3.678E+00	5.066E+02	6.645E-01	3.247E+06	5.323E-02	2.129E-01	1.139E-04	7.336E-01	3.655E+01	4.233E+03
25	.601	3.514E+00	5.052E+02	6.664E-01	3.249E+06	5.331E-02	2.132E-01	1.081E-04	7.333E-01	3.717E+01	4.471E+03
26	.618	3.361E+00	5.038E+02	6.682E-01	3.251E+06	5.338E-02	2.135E-01	1.027E-04	7.329E-01	3.801E+01	4.669E+03
27	.634	3.216E+00	5.025E+02	6.700E-01	3.252E+06	5.345E-02	2.138E-01	9.782E-05	7.326E-01	3.902E+01	4.923E+03
28	.651	3.081E+00	5.012E+02	6.716E-01	3.254E+06	5.352E-02	2.141E-01	9.335E-05	7.322E-01	4.022E+01	5.234E+03
29	.668	2.956E+00	5.001E+02	6.732E-01	3.256E+06	5.358E-02	2.143E-01	8.933E-05	7.319E-01	4.159E+01	5.603E+03
30	.681	9.558E-01	4.230E+02	7.956E-01	3.292E+06	5.501E-02	2.200E-01	0	7.249E-01	4.176E+01	5.656E+03

PMI= 0
CMUCD= .111
VISCOSITY----

PMI=-5.708E-02
CMU= .600

PSII= 0
CD= .230

PSIE=1.340E-02
CUMODS=1.600

PEI=1.340E-02
C2MODS,1.920

3.628E-05	5.238E-03	5.658E-03	7.273E-03	8.537E-03	9.478E-03	1.021E-02	1.078E-02	1.121E-02	1.156E-02
1.167E-02	1.172E-02	1.165E-02	1.151E-02	1.143E-02	1.168E-02	1.281E-02	1.533E-02	1.878E-02	2.161E-02
2.200E-02	2.231E-02	2.256E-02	2.274E-02	2.286E-02	2.295E-02	2.301E-02	2.304E-02	2.307E-02	9.045E-06

*****IGNITION HAS BEEN DETECTED-----IGNITION TEMPERATURE=1.741E+03
DETECTED AT-----XU=1.776E-01 ISTEP= 377 IRUN= 5 WITH DELTA=4.000E+00 AND TERROR=1.000E+00

*****STEP OUTPUT*****

IRUN= 6

ISTEP= 600

XU=2.854E-01

X/C=1.475E+01

I	Y	U	TEMP	DENSITY	ENTHALPY	JF	JOX	JCO2	JN2	/K	J2
1	.019	6.418E+01	8.372E+02	4.034E-01	2.935E+06	3.792E-02	1.517E-01	6.736E-03	7.981E-01	1.751E+02	1.053E+05
2	.036	6.418E+01	8.372E+02	4.034E-01	2.935E+06	3.792E-02	1.517E-01	6.736E-03	7.981E-01	1.751E+02	1.053E+05
3	.057	6.418E+01	8.372E+02	4.034E-01	2.935E+06	3.792E-02	1.517E-01	6.736E-03	7.981E-01	1.751E+02	1.053E+05
4	.077	6.418E+01	8.372E+02	4.034E-01	2.935E+06	3.792E-02	1.517E-01	6.736E-03	7.981E-01	1.751E+02	1.053E+05
5	.098	6.418E+01	8.372E+02	4.034E-01	2.935E+06	3.792E-02	1.517E-01	6.736E-03	7.981E-01	1.751E+02	1.053E+05
6	.119	6.418E+01	8.372E+02	4.034E-01	2.935E+06	3.792E-02	1.517E-01	6.736E-03	7.981E-01	1.751E+02	1.053E+05
7	.140	6.418E+01	8.372E+02	4.034E-01	2.935E+06	3.792E-02	1.517E-01	6.736E-03	7.981E-01	1.751E+02	1.053E+05
8	.163	6.418E+01	8.372E+02	4.034E-01	2.935E+06	3.792E-02	1.517E-01	6.736E-03	7.981E-01	1.751E+02	1.053E+05
9	.188	6.418E+01	8.372E+02	4.034E-01	2.935E+06	3.792E-02	1.517E-01	6.736E-03	7.981E-01	1.751E+02	1.053E+05
10	.214	6.418E+01	8.372E+02	4.034E-01	2.935E+06	3.792E-02	1.517E-01	6.736E-03	7.981E-01	1.751E+02	1.053E+05
11	.242	6.418E+01	8.372E+02	4.034E-01	2.935E+06	3.792E-02	1.517E-01	6.736E-03	7.981E-01	1.751E+02	1.053E+05
12	.273	6.418E+01	8.372E+02	4.034E-01	2.935E+06	3.792E-02	1.517E-01	6.736E-03	7.981E-01	1.751E+02	1.053E+05
13	.307	6.418E+01	8.372E+02	4.034E-01	2.935E+06	3.792E-02	1.517E-01	6.736E-03	7.981E-01	1.751E+02	1.053E+05
14	.347	6.418E+01	8.372E+02	4.034E-01	2.935E+06	3.792E-02	1.517E-01	6.736E-03	7.981E-01	1.751E+02	1.053E+05
15	.394	6.418E+01	8.372E+02	4.034E-01	2.935E+06	3.792E-02	1.517E-01	6.736E-03	7.981E-01	1.751E+02	1.053E+05
16	.452	6.418E+01	8.372E+02	4.034E-01	2.935E+06	3.792E-02	1.517E-01	6.736E-03	7.981E-01	1.751E+02	1.053E+05
17	.522	6.418E+01	8.372E+02	4.034E-01	2.935E+06	3.792E-02	1.517E-01	6.736E-03	7.981E-01	1.751E+02	1.053E+05
18	.607	6.418E+01	8.372E+02	4.034E-01	2.935E+06	3.792E-02	1.517E-01	6.736E-03	7.981E-01	1.751E+02	1.053E+05
19	.703	6.418E+01	8.372E+02	4.034E-01	2.935E+06	3.792E-02	1.517E-01	6.736E-03	7.981E-01	1.751E+02	1.053E+05
20	.725	6.418E+01	8.372E+02	4.034E-01	2.935E+06	3.792E-02	1.517E-01	6.736E-03	7.981E-01	1.751E+02	1.053E+05
21	.747	6.418E+01	8.372E+02	4.034E-01	2.935E+06	3.792E-02	1.517E-01	6.736E-03	7.981E-01	1.751E+02	1.053E+05
22	.769	6.418E+01	8.372E+02	4.034E-01	2.935E+06	3.792E-02	1.517E-01	6.736E-03	7.981E-01	1.751E+02	1.053E+05
23	.791	6.418E+01	8.372E+02	4.034E-01	2.935E+06	3.792E-02	1.517E-01	6.736E-03	7.981E-01	1.751E+02	1.053E+05
24	.814	6.418E+01	8.372E+02	4.034E-01	2.935E+06	3.792E-02	1.517E-01	6.736E-03	7.981E-01	1.751E+02	1.053E+05
25	.837	6.418E+01	8.372E+02	4.034E-01	2.935E+06	3.792E-02	1.517E-01	6.736E-03	7.981E-01	1.751E+02	1.053E+05
26	.860	6.418E+01	8.372E+02	4.034E-01	2.935E+06	3.792E-02	1.517E-01	6.736E-03	7.981E-01	1.751E+02	1.053E+05
27	.883	6.418E+01	8.372E+02	4.034E-01	2.935E+06	3.792E-02	1.517E-01	6.736E-03	7.981E-01	1.751E+02	1.053E+05
28	.906	6.418E+01	8.372E+02	4.034E-01	2.935E+06	3.792E-02	1.517E-01	6.736E-03	7.981E-01	1.751E+02	1.053E+05
29	.922	6.418E+01	8.372E+02	4.034E-01	2.935E+06	3.792E-02	1.517E-01	6.736E-03	7.981E-01	1.751E+02	1.053E+05

RMI= 0
CUMCO= .677
VISCOSITY----

RMI=-4.445E-02
CUMU= .600

PSII= 0
CD= .230

PSIE=1.896E-02
CUMOC5=1.600

PEI=1.896E-02
C2MOC5,1.920

3.583E-05	9.038E-03	9.126E-03	9.265E-03	9.444E-03	9.642E-03	9.836E-03	1.000E-02	1.012E-02	1.017E-02
1.014E-02	1.002E-02	9.810E-03	9.523E-03	9.220E-03	9.082E-03	9.521E-03	1.110E-02	1.371E-02	1.601E-02
1.634E-02	1.660E-02	1.680E-02	1.695E-02	1.705E-02	1.712E-02	1.716E-02	1.718E-02	1.719E-02	9.045E-06

SPECIFIC HEAT-----

1.237E+03	1.237E+03	1.236E+03	1.233E+03	1.230E+03	1.227E+03	1.223E+03	1.218E+03	1.213E+03	1.207E+03
1.201E+03	1.195E+03	1.189E+03	1.182E+03	1.175E+03	1.168E+03	1.162E+03	1.157E+03	1.153E+03	1.151E+03
1.150E+03	1.150E+03	1.149E+03	1.149E+03	1.149E+03	1.148E+03	1.148E+03	1.148E+03	1.148E+03	1.121E+03

-----NO IGNITION HAS BEEN DETECTED,-----JET TEMPERATURE=1.739E+03
THIS IS AFTER-----ISTEP= 734 AT XU=3.500E-01 AFTER IRUN= 6 WITH TDELTA=2.000E+00 AND TERFOR=1.000E+00

*****STEP OUTPUT*****

IRUN= 7

ISTEP= 600

XU=2.854E-01

X/D=1.475E+01

I	Y	U	TEMP	DENSITY	ENTHALPY	JF	JOX	JCO2	JN2	/K	J2
1	.0	6.438E+01	8.553E+02	3.949E-01	2.935E+06	3.738E-02	1.495E-01	8.152E-03	7.983E-01	1.755E+02	1.058E+05
2	.019	6.438E+01	8.553E+02	3.949E-01	2.935E+06	3.738E-02	1.495E-01	8.152E-03	7.983E-01	1.755E+02	1.058E+05
3	.038	6.438E+01	8.553E+02	3.949E-01	2.935E+06	3.738E-02	1.495E-01	8.152E-03	7.983E-01	1.755E+02	1.058E+05
4	.058	6.438E+01	8.553E+02	3.949E-01	2.935E+06	3.738E-02	1.495E-01	8.152E-03	7.983E-01	1.755E+02	1.058E+05
5	.078	5.728E+01	8.193E+02	4.121E-01	2.962E+06	3.894E-02	1.558E-01	6.989E-03	7.926E-01	1.867E+02	1.191E+05
6	.098	5.364E+01	8.007E+02	4.216E-01	2.976E+06	3.976E-02	1.590E-01	6.413E-03	7.896E-01	1.870E+02	1.195E+05
7	.120	4.959E+01	7.799E+02	4.328E-01	2.992E+06	4.067E-02	1.627E-01	5.790E-03	7.861E-01	1.837E+02	1.158E+05
8	.142	4.525E+01	7.574E+02	4.456E-01	3.010E+06	4.167E-02	1.667E-01	5.146E-03	7.823E-01	1.764E+02	1.088E+05
9	.165	4.075E+01	7.337E+02	4.598E-01	3.030E+06	4.272E-02	1.709E-01	4.502E-03	7.782E-01	1.652E+02	9.646E+04
10	.189	3.616E+01	7.093E+02	4.756E-01	3.050E+06	4.381E-02	1.752E-01	3.873E-03	7.739E-01	1.507E+02	8.244E+04
11	.215	3.157E+01	6.845E+02	4.927E-01	3.072E+06	4.494E-02	1.797E-01	3.272E-03	7.694E-01	1.335E+02	6.715E+04
12	.243	2.703E+01	6.591E+02	5.113E-01	3.095E+06	4.608E-02	1.843E-01	2.707E-03	7.647E-01	1.145E+02	5.183E+04
13	.274	2.260E+01	6.343E+02	5.315E-01	3.118E+06	4.724E-02	1.890E-01	2.183E-03	7.598E-01	9.467E+01	3.754E+04
14	.309	1.835E+01	6.092E+02	5.532E-01	3.143E+06	4.840E-02	1.936E-01	1.704E-03	7.549E-01	7.466E+01	2.514E+04
15	.349	1.435E+01	5.845E+02	5.763E-01	3.167E+06	4.956E-02	1.983E-01	1.276E-03	7.499E-01	5.621E+01	1.523E+04
16	.396	1.074E+01	5.600E+02	6.007E-01	3.192E+06	5.069E-02	2.028E-01	9.058E-04	7.449E-01	4.002E+01	8.163E+03
17	.453	7.739E+00	5.394E+02	6.245E-01	3.214E+06	5.171E-02	2.068E-01	6.103E-04	7.403E-01	2.781E+01	3.904E+03
18	.523	5.556E+00	5.225E+02	6.444E-01	3.233E+06	5.253E-02	2.101E-01	4.035E-04	7.366E-01	2.036E+01	1.853E+03
19	.607	4.146E+00	5.105E+02	6.595E-01	3.247E+06	5.312E-02	2.125E-01	2.762E-04	7.339E-01	1.682E+01	1.048E+03
20	.703	3.242E+00	5.023E+02	6.702E-01	3.256E+06	5.353E-02	2.141E-01	1.999E-04	7.320E-01	1.571E+01	7.947E+02
21	.725	3.095E+00	5.009E+02	6.721E-01	3.258E+06	5.360E-02	2.144E-01	1.880E-04	7.317E-01	1.570E+01	7.793E+02
22	.747	2.958E+00	4.995E+02	6.739E-01	3.259E+06	5.367E-02	2.147E-01	1.771E-04	7.313E-01	1.575E+01	7.744E+02
23	.769	2.831E+00	4.983E+02	6.756E-01	3.261E+06	5.373E-02	2.149E-01	1.671E-04	7.310E-01	1.588E+01	7.792E+02
24	.792	2.712E+00	4.971E+02	6.772E-01	3.262E+06	5.379E-02	2.152E-01	1.580E-04	7.308E-01	1.608E+01	7.935E+02
25	.814	2.600E+00	4.960E+02	6.787E-01	3.264E+06	5.385E-02	2.154E-01	1.497E-04	7.305E-01	1.635E+01	8.173E+02
26	.837	2.496E+00	4.949E+02	6.801E-01	3.265E+06	5.390E-02	2.156E-01	1.420E-04	7.302E-01	1.669E+01	8.507E+02
27	.860	2.399E+00	4.939E+02	6.815E-01	3.266E+06	5.395E-02	2.158E-01	1.349E-04	7.300E-01	1.712E+01	8.941E+02
28	.883	2.306E+00	4.930E+02	6.828E-01	3.267E+06	5.400E-02	2.160E-01	1.285E-04	7.298E-01	1.762E+01	9.481E+02
29	.906	2.225E+00	4.921E+02	6.840E-01	3.269E+06	5.404E-02	2.162E-01	1.227E-04	7.296E-01	1.820E+01	1.012E+03
30	.922	9.558E-01	4.230E+02	7.956E-01	3.292E+06	5.501E-02	2.200E-01	0	7.249E-01	1.825E+01	1.018E+03

RMI= 0
CHUCD= .077
VISCOSITY=----

RME=-4.458E-02
CMU= .600

PSII= 0
CD= .230

PSIE=1.897E-02
CUMOD5=1.600

PEI=1.897E-02
C2MOD5=1.920

3.593E-05	8.847E-03	8.942E-03	9.091E-03	9.282E-03	9.493E-03	9.701E-03	9.880E-03	1.001E-02	1.008E-02
1.006E-02	9.958E-03	9.762E-03	9.489E-03	9.201E-03	9.074E-03	9.517E-03	1.109E-02	1.369E-02	1.601E-02
1.633E-02	1.660E-02	1.660E-02	1.695E-02	1.705E-02	1.712E-02	1.716E-02	1.718E-02	1.719E-02	9.0+5E-06
1.242E+03	1.242E+03	1.241E+03	1.238E+03	1.235E+03	1.231E+03	1.226E+03	1.221E+03	1.215E+03	1.209E+03
1.203E+03	1.196E+03	1.190E+03	1.183E+03	1.176E+03	1.169E+03	1.162E+03	1.157E+03	1.153E+03	1.151E+03
1.150E+03	1.150E+03	1.150E+03	1.149E+03	1.149E+03	1.148E+03	1.148E+03	1.148E+03	1.148E+03	1.121E+03

-----NO IGNITION HAS BEEN DETECTED,-----JET TEMPERATURE=1.740E+03
THIS IS AFTER-----ISTEP= 734 AT XU=3.500E-01 AFTER IRUN= 7 WITH TDALTA=1.000E+00 AND TERFOR=1.000E+00

APPENDIX E

PRESSURE GRADIENT CALCULATIONS

For a steady free jet, the pressure gradient, $\frac{dp}{dx}$, is zero. For a confined co-axial flow the pressure gradient is calculated from the following considerations⁴⁷:-

From the continuity equation, the cross-section area of the flow, A_{flow} , which includes both the primary and secondary flows, is given by:

$$A_{flow} = \int_I^W \frac{1}{\rho u} d\psi \quad \text{----- (1)}$$

where W is the wall of the secondary flow, i.e. the wall of the glass cylinder.

If the flow properties ρ, u, ψ , etc. were correctly calculated, the flow area A_{flow} would remain a constant and would be equal to the area of the duct, A_{duct} . However, a calculated error area, dA , may be found because of a change in the streamwise pressure. From equation 1 this erroneous area dA is related to the change of pressure, dp , by:-

$$\frac{dA}{dp} = \frac{d}{dp} \int_I^W \frac{1}{\rho u} d\psi = - \int_I^W \left(\frac{1}{\rho u}\right)^2 \frac{du}{dp} du \quad \text{----- (2)}$$

As an approximation, $\frac{du}{dp} \approx -\frac{1}{\rho u}$ (by neglecting the lateral convection and diffusion terms in the momentum equation) and $\frac{dp}{dp} \approx \frac{M^2}{u^2}$ (i.e. isentropic flow), where M is the Mach number of the flow. Furthermore, $M^2 \ll 1$, thus:-

$$\frac{dA}{dp} \approx \int_I^W \frac{1}{\rho^2 u^3} du = I' \quad \text{----- (3)}$$

The erroneous area, dA , is at any step, equal to the difference between the calculated and the actual flow areas:-

$$\text{i.e. } dA = A_{duct} - A_{flow} \quad \text{----- (4)}$$

Therefore, from equations 3 and 4:-

$$dp = \frac{1}{I} (A_{\text{duct}} - A_{\text{flow}}) \quad \text{————— (5)}$$

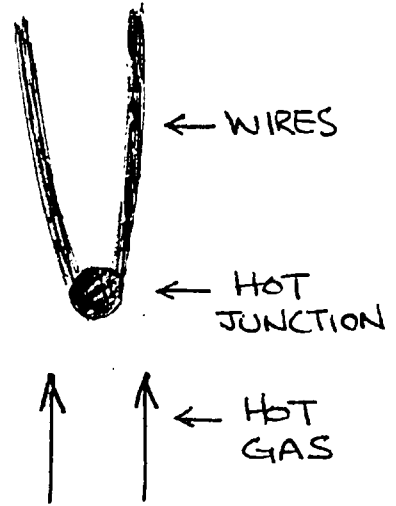
The procedures of evaluating the pressure gradient is as follows:-

- (i) Based on the upstream values of ρ , u , etc. the flow area A_{flow} is calculated. This value is then used to calculate the erroneous area dA and the pressure change, dp .
- (ii) The deduced dp is used in the source term of the momentum equation to calculate the downstream ρ , u , etc.
- (iii) From the downstream values, the pressure change dp is recalculated. Using this corrected 'dp' value, the flow properties ρ , u are adjusted.

APPENDIX F

RADIATION LOSS CALCULATION

Consider the diagram on the right.
A spherical hot junction is immersed
in a hot stream of nitrogen gas.
Assuming the temperature of the
nitrogen gas is uniform, the
conduction loss from the spherical
junction to the wires is negligible.
Thus, the heat balance at equilibrium
state is:-



$$\text{radiation loss} = \dot{Q}_R = \text{Convective gain} = \dot{Q}_C \quad \text{-----} \quad (1)$$

radiation loss is given by:

$$\dot{Q}_R = \epsilon \cdot \sigma \cdot (T_s^4 - T_a^4) \cdot A \quad \text{-----} \quad (2)$$

where ϵ = the emissivity of the hot junction
 T_s = the temperature of the hot junction
 A = the surface area of the hot junction
 σ = Stefan-Boltzman's constant
and T_a = the ambient air temperature.

and the convective heat gain is given by:-

$$\dot{Q}_C = h \cdot A \cdot (T_g - T_s) \quad \text{-----} \quad (3)$$

where T_g is the temperature of the nitrogen gas.

The coefficient of heat transfer, h , over a sphere is given by various authors. The expression adopted here is as follows¹¹⁶:-

$$h = 0.37 (R_e)^{0.6} \frac{k}{d} \quad \text{-----} \quad (4)$$

where R_e = the Reynolds number
 k = the thermal conductivity
and d = the diameter of the sphere.

From equations 1 to 4,

$$T_s^4 - T_a^4 = \frac{0.37 (R_e)^{0.6} k}{\epsilon \cdot \sigma \cdot d} (T_g - T_s) \quad \text{----- (5)}$$

In the range between 1000°C to 1500°C the thermal conductivity of nitrogen may be expressed as:-

$$k = -4.606 \times 10^{-12} T_g^3 - 2.397 \times 10^{-10} T_g^2 \\ + 4.53 \times 10^{-5} T_g + 2.971 \times 10^{-2}$$

the units of k and T_g are W/m°C and °C respectively.

An uncertain value in equation 5 is the emissivity of the platinum-rhodium alloy. ϵ varies with the nature of the junction surface and the temperature of the sphere. The value used by the present calculation is extracted from the table compiled by Dr. Margaret Fishenden¹¹⁷, and is put at $\epsilon = 0.16$ within the temperature range covered by the present study.

T_a may be conveniently given the value of 20°C (297°K), thus equation 5 is rewritten as:-

$$T_s = \frac{2.719 \times 10^{10} (R_e)^{0.6} k T_g + 7.37 \times 10^9}{T_g^3 - 2.719 \times 10^{10} (R_e)^{0.6} k} \quad \text{----- (6)}$$

From this equation, T_s may be readily deduced by iteration process. The radiation loss, i.e. $(T_g - T_s)$, is given as a function of R_e and T_g in Figure 37.

TABLE 1 DETAIL OF THE THERMOCOUPLES

TYPE	COPPER- CONSTANTAN	CHROMEL- ALUMEL	Pt to Pt - 13% Rh
REFERENCE	B.S. 1828 (1961)	B.S. 1827 (1952)	Manufacturer's Calibrated Table
MAXIMUM MEASURABLE TEMPERATURE	400°C	1300°C	1600°C
Location of the Thermocouples	(a) upstream of the orifice plate (4)* (b) cooling water inlet and outlet (2)* (c) working- section (secondary flow) (d) outlet of Secomake heater (e) settling chamber	(a) pre-heating heater (4)* (b) connector heater (3)*	(a) working section - primary flow
Cold Junction	Yes	No	Yes
Measurement of D.C. voltage	"Advance D.V.M. (± 0.01 mv)	"Solartron" D.V.M. (± 0.1 mv)	"Solartron" D.V.M. (± 0.001 mv)
Diameter of wire	0.5 mm	0.5 mm	0.5 mm

* Number of thermocouples used

TABLE 2 DETAILS OF THE ORIFICE METERS

LOCATION AND FUNCTION	PIPE DIAMETER (mm)	THROAT DIAMETER (mm)	PIPE LENGTH (mm)	MANOMETER FLUID FOR PRESSURE DIFFERENCE MEASUREMENT	MANOMETER FLUID FOR UPSTREAM PRESSURE MEASUREMENT	UPSTREAM TEMPERATURE SENSOR
Primary flow, air and nitrogen	25.4	8.76	1780	paraffin (s.g. 1.58)	mercury	copper-constantan
Secondary flow, air	76.2	38.1	5820	paraffin (s.g. 0.784)	paraffin (s.g. 1.58)	copper-constantan
Secondary flow, nitrogen	25.4	12.7	1780	paraffin (s.g. 1.58)	mercury	copper-constantan
Secondary flow, methane	25.4	10.2	1780	paraffin (s.g. 0.784)	paraffin (s.g. 1.58)	copper-constantan

TABLE 3 THE REFERENCE FLOW CONDITIONS

Measurements of M.I.T. were checked for each set of experiment under the following reference conditions:-

- (i) Jet diameter of the primary flow
 $d_p = 19.35 \text{ mm}$ or $d_p = 15.0 \text{ mm}$
- (ii) Mass flow rate of the primary flow
 $\dot{m}_p = 2.05 \times 10^{-3} \text{ Kg/s}$
- (iii) Temperature of the secondary flow
 $T_s = 150^\circ\text{C}$
- (iv) Mass flow rate of the secondary flow
 $\dot{m}_s = 50 \times 10^{-3} \text{ Kg/s}$
- (v) Equivalence ratio of the secondary flow
 $\eta = 1.0$
- (vi) Oxygen index of the secondary flow
 $\xi = 0.233.$

The measured M.I.T. over five different sets of experiment under these flow conditions were found to be:-

for $d_p = 19.35 \text{ mm}$

M.I.T. = 1279°C ; 1280°C ; 1288°C ; 1283°C ; 1284°C
average = 1283°C .

for $d_p = 15.0 \text{ mm}$

M.I.T. = 1378°C ; 1372°C ; 1379°C ; 1378°C ; 1374°C
average = 1376°C .

TABLE 4 EFFECT OF PRIMARY MASS FLOW RATE

$d_p = 19.35 \text{ mm}$ $\dot{m}_S = 50 \times 10^{-3} \text{ kg/s}$ $T_S = 150^\circ\text{C}$ $\eta = 1.0$ $\xi = 0.233$		$d_p = 15.0 \text{ mm}$ $\dot{m}_S = 50 \times 10^{-3} \text{ kg/s}$ $T_S = 150^\circ\text{C}$ $\eta = 1.0$ $\xi = 0.233$	
$\dot{m}_p \times 10^3 \text{ kg/s}$	M.I.T. ($^\circ\text{C}$)	$\dot{m}_p \times 10^3 \text{ kg/s}$	M.I.T. ($^\circ\text{C}$)
1.41	1242	1.59	1341
1.64	1260	1.76	1358
1.89	1267	1.93	1366
2.05	1279	2.05	1378
2.25	1291	2.16	1389
2.42	1302	2.42	1397
2.66	1317	2.64	1412
2.95	1332	2.81	1430
3.20	1341	3.04	1437
3.40	1355	3.22	1448
3.59	1364	3.39	1462

TABLE 5 EFFECT OF EQUIVALENT RATIO

$d_p = 19.35 \text{ mm}$ $\dot{m}_p = 2.05 \times 10^{-3} \text{ kg/s}$ $\dot{m}_s = 50 \times 10^{-3} \text{ kg/s}$ $T_s = 150^\circ\text{C}$ $\xi = 0.233$		$d_p = 15.0 \text{ mm}$ $\dot{m}_p = 2.05 \times 10^{-3} \text{ kg/s}$ $\dot{m}_s = 50 \times 10^{-3} \text{ kg/s}$ $T_s = 150^\circ\text{C}$ $\xi = 0.233$	
η	M.I.T. ($^\circ\text{C}$)	η	M.I.T. ($^\circ\text{C}$)
0.56	1299	0.67	1397
0.64	1291	0.73	1388
0.69	1286	0.79	1378
0.76	1282	0.86	1373
0.84	1280	0.95	1372
0.92	1279	1.0	1372
1.0	1280	1.12	1374
1.13	1283	1.28	1379
1.24	1286		
1.36	1289		

TABLE 6 EFFECT OF OXYGEN INDEX

$d_p = 19.35 \text{ mm}$ $\dot{m}_p = 2.05 \times 10^{-3} \text{ kg/s}$ $\dot{m}_s = 50 \times 10^{-3} \text{ kg/s}$ $T_s = 150^\circ\text{C}$ $\eta = 1.0$		$d_p = 15.0 \text{ mm}$ $\dot{m}_p = 2.05 \times 10^{-3} \text{ kg/s}$ $\dot{m}_s = 50 \times 10^{-3} \text{ kg/s}$ $T_s = 150^\circ\text{C}$ $\eta = 1.0$	
ξ	M.I.T. ($^\circ\text{C}$)	ξ	M.I.T. ($^\circ\text{C}$)
0.188	1344	0.194	1436
0.192	1338	0.197	1431
0.196	1331	0.201	1420
0.2	1326	0.206	1410
0.207	1316	0.213	1401
0.212	1311	0.217	1393
0.218	1304	0.221	1392
0.222	1298	0.227	1384
0.226	1294	0.233	1379
0.23	1290		
0.233	1288		

TABLE 7 EFFECT OF SECONDARY FLOW TEMPERATURE

$d_p = 19.35 \text{ mm}$ $\dot{m}_p = 2.05 \times 10^{-3} \text{ kg/s}$ $\dot{m}_s = 50 \times 10^{-3} \text{ kg/s}$ $\eta = 1.0$ $\xi = 0.233$		$d_p = 15.0 \text{ mm}$ $\dot{m}_p = 2.05 \times 10^{-3} \text{ kg/s}$ $\dot{m}_s = 50 \times 10^{-3} \text{ kg/s}$ $\eta = 1.0$ $\xi = 0.233$	
$T_s (^{\circ}\text{C})$	M.I.T. ($^{\circ}\text{C}$)	$T_s (^{\circ}\text{C})$	M.I.T. ($^{\circ}\text{C}$)
18.	1339	22.	1452
37.	1337	39.	1438
58.	1321	59.	1432
76.	1315	79.	1425
106.	1311	98.	1410
122.	1302	120.	1394
144.	1286	138.	1381
150.	1283	150.	1378
165.	1277	159.	1371
186.	1270	180.	1363
187.	1265	187.	1352
167.	1278	169.	1362
150.	1284	150.	1374
139.	1294	133.	1386
118.	1304	111.	1395
107.	1311	87.	1409
93.	1317	62.	1421
74.	1330	45.	1432
52.	1340		
33.	1351		

TABLE 8. REACTIONS OF METHANE OXIDATION

<u>REACTIONS</u>	<u>REFERENCES</u>
1. $\text{CH}_4 + \text{O}_2 \rightarrow \text{CH}_3 + \text{HO}_2$	94, 137
2. $\text{CH}_4 + \text{O}_2 \rightarrow \text{CH}_2\text{O} + \text{H}_2\text{O}$	139
3. $\text{CH}_4 + \text{H} \rightarrow \text{CH}_3 + \text{H}_2$	3, 140
4. $\text{CH}_4 + \text{O} \rightarrow \text{CH}_3 + \text{OH}$	3
5. $\text{CH}_4 + \text{O} \rightarrow \text{CH}_2 + \text{H}_2\text{O}$	141
6. $\text{CH}_4 + \text{OH} \rightarrow \text{CH}_3 + \text{H}_2\text{O}$	3, 138
7. $\text{CH}_4 + \text{HO}_2 \rightarrow \text{CH}_3 + \text{H}_2\text{O}_2$	94
8. $\text{CH}_4 + \text{M} \rightarrow \text{CH}_3 + \text{H} + \text{M}$	141, 150
9. $\text{CH}_3 + \text{O}_2 \rightarrow \text{CH}_2\text{O} + \text{OH}$	3, 94, 142
10. $\text{CH}_3 + \text{O}_2 \rightarrow \text{CH}_3\text{O}_2$	91
11. $\text{CH}_3\text{O}_2 \rightarrow \text{CH}_2\text{O} + \text{OH}$	91
12. $\text{CH}_3 + \text{H}_2 \rightarrow \text{CH}_4 + \text{H}$	144
13. $\text{CH}_3 + \text{CH}_2\text{O} \rightarrow \text{CHO} + \text{CH}_4$	143
14. $\text{CH}_3 + \text{OH} \rightarrow \text{CH}_2\text{O} + \text{H}_2$	151
15. $\text{CH}_3 + \text{O} \rightarrow \text{CO} +$	126
16. $\text{CH}_2\text{O} + \text{O}_2 \rightarrow \text{CHO} + \text{HO}_2$	3, 94
17. $\text{CH}_2\text{O} + \text{O} \rightarrow \text{CHO} + \text{OH}$	146
18. $\text{CH}_2\text{O} + \text{OH} \rightarrow \text{CHO} + \text{H}_2\text{O}$	94
19. $\text{CH}_2\text{O} + \text{H} \rightarrow \text{CHO} + \text{H}_2$	145
20. $\text{CH}_2\text{O} + \text{HO}_2 \rightarrow \text{CHO} + \text{H}_2\text{O}_2$	94
21. $\text{CH}_2\text{O} + \text{M} \rightarrow \text{CHO} + \text{H} + \text{M}$	152
22. $\text{CHO} + \text{OH} \rightarrow \text{CO} + \text{H}_2\text{O}$	3
23. $\text{CHO} + \text{O} \rightarrow \text{CO} + \text{OH}$	129
24. $\text{CHO} + \text{H} \rightarrow \text{CO} + \text{H}_2$	129

Contd....

