# AN OPTICAL STUDY OF THE STRUCTURE 

OF DIFFUSION FLAME.

A thesis submitted for the degree of

Doctor of Philosophy at the University of London
by

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## AB:STRACT

This research is concerned with the estoblisment of a flat diffusion flame in the counter-flow region of two directly opposed jets, the study of its structure, aerodynamic as well as thermal, and the in situ determination of heat release rate in such a flame. The burner developed was a refined version of the opposed jet burner used in blow out studies. Large flat diffusion flames were stabilised in mixtures of oxygen, nitrogen and ethylene. The flow pattern was investigated and was found to correspond to that of two jets impinging on the faces of a flat plate, modified by a gas source in the region of highest tomperature.

Methods based on both geometrical and physical optics were developed for the study of temperature distribution. Deflection mapping studies were made using half wave steps while a version of a 2-grating interferometer was modified for these studies. To improve the accuracy of the method, the interferogram was pegged to a reference point in the high temperature region, deternined by thermocuple and sodium line reversal method.

The system was considered theoretically to allow analysis for the rate of heat release and corrections for composition induced changes on the physical properties involved in such an analysis. The heat release rate per unit area extended over a thickness of about five millimetres and agreed well with the

## 2.

theoretical value for reaction proceeding to completion although negative heat release rates were found on both the fuel and oxidant sides. The cause of this was investigated further by ampling and gas chromatographic analysis.

It has been found that these flames can be used for a study of the kinetics of "fast" reactant combinations and the method has therefore been outlined. Recommendations for improvements and applications of the burner used have also been incorporated.

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## CHAPTER 1. <br> INTRODUCTION

### 1.1 Flame-processes

All fast exothermic reactions in gases tend spontaneously to assume the characteristics of flame processes. These reactions then occur under extreme conditions of high temperatures, short residence times and steep gradients of temperature, velocity and concentration. It is on account of these difficulties that the understanding of flames is far from complete in spite of the fact that this was a very early discovery of man and of the prodigious amount of work which has been done in this field ever since.

In addition to the more obvious uses, the flames afford a means of studying high temperature kinetics of combustible gases. Moreover, because of the extreme conditions which cannot be reproduced outside flames, only kinetics determined in this way are reliably applicable to combustion processes. Flames can be broadly divided into two categories - a) pre-mixed flames in which the reactants are pre-mixed before burning and b) diffusion flames in which they are initially separate. The latter can be either homogeneous or heterogeneous. In pre-mixed flames, fuel and oxygen are in a position to react without a mixing step and the flame front travels through the mixture at a rate determined by the intial state of the reactants - composition, temperature and pressure. In the steady state, the flame front is time-invariant, whether or not the flame is stabilised on a burner and there exists a constant burning velocity. Due to heat transfer from the hotter parts of the flame and to heat release by reaction, the temperature of the mixture goes on increasing until the reaction is completed.

In diffusion flames, on the other hand, the reactants are not premixed and oxidation of fuel can take place only in the mixing zone where fuel and oxygen exist simultaneously. The heat released travels down the temperature gradient on either side of the reaction zone and, due to the absence of oxygen, may cause pyrolysis or cracking of the fuel. 1.2 Pre-mixed Flames

Two approaches are generally available for the study of high temperature kinetics in pre-mixed flames - based on blow-out in highly stirred reactors and flame structure studies. In the former case, the study of kinetics is based upon the premise of a single overall reaction. It is, however, now generally accepted that the high temperature reactions take place through a series of radical reactions, which trigger the heat releasing steps. In view of this and also of the invariant temperature and concentration during each "perfectly mixed" reaction, the results are less detailed than those of flame structure studies.