TABLE 8. Continued

	<u>REACTIONS</u>	<u>REFERENCES</u>
25.	$\text{CHO} + \text{M} \longrightarrow \text{CO} + \text{H} + \text{M}$	130
26.	$\text{CO} + \text{O}_2 \longrightarrow \text{CO}_2 + \text{O}$	3
27.	$\text{CO} + \text{OH} \longrightarrow \text{CO}_2 + \text{H}$	96
28.	$\text{H} + \text{O}_2 \longrightarrow \text{OH} + \text{O}$	3, 130
29.	$\text{O} + \text{H}_2 \longrightarrow \text{OH} + \text{H}$	3, 130
30.	$\text{O} + \text{H}_2\text{O} \longrightarrow \text{OH} + \text{OH}$	3
31.	$\text{OH} + \text{H}_2 \longrightarrow \text{H}_2\text{O} + \text{H}$	3, 96
32.	$\text{H} + \text{H}_2\text{O} \longrightarrow \text{H}_2 + \text{OH}$	3, 96
33.	$\text{OH} + \text{OH} \longrightarrow \text{H}_2\text{O} + \text{O}$	3, 96
34.	$\text{H} + \text{O} + \text{M} \longrightarrow \text{OH} + \text{M}$	148
35.	$\text{H} + \text{O}_2 + \text{M} \longrightarrow \text{HO}_2 + \text{M}$	3, 149
36.	$\text{OH} + \text{OH} + \text{M} \longrightarrow \text{H}_2\text{O}_2 + \text{M}$	147
37.	$\text{H} + \text{H} + \text{M} \longrightarrow \text{H}_2 + \text{M}$	3, 148
38.	$\text{O} + \text{O} + \text{M} \longrightarrow \text{O}_2 + \text{M}$	3, 148
39.	$\text{H} + \text{OH} + \text{M} \longrightarrow \text{H}_2\text{O} + \text{M}$	3, 148

TABLE 9 VELOCITY MEASUREMENT - FREE JET

$d_p = 15.0 \text{ mm}$	$\dot{m}_s = 0$
$\dot{m}_p = 2.25 \times 10^{-3} \text{ Kg/s}$	$T_p = T_s = 20^\circ\text{C}$

AXIAL PROFILE	
$\frac{x}{d_p}$	U (m/s)
1	13.8
2	13.8
3	13.8
4	13.7
5	13.4
6	12.8
7	12.1
8	11.2
9	10.4
10	9.6
11	9.0
12	8.4
13	7.8
14	7.4
15	7.0
16	6.6
17	6.2
18	5.8
19	5.6
20	5.3

RADIAL PROFILE $\frac{x}{d_p} = 4$	
r (mm)	U (m/s)
1	13.69
3	13.02
5	12.41
7	9.31
9	7.63
11	5.77
13	4.18
15	2.82
17	2.70
19	0.95
21	0.56
23	0.43

TABLE 9 CONTINUED

$d_p = 15.00 \text{ mm}$	$\dot{m}_s = 0$
$\dot{m}_p = 2.25 \times 10^{-3} \text{ Kg/s}$	$T_p = T_s = 20^\circ\text{C}$

RADIAL PROFILE $\frac{x}{dp} = 8$	
r (mm)	U (m/s)
1	11.04
3	10.04
5	8.71
7	7.73
9	6.5
11	5.64
13	4.55
15	3.57
17	2.87
19	1.73
21	1.66
23	1.22
25	0.92
27	0.58

RADIAL PROFILE $\frac{x}{dp} = 12$	
r (mm)	U (m/s)
1	8.29
3	7.93
5	7.37
7	6.73
9	6
11	5.32
13	4.62
15	3.92
17	3.63
19	2.81
21	2.12
23	1.85
25	1.45
27	1.08

TABLE 9 CONTINUED

$d_p = 15.0 \text{ mm}$	$\dot{m}_s = 0$
$\dot{m}_p = 2.25 \times 10^{-3} \text{ Kg/s}$	$T_p = T_s = 20^\circ\text{C}$

RADIAL PROFILE $\frac{x}{d_p} = 16$	
r (mm)	U (m/s)
0	6.53
3	6.28
6	6.02
9	5.44
12	4.82
15	4.08
18	3.53
21	2.6
24	2.38
27	1.61
30	1.31
33	1.23
36	0.67
39	0.35

RADIAL PROFILE $\frac{x}{d_p} = 20$	
r (mm)	U (m/s)
1	5.29
5	5.02
9	4.73
13	4.11
17	3.80
21	3.21
25	2.56
29	1.88
33	1.45
37	1.08
41	0.95
45	0.72
49	0.48

TABLE 10 VELOCITY MEASUREMENT - CONFINED JETS

$d_p = 15.0 \text{ mm}$	$\dot{m}_s = 50 \times 10^{-3} \text{ Kg/s}$
$\dot{m}_p = 2.0 \times 10^{-3} \text{ Kg/s}$	$T_p = T_s = 20^\circ\text{C}$

AXIAL PROFILE	
$\frac{x}{d_p}$	U (m/s)
0.67	11.80
2.07	11.69
4.2	11.56
10.73	7.81
15.2	5.97
19.0	4.98
23.0	4.24

RADIAL PROFILE $\frac{x}{d_p} = 4.2$	
r (mm)	U (m/s)
0	11.56
2	11.29
4	10.37
6	8.88
8	7.03
10	5.74
12	4.33
14	3.03
16	1.99
18	1.25
20	0.72
22	0.54

TABLE 10 CONTINUED

$d_p = 15.0 \text{ mm}$	$\dot{m}_s = 50 \times 10^{-3} \text{ Kg/s}$
$\dot{m}_p = 2.0 \times 10^{-3} \text{ Kg/s}$	$T_p = T_s = 20^\circ\text{C}$

RADIAL PROFILE $\frac{x}{d_p} = 10.73$	
r (mm)	U (m/s)
0	7.81
2	7.55
4	7.12
6	6.61
8	5.75
10	4.87
12	4.26
14	3.57
16	3.05
18	2.62
20	2.04
22	1.71
24	1.32
26	1.05
28	0.89
30	0.79
40	0.66

RADIAL PROFILE $\frac{x}{d_p} = 15.2$	
r (mm)	U (m/s)
0	5.97
2	5.86
4	5.67
6	5.36
8	5.09
10	4.58
12	4.18
14	3.71
16	3.18
18	2.9
20	2.53
22	2.21
24	2.27
26	1.67
28	1.78
30	1.70
32	0.89
34	0.78
36	0.66
38	0.87
40	0.66

TABLE 10 CONTINUED

$d_p = 15.0 \text{ mm}$	$\dot{m}_s = 50 \times 10^{-3} \text{ Kg/s}$
$\dot{m}_p = 2.0 \times 10^{-3} \text{ Kg/s}$	$T_p = T_s = 20^\circ\text{C}$

RADIAL PROFILE $\frac{x}{d_p} = 19$	
r (mm)	U (m/s)
0	4.98
2	4.94
4	4.82
6	4.7
8	4.46
10	4.2
12	3.95
14	3.79
16	3.4
18	3.18
20	2.77
22	2.71
24	2.4
26	2.15
30	1.78
34	1.16
38	0.89
40	0.78
45	0.65
50	0.59

RADIAL PROFILE $\frac{x}{d_p} = 23$	
r (mm)	U (m/s)
0	4.24
5	4.06
10	3.63
15	3.24
20	2.72
25	2.53
30	2.09
35	1.78
40	1.06
45	0.96
50	0.79
55	0.8

TABLE 11 LAMINAR VISCOSITIES

(a) $(\mu_{1,j})_{\text{Ref}}$ at 500°C (Kaye and Laby) x 10⁵ N-s-m²

$\frac{\text{CH}_4}{2.33}$ $\frac{\text{O}_2}{4.13}$ $\frac{\text{CO}_2}{3.41}$ $\frac{\text{H}_2\text{O}}{2.80}$ $\frac{\text{N}_2}{3.49}$

(b) Comparison of Kaye and Laby and Sutherland's Law

	<u>100°C</u>		<u>300°C</u>		<u>500°C</u>		<u>600°C</u>	
	A	B	A	B	A	B	A	B
CH ₄	1.35	1.19	1.88	1.80	2.33	2.33	2.53	2.58
O ₂	2.44	2.11	3.37	3.18	4.13	4.13	4.47	4.56
CO ₂	1.86	1.74	2.70	2.63	3.41	3.41	3.73	3.77
H ₂ O	1.21	1.43	2.02	2.16	2.80	2.80	3.0	3.09
N ₂	2.12	1.78	2.86	2.69	3.49	3.49	3.78	3.86

A = Kaye and Laby

B = Sutherland's Law

(c) Sutherland's Law

	700°C	1100°C	1500°C	1900°C
CH ₄	2.81	3.64	4.35	4.98
O ₂	4.98	6.45	7.71	8.83
CO ₂	4.11	5.33	6.37	7.29
H ₂ O	3.37	4.37	5.23	5.99
N ₂	4.21	5.45	6.52	7.47

TABLE 12 SPECIFIC HEAT OF CHEMICAL SPECIES

Effective specific heat is defined as:-

$$C_p = \sum_{j=1}^n \frac{m_j}{w_j} : C_{p,j} \quad \text{KJ/Kg-K}$$

where $C_{p,j} = a_j + b_j T + c_j T^2 \quad (\text{KJ/Kg-K}^0\text{-mol})$

	a_j (KJ/Kg-K-mol)	$b_j \times 10^3$ (KJ/Kg-K ² -mol)	$c_j \times 10^6$ (KJ/Kg-K ³ -mol)
H ₂ O	30.370	9.618	1.184
CO ₂	26.009	43.512	-14.838
O ₂	25.732	12.983	- 3.863
CH ₄	14.151	74.941	-17.529
N ₂	27.306	5.232	- 0.004

TABLE 13

COMPARISON OF M.I.T. OF CH₄ - O₂ MIXTURES

By Laminar (L) or Turbulent (T) jets	By Air (A) or Nitrogen (N) jets	Ts (°C)	dp (mm)	$\dot{m}_p$ (Kg/s) x10 ³	M.I.T. (°C)	M.I.T. Adjusted for Ts effect (°C)	$\ln(\frac{\dot{m}_{pT}}{dp^2})$	Reference
T	N	150	19.35	1.41	1242	1307	1.78	Present - Study
"	"	"	"	2.05	1283	1348	2.18	
"	"	"	"	3.20	1341	1406	2.66	
"	"	"	15.0	1.59	1341	1401	2.47	
"	"	"	"	2.05	1376	1436	2.74	
"	"	"	"	3.04	1437	1497	3.17	
L	N	Ambient	4.0	.042	1425	1425	1.49	22
"	"	"	6.4	.070	1436	1436	1.07	26
"	"	"	7.0	.071	1200	1200		17
"	"	"	10.0	.119	1325	1325	0.64	22
"	"	"	15.0	.143	1265	1265	-0.02	26
"	"	"	17.0	.154	1240	1240	-0.21	22
L	A	Ambient	4.0	.042	1180, 1190	1180, 1190	1.34	17, 21
"	"	"	7.0	.070	1135	1135	.7	17
"	"	"	10.0	.119	1040	1040	.44	22

TABLE 14 DI-ELECTRIC STRENGTH OF ALUMINA CEMENT

(a) At Temperature up to 1000°C

<u>Di-electric Strength (Volts/mm)</u>	<u>References</u>
1.5 x 10 ³	54
4.8 x 10 ⁴	102
4.8 x 10 ⁴	103
2 x 10 ⁵	104
6-11 x 10 ⁵	105

(b) At Temperature Near the Fusion of Cement

<u>Di-electric Strength (Volts/mm)</u>	<u>References</u>
25	54
50 (porous)	106
230 (dense)	
40 - 100	107
40 - 160	108
50 (porous)	
160 - 1100 (sintered)	109
200	110
250	111

TABLE 15

THERMAL CONDUCTIVITY OF CERAMIC OXIDES

(Reference 89)

OXIDES	MELTING POINT (°C)	THERMAL CONDUCTIVITY W/m-°C		REMARKS
		200°C	1400°C	
Alumina (Al_2O_3)	2015	22.5	5.5	Low melting point
Beryllia (BeO)	2550	174.6	16.4	High conductivity but toxic
Calcium (CaO)	2600	11.1		Chemically unstable
Magnesia (MgO)	2800	38.3	6.0	High porosity
Thoria (ThO_2)	3300	8.5	2.5	Radioactive
Uranium Oxide (UO_2)	2280	4.2		Unstable
Zirconia (ZrO_2)	2677	2.0	2.44	Not available in long tube form
Zircon ($\text{ZrO}_2 \cdot \text{SiO}_2$)	2420	5.7	3.8	Not available in long tube form

TABLE 16 COMPARISON OF ACTIVATION ENERGY
OF METHANE AIR MIXTURE

METHOD	FUEL/AIR RATIO (EQUIVALENCE)	PRESSURE RATIO (x ATMOS. PRESSURE)	TEMPERATURE RANGE (°K)	ACTIVATION ENERGY (J/Kg-mole) x10 ⁻⁸	REFERENCE
Hot Gas (Turbulent)	0.56-1.36	1.0	1515-1725	2.15	Present Study
Hot Gas (Laminar)	0.8 -1.0	1.0	1538-1709	2.102	26
Shock Tube	0.2-5.0	1.5-4.0	1350-1900	2.152	119
Shock Tube	1.0	11.22-15.13	1476-1900	2.09	6
Flow Reactor	0.5-0.8	0.3-0.8	1450-1750	2.38 [±] 0.2	120
Flow Reactor	0.4-2.5	1.0	1180-1282	2.386	8
Fully Stirred Reactor	lean	up to 2	1300-1400	2.38	123
Free Flame	1.08-1.32	1.0	2180-2520	1.6	5
Static Reactor	1.5-9.0	103	630	1.8	7

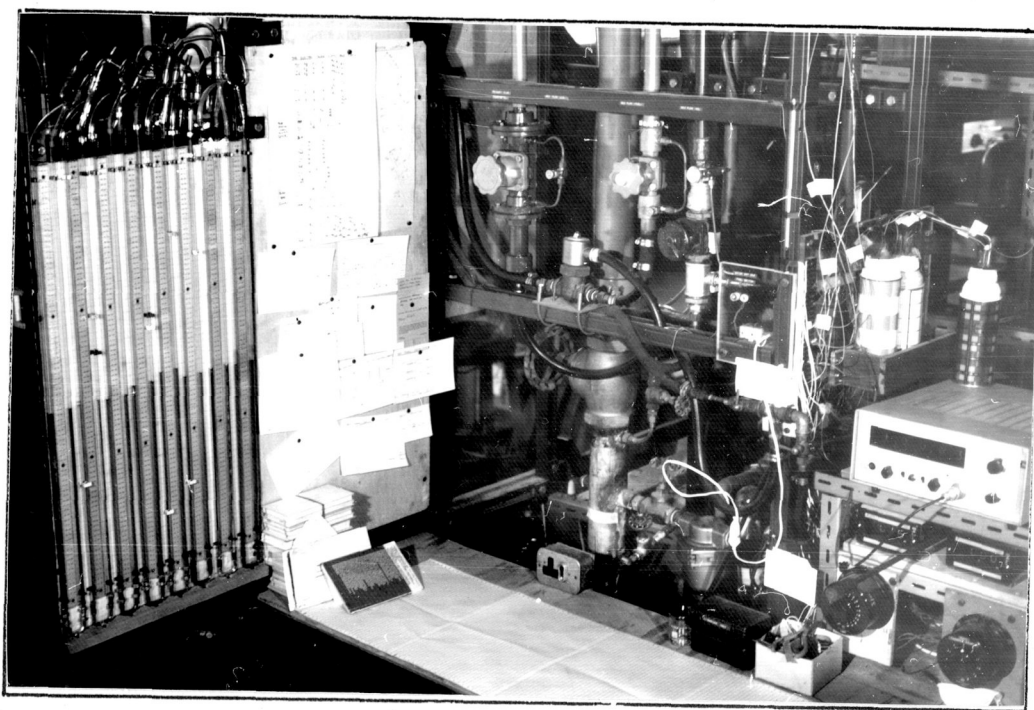
METHOD	UNADJUSTED EXPRESSION	ADJUSTED FOR PRESSURE AND TEMPERATURE	ADJUSTED FOR CONCENTRATION	REFERENCE
Hot Gas (Turbulent)	$7.88 \times 10^6 m_{CH_4} \cdot m_{O_2} \cdot p^2 \cdot T^{-3/2}$ $\exp(-2.15 \times 10^8 / RT)$	$1.18 \times 10^{12} \cdot m_{CH_4} \cdot m_{O_2} \cdot$ $\exp(-2.15 \times 10^8 / RT)$	$1.43 \times 10^{10} \cdot \exp(-2.15 \times 10^8 / RT)$	Present Study
Hot Gas (Laminar)	$4.64 \times 10^{11} m_{O_2}^{1.1} (p/RT)$ $\cdot \exp(-2.1 \times 10^8 / RT)$	$4.72 \times 10^{10} \cdot m_{O_2}^{1.1}$ $\cdot \exp(-2.1 \times 10^8 / RT)$	$8.93 \times 10^9 \cdot \exp(-2.1 \times 10^8 / RT)$	26
Flow Reactor	$3.31 \times 10^{14} \cdot m_{CH_4} \cdot m_{O_2}^{0.5} \cdot m_{H_2O}^{0.5}$ $\cdot (p/RT)^2 \cdot \exp(-2.38 \times 10^8 / RT)$	$1.69 \times 10^{12} \cdot m_{CH_4} \cdot m_{O_2}^{0.5} \cdot m_{H_2O}^{0.5}$ $\cdot \exp(-2.38 \times 10^8 / RT)$	$1.53 \times 10^{10} \cdot \exp(-2.38 \times 10^8 / RT)$	120
Flow Reactor	$6 \times 10^{10} \cdot m_{CH_4}^{-0.4} \cdot m_{O_2}^{1.4}$ $\cdot \exp(2.39 \times 10^8 / RT)$		$2.30 \times 10^{10} \cdot \exp(-2.39 \times 10^8 / RT)$	8

TABLE 17

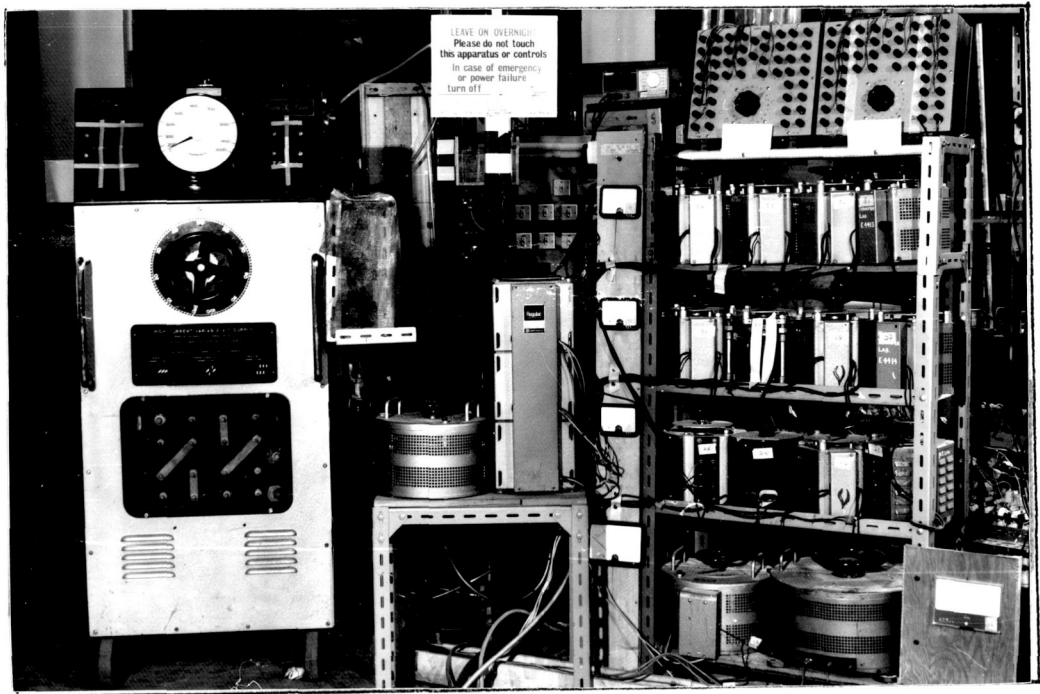
COMPARISON OF REACTION RATE OF METHANE AIR MIXTURE



PLATE(1) MAIN BODY



PLATE(2) FLUID FLOW SUPPLY & CONTROL



PLATE(3) ELECTRIC POWER SUPPLY & CONTROL

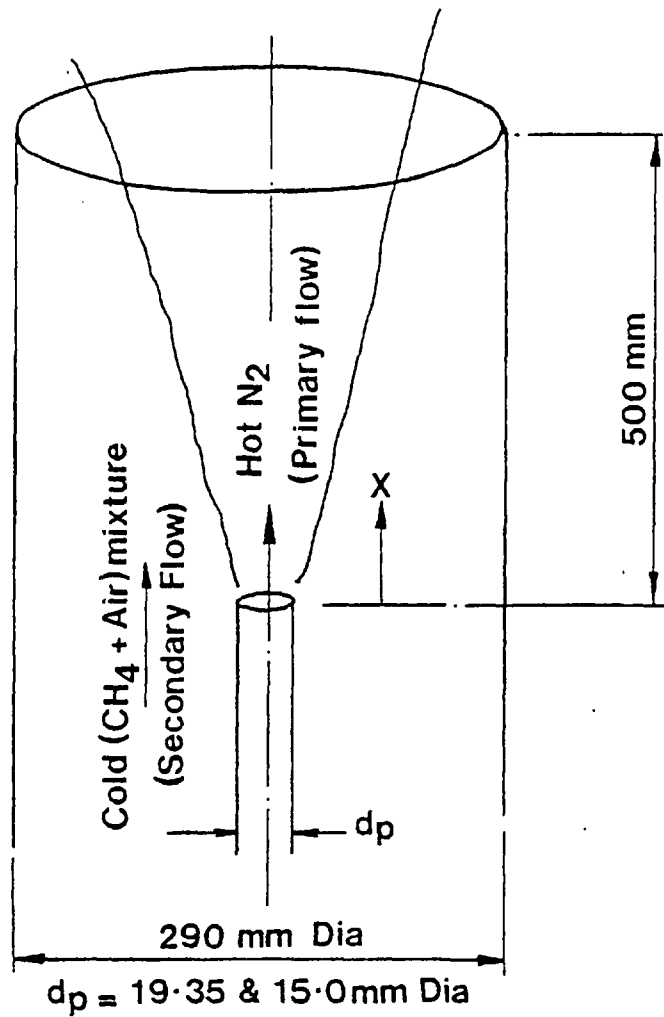


Fig 1 THE GEOMETRY OF THE FLOW

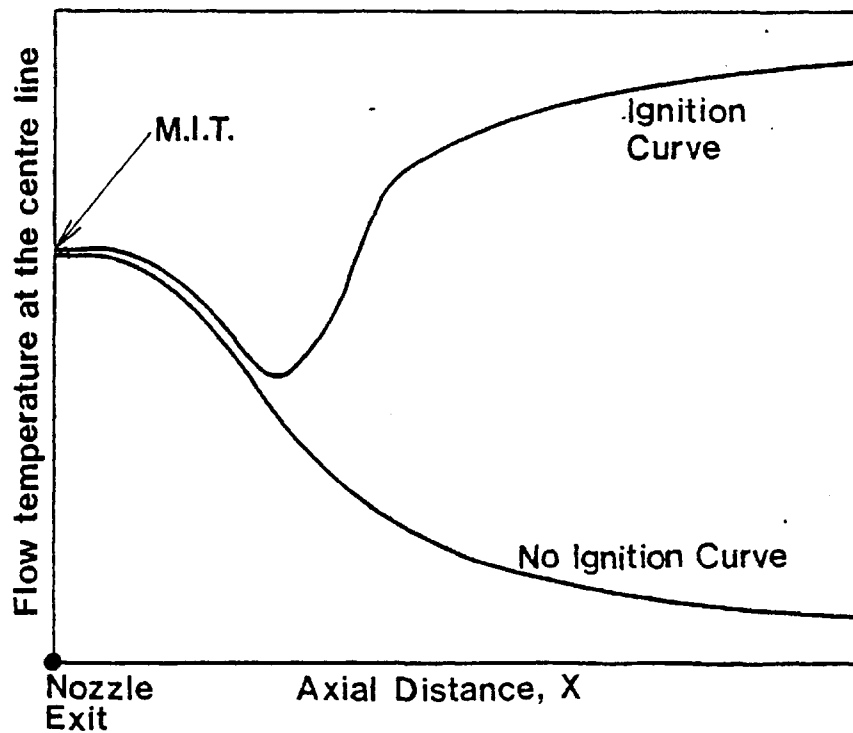


Fig 1A AXIAL TEMPERATURE DIFFERENCE BETWEEN IGNITION AND NO IGNITION

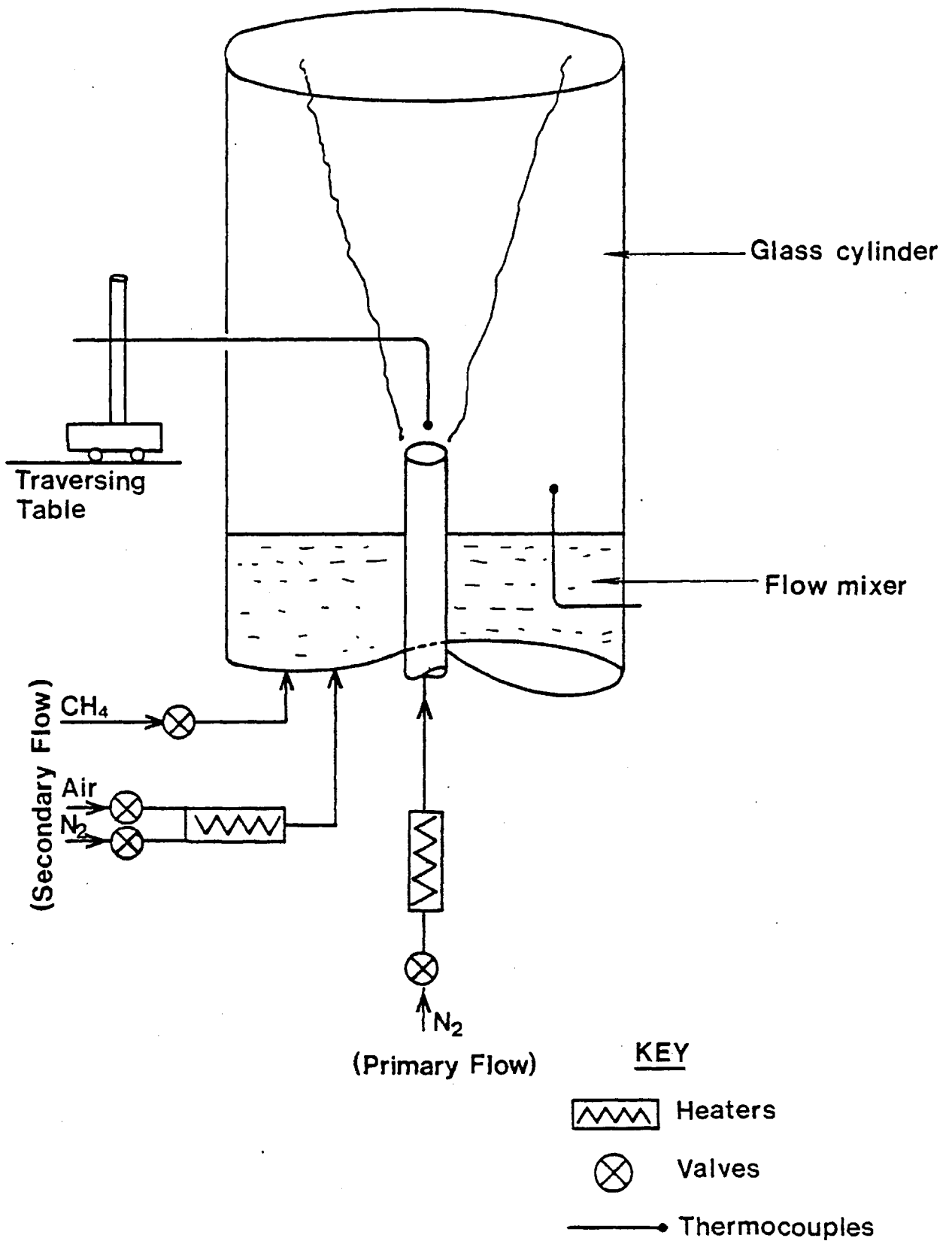
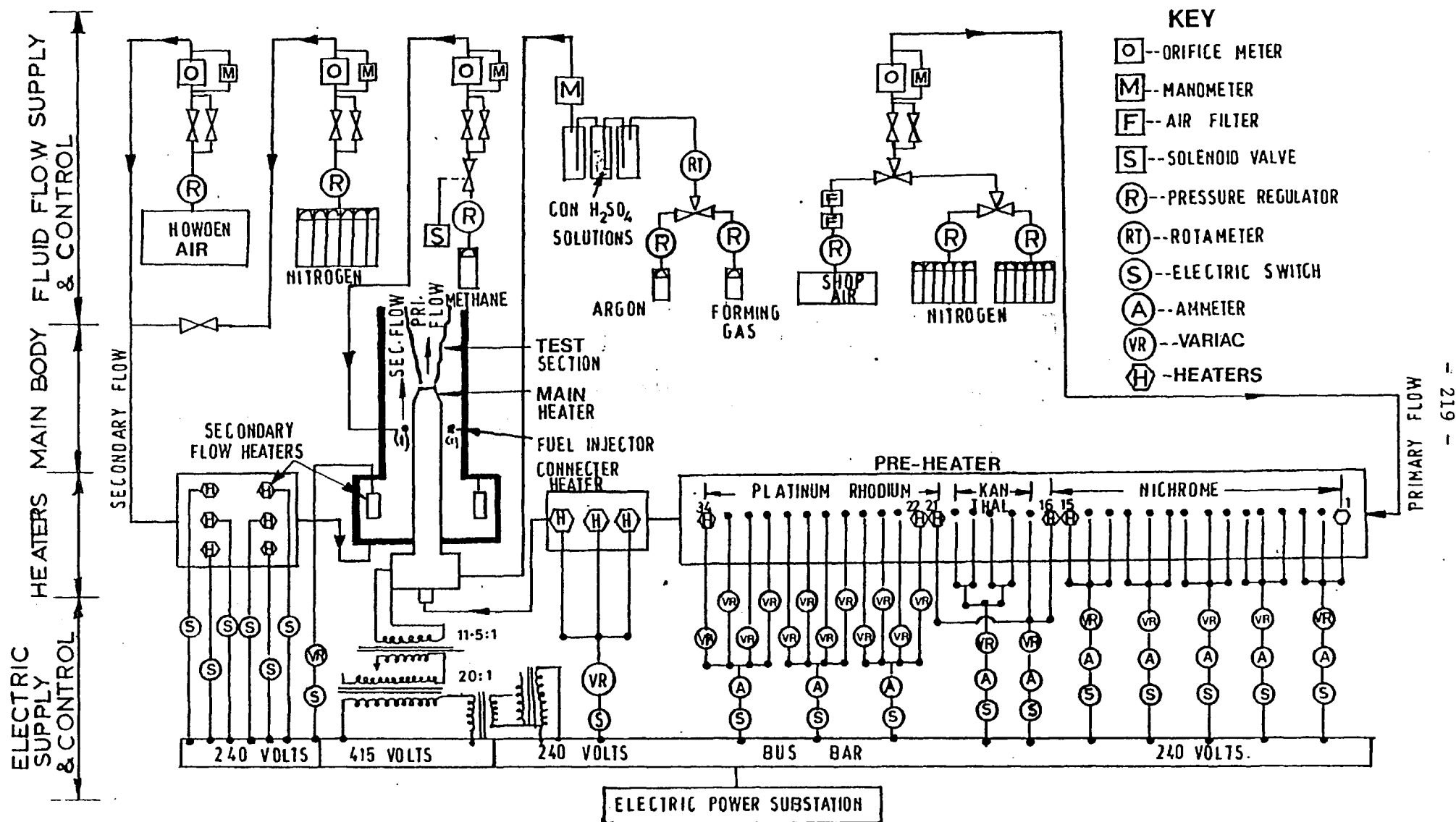
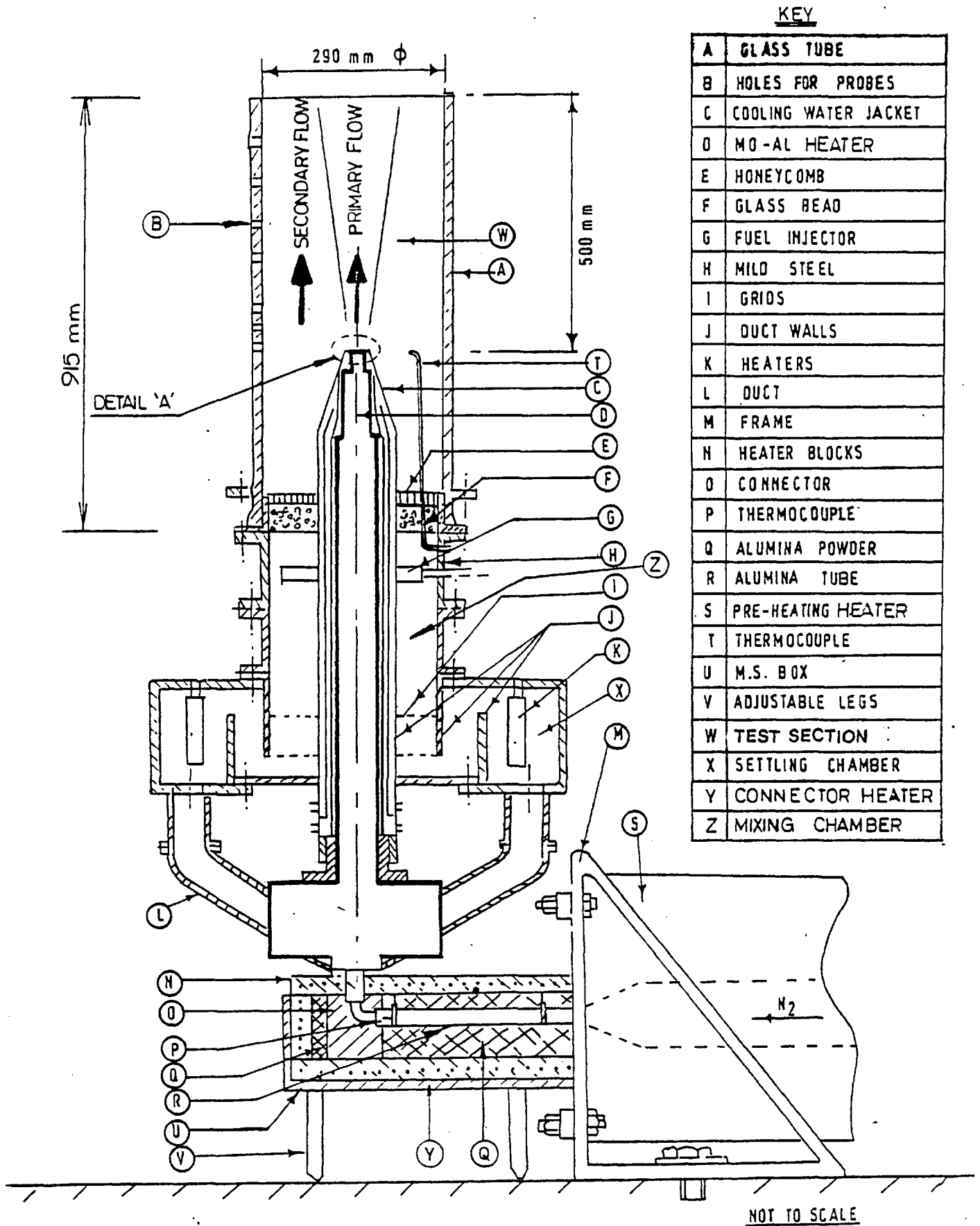