While major advances $(1,2)$ were made in the theoretical field, the understanding of the mechanism of pre-mixed flames (3) and their kinetics (4) was accelerated by the development of flat flame burner (5). More recently (6) this type of burner has been used for the study of detailed radical processes taking place in the flame. This approach, which makes possible the in situ determination of heat release rate and its distribution, is however limited, at atmospheric pressure to nearlimit mixtures. Unless recourse is taken to reduce pressures, it is impossible to study the structure of flames of burning velocities much in excess of $12 \mathrm{~cm} . / \mathrm{sec}$. - not to mention raactants which are too active to be pre-mixed and are becoming increasingly important.


Fig. 1 Wolfhard \& Parker burner

### 1.3 Diffusion flames

The absence of a burming velocity and of flash-back makes diffusion flames safer than pre-mixed ones. It is on account of this that many practical combustion systems make use of such flames. They, therefore, provide the only means of using highly reactive fuel-oxidant combinations. The absence of these properties in diffusion flames is, however, also responsible for the lack of quantitative studies of such flames. Early studies $(7,8,9)$ on the subject were, therefore, confined to determination of flame shapes and heights. These were based on the concept that in these flames the chemical reaction rates were potentially fast as compared with the rate of mass transfer by diffusion. Thus the reactants were consumed as fast as they arrived along a surface most favourable for fast reactions, viz. the stoichiometric surface, which became a source for the products of combustion. This was the only place where fuel and oxidant were supposed to exist simultaneously. The approximate validity of the concepts of theory were provided by the results (10) of Hottel and Hawthorne.

The fact that the reaction zone in a laminar diffusion flame is not infinitely thin is well illustrated by the spectroscopic studies of their structure (11) made by Wolfhard and Parker. A special reactangular burner (Fig.1) was used in these investigations. It consisted mainly of two rectangular channels having one face common With oxygen and fuel flowing with equal velocities. The gases rise
vertically and diffuse laterally as they ascend. A flat diffusion flame was obtained on ignition. This could be kept steady by a surrounding stream of nitrogen. The temperature across the flame was determined by a spectral line reversal method. A spectroscopic study for determining the concentrations of various species was also carried out. The main results can be summarised as follows :

1. The main reaction zone is in thermal and chemical equilibrium and is several millimetres thick. The average temperature in this zone is of the order of the theoretical maximum.
2. On either side of this zone the temperature falls, the gradient on the fuel side being greater than that on the oxygen side.
3. On the fuel side of the reaction zone there is a pre-heating zone where the fuel cracks in the absence of oxygen.

From these studies of diffusion flames, the fact that diffusion is the only rate determining process emerges clearly. The evidence in support of this includes the fact (12) that the average rate of consumption of oxygen in diffusion flames is about $10^{-5}$ times too slow as compared with pre-mixed flames, in spite of the fact that the average temperature in the reaction zone of the former is of the order of theoretical maximum $(13,14,15)$. If, as indicated, chemical reaction is not the rate determining factor, it should be influenced by changing the rate of mixing of fuel and oxygen. In fact, it has been theoretically predicted, indopendently by Zeldovich (13) and Spalding (14) that


Fig. 2 Opposed get burner (Potter et al)
as the rate of mixing of the reactants is increased, the reaction zone becomes thicker and the maximum temperature falls. This lowering of temperature reduces the reaction rate much more than the increase caused due to the thickening of the reaction zone. If the increase in mixing is continued, the flame is blown out at a critical rate of mixing which is specific to the fuel-oxidant combination. 1.4 The Opposed yet Diffusion Flame

The extinction of diffusion flames, as suggested by the theory, has been demonstrated by the experiments of Potter and co-workers (16). In these experiments the flame was established between two directly opposed jets, one of fuel and the other of oxidant (Fig.2). The flame, which was bell shaped and surrounded the air-jet, was found to develop a hole in the middle when the mass flow rate per unit area of the reactants exceeded a critical valuc called the "flame strength". Bxcepting a few fuel-air combinations, the flame strength was found to be directly proportional to the mass of fucl consumed per unit area by the flame front propagating through the corresponding fuel-air mixture. It has, however, been shown (17) by Spalding that this relationship should be quadratic rather than linear. Nevertheless, it has been established experimentally that "apparent flame strength" is principally a function of the maximum reaction rate in diffusion flame and thus can be used for determining the kinetics of fuel-oxidant combinations.

### 1.5 Aims of the present investigation.

While the experiments of Potter et al provide a method of determining the overall kinetics of highly reactive fuel-oxidant combinations, the interpretation leaves much to be desired. Mention might be made, for instance, of their method of finding the flame strength, which was defined as the maximum mass flow per unit area in the jets at blow out. For laminar flow it was twice the mass flow while for turbuient fiow, it was taken to be 1.22 times the mean flow: The temperature at the tube outiets was assumed to be that of the Laboratory and no account was taken of the possible (18) loss of fuel escaping unbumt, The approach, like that of the "well stirred reactor", is essentially too gross to bring out the kinetic structure of flames. Nevertheless, the counter-fiow diffusion flame offers a powerfui tool for the study of high temperature kinetics of reactants which are not safe to be premixed.

The approach in the present investigation was baced on an in situ determination of the heat release rate and its distribution in countermflow diffusion flames. Methods based on refractive index measurement have proved to be well suited for such a determination in the case of flat pre-mixed flames (3, 4). The aims of the present inveatigation, therefore, were:
(1) to develop a flat counter-flow diffusion flame suitable, inter alia, for optical analysis;
(ii) to establish the properties of such flames;
(iii) to establish optical methods for the analysis of their structure, and
(iv) to determine the heat release rate and its distribution in such flames.

The system developed for this was an adaptation of Potter's burner. 1.6 Theory.

The system is axially symmetrical: Conservation equations can therefore be expressed in terms of $z$ and $r$; the axial and radial comordinates respectively. This is convenient for a general approach but is not necessarily the most suitable frame of reference: In particular cases, it may be more convenient to resolve along and at right angles to lines of flow. The generalised steady-state equation for any gas property whose flow rate is f per unit area and whose rate of generation is $q$ per unit volume,is :

$$
\frac{1}{r} \frac{\partial}{\partial r}\left(r \dot{F}_{r}\right)+\frac{\partial F z}{\partial z}-q=0 \quad \therefore \because(1.1)
$$

where suffixes denote axes along which components of vectors are taken. For heat, the flow rate per unit area along any co-ordinate p is given, under conditions of laminar flow by :

$$
F_{p}=-K \frac{\partial T}{\partial p}+\rho V_{p} H+R \quad \therefore(1.2)
$$

where $V, K, \rho$ and $H$ are respectively the local velocity, thermal conductivity, density and enthalpy of the gas. $B$ is the radiont energy flow rate which is negligible in the absence of an appreciable concentration of radiating and absorbing soot particles. Apart from
this, only frictional terms will be neglected. The source term $q$ becomes $W Q$ where $w$ is the rate of reaction and $Q$ the heat of reaction such that the product is the rate of heat release per unit volume. The full equation is, therefore,

$$
\frac{1}{r} \frac{\partial}{\partial r}\left(-r K \frac{\partial T}{\partial r}+r \rho V_{r} H\right)+\frac{\partial}{\partial z}\left(-K \frac{\partial T}{\partial z}+\rho V_{z} H\right)-w Q=0, \ldots(1.3)
$$

Away from zones of reaction, the equation must balance without the last tern. Elsewhere, the differentials must be detarmined experimentally in order to deduce the heat release rate. It is worth noting that in the presence of appreciable pyrolysis, a heat sink rather than a source term can appear on the fuel side.

Inspection of the heat conservation equation (1.3) reveals that the deduction of local reaction rate, defined in terms qf heat release, demands knowledge of the following data:
i) The distribution of temperature. This can be ascertained, for instance, by the methods for measuring the refractive index distribution in the combustion zone. It has been shown (19) that, in flame systems, refractive index variation is occastioned mainly by changes in temperature. Secondary composition variations can be corrected for as indicated below.
ii) Calculation of local values of thermal conductivity density and enthalpy . In the case of the reactants nitrogen, oxygen and ethylene, the major component in the variation of each of these parameters is temperature, which can be found at every point.