Fig.1B SCHEME FOR M.I.T MEASUREMENT





FIG(3) LAYOUT OF THE MAIN BODY

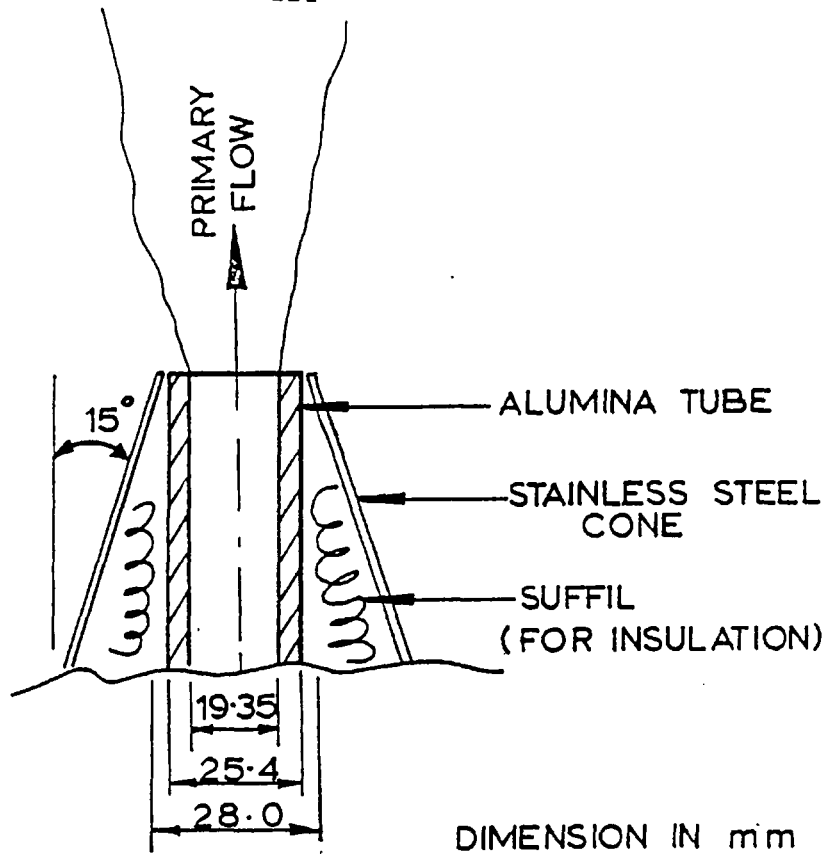


FIG (4) DETAIL 'A' OF FIG (3)

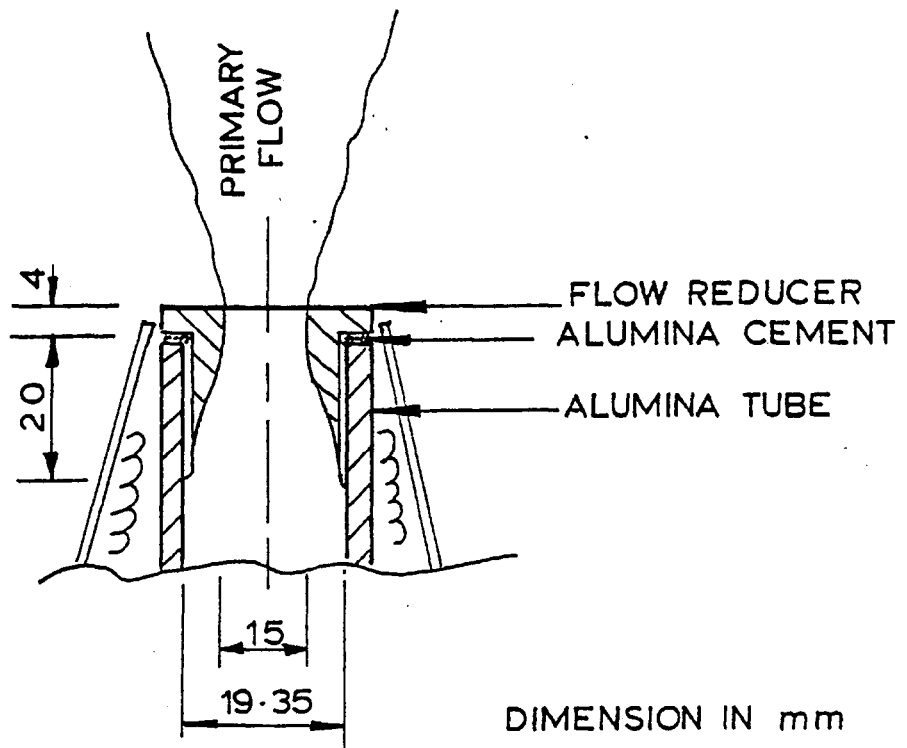


FIG (5) THE FLOW REDUCER

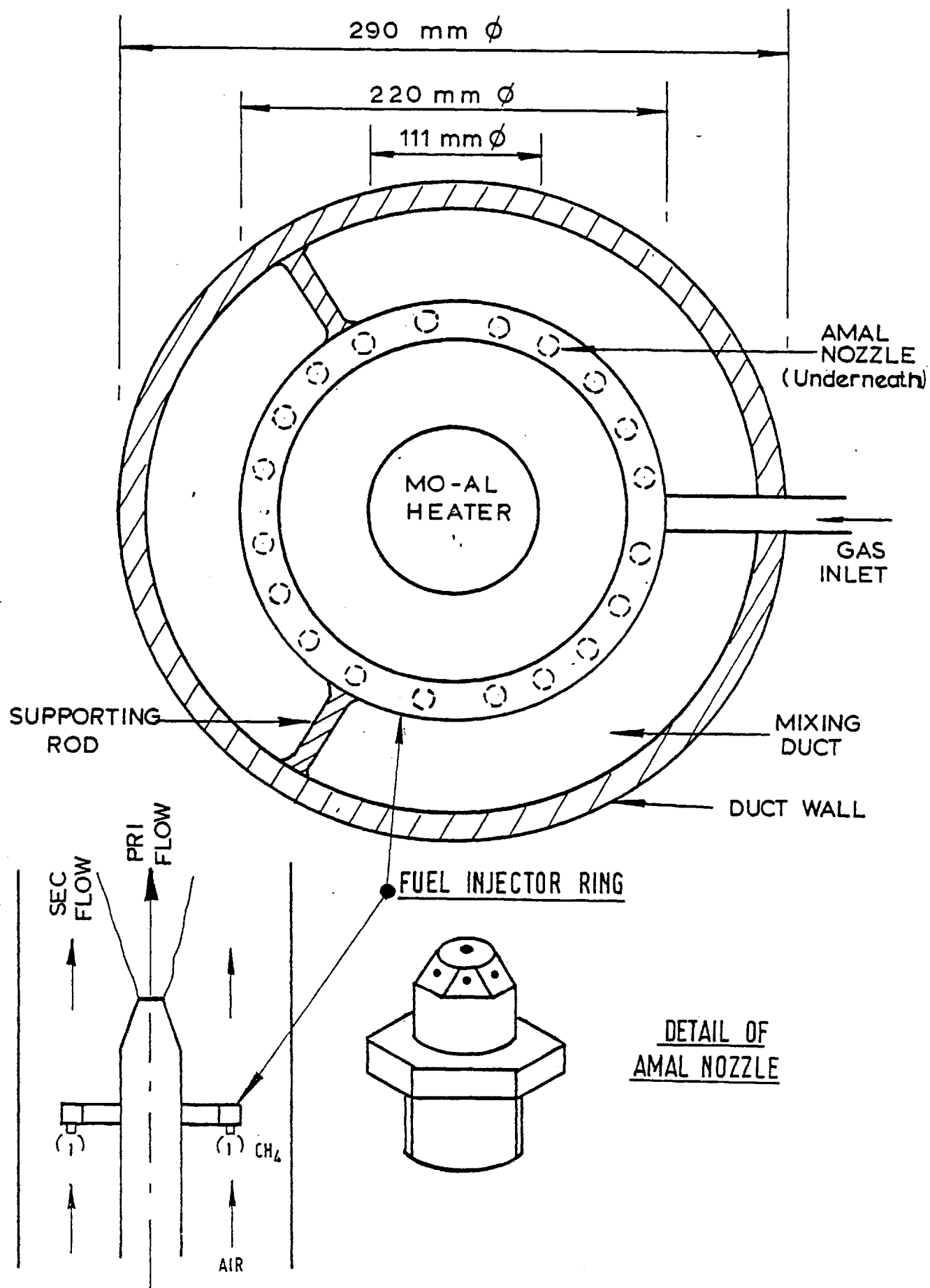
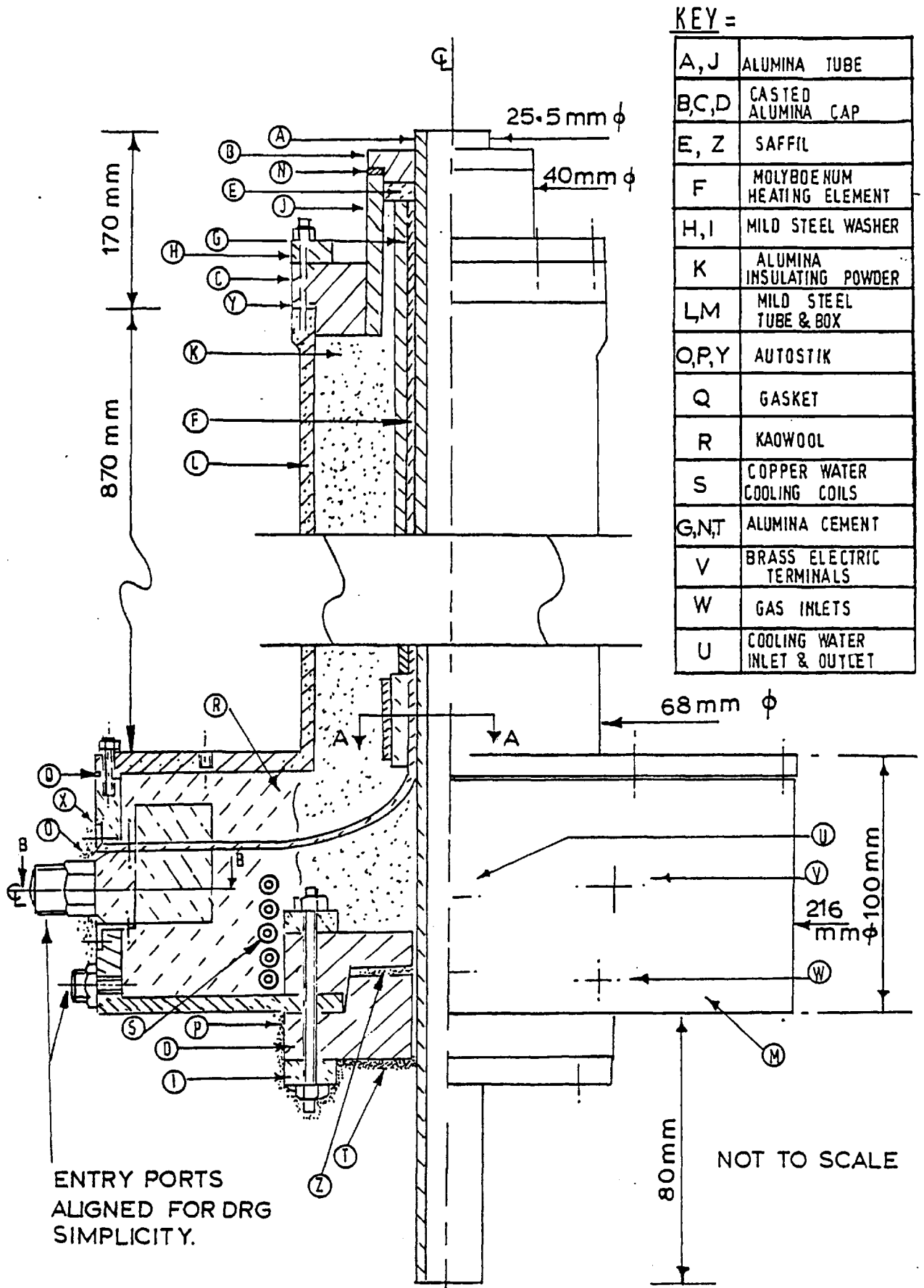


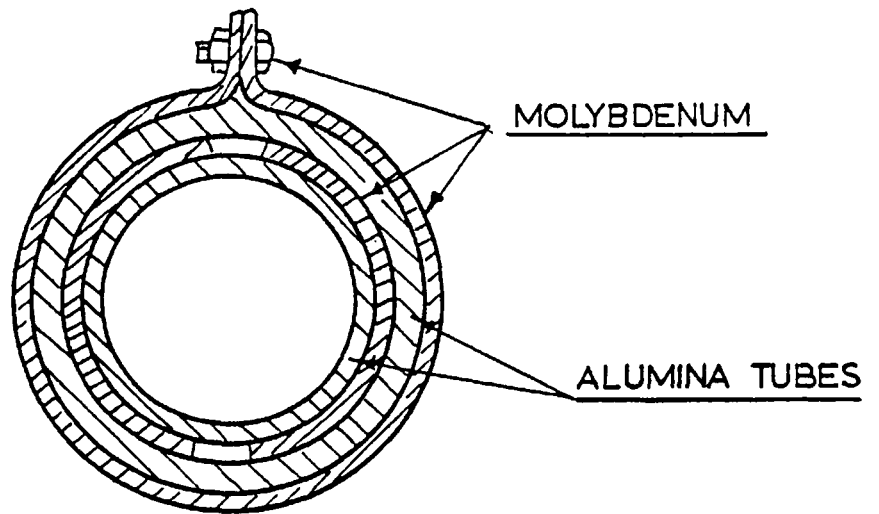
FIG (6)

FUEL INJECTOR



FIG(7) THE MOLYBDENUM - ALUMINA HEATER

SECTION A-A



SECTION B-B

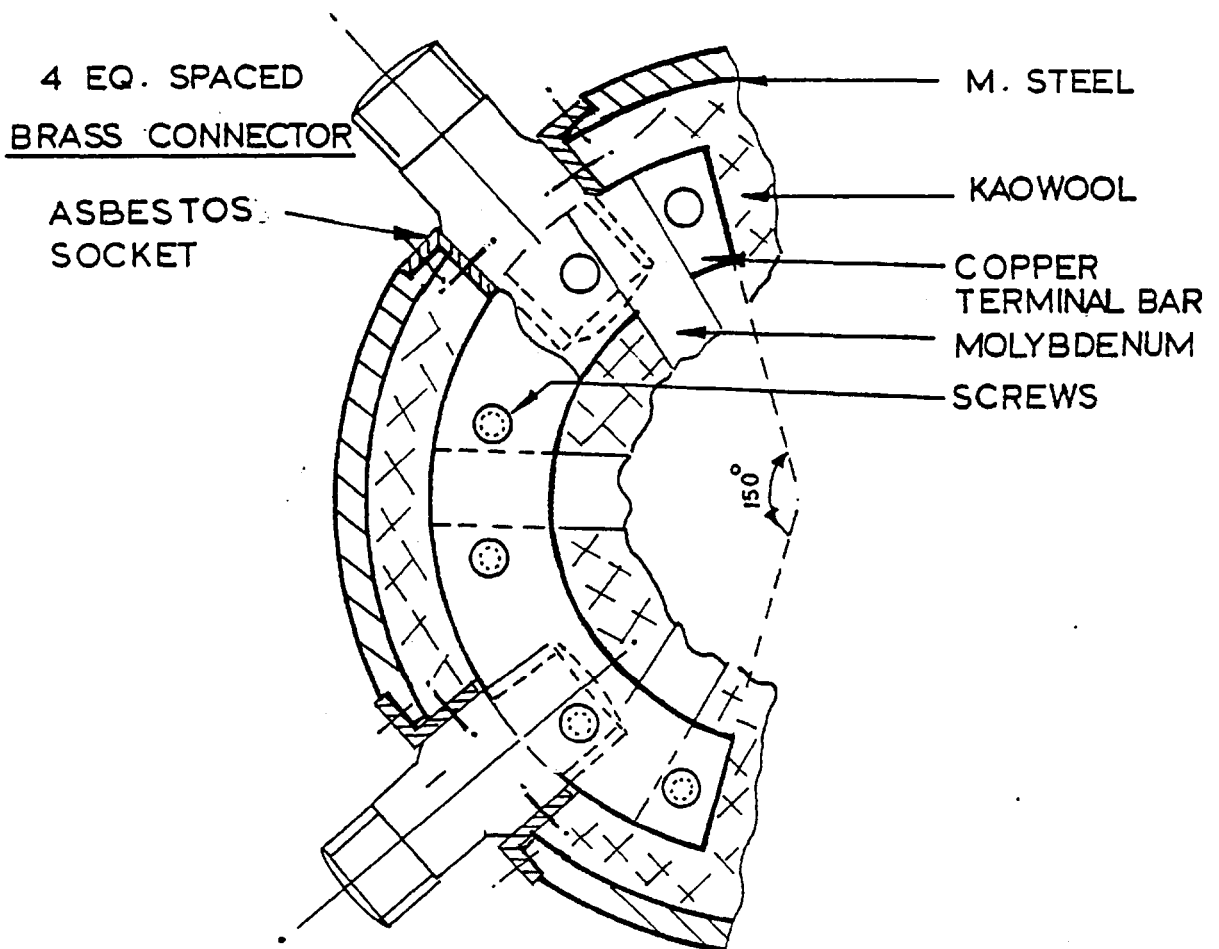
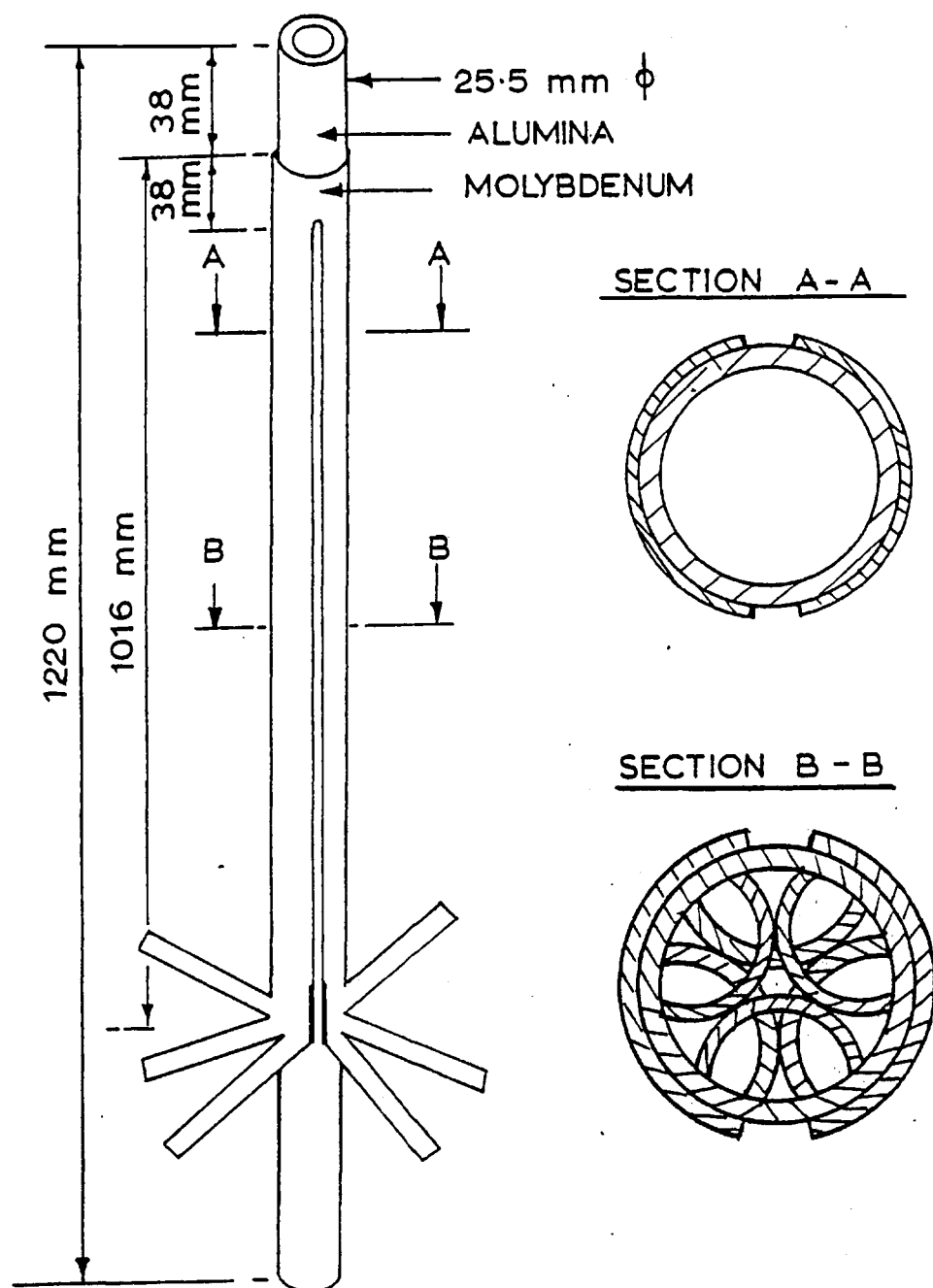


FIG.(8) SECTION A-A & B-B OF FIG.(7)



FIG(9) DETAIL OF THE MOLYBDENUM HEATING ELEMENT

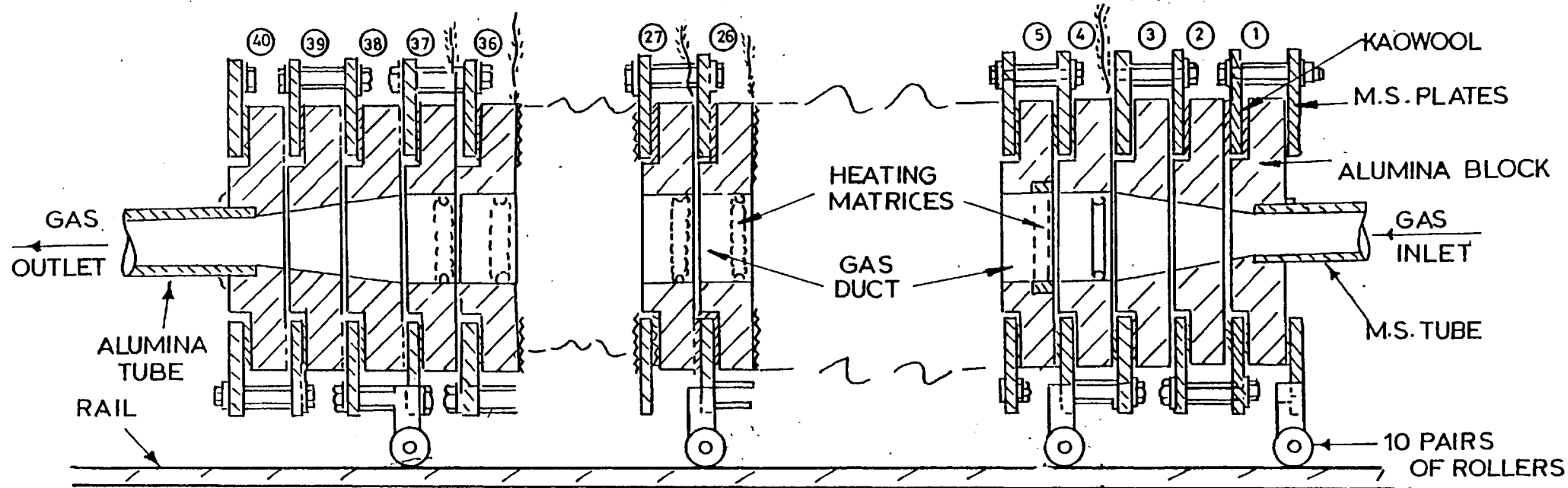
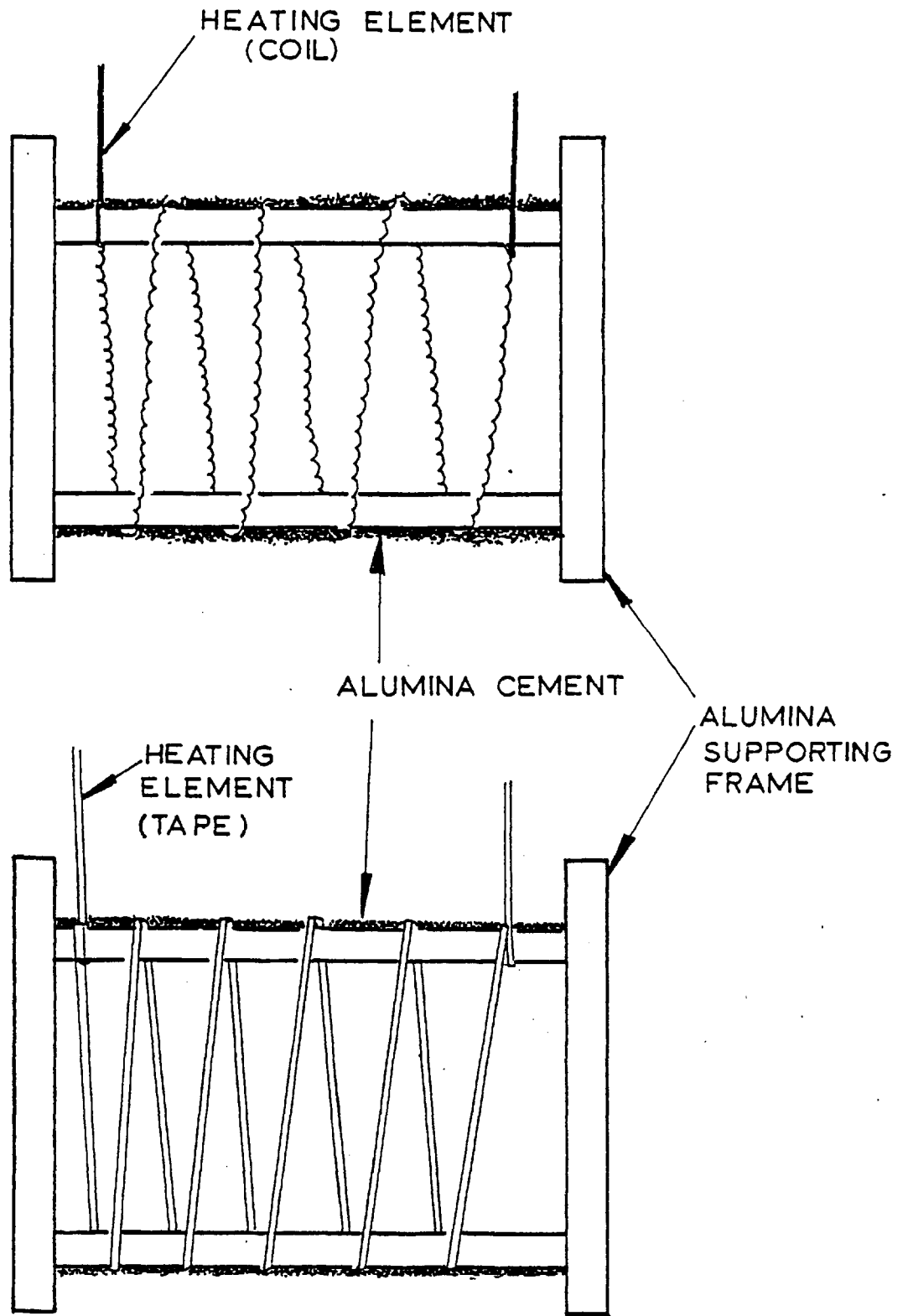
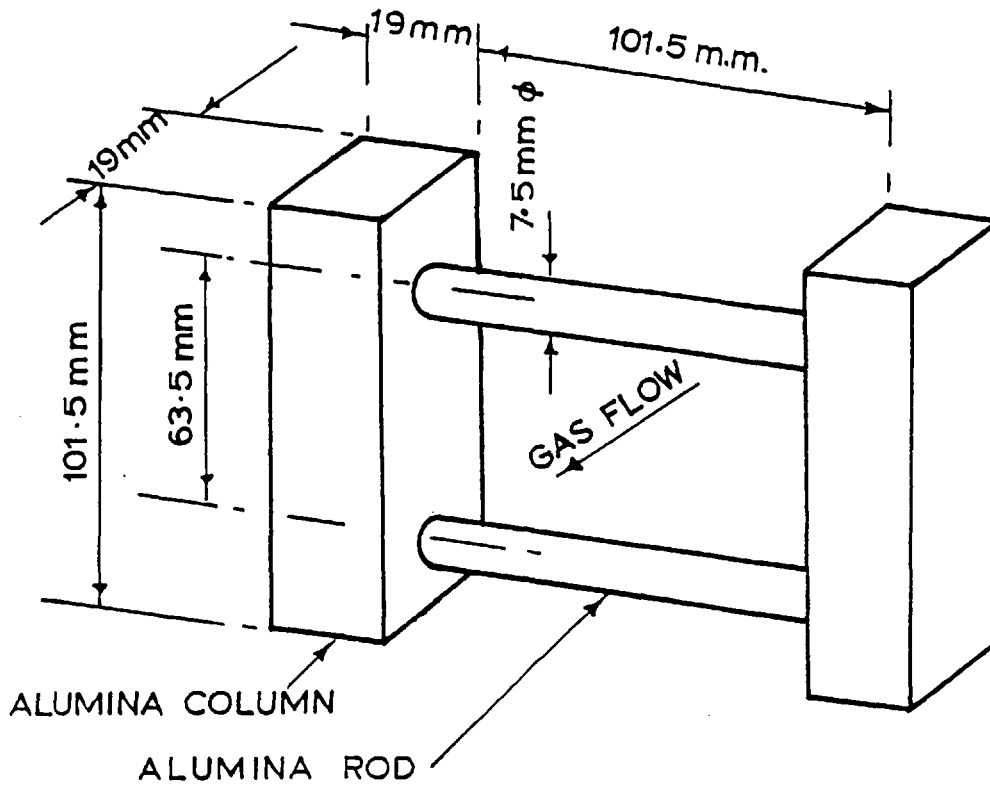