The remaining composition induced variation is largely due to diffusion. Only near the central zone of the flames is reaction likely to contribuite appreciably. Calculation of composition effects can be based on theories $(13,14,15)$ of diffusion flame structure. These theories involve assumptions concerning inter-relation between transport properties (in particular, equality of iffusion coefficient and thermal diffusivity). Because of the secondary importance of composition effects, it follows that these approximations are much less significant here than in the theories from which they derive. The same approach is involved in correcting the refractive index temperature conversion for composition effects.
iiii) The distribution of flow velocity in $r$ and 2 . This can be obtained directly from photographs of particle tracks illuminated by an interrupted Tyndal beran.

Thus, the fulfilment of the aims of the investigation depends primarily on the development of a suitable flame and of methods for the measurement of these variables.

## CHiPTER 2.

## THE BURNER AND FLOW SYSTEM

### 2.1 Choice of burner

The diffusion flame which appeared most suitable for an optical study was, in principle, of the type stabilised by Potter and co-workers in the counter-flow region of two directly opposed jets (Fig.2). In addition to the variables - the composition of the reactents, the Reynold's numbers of the gas streans, quailable to the experimenter in the field of diffusion flemes, the opposed jet burner has the additional advantage that the inlet temperature and velocity of the gas streams can be varied independently with a minimum of interaction between the two streams. Such a system, with certain modifications wes, therefore, adapted for the present work.

### 2.2 The burner assembly

The burner essentially consisted of two brass tubes each 23 cms. long cut from a length of a single drawn brass tube of internal diemeter 6.31 cms. One end of these tubes was fitted with matrices of flame trap material. These were constructed by spirally winding two adjecent strips ( 3.2 cms . wide) of plane and corrugated strips of cupronickel. The diameter of those matrices was so arrenged that they would just fit into the burner tubes and be held by their spring action. The surface of the matrix was made as plane as possible by gently pressing it against a flat surface. The burners could then be packed with glass beads and closed at the other ends by rubber bungs carrying glass tubes as inlets for the reactants. With the help of this arrangement, the reactant flow velocity distributions
could be rectified to approach constant and uniform values ecross the burner mouths. The method employed was analogous to that used in the flat flame burner (5), where the approach velocity distributions are first randomized by the beds of glass beads and tlen streamlined by matrices of fleme trap material.

Before the bumers were packed with glass beads and sealed, six thermocouples were spot-welded onto the downstream face of each metrix. The two metals constituting the thermocouples were nichrome wire (S.W.G.33) and cupronicket (matrix itself). An innovation introduced was the use of very fine borc tubes of fused quartz, each two inches long, for insulating the nichrome wire from the matrix itself. The thrcading of S.W.G. 33 nichrome wires into these fine tubes was mechanically difficult in view of the fact that their average bore and wall thickness respectively ranged from 0.25 to 0.35 mms . and .035 to .05 mms . This was accomplished by selecting wires free from bends and then sliding the tubes ovor them. Once in position, the tubes cid not slip along the length of the wires because of the close fit between the two. Also the outer diameter of these tubes was such that they just fitted in the triangular holes of the matrices ance thus insulated the encased nichrome wires from the matrices over the depth of the matrix. The rest of the length of the wires was insulated by silice sleeving.

The wires were then spot-welded onto the downstream fece of the two matrices in an inert atmosphere. The six (hot) junctions on each matrix, which were the only places at which the two metals were in clectrical contact, were arranged to be in a spiral. A strip of cupronickel, soldered at the top of each matrix, served as the common terminal for the


Fig. 3 Circuit for thermocouples.

$$
22
$$


correspondine six nichrome wires, which were of equal length. It wes found necessary to insulate the length of this strip from the bress tube and a mica lining was used in the tubes for this purpose.

The cold junction, also made by electricelly welding the nichrome wire and a strip of cupronickel matrix in an inert etmosphere, was maintained at ice point. Any (hot) junction could be brought into serics with $\varepsilon$ gulranometer and the cole junction with the help of selector switches. The electrical circuit is shown in Fig.3. To convert the deflections of the galvanometer directly into temperature, the themocouple was calibrated against mercury in glass thermometer by means of a potentiometer.

With the aid of these thermocouples the temperature and its distribution across the downstream face of each matrix could be determined. It has been shown (20) that this temperature is very nearly the temperature of the outcoming geses.

The burners were then packed with glass beads and sealed ges tight. They were mounted on a dexion framework (Fig. 4) with the help of collars, each of which was provided with three screws for making the two burners co-axial. However, after the preliminary experiments, it was found that this mounting was not very convenient. It was, therefore, repleced by a heavier and more rigid framework of cast iron, which held the verticelly opposed burners co-axielly permenently. The. were firmly attachec to square brackets and centred with the help of insuleting pieces of perspex end boss screws. The arrangement is shown in Plate 1.


Plate 1. Buzner Assembly

### 2.3 The flow systems

Another modification introduced was to make the volume flows of oxident and fuel jets very nearly the same by dividing the nitrogen of air between the two, while the reactant supply rates were in stoichiometric ratio. This bestows kinetic, as well as aerodynamic advantages. Without this device, the large difference in jet momonte involved at stoichiometric with air sets a limit to flame flatness. As regerds reaction velocity, the admixture of diluent makes possible the approach to blow-out conditions at conveniently low flow rates. Furthermore, when the nature of the temperature gradients involved were found, the positioning of the flame near the middle of the gap between the two burners proved to be a great asset.

Two identical flow systems, one for the fuel jet and the other for the oxident jet, were used. They are shown in Fig.5. The reactants were supplied from commercial gas cylinders, the nitrogen usec being oxygen free. The gases drawn from these cylinders - fitted with their reducing valves, passed through the flow meters while their rates of flow and also the line pressure could be controlled by two diaphragm velves inscred in ea. 1 line immediately before and after the flow meters. $\Lambda$ mercury menometer introduced into cach line just after the second valve indicated its line pressure. The sum of barometric plus line pressure was maintained constant. The two gas streams, nitrogen and fuel/oxygen wore mixed in glass towers packed with glass beads. The fuel-bearing ges stream was then fed into the lower jet while the oxyeen bearine one was led into the upper jet.


Fig. 5 Flow measuring Apparatus


Fig. 6 Capillaiy Flowmeter
28.

The flow rates of the two nitorgen streams were measured by rotameters, while capillary flow meters (Fig. 6) were used for metoring the fuel and oxygen flows. On account of its finite vapour pressure at room temperature, together with the fact that ethylene is appreciably soluble in water, it was found desirable to use di-butyl phthalate in the menometers of the capillary flow meters. To cover a wide range of fuel and oxygen flows, a large number of capillary tubes were selected in such a way that, on calibration, which was carried out by the soap bubble method (21), an approximately linear relationship between volume flow rate and pressure drop across the capillary was obtainec, each oapillary being used only over its linear range.

## CHAPTER 3.

## THE FLAT COUNTER-FLON DIFFUSION FLINE

3.1. The fleme

Ifter the first attempt at stabilisation of a counter-flow diffusion flame of ethylene and air, it became apparent that a few more modifications were needed in order to obtain a flame of appreciable area which micht be sultable for an optical analysis. It was observed that with a gap of only a few millimetres, a diffusion flane could be stabilised, provided the flow rates of the reactants were exceedingly small. If the flow rates were iaoreased, the flame spread beyond the burmer diemeter and curled upwards, thereby coming in contact with the oxidant-bearing tube. Increasing the gap did not appreciably affect this general behaviour. It was therefore thought desirable to prevent this by atteching annular flanges to the two burners. Syndanio rings, two centimetres wide, were screwed on flush with the matrices of the two burners. This produced the desired effect; the gap could now be increased to about $1.5 \mathrm{cms} .$, while a flame could be stabilised over a wide range of reactant flow rates.