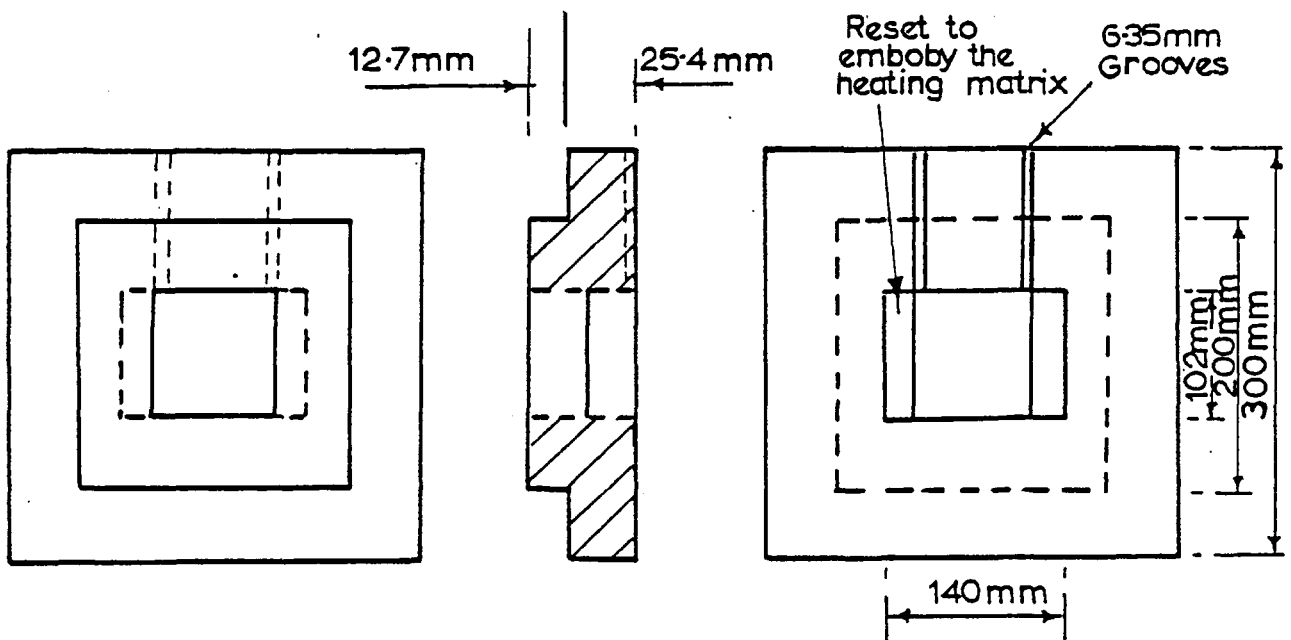
FIG (10) THE PRE - HEATING HEATER



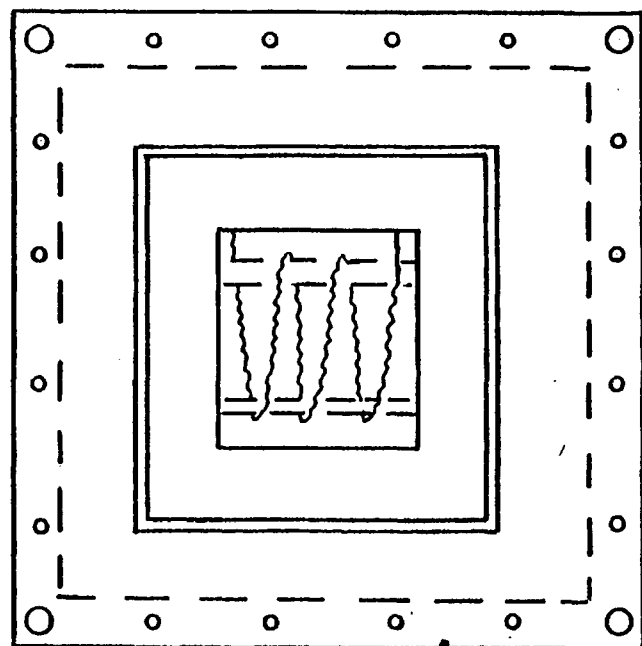
FIG(11) THE HEATING MATRICES



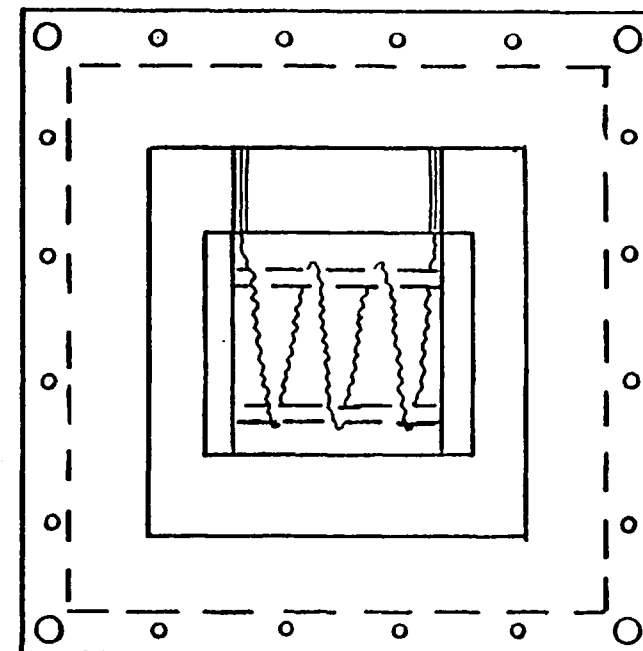
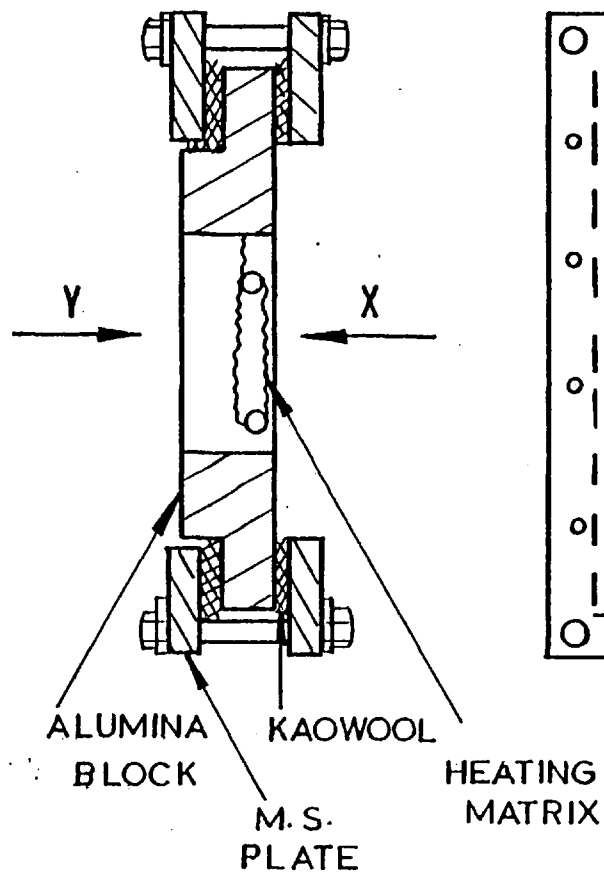
FIG(12) THE ALUMINA SUPPORTING FRAME OF A HEATING MATRIX



FIG(13) THE ALUMINA BLOCK OF THE PRE-HEATING HEATER



VIEW ON Y



VIEW ON X

FIG(14) ASSEMBLE OF HEATING MATRIX

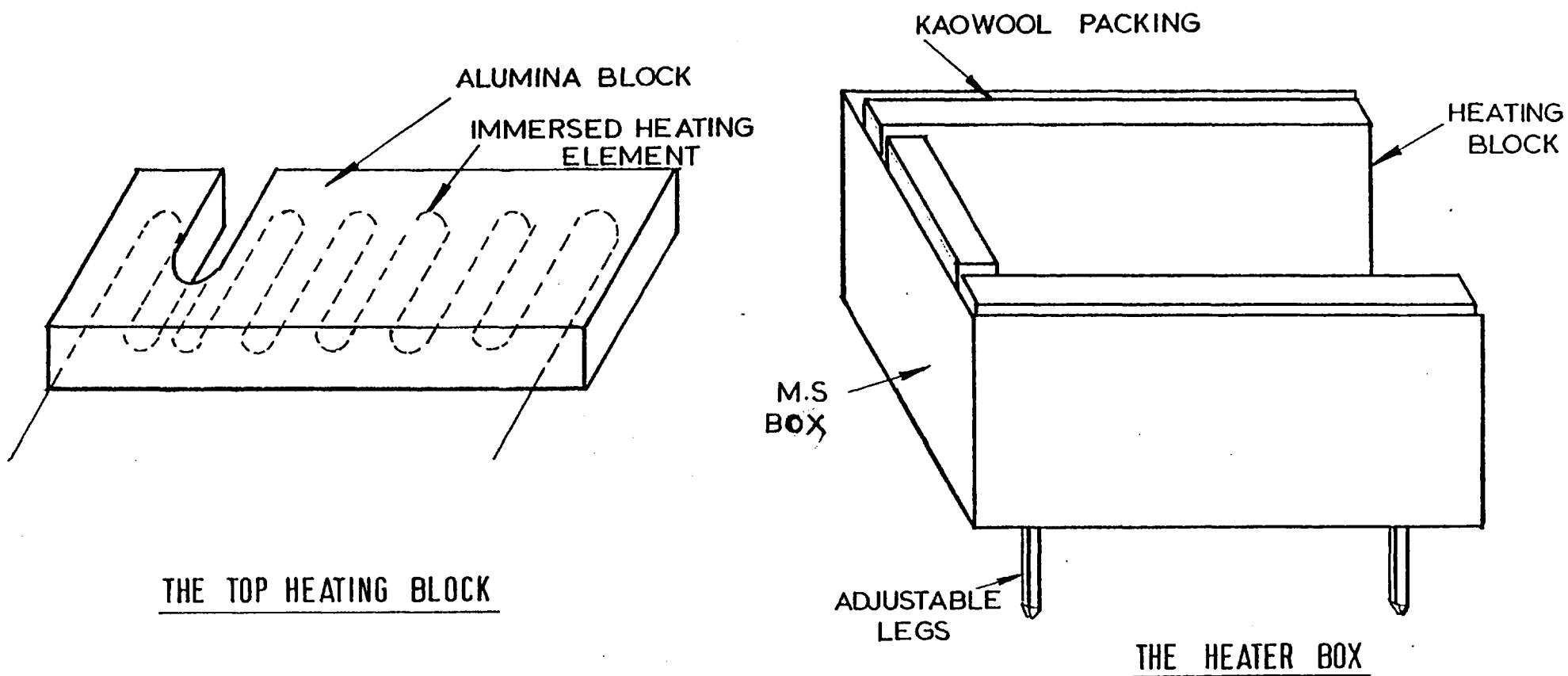
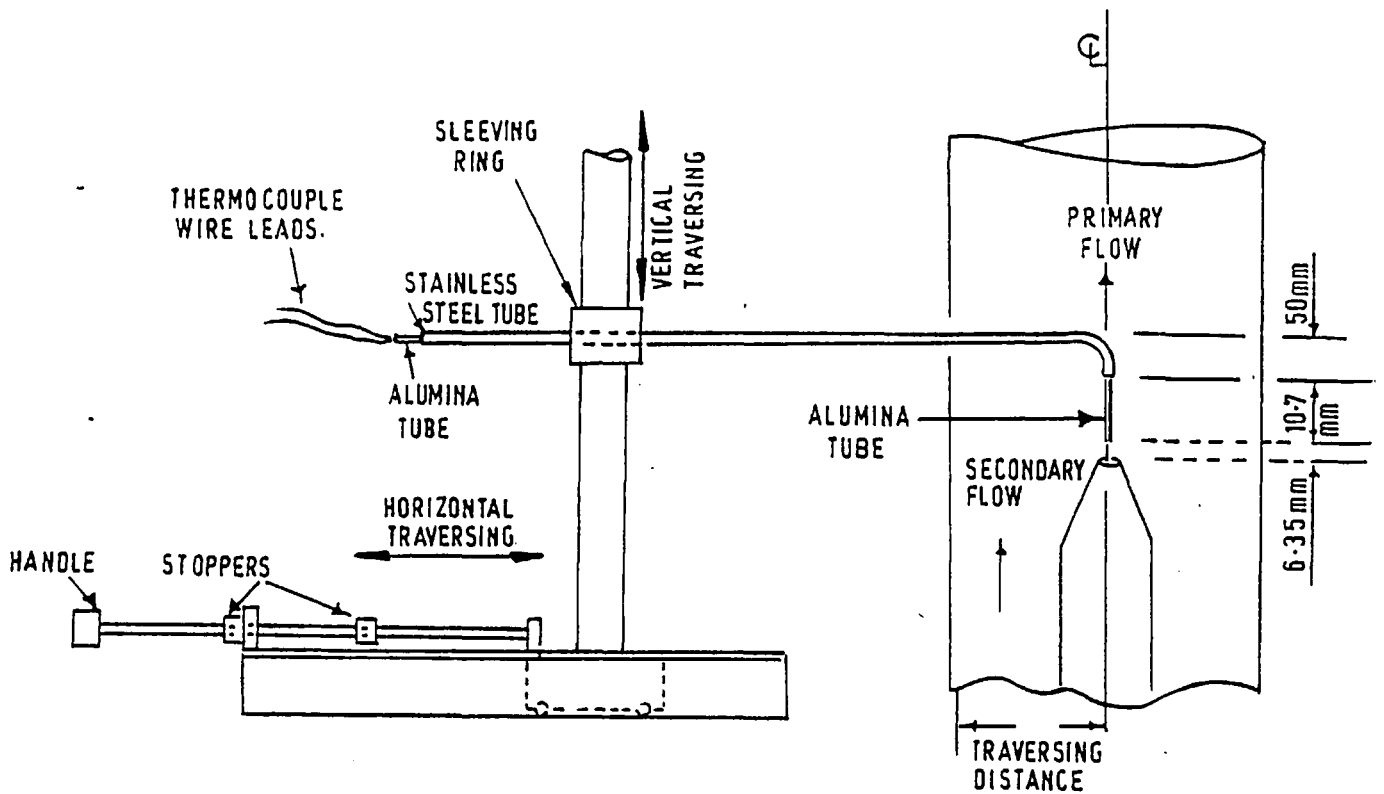
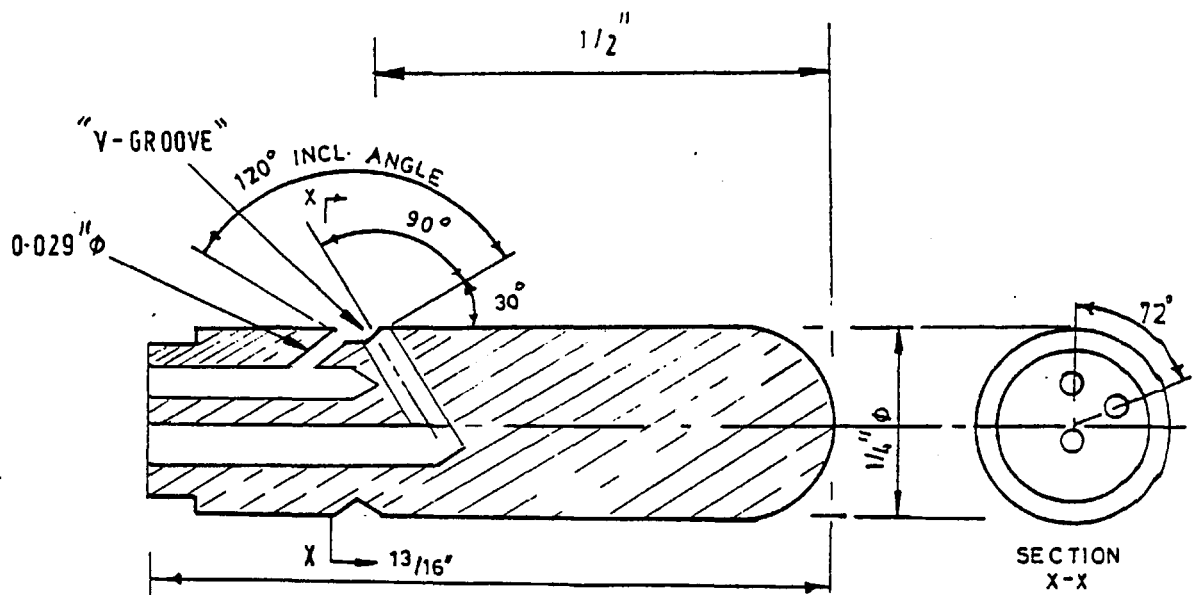


FIG (15) THE CONNECTOR HEATER



FIG(16) THE TRAVERSING TABLE AND THERMOCOUPLE PROBE



FIG(17) THE 3- HOLES PRESSURE PROBE

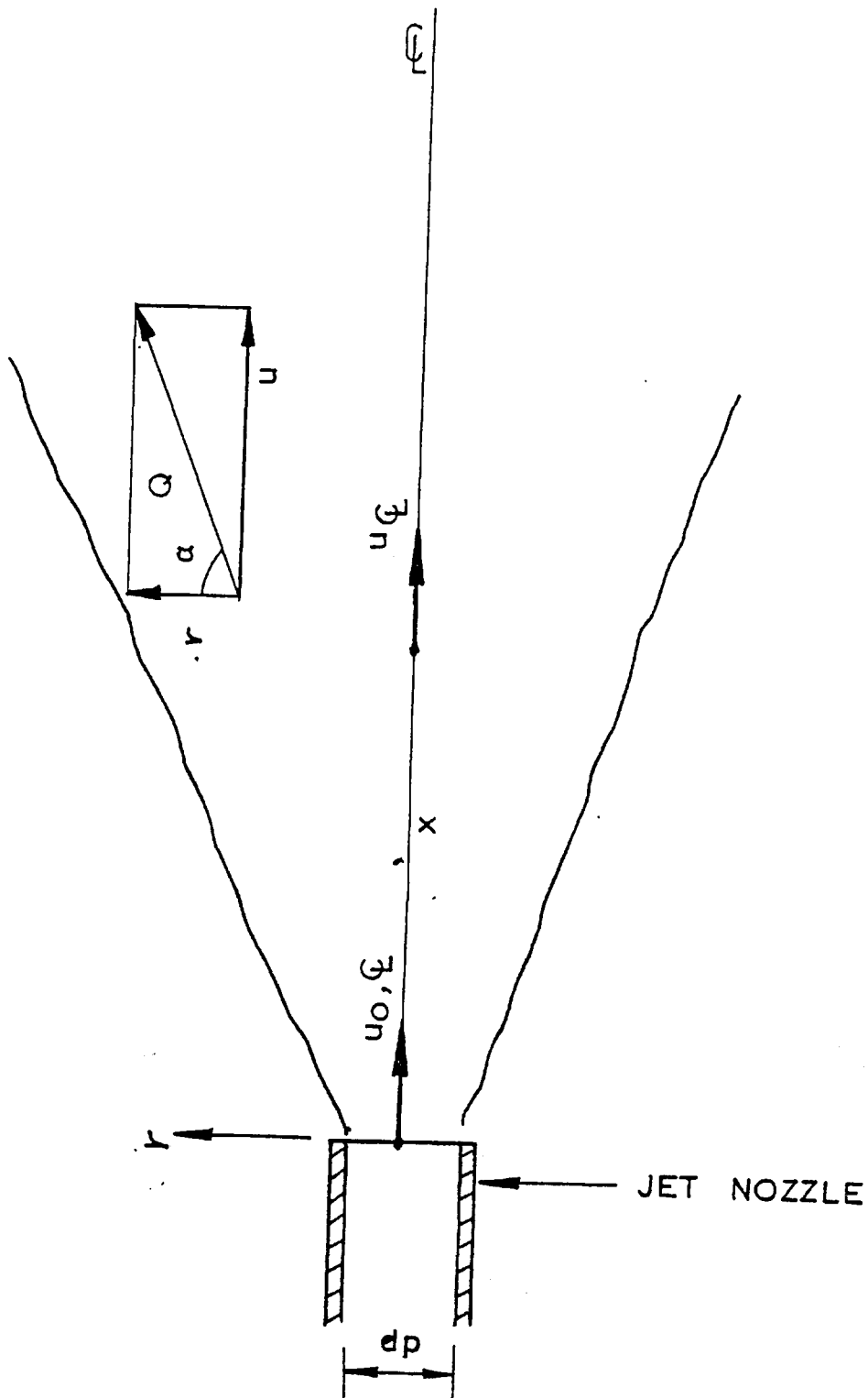
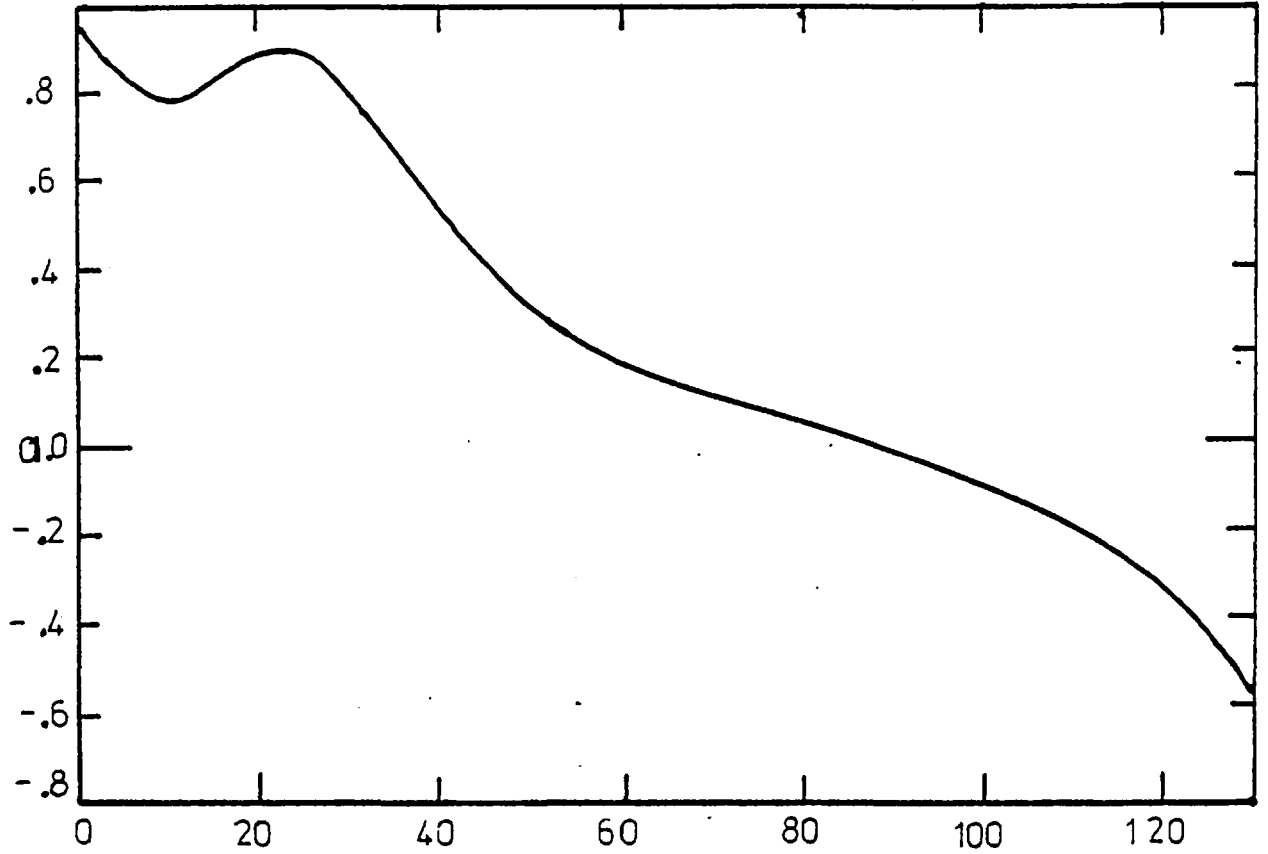


Fig.(18) Symbols for Fig.(19) and Fig (26) to Fig (30)

$$\frac{P_1 - P_3}{P_1 - P_2}$$



$\theta = \text{YAW ANGLE (DEGREE)}$

$$\frac{P_1 - P_2}{V.H.}$$

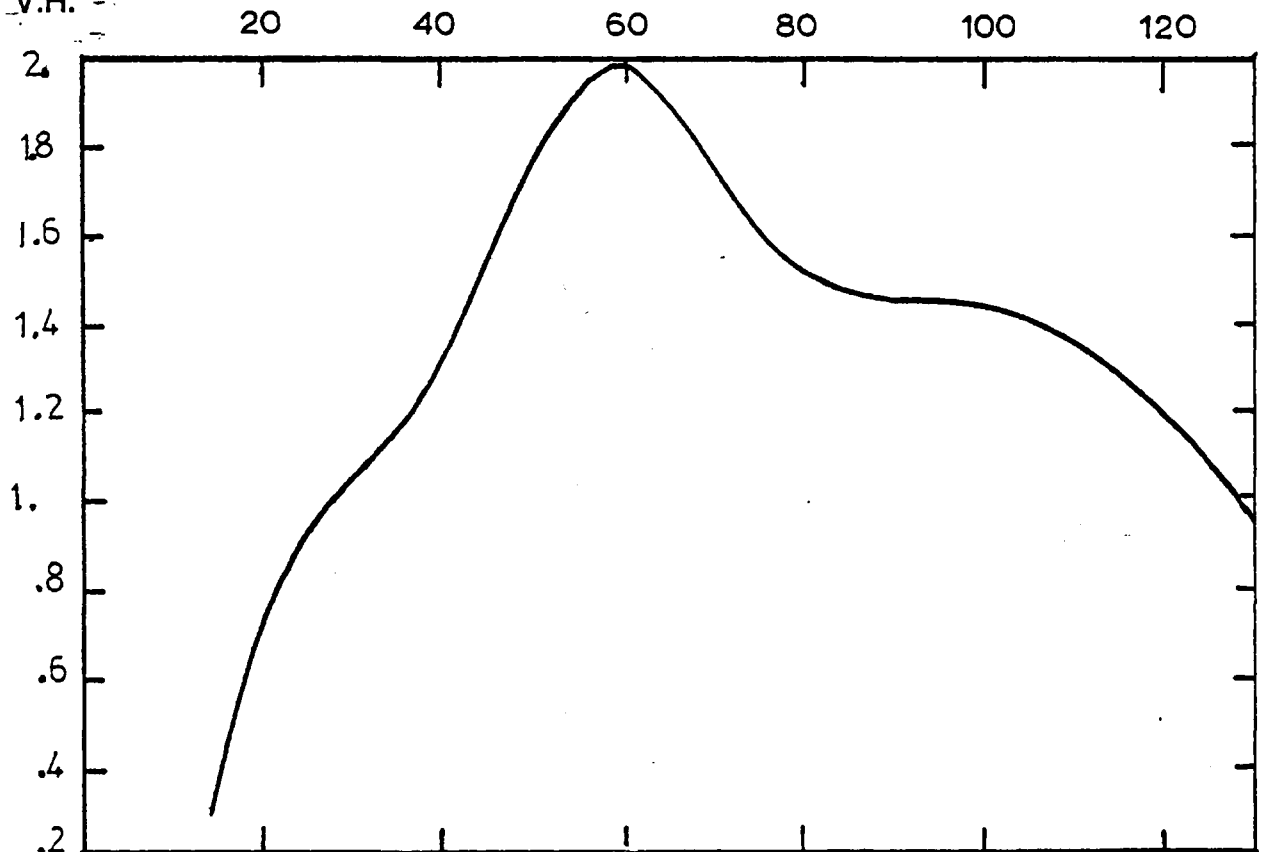


FIG (19) CALIBRATION CHARTS FOR THE 3-HOLE PROBE

(°C)	EXPERI- MENT (I)	(2)	(3)	(4)	(5)
$d_p = 19.35$ mm	1283	1279	1280	1288	1284
$d_p = 15.0$ mm	1378	1374	1378	1372	1379

Fig.20 M.I.T. REPRODUCIBILITY TEST - SINGLE POINTS
UNDER REFERENCE CONDITIONS (TABLE 3)