It was noticed that the rising hot products made the oxidantbearing burner very hot. In order to prevent this and also to control the approach stream temperatures, the burner tubes were provided with water jackets.



Fig.7. Framework for mica chimncy

These measures proved successful and led to the stabilisation of suitablo flames. When the fuel and air were arranged to be in stoichiometric proportions, the flane apneared as a palc blue disc with an intense yellow pyrolysis zone of appreciable thickness immediately adjacent to it on the fuel side (Plate 2). Is the two jets were diluted with more and more nitrogen, the pyrolysis zone sterted losing its brightness till it disappeared altosether. The flame under this condition was simply a dull blue disc with skirts on the edges. It was also noted that, as the amount of nitrogen was increased in both the jets, the diameter of the luminous zone increased. is expected, the temperature distribution across the two matrices was governed by the nature of the flame. The mean temperatures, as well as the steepness of the distributions, were usually higher in the presence of the pyrolysis zone than in its absence.

To investigate the possibility of stabilising a flat flame, the combustion zone was enclosed by a mica chimney. For this, the width of the annular syndenio rings was reduced to about one centimetre. A rectangular sheet of mica rolled in the form of a cylinder was held against a cylindrical framework of brass (Fig. 7) by circlips at the top and bottom rings. The diameter of this cylindrical franework was such that it was about two millimetres ereater than the outer diameter of the syndanio rings screwed on to the burners. This framework, and hence the chimney, could then be
freely suspended from screws atteched to the top syndanio rine (FiE. 7 ). Once in position, the chimney provided e one millimetre annular gap through which the product gases could escepe. The flame was lit by an electric sperk across two wires introduood through the top and bottom syndanio rings and connected ecross the secondary of an induction coil.

The flame in the presence of the mice chimney was reasonably flat (Plate 3). However, it was found thet, on changing the flow rate, the diameter of the chimney had to be altered. The increase In flow rate of reactents necessitates this chenge. The diameter of the chimney hed to be adjusted so that it was just less than the free flame diameter.

### 3.2. Hlow Visualisation

hs mentioned earlier, the in situ detemination of heat release rate requires, among ther information, a knowledge of the local stream velocity. This was sousht from particle track photogrephs. In principle, microscopically small particles of bentonite were entrained in each gas stream: On emerging from the two matrices, they were illuminetcd by a powerful Tyndall beam. $A$ high pressure mercury vepour lamp run on d.C. served as the light source. hssuming the frequency of the mains to be 50 cycles per second, the particles would be illuminated at regular intervals of ten milliseconds. The photograph of these particles will,


Plate 3. Flat counterflow diffueion flame.
therefore, give intermpted streaks, while the trajectory traced by sı particle will give to a good epproximation (hipendix A) the local direction of the streamline. From a knowledge of the exact time base: furnished by the electricity supply company, and the lengtin of the treoks, the flow velocities oan be determined. A very simple method introducing the bentonite particles into the gas streams was used. Each flow line was broken just before the inlet to the burners and a T-tube inserted. A test tube containing the bentonite particles was connected to the vertical leg of the T-tube. This device, ensured thet the mein ges strecms pessed ancontaminated unless it was desired to introduce the particles. This was done by gently tapping the test tubes so that a burst of particles was entrained in the gas streams.

The optical system for illuminating these particles is shown in Figure 8. A slit about three millimetres wide was pleced next to the window of the mercury lamp. The cone of light emerging through st was brought to a focus on the axis of the jets with the help of condenser lenses. These lenses were sugh that the Tyndail cone just fitted the gap between the two matrices. in image of the slit was then thrown horizontally across the top and bottom matrices. The "flame" cemera was placed at right angles to this Tyndall bean and was focused on the illuminated diameter of the matrices. This camera, therefore, photographed only those particles


Fig. 8 Optical System for Flow Visualization



Plate 5, Particle track photograph of a "stoichiemetric " flame.
emerging elong the illuminated diametrical section, together with the fleme. it "Kodak Speciolist" camere with a lens of focal length 105 mms. was used. The photographs were teken on H.P.S. plates which were developed in Promicrol. a typical photograh of perticles in the two directly impinging jets (without the fleme) is show in Plate 4 . This was taken at $f / 8$ with an exposure time of one second. Having set up a reasonably good optical system, it seemed a simple task to record particle tracks in the presence of the fleme. i.ttempts were therefore made to obtain such e photograph for a flame to which the reactants were fed at the following rates :

$$
\begin{aligned}
& \text { Ethylene }=7.5 \mathrm{ccs} / \mathrm{sec} ., \mathrm{O}_{2}=22.5 \mathrm{cos} / \mathrm{sec} . \\
& \mathrm{N}_{2}\left(\mathrm{C}_{2} \mathrm{H}_{4} \text { side }\right)=75 \mathrm{ccs} / \mathrm{sec} . \quad \mathrm{N}_{2}\left(\mathrm{O}_{2} \text { side }\right)=60 \mathrm{ccs} / \mathrm{sec} .
\end{aligned}
$$

all at S.T.P. The total volume flow rate from either jet is seen to be $82.5 \mathrm{ccs} / \mathrm{sec}$. (at S.T.P.). The flow pattern in this case has been reproduced in Plate 5 . The optical setting, the f-number and the exposure time were the same as before. It is apparent from this photegraph that the image of the fleme masks the particle tracks, if partioles are there at all, in the regions of highest temperatures. A quịck visual check was therefore mede to find out if the bentonite particles entered this flame at all. In fact it was obscrved that there was a narrow zone on either side of the Iuminous region isto which no particles found their way.
3.3. Emission Spectrum of the flame.

To investigate this point further, it was decided to eliminate, as far as possible, the flame emission from the perticle track photographs. The obvious method was to put a filter before the camera lens in order to cut off most of the visible radietion from the flame. The flame was therefore observed through a calibrated direct vision spectroscope and the positions of the bandheads were very roughly read off. These were (i) $6500 \AA^{\circ}$ (ii) $56504^{\circ}$ (iii) $5160 \Lambda^{\circ}$ (iv) $4750 \Lambda^{\circ}$ (v) $4350 \Lambda^{\circ}$. Only the intensity of these bands varied as the concentration of the fuel was altered, it being strongest when oxygen and fuel were in stoichiometric proportions. Superimposed upon this, there was a very faint continuum. On introducing the bentonite particles, the only chenge observed was the appearance of sodium lines along with an increase in intensity of the continuum in the red region. A photograph of the emission spectrum of the flame, along with the axc spectrum of iron, has been reproduced in Plate 6. It was found that the most intense bands occurred in the green region which, of course, contains the strongest visible line of mercury. Furthermore, the intensity of these green bands did not show any merked change when the fuel concentration was decreased.
3.4. Modifications of the flow visualisetion system.

The commercial mercury green filter was, therefore immediately ruled out. A filters presumably Wratten $77 h_{\text {, }}$ was seen to


Plater. P.T. photograph taken through a filter.
cut off most of the radiations from the flame. This, however, had a very low transmission efficiency and cut down the intensity heavily. The Tyndall beam system was therefore modified to increase the intensity of illumination. The slit placed Defore the mercury lamp was removed and only one condenser was used to throw the image of the mercury arc on the axis of the co-axial jets. The mercury lamp itself was enclosed in a water-cooled jacket and a "toughened" heat filter was put in front of the window to cut off all the infra red radiations. This was done to avoid unwented convection currents which, as discussed later on, proved to be a major obstacle in the present work. The camera was still focused, through the filter, on the illuminated diameter of the matrices. The exposure time was kept the same but the $f$-number was changed to $f / 4 \cdot 5$. With these modifications, a particle track photograph of a diluted flame in which the fuel and oxygen were in stoichiometric proportions (flow rates cited before) was again taken. The visual observations were confirmed, for the photograph revealed a particle-free zone on either side of the luminous flame. To prove this point beyond doubt, bentonite particles were injected in much higher concentration then would be used normally in either jet and still there appeared a particle-free zone. This is shown in Plate 7 .