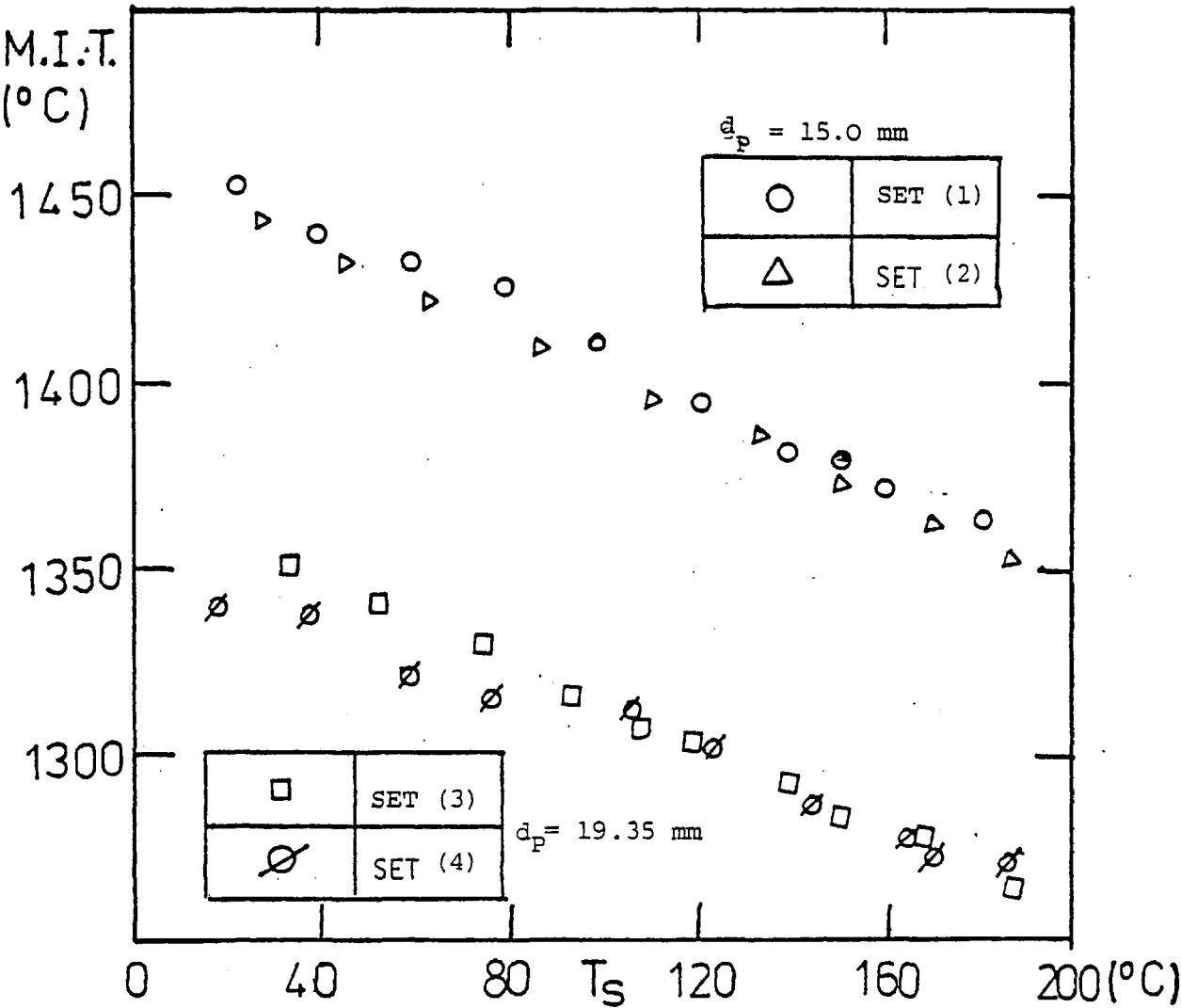


Fig. 21 M.I.T. REPRODUCIBILITY TEST - SET OF EXPERIMENTS

Fig. 22 EFFECT OF SECONDARY FLOW TEMP

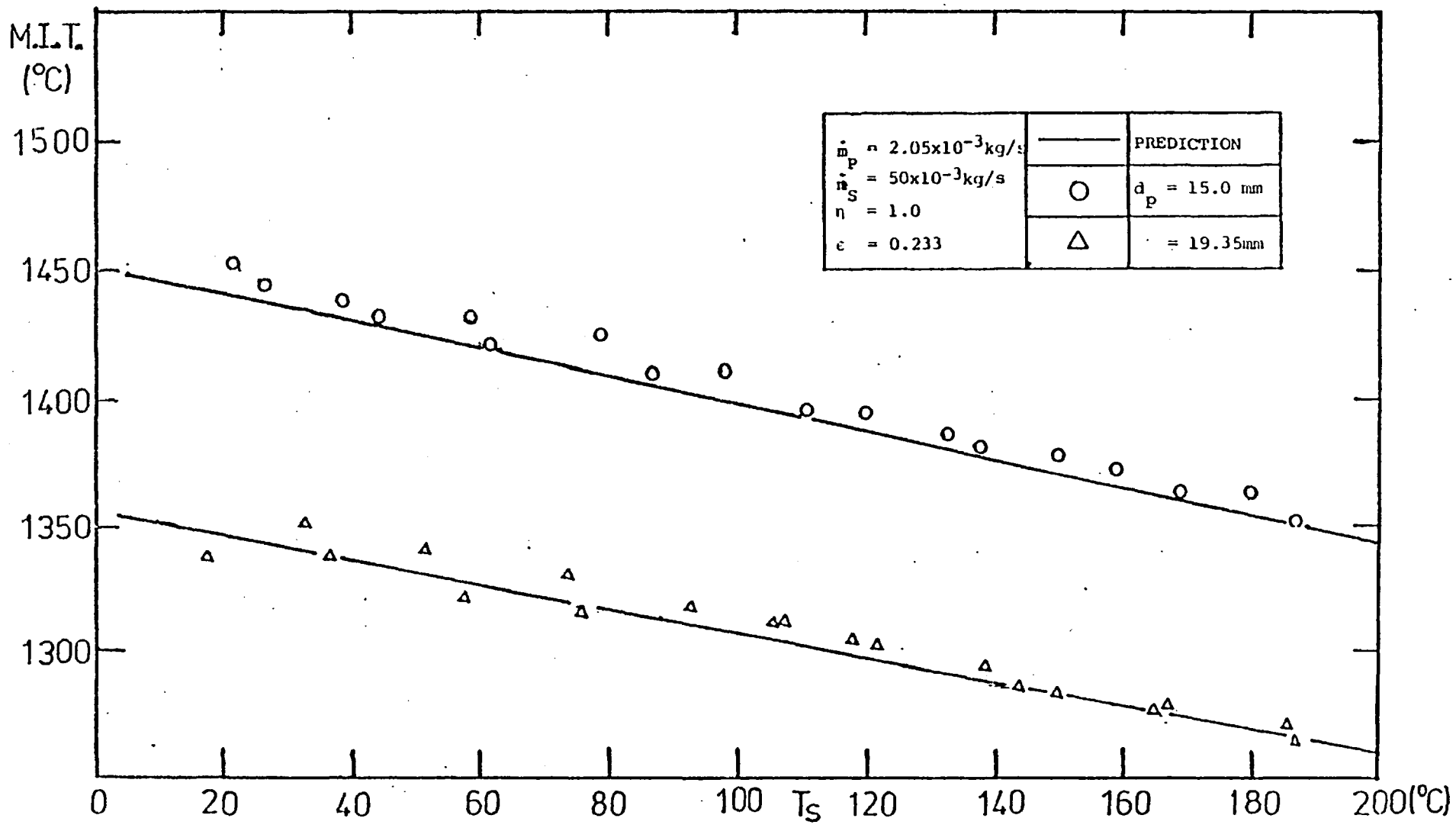


Fig. 23 EFFECT OF PRIMARY FLOW RATE

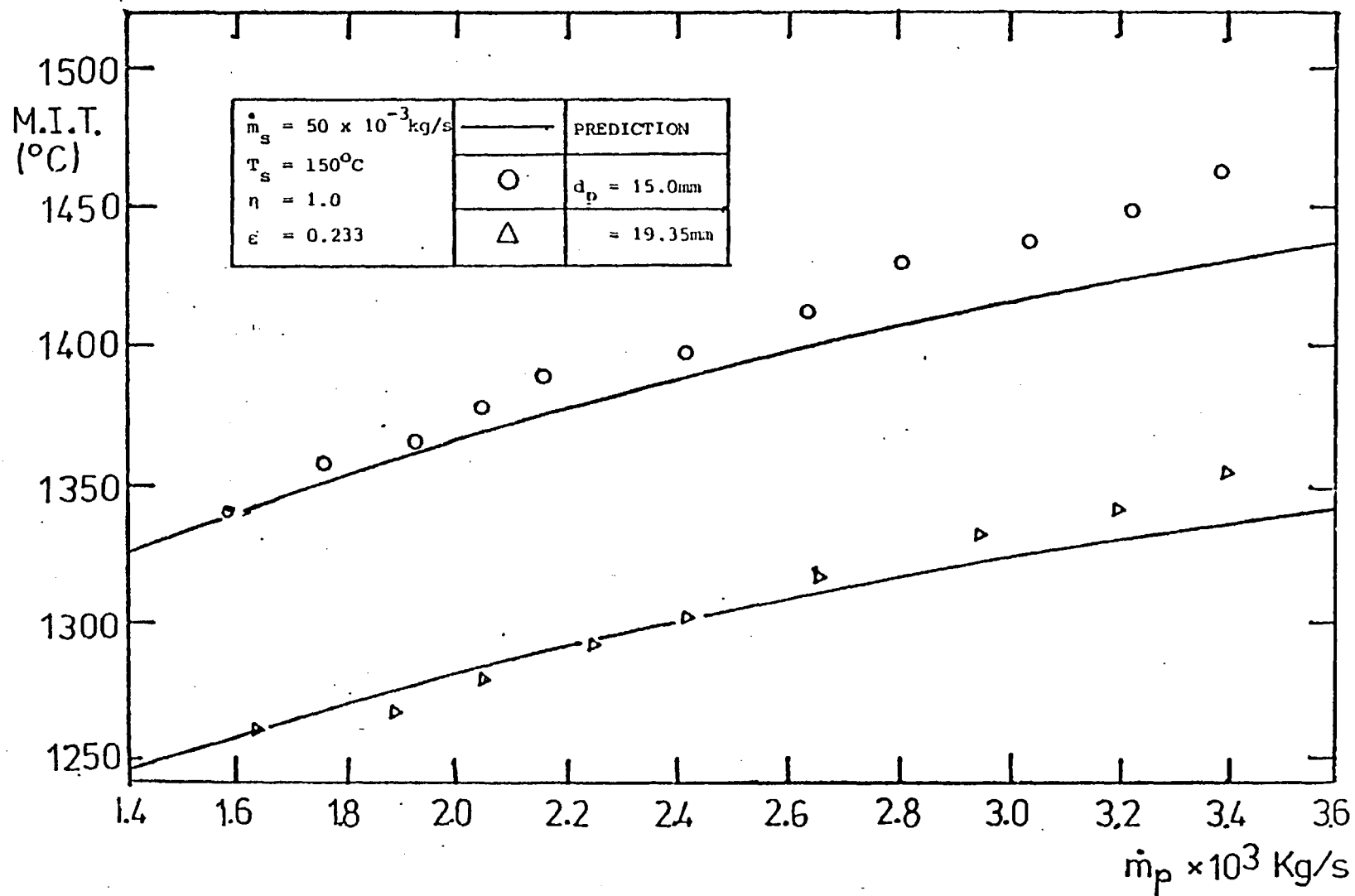


Fig. 24 EFFECT OF SEC. FLOW OXYGEN INDEX

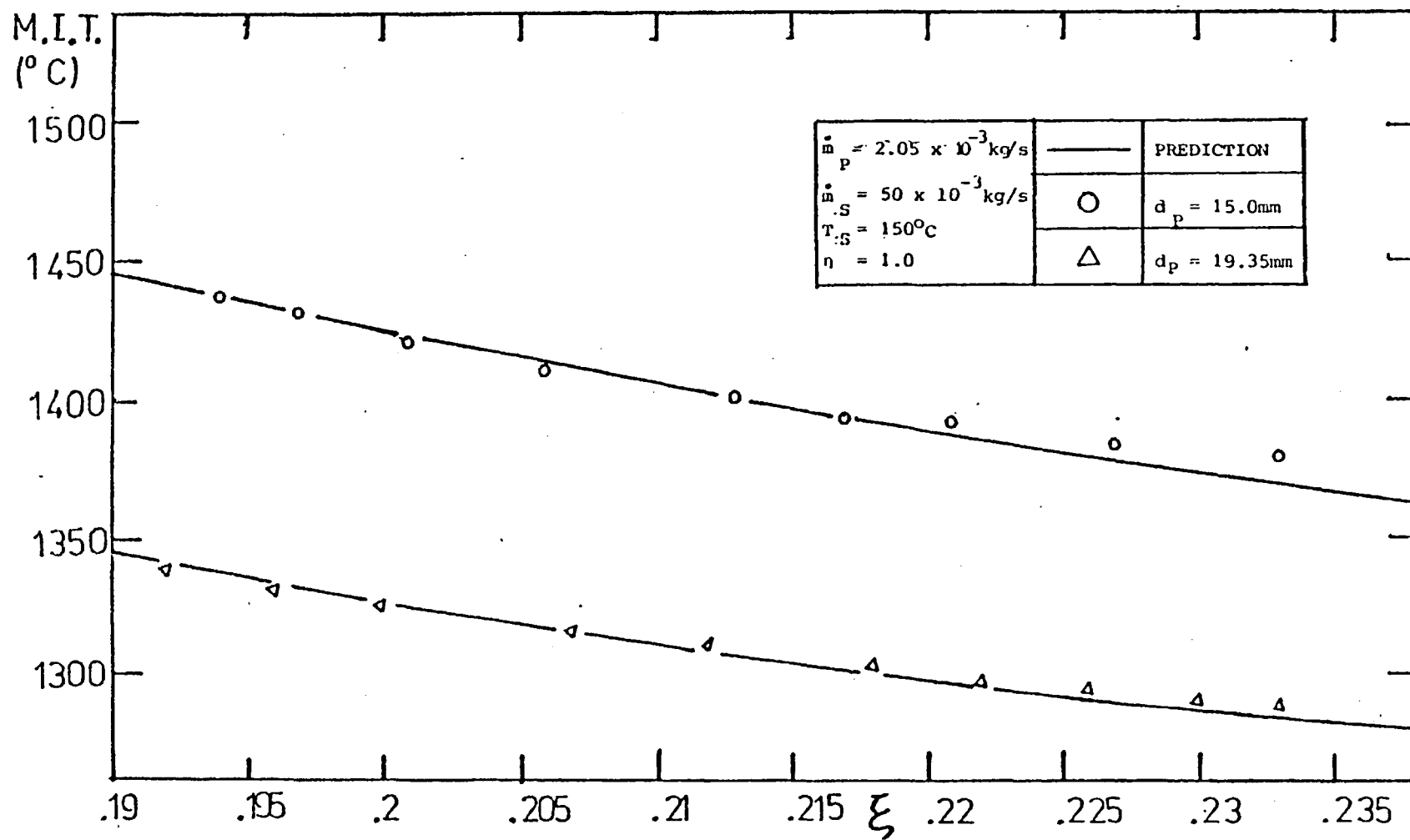
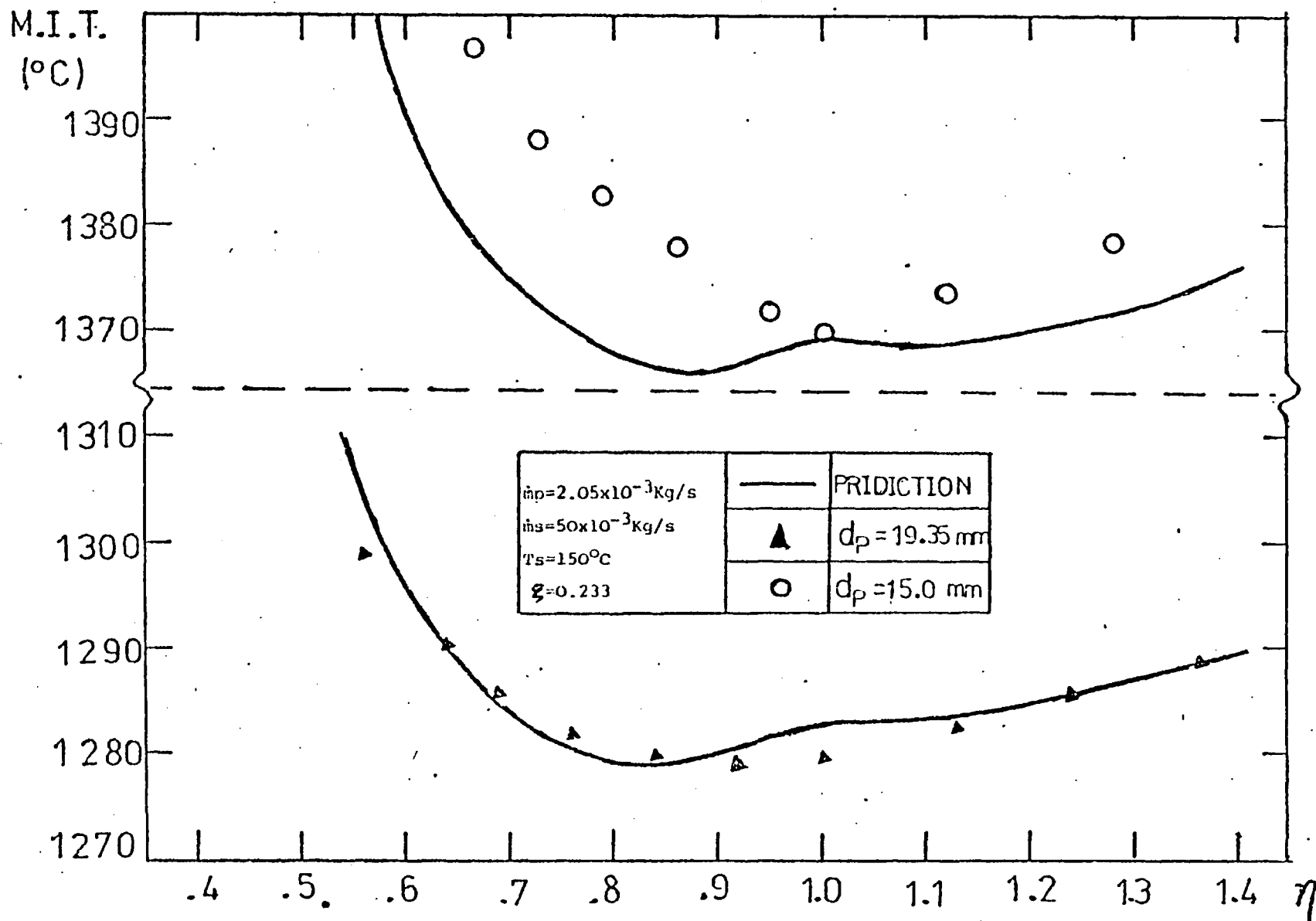


Fig. 25 EFFECT OF SEC. FLOW EQUIVALENCE RATIO



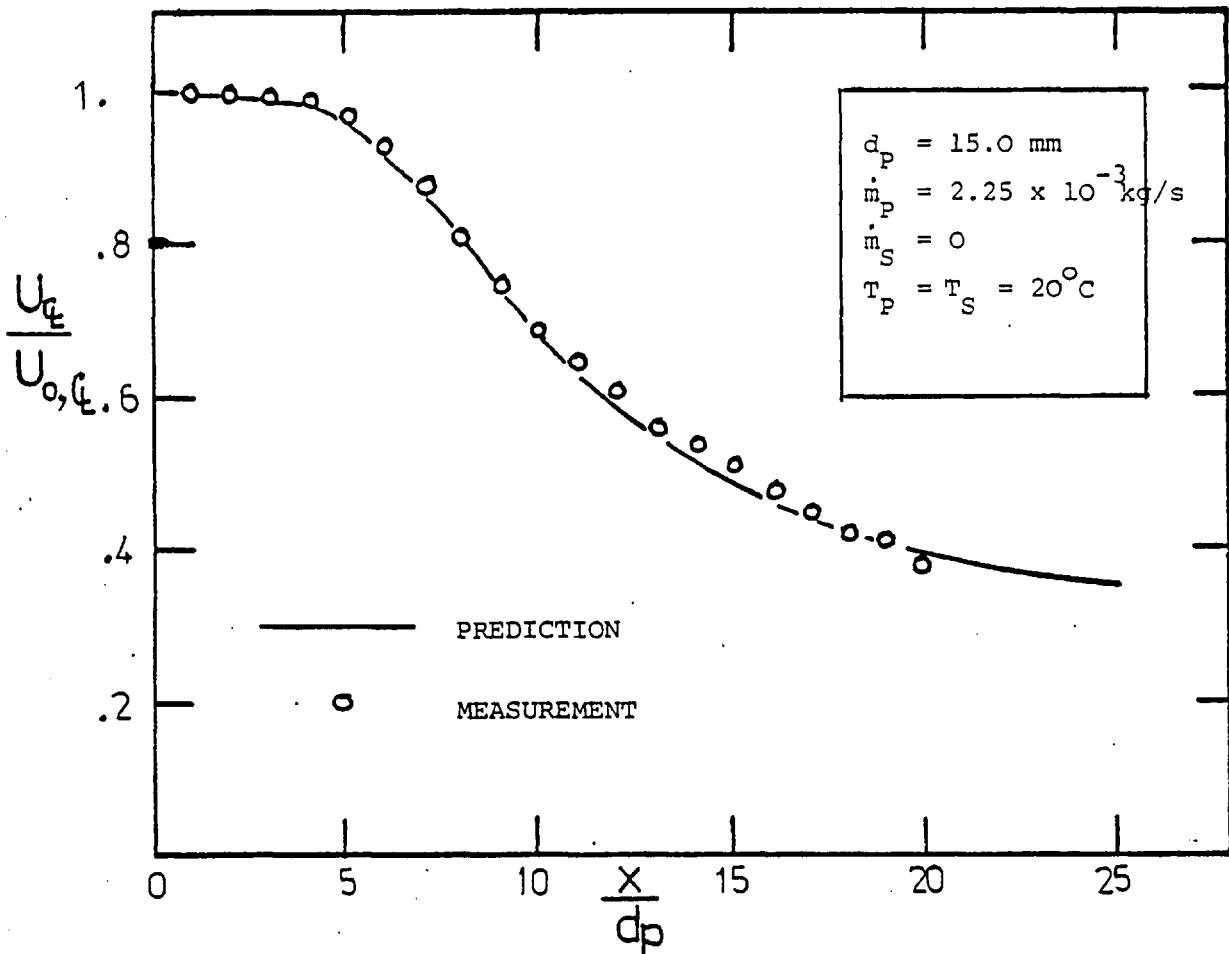


Fig. 26 AXIAL PROFILE - FREE JET

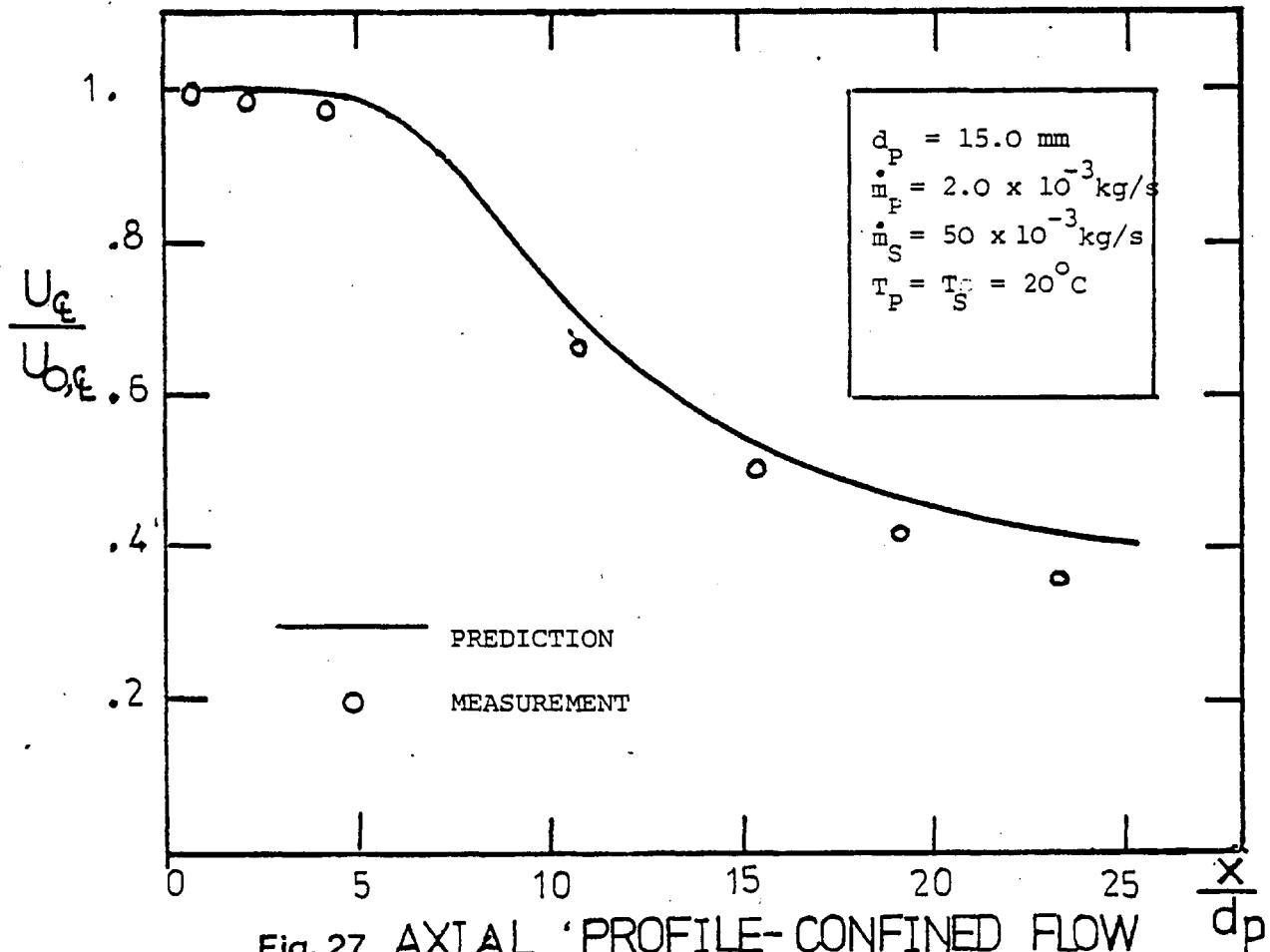


Fig. 27 AXIAL PROFILE - CONFINED FLOW

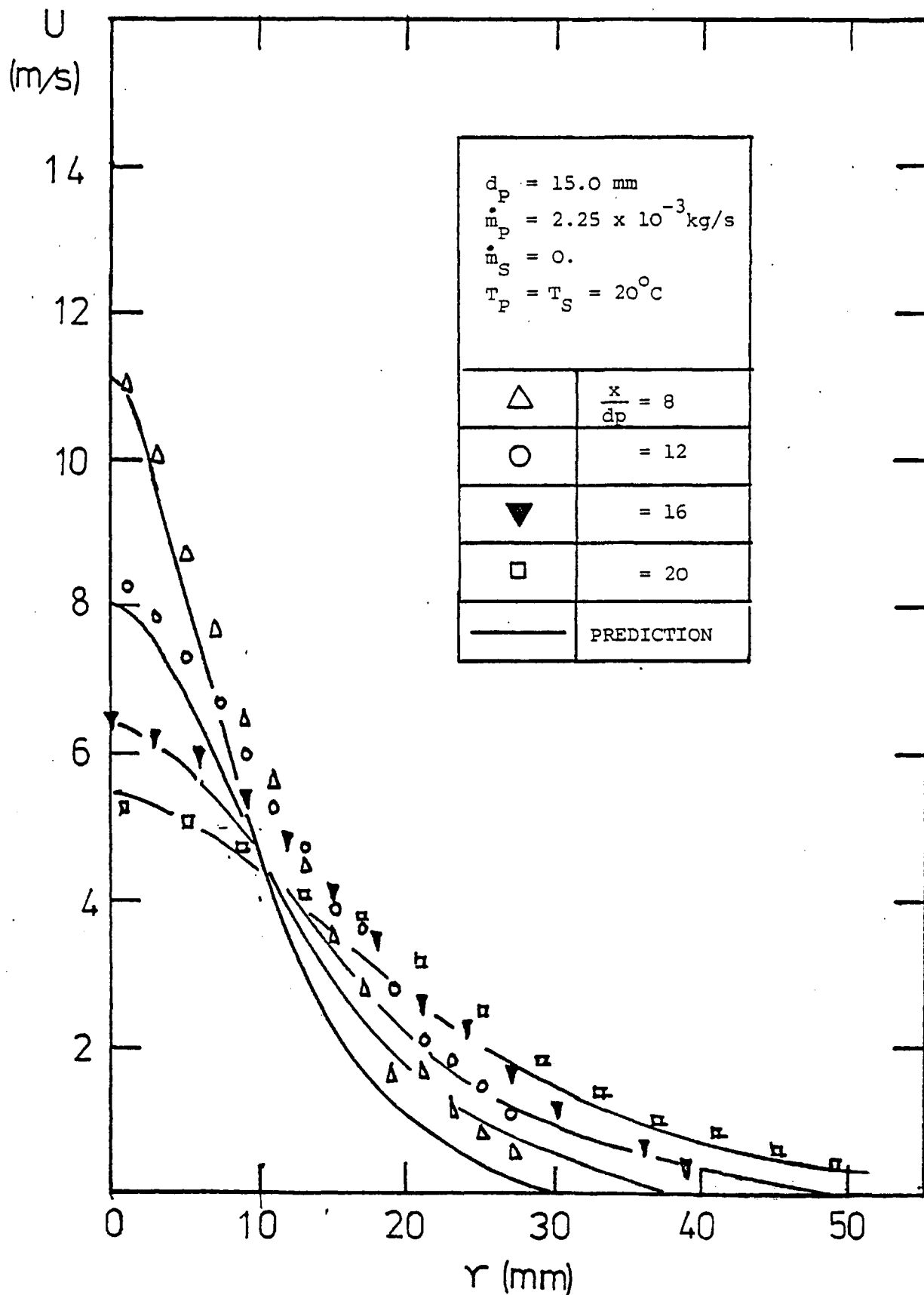


Fig. 28 RADIAL PROFILE - FREE JET

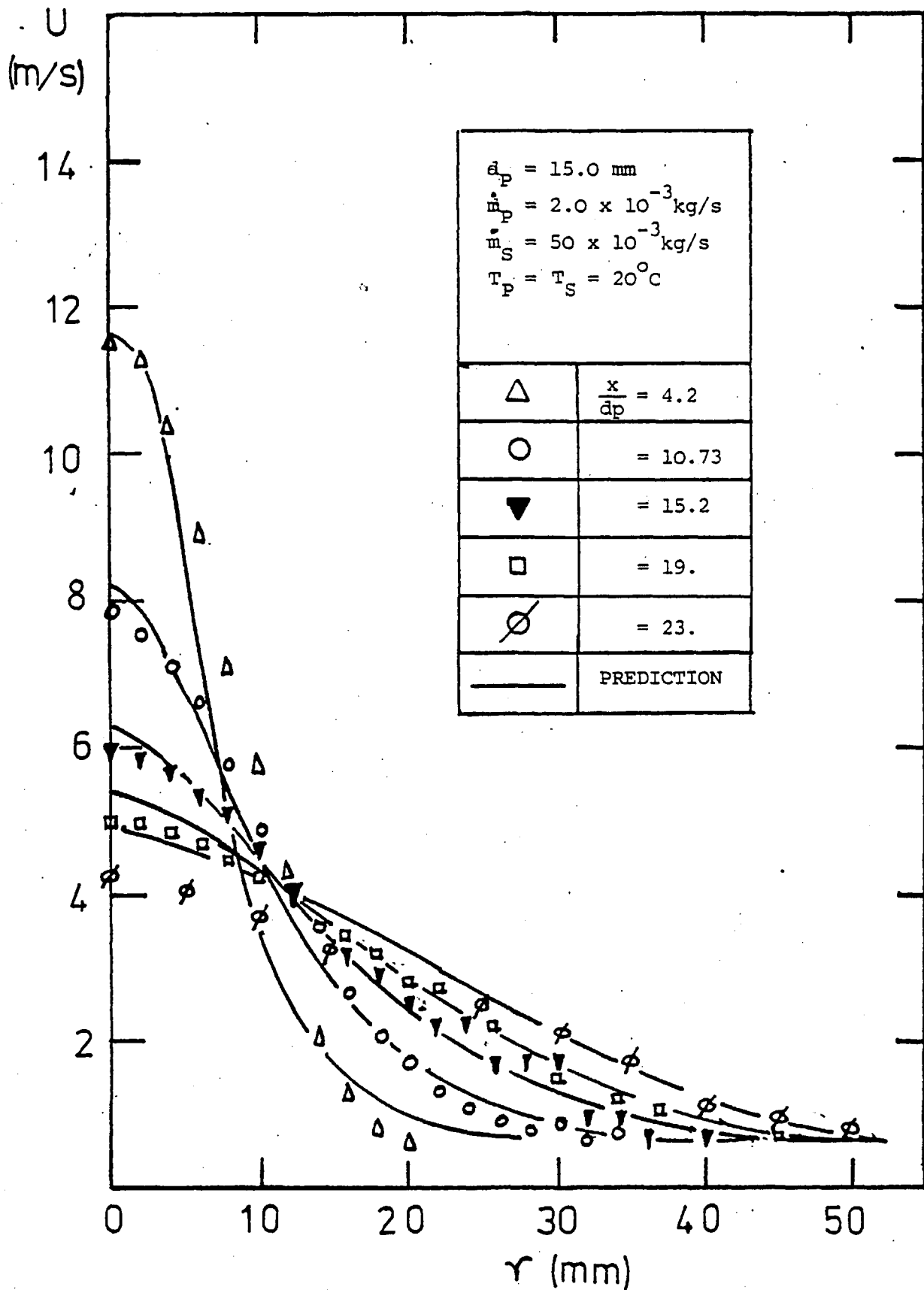


Fig. 29 RADIAL PROFILE — CONFINED FLOW

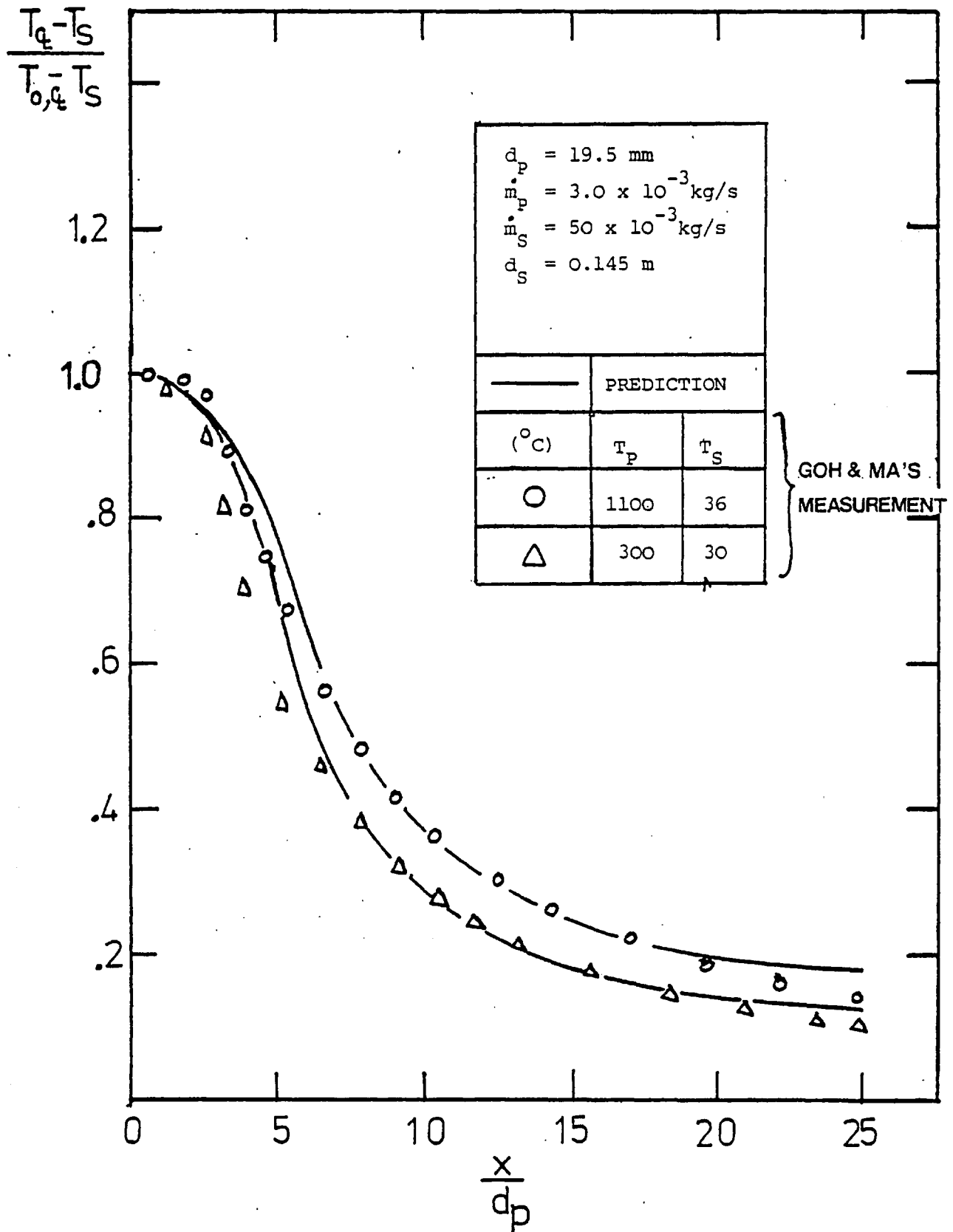


Fig.30 AXIAL TEMP PROFILE - CONFINED FLOW

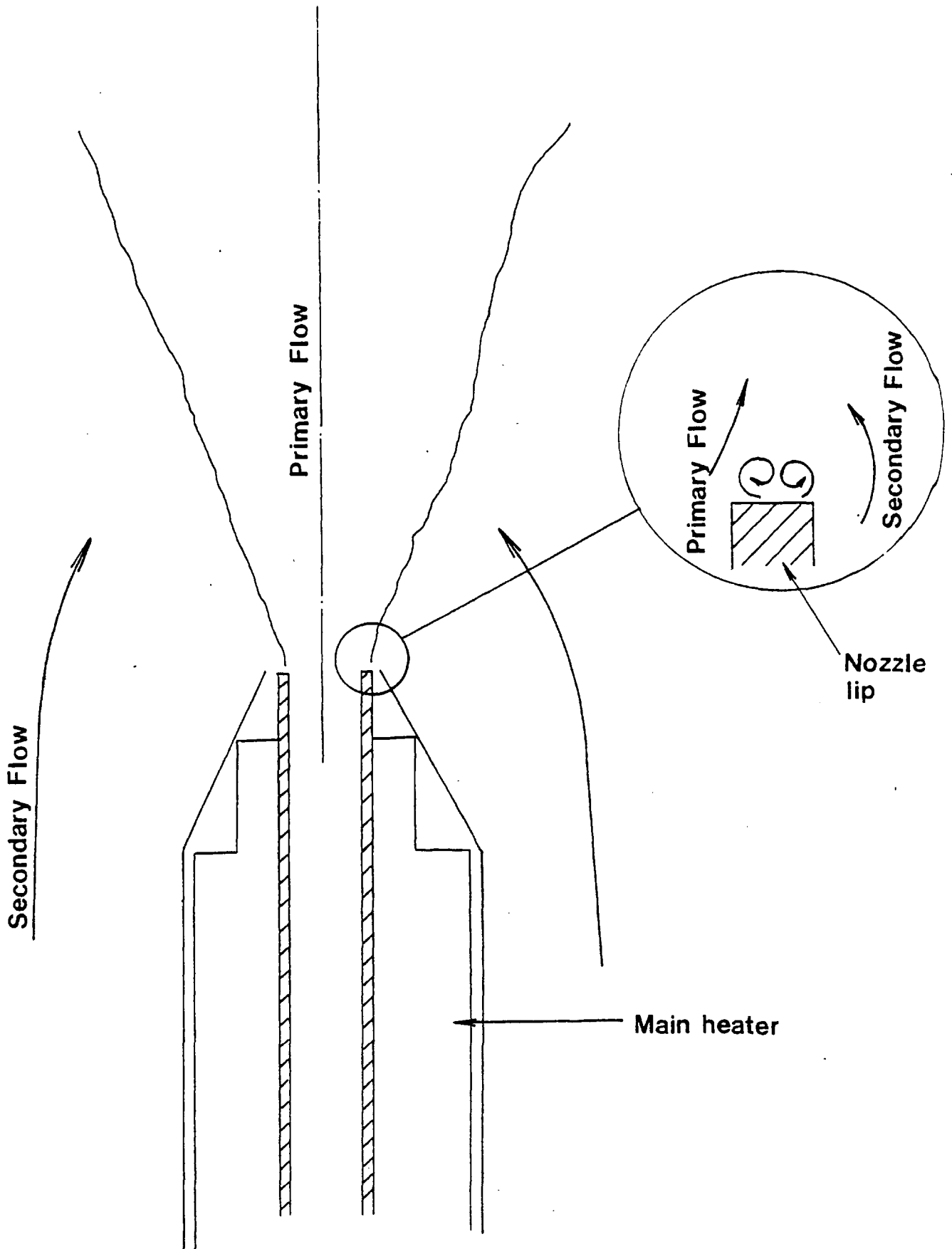
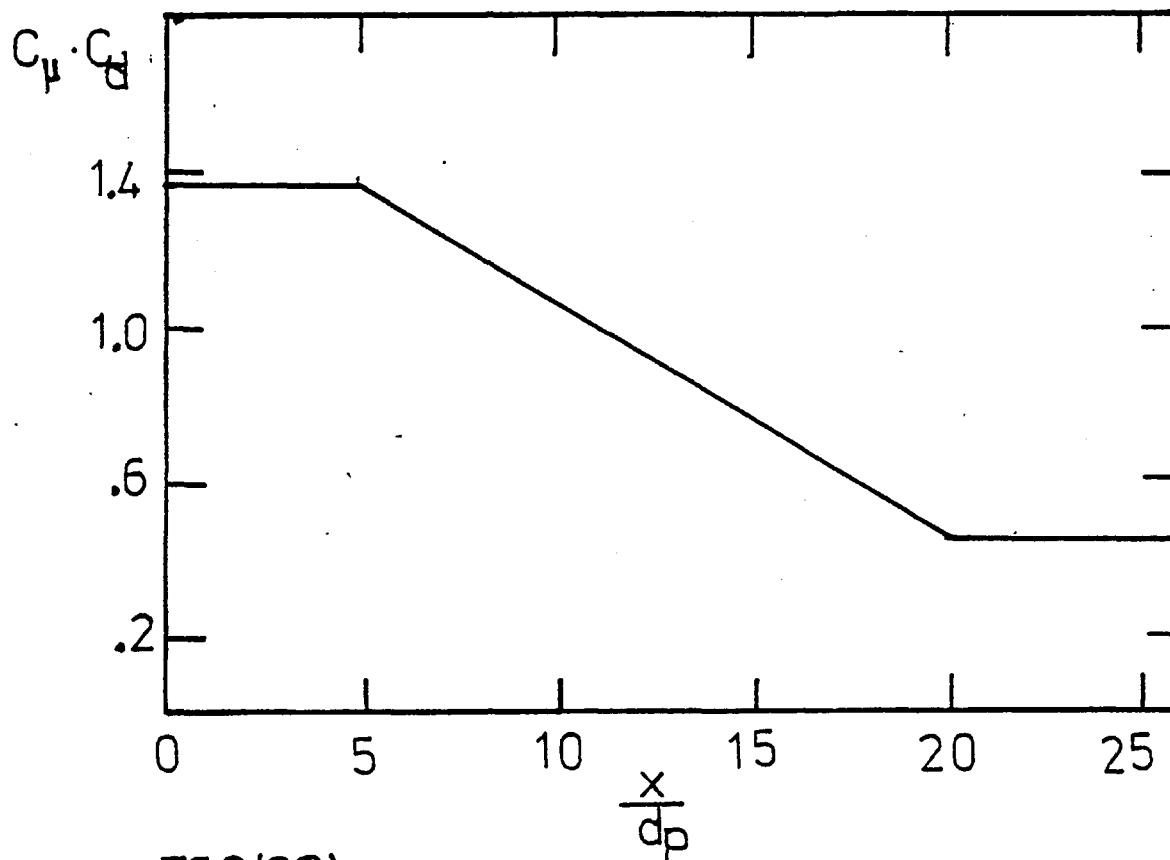


Fig. 31 RECIRCULATION ZONE AT NOZZLE EXIT

	Rodi (Ref 72)	Bradshaw (Ref 74)
Range	$\frac{x}{d_o} > 20$	$\frac{x}{d_o} < 5$
$\overline{uv}/U_o^2$	0.0186	0.01
k/U_o^2	0.09	0.027
$\tau/\rho k$	0.207	0.37
C_u	0.45	0.6
C_d	0.095	0.228
$C_u \cdot C_d$	0.045	0.137

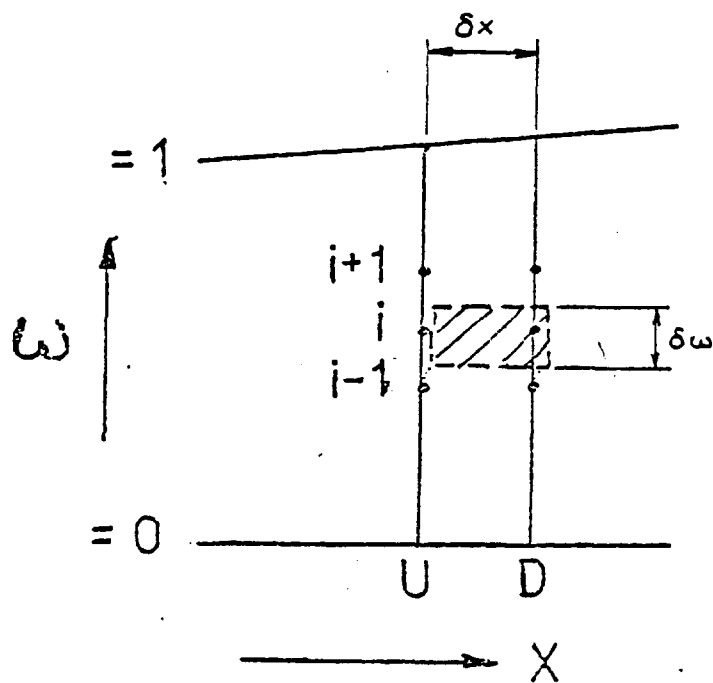
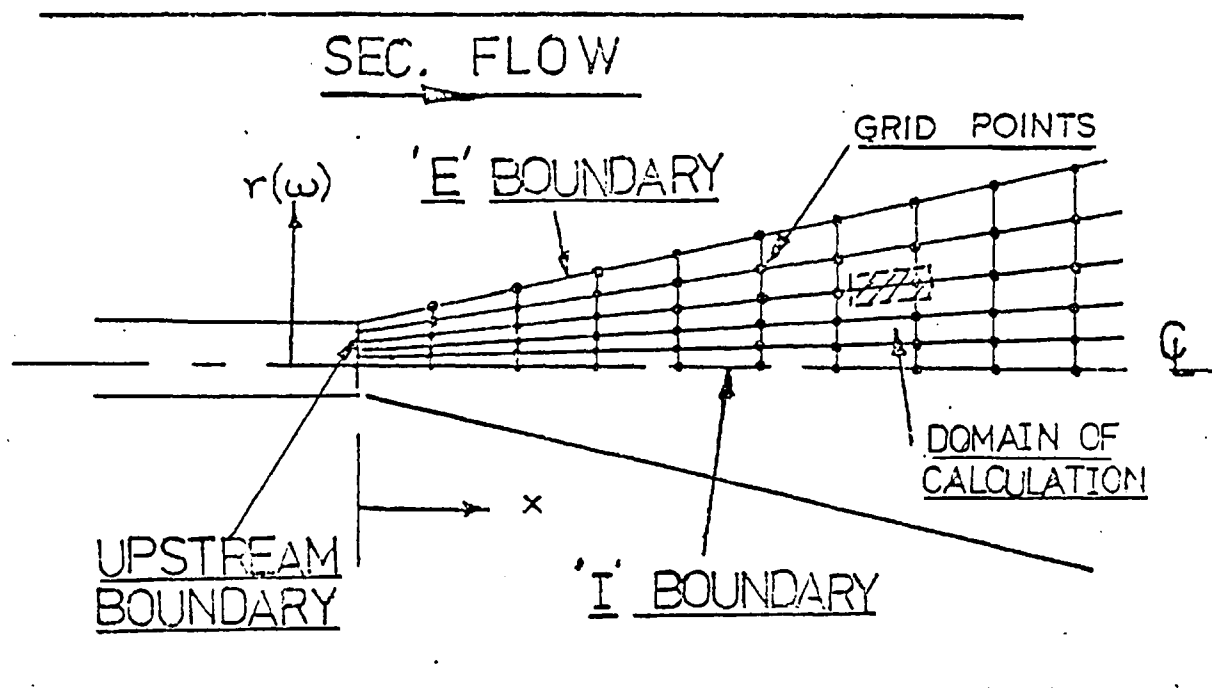
FIG(32)

C_u & C_d VALUES FOR ROUND JETS



FIG(33)

AXIAL PROFILE OF $C_u \cdot C_d$



U: UPSTREAM
D: DOWNSTREAM

FIG(34) DOMAIN OF CALCULATION AND GRID DISTRIBUTION

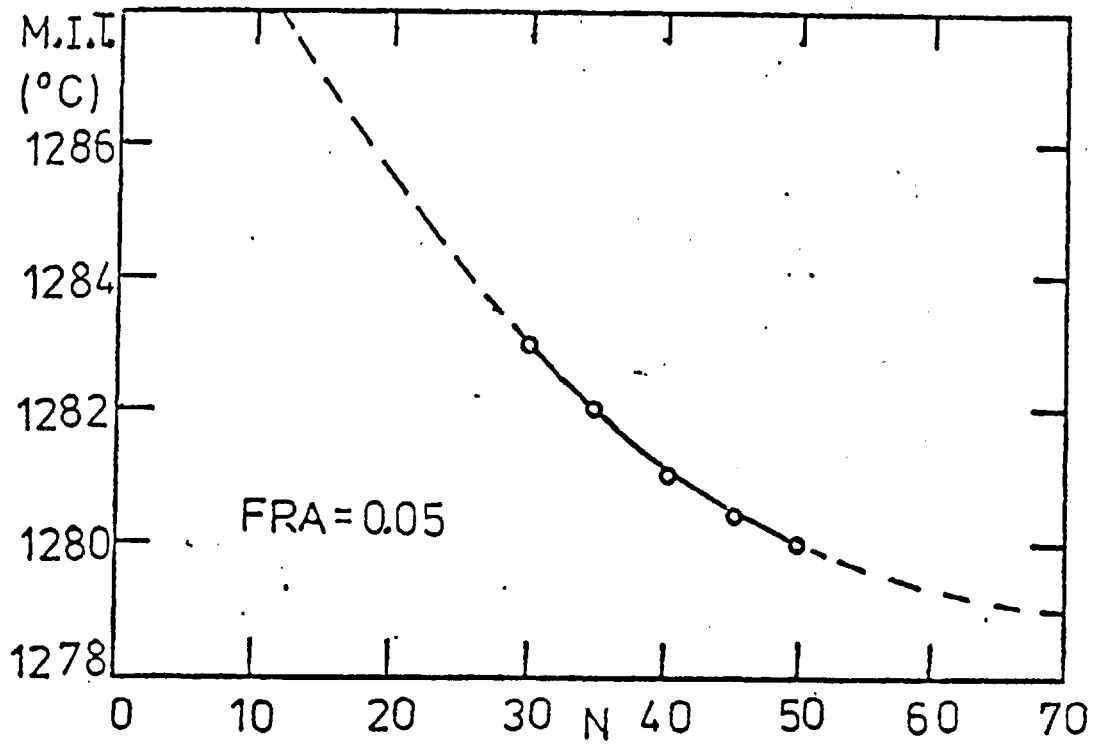


Fig. 35 EFFECT OF GRID POINTS

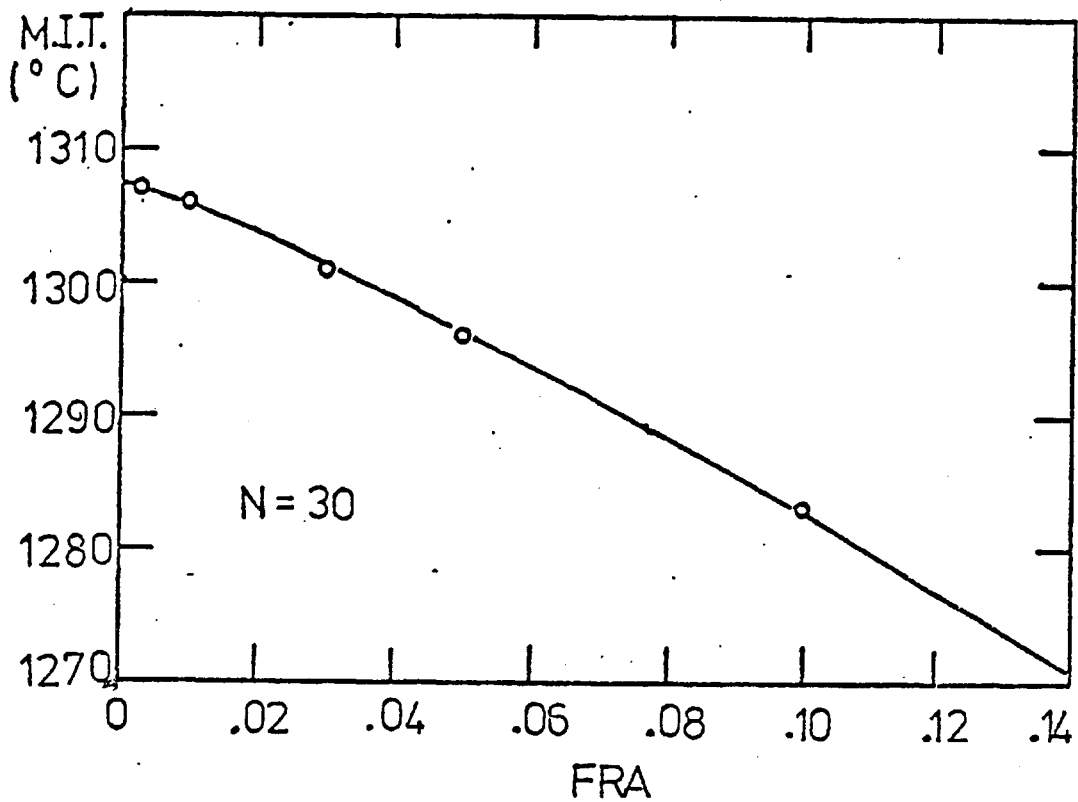


Fig 36 EFFECT OF FORWARD STEP SIZE

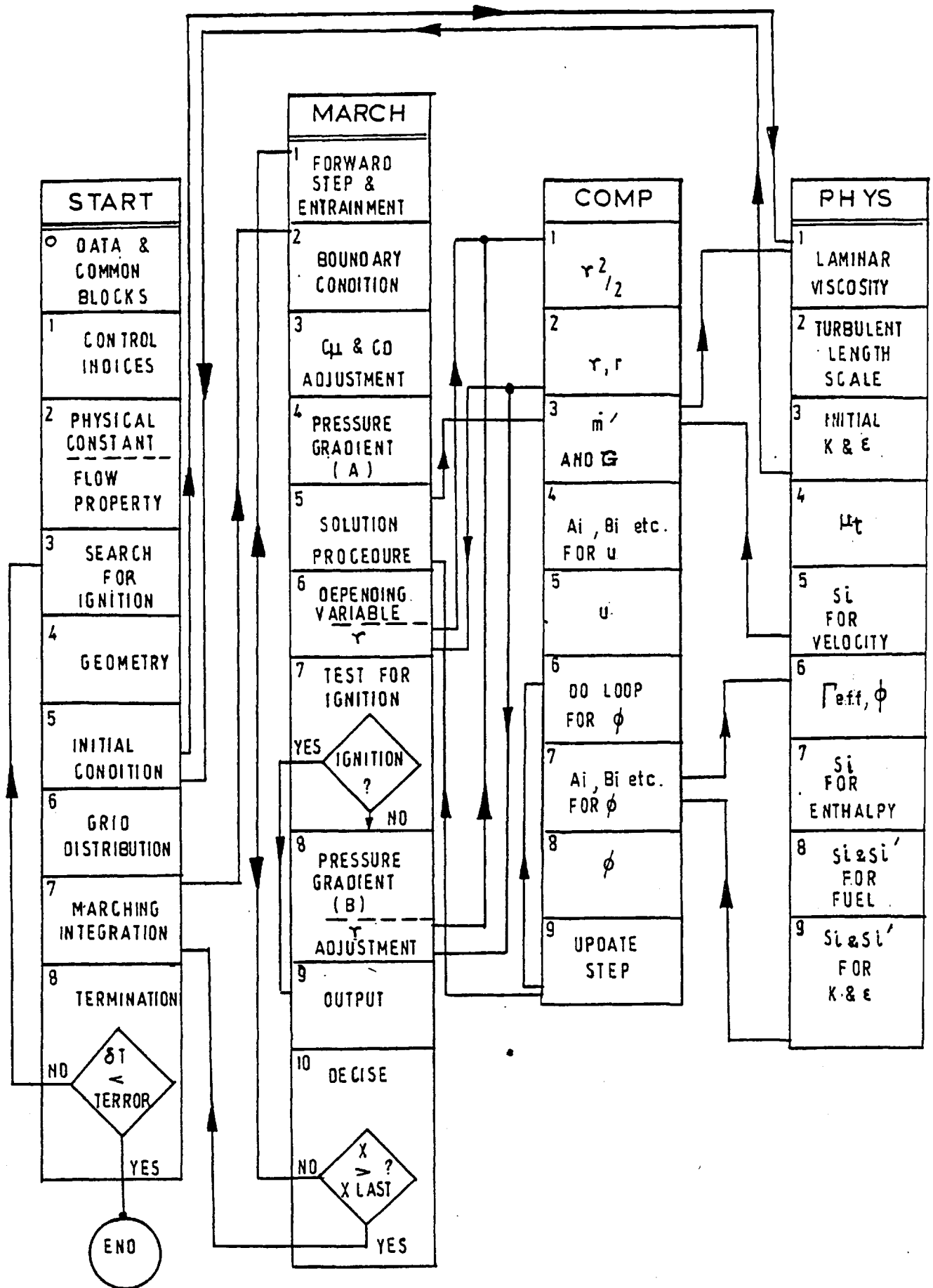


Fig.37 FLOWCHART FOR PROGRAM METHANE

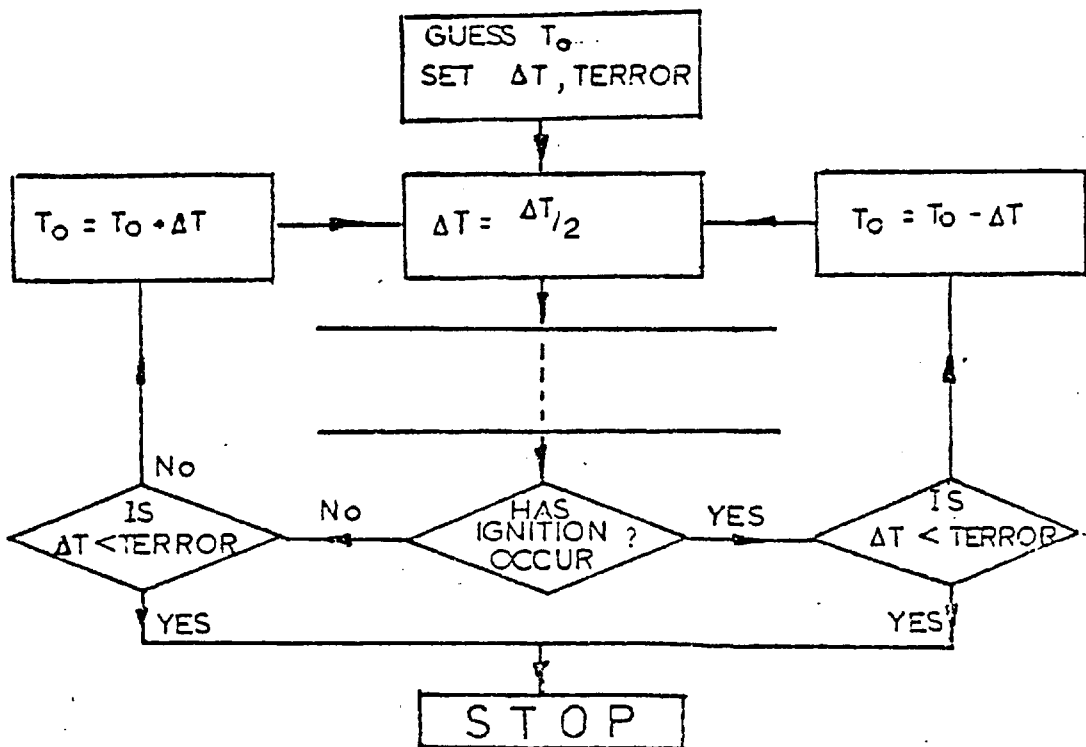
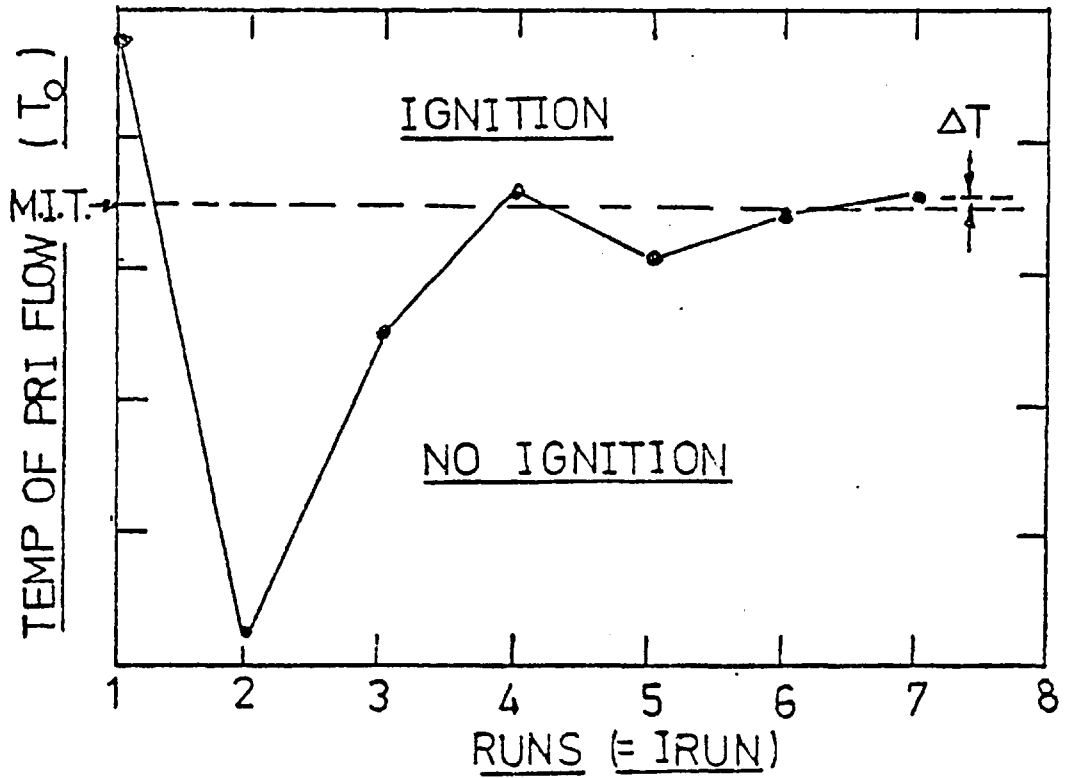


Fig. 38 SEARCHING FOR M.I.T.

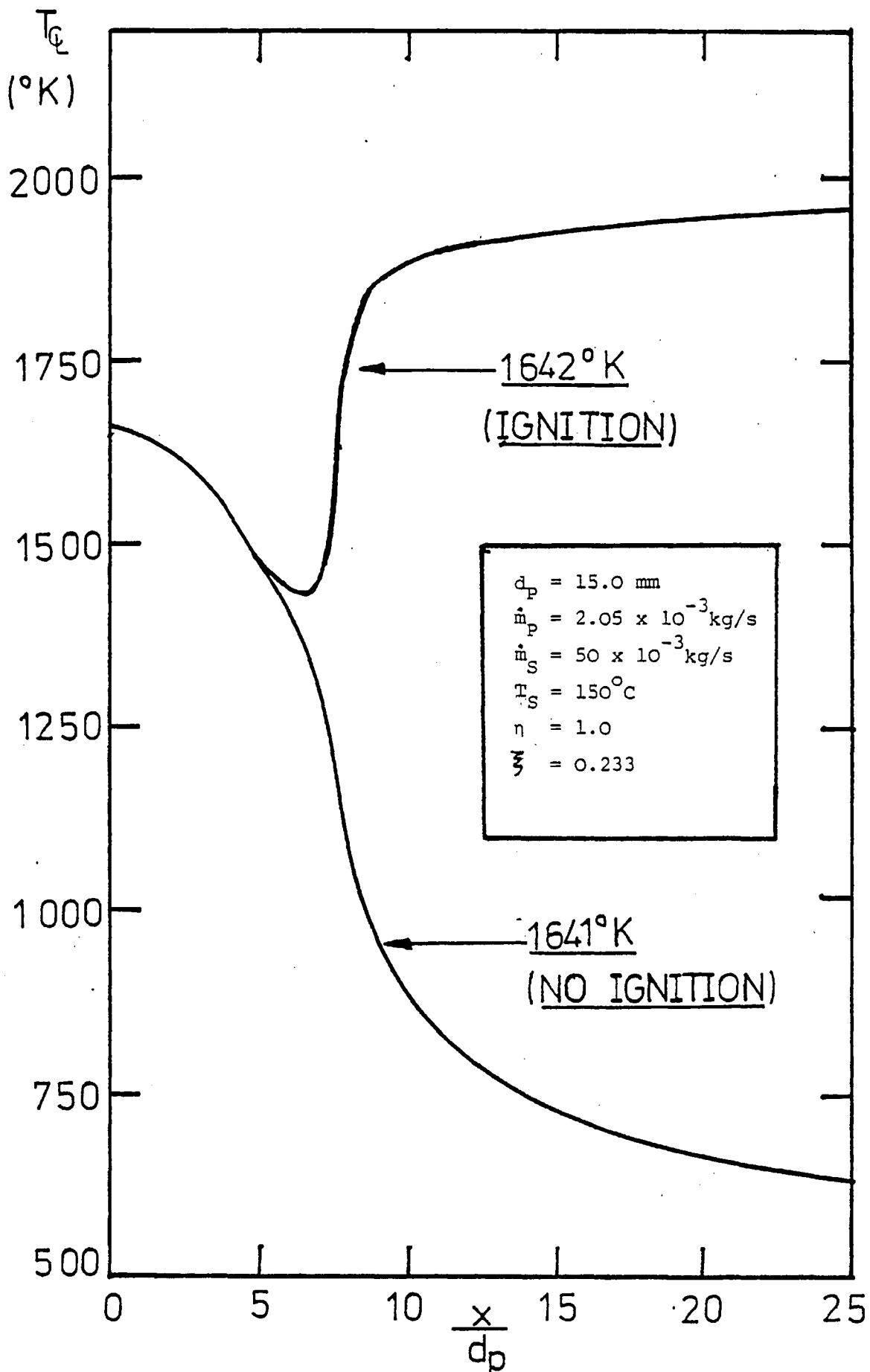


Fig. 39. AXIAL TEMPERATURE PROFILE - DIFFERENCE BETWEEN
IGNITION AND NO IGNITION

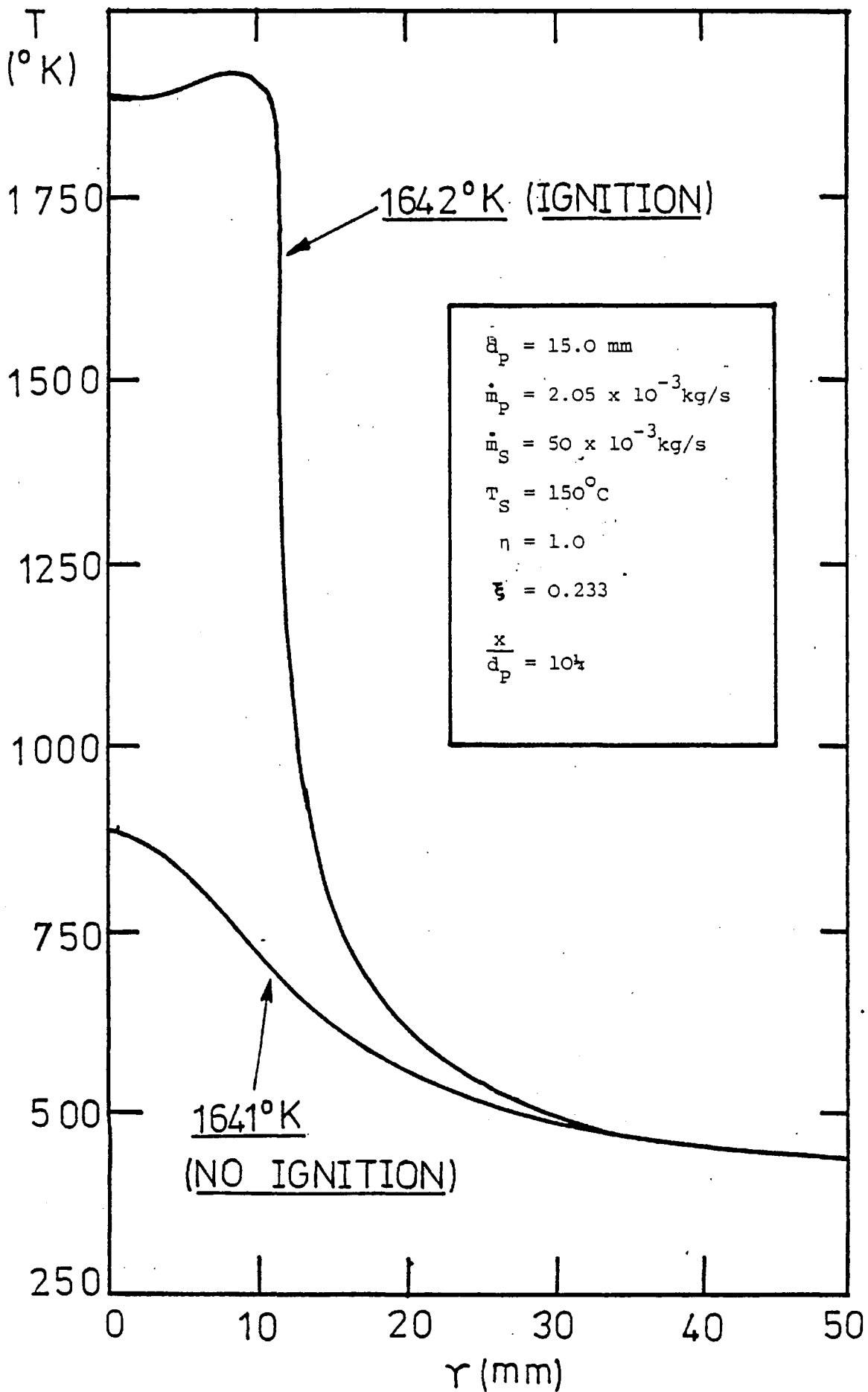


Fig. 40 RADIAL TEMPERATURE PROFILE - DIFFERENCE BETWEEN
IGNITION AND NO IGNITION

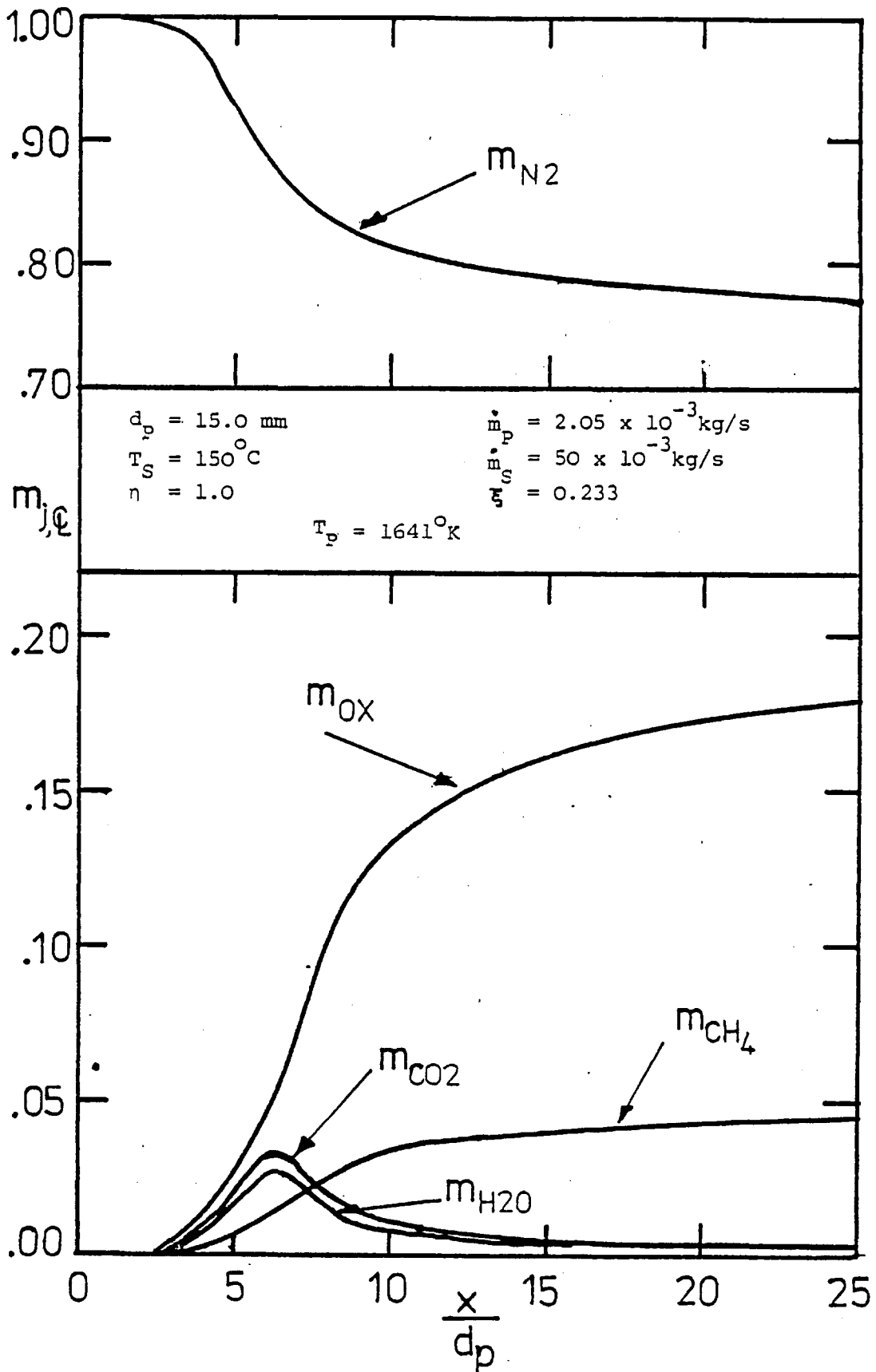


Fig. 41

AXIAL CONCENTRATION PROFILES - NO
IGNITION AT 1641°K

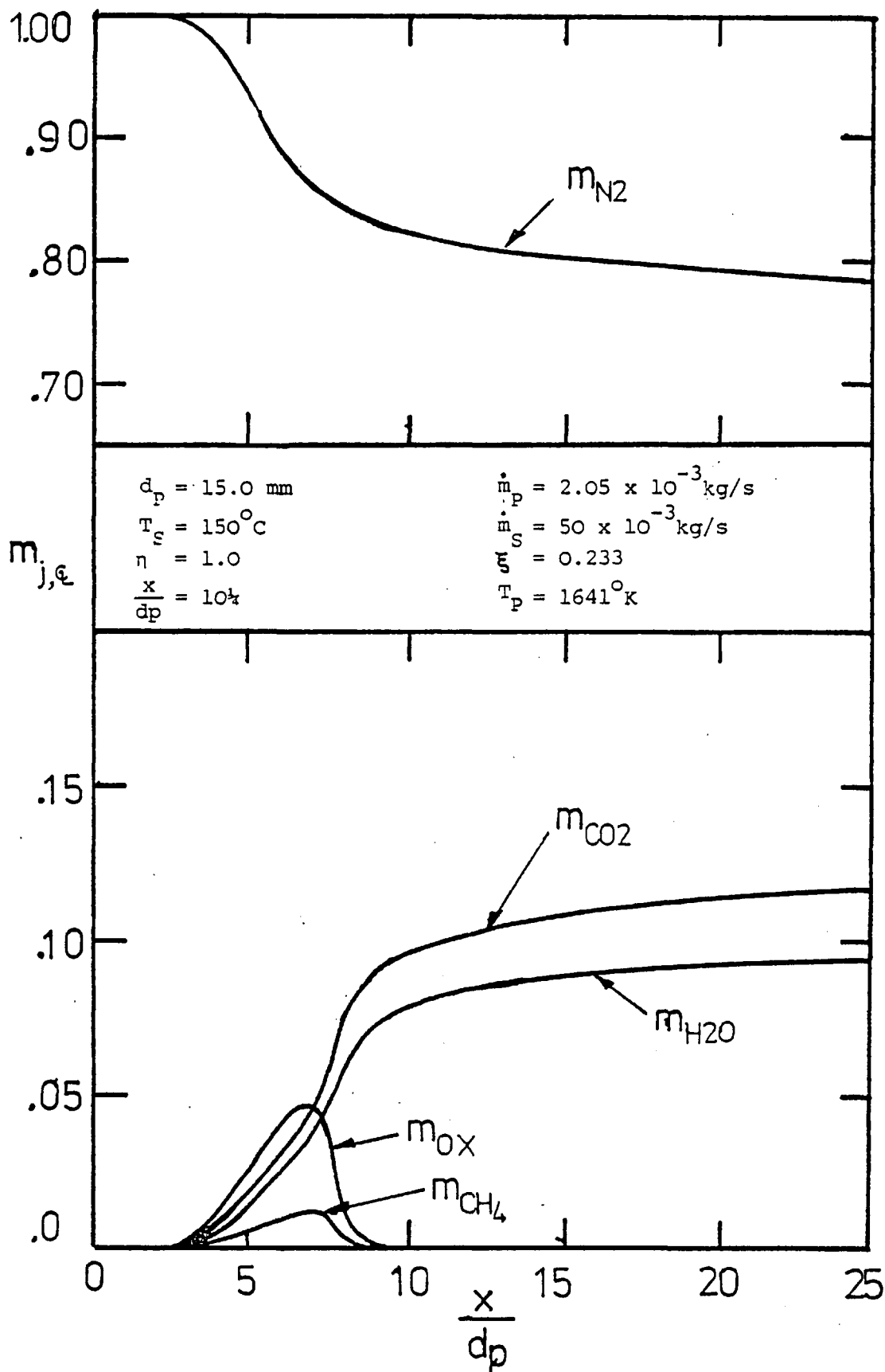


Fig. 42 AXIAL CONCENTRATION PROFILES - WITH
IGNITION AT 1642°K

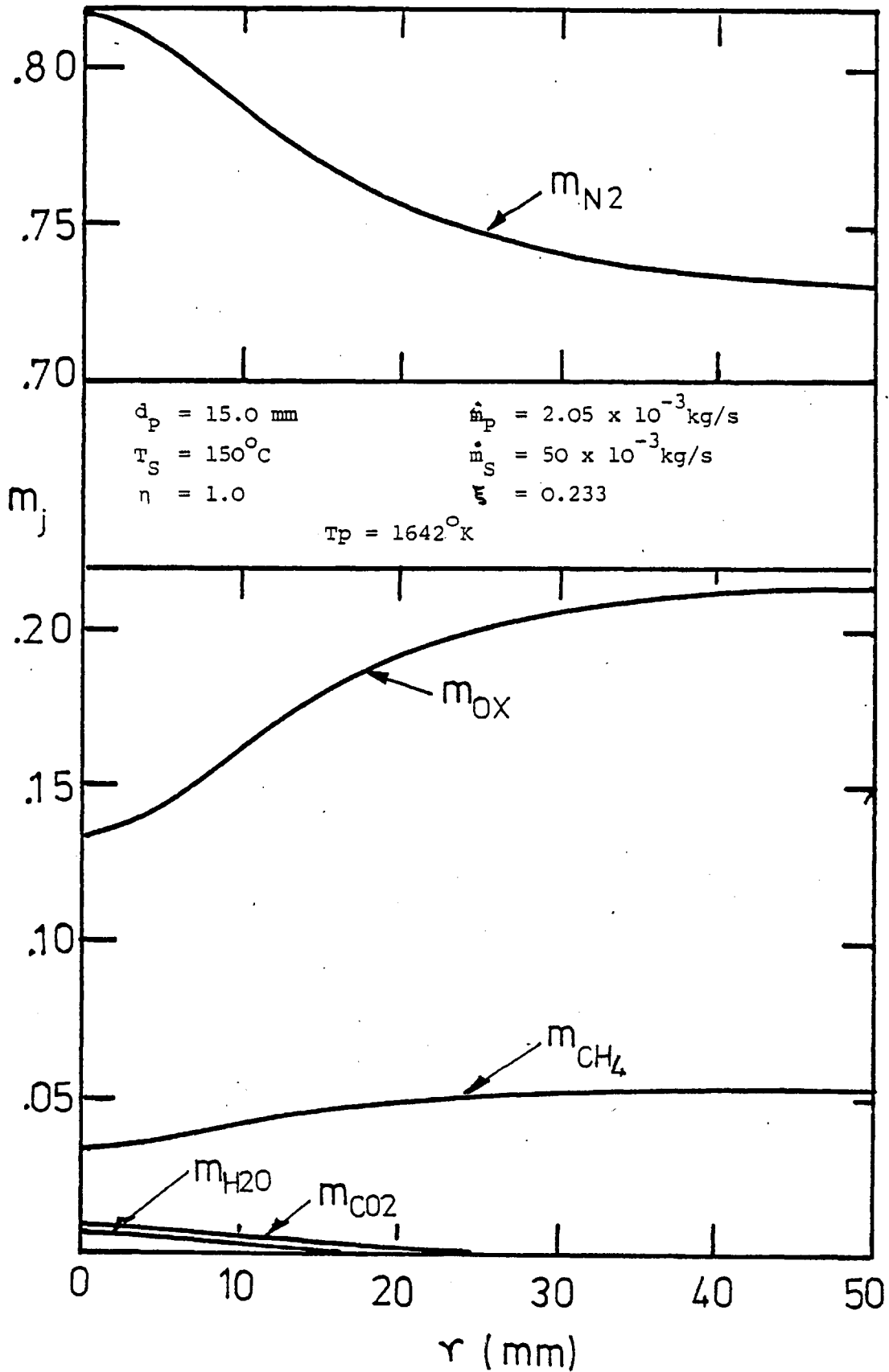


Fig.43_ RADIAL CONCENTRATION PROFILES - NO
IGNITION AT 1641°K

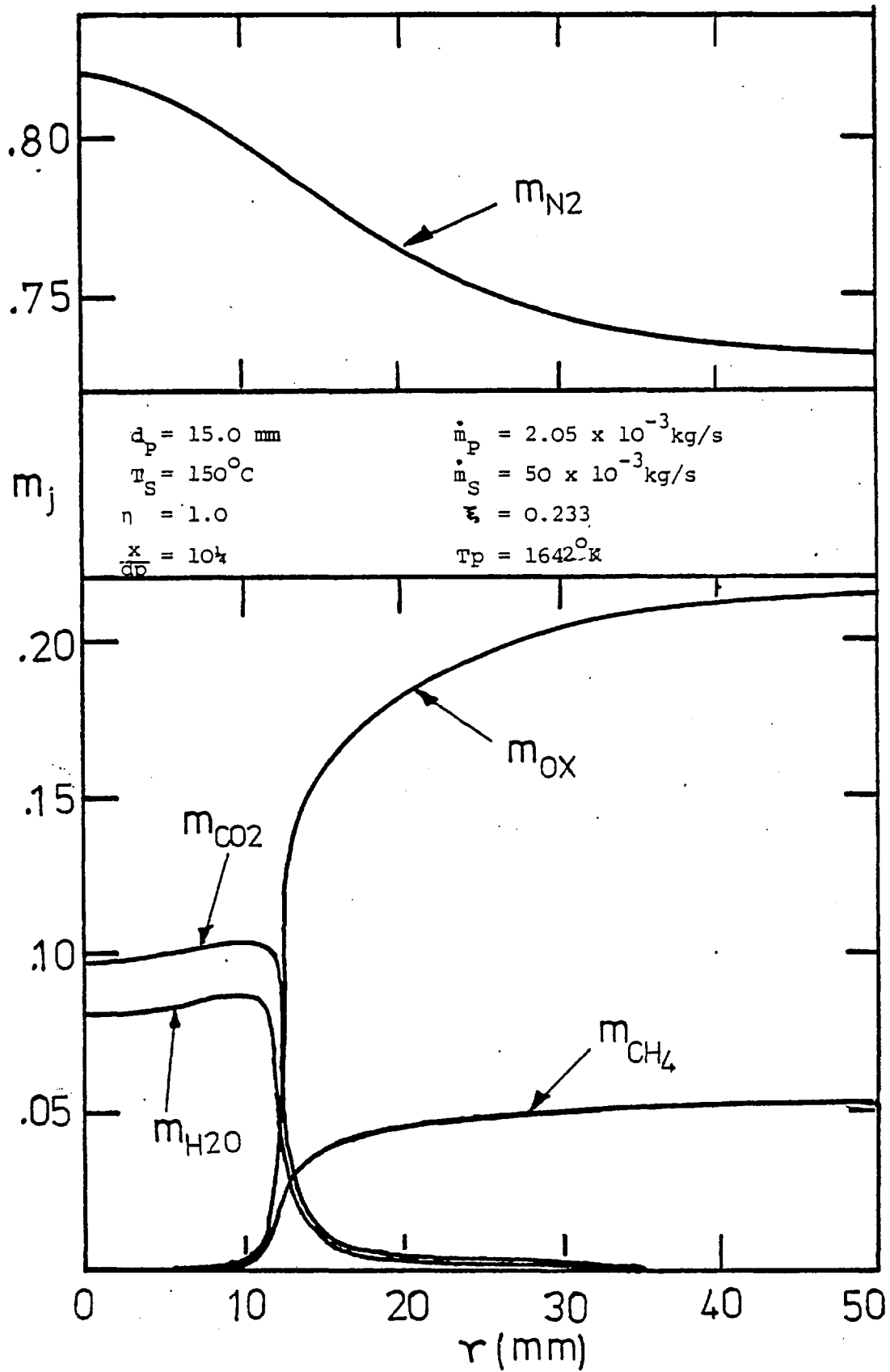


Fig. 44

RADIAL CONCENTRATION PROFILES - WITH
IGNITION AT 1642°K

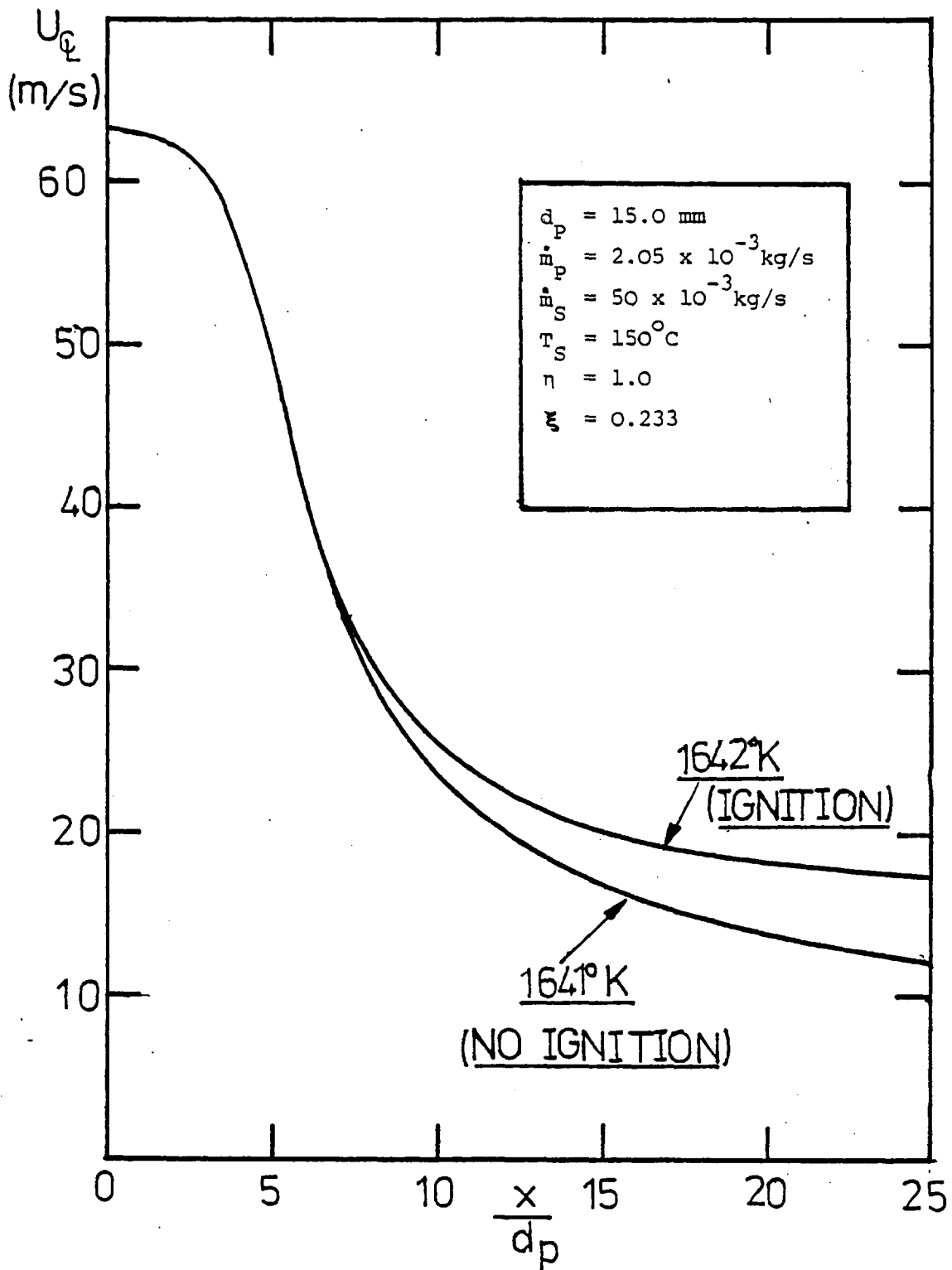


Fig. 45_ AXIAL VELOCITY PROFILE - DIFFERENCE BETWEEN
IGNITIONS AND NO IGNITION

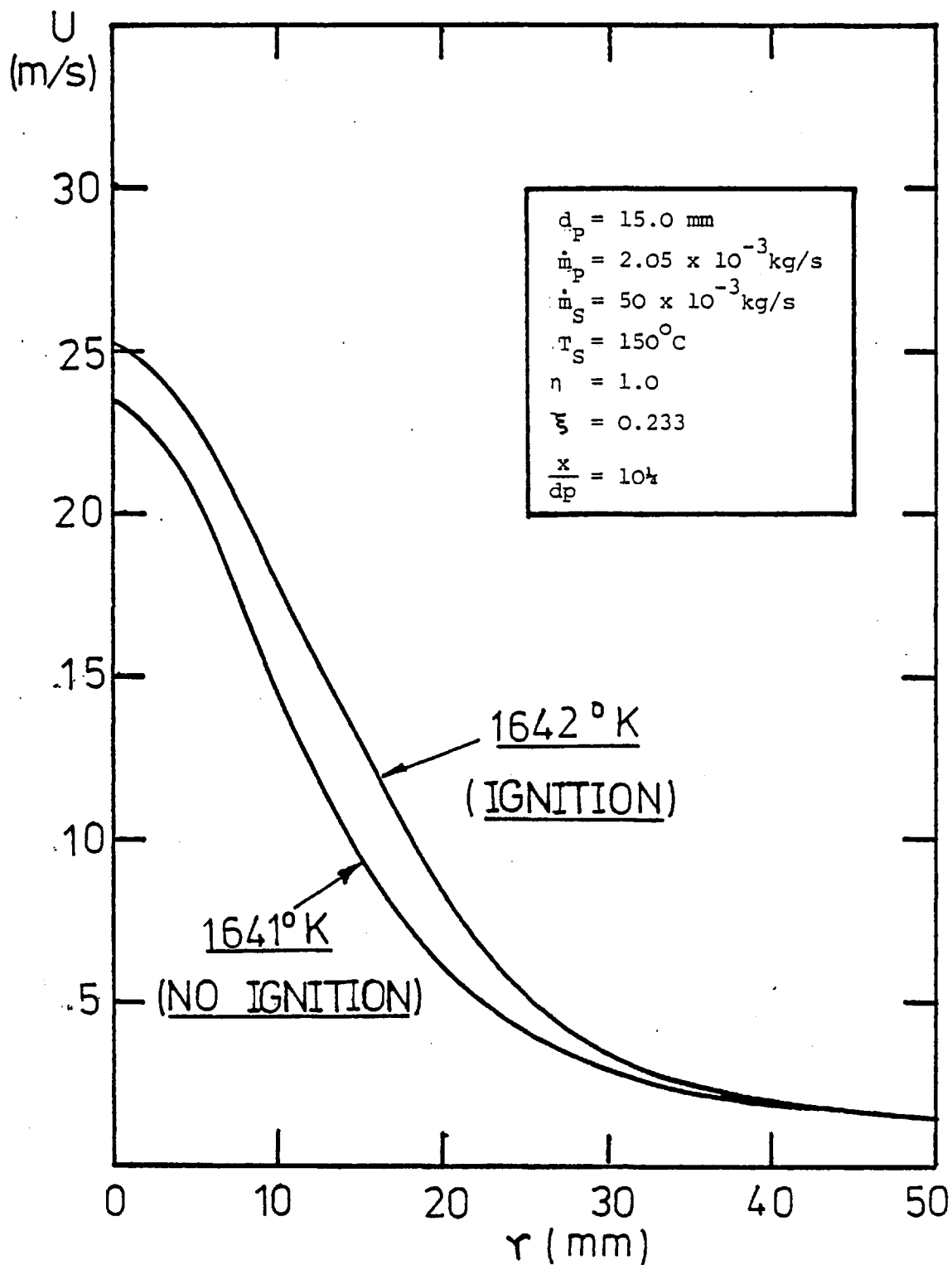


Fig. 46 RADIAL VELOCITY PROFILE - DIFFERENCE BETWEEN
IGNITION AND NO IGNITION

Fig. 4.7 PREDICTION OF M.I.T. OUTSIDE EXPERIMENTAL RANGE

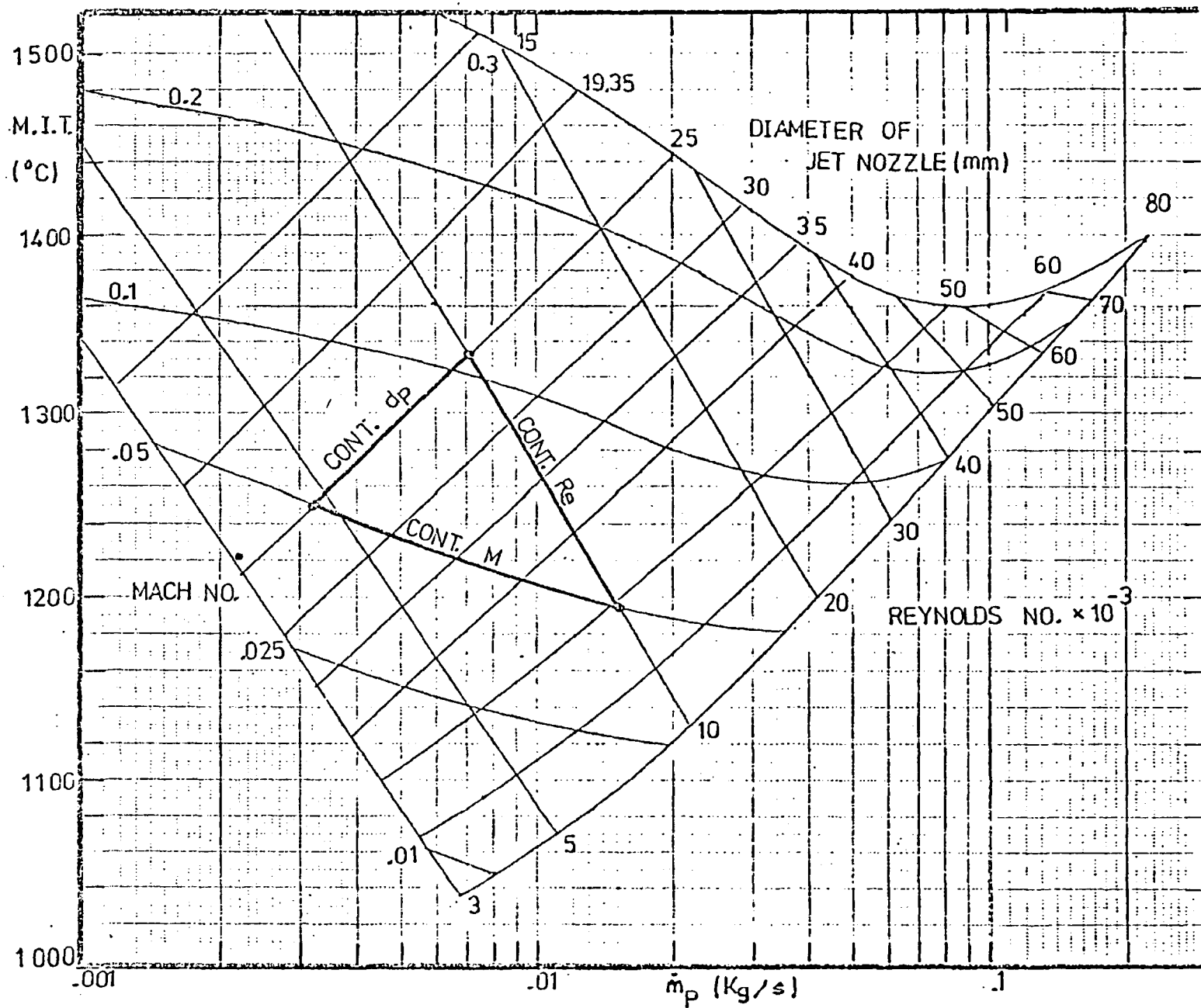
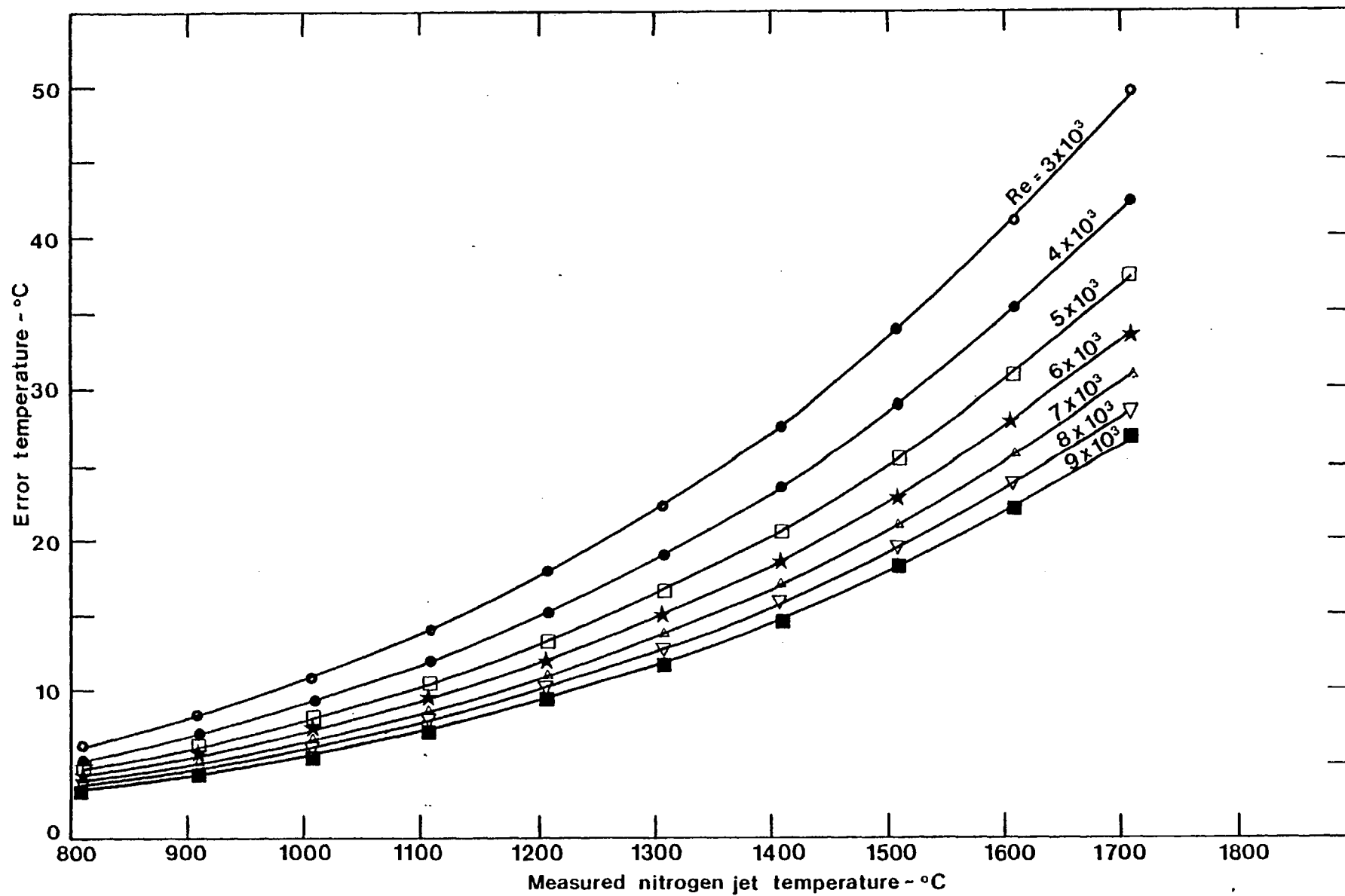


Fig. 48 RADIATION LOSS OF THE HOT JUNCTION



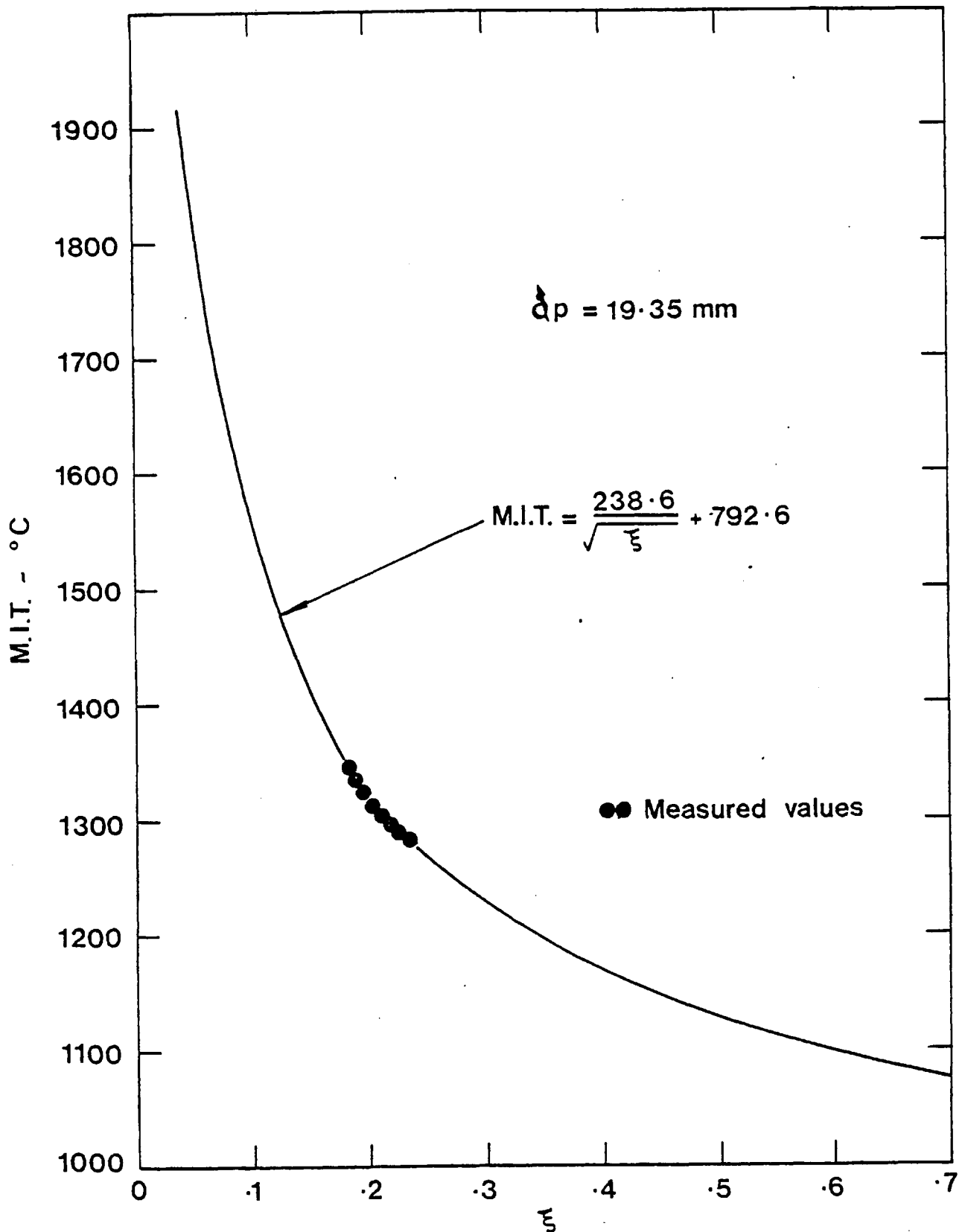


Fig. 49 INVERSE SQUARE LAW FOR M.I.T. Vs ξ

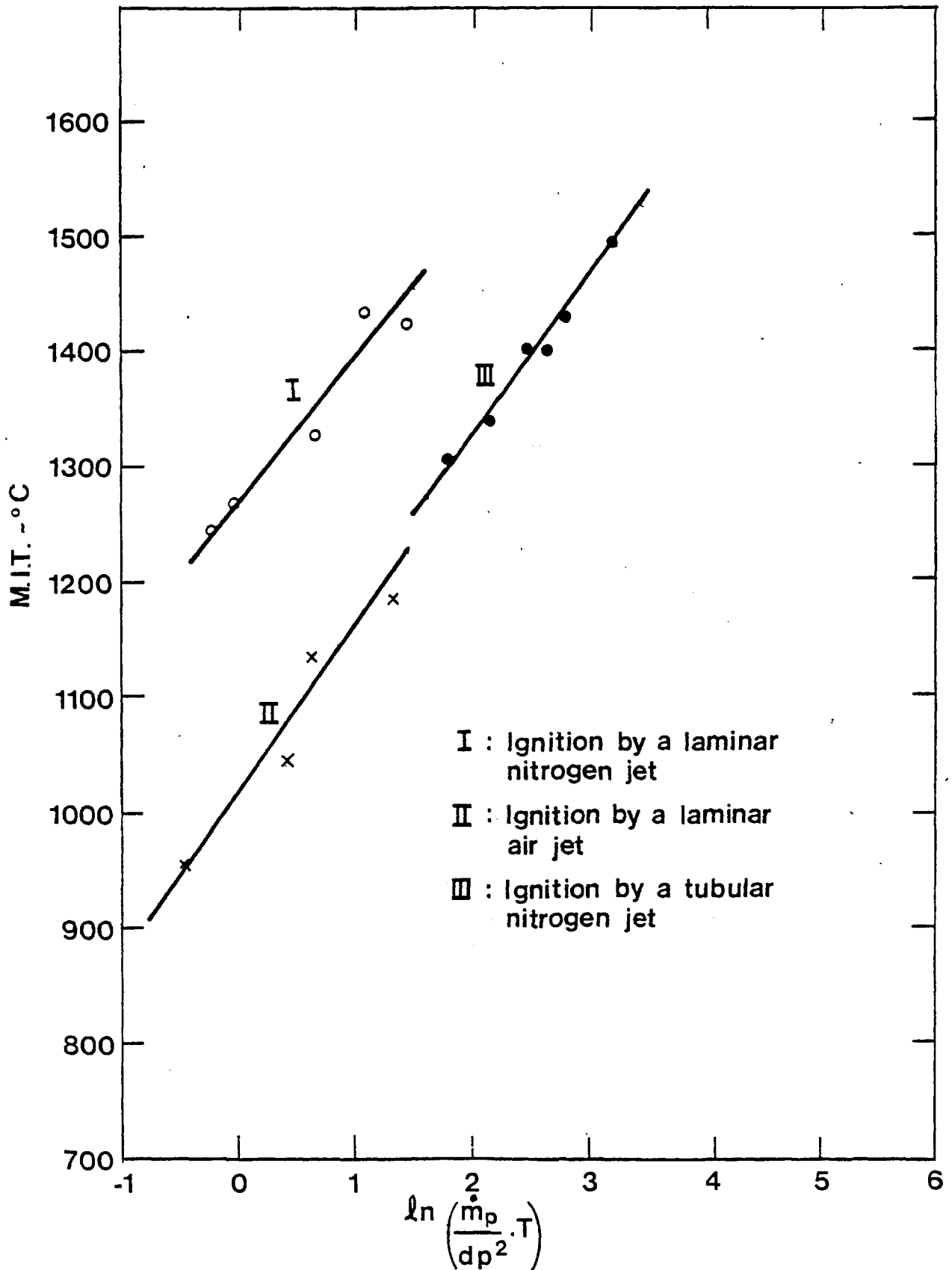


Fig.50 COMPARISON OF MEASURED M.I.T.

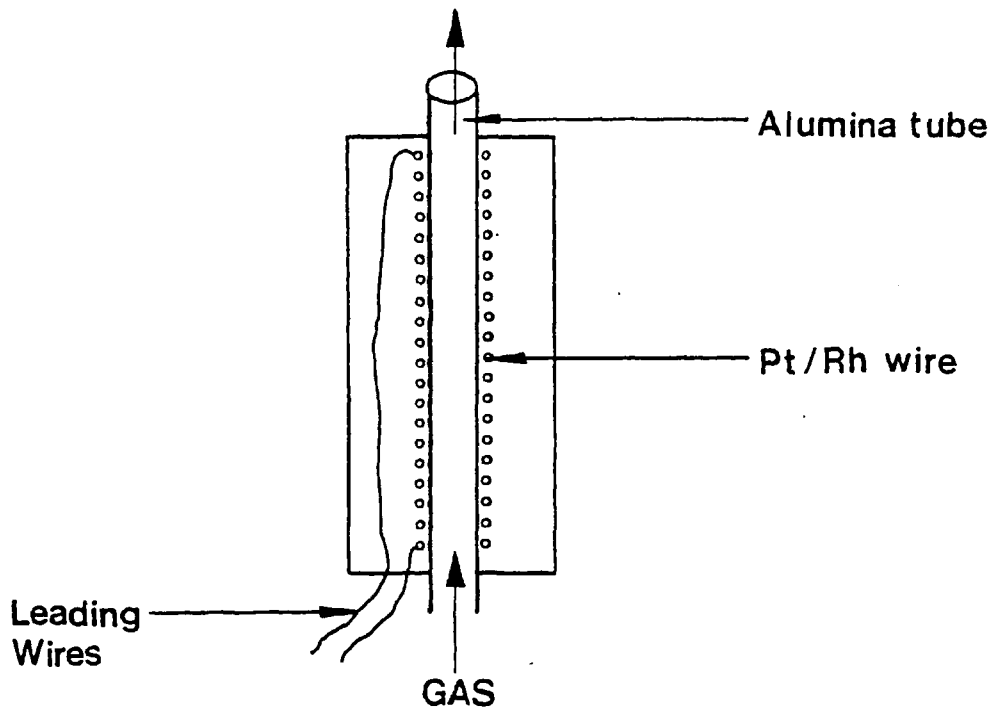


Fig. 51 CONVENTIONAL HEATER USED IN HOT GAS IGNITION EXPERIMENTS

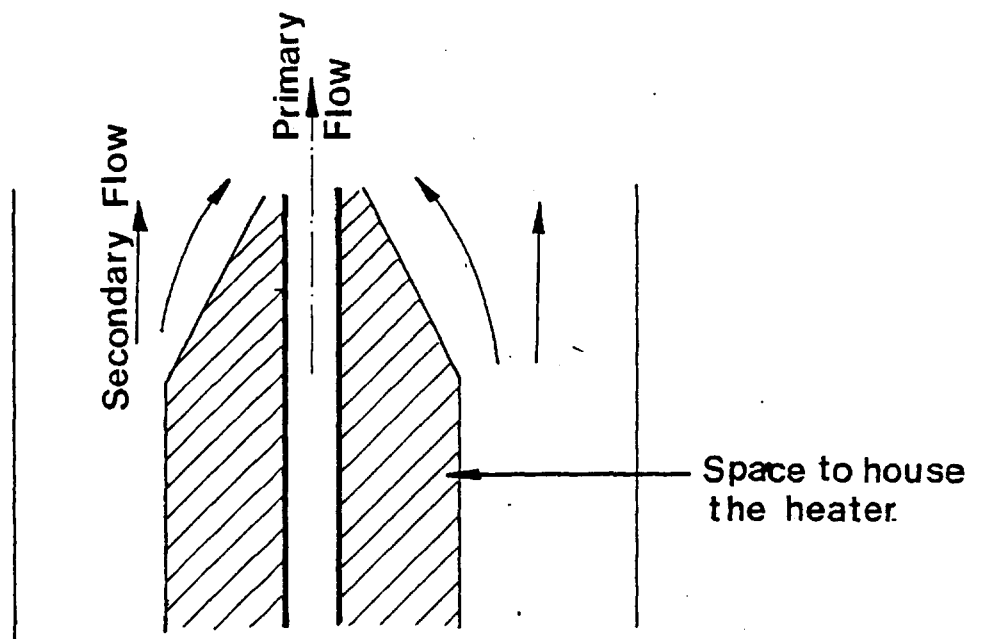


Fig. 52 PROBLEM OF HEATER SPACING

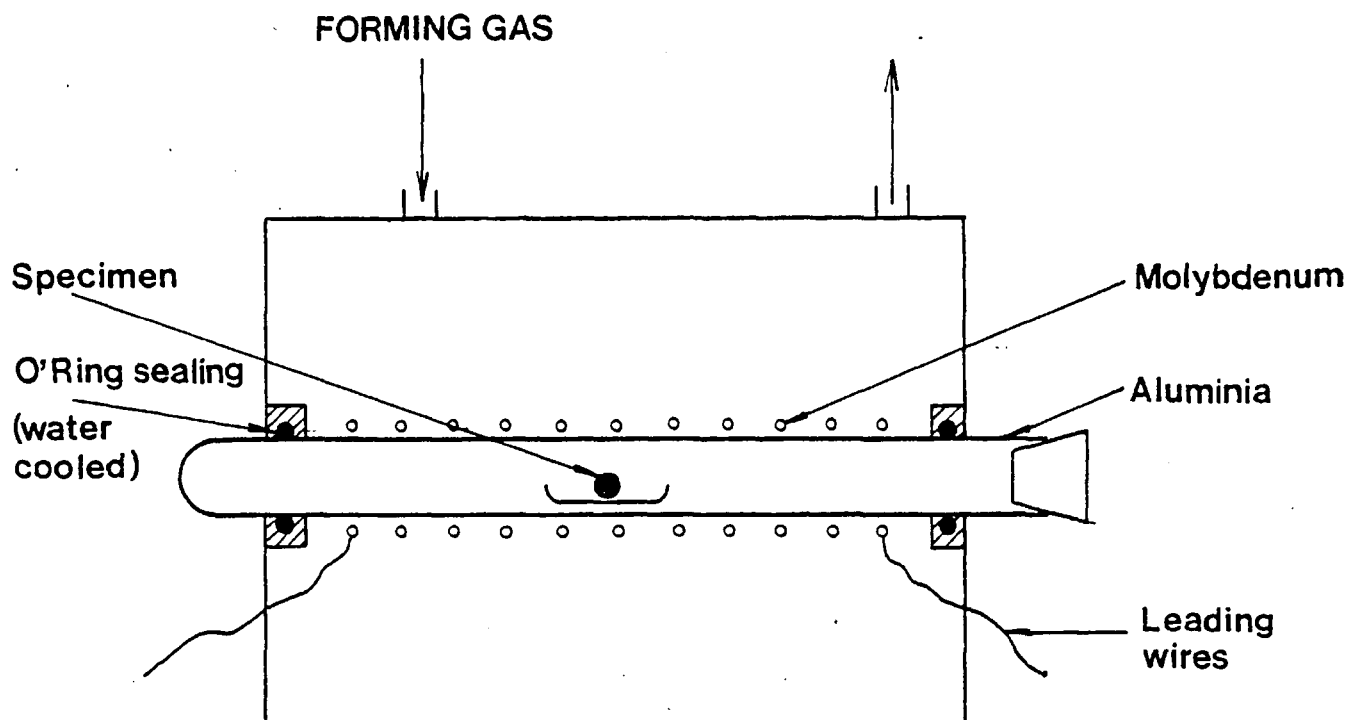


Fig. 53 METALLURGIST'S FURNACE

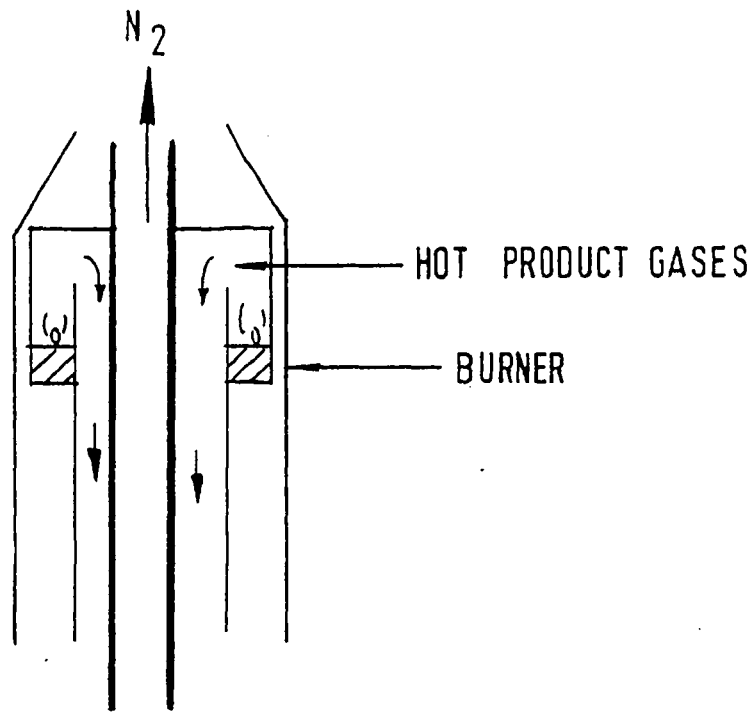


Fig. 54 COMBUSTION HEATING

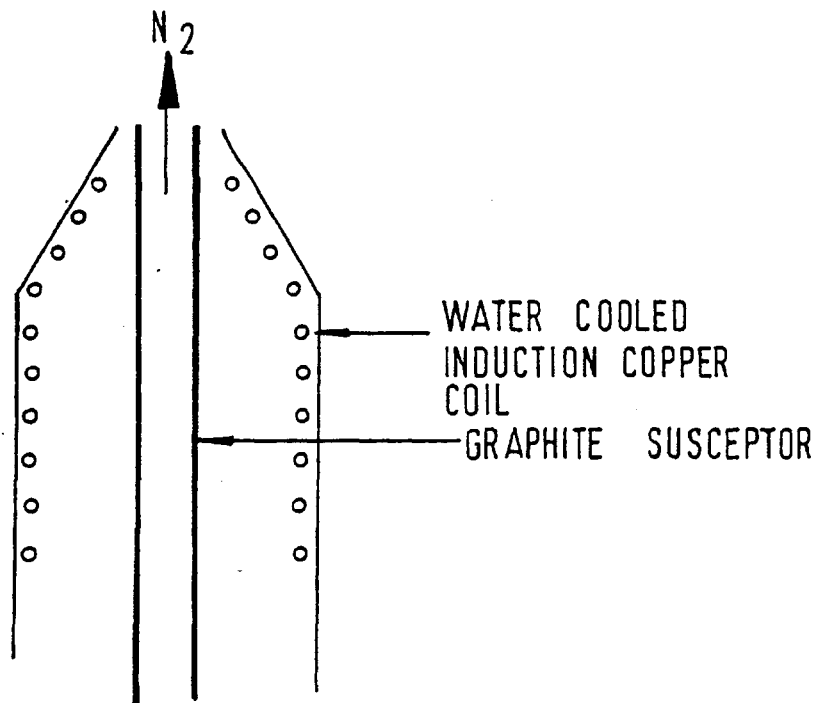


Fig. 55 INDUCTION HEATING

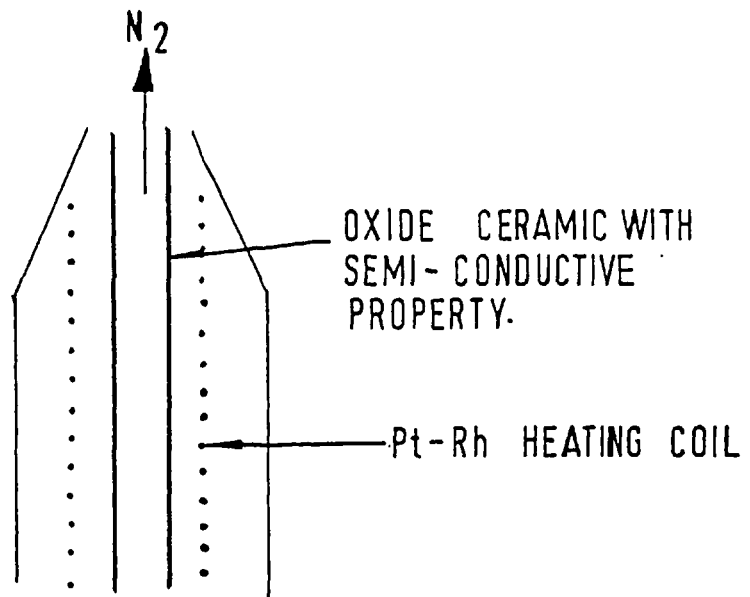


Fig. 56 DIRECT HEATING (A)

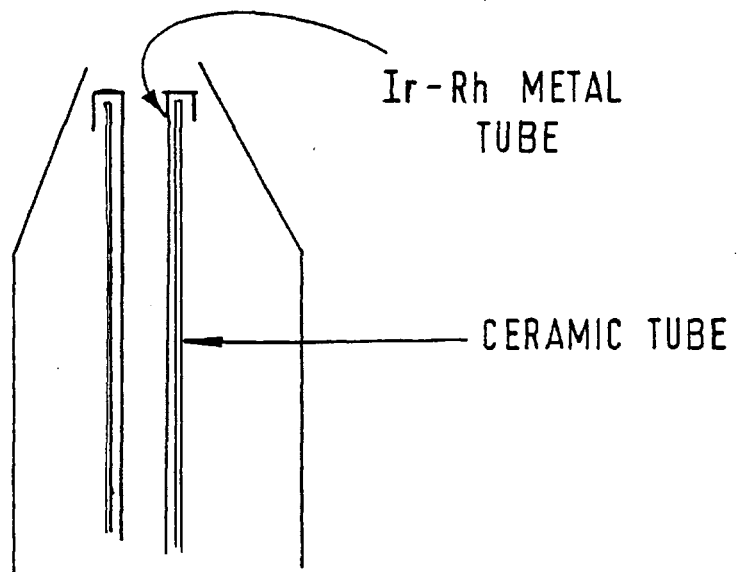


Fig. 57 DIRECT HEATING (B)

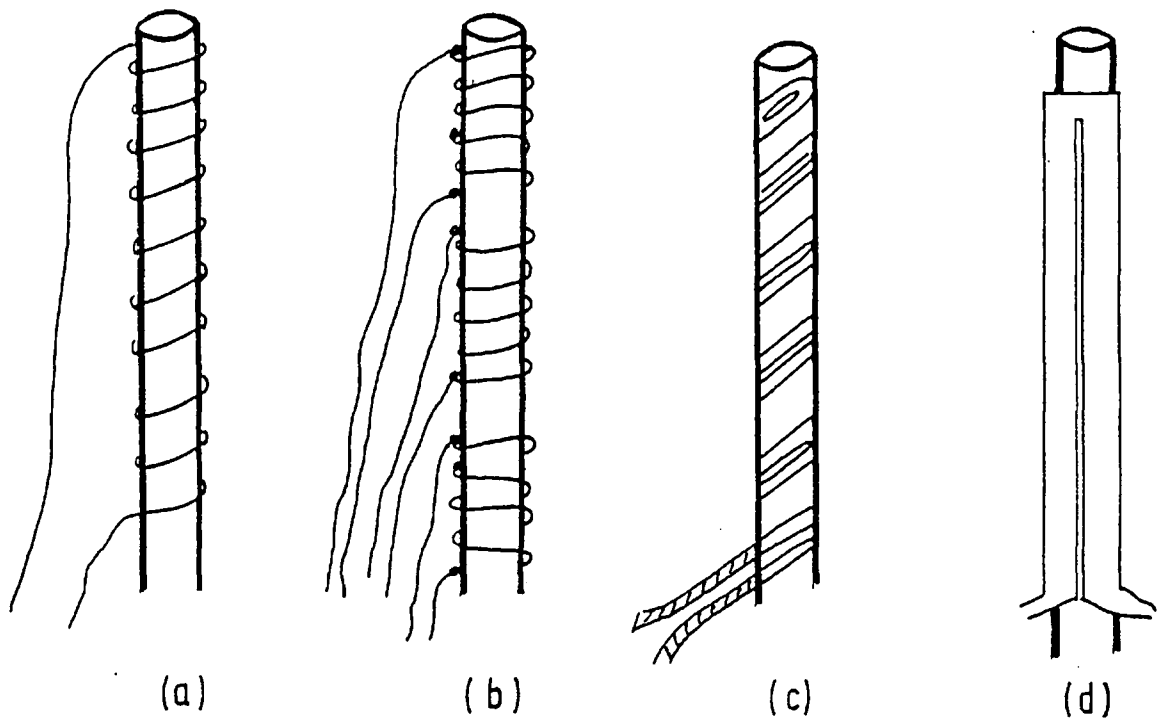


Fig. 58 ALTERNATIVE WINDING METHODS

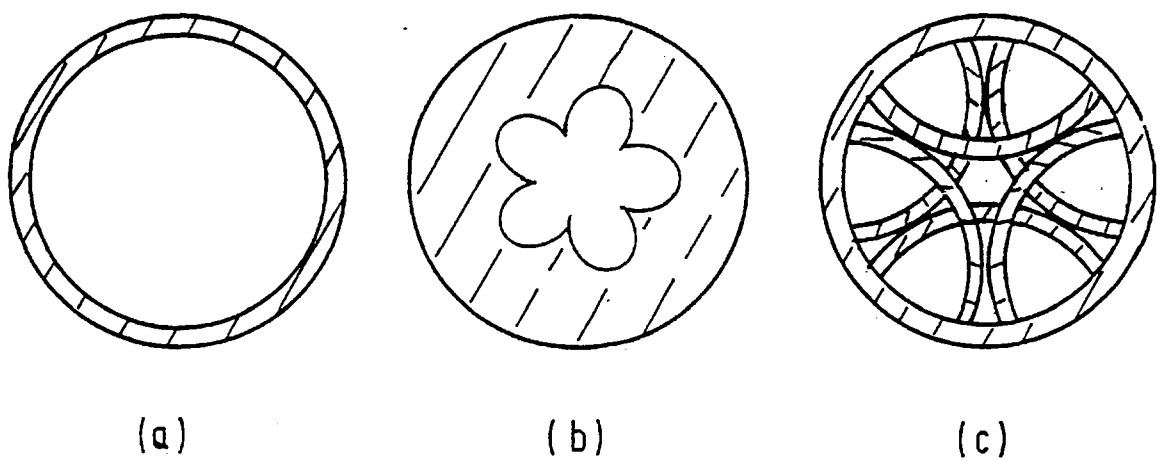


Fig. 59 ALTERNATIVE HEAT TRANSFER SURFACES

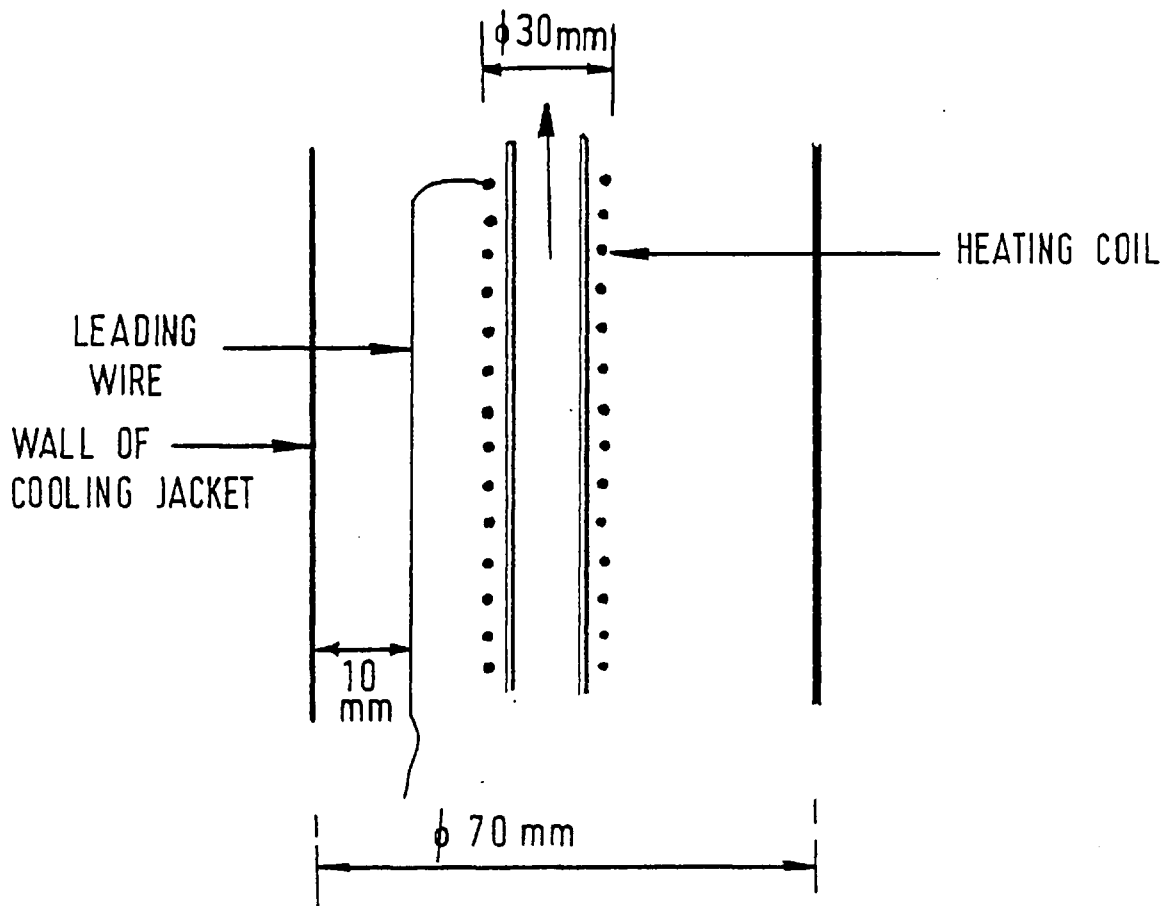


Fig. 60 SPACING BETWEEN COIL AND WIRE

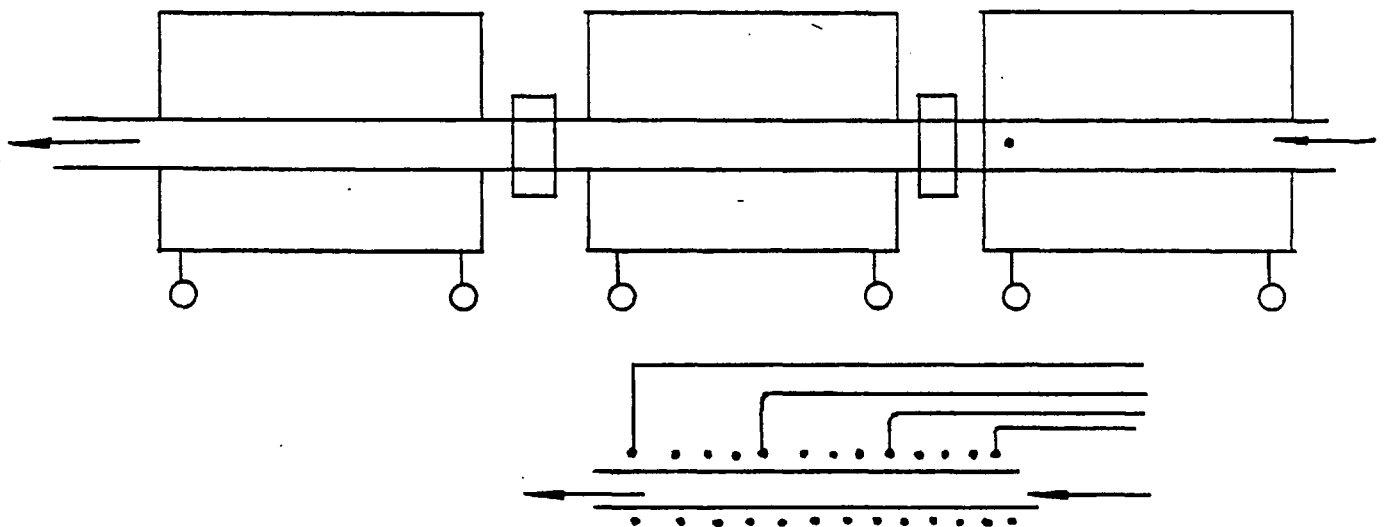


Fig. 61 PRE - HEATER OF THE EARLY DESIGN

Fig. 62 THERMAL EXPANSION OF Al_2O_3 AND Mo