Before discussing this phenomenon further, enother modification for taking the particle track photographs will be discussed first for the sake of continuity. It will be seen from Plate 7


$\rightarrow$

$11: 2187 \% \mathrm{NWN}$

Lean
(a)

thet there are herdly any tracks on which measurements could be made. The other eilternative, of reducing the exposure time, which might give a less dense image of the flame was therefore tried. For this, the Tyndell beam system was kept, as described in this section, but the filter in front of the camera lens was renoved and the camera refocused. Verious combinations of f-numbers and exposure times wero tried and it was found that an exposure of one-fifth of a second at $f / 8$ gave the best results. This arrangement and camera setting was, therefore, used for further work. 3.5. Lerodynamics of the Counter-flow Diffusion Flame.

To investigete the flow pattern of geses in the fleme, it was deciced to keep the flow rates of oxygen and the two nitrogen streans constant and vary the flow rate of ethylene. iccordingly, the following rates were maintained constant :


The flow rate of ethylene was systematically veried starting from lean and going to rich. The particle track photographs for the flames thus stabilised are shown in Plate 8 . It will be noticed that, if the flame is on the "leaner" side, it lies on the fuel side of the stagnation point (Plate Ba), as would be expected if it coincides with the surface of stoichiometric composition.

This is indicated by the fact that bentonite particles from the fuel side cross the flame and enter on the oxysen side of the flame. is the concentration of the fuel is increased, the flame moves more and more towards the stagnationpoint of the opposed jets. When the fuel and oxygen are in stoichiometric proportions (Plate 8b), particles from neither side enter the flame. If the amount of fuel is further increased, the flame stabilises on the oxygen side of the stagnation point.

It is apparent that the position of the flame with respect to the stagnation point is determined by stoichicmetry. It therefore follows that, depending on the fuel-air ratio, the aerodynamics of the two directly opposed jets is modified by the presence of the flame. For example, when the fuel and oxygen are in stoichiometric proportions, the jet momenta (without the flame) are nearly the ame and the impingement zone is in the middle of the tost spece (Plate 4). In the absence of flame, the gas velocity can be found at all the points with the help of particle tracks. However, as soon as the fleme is lit, the two jets of bentonite gas streams no longer impinge but leave a particle-free zone on either side of the flame. What is thought to happen is thet, as the fuel burns, hot products are liberated at volumetric rates greater than those of reactant consumption. If, for the sake of simplicity, it is assumed that most of the reaction is completed at the stoichiometric surface, the latter would behave as a plane source of hot


Fig. 9. Flow pattern in counterflow diffusion flame.
products. These products, being at the maximum temperature in the test space, are expanded and in trying to escape they make room for themselves by displacing both the fael and oxygen bearing jets. The situation is sketched in Fig. 9 . There develops a momentum barrier through which the bentonite particles in the gas streams can no longer penetrate. For flames on either side of thisstoichiometric Locus the products expand only against the jet whose momentum is smaller. Thus, if the flame is on the fuel side of stagnation point, the products expand against the oxygen bearing jet and vice versa. Particles can then traverse the flame.

This situation can now be compared with the theoretical model used by Spalding (17). In this it was assumed that the aerodynamics of the opposed jets was the same as that of two jets impinging on opposite sides of an infinitely thin flat plate and remains unaltered even when the flame is lit. It has been found by Le clerc (22) that for such a case the radial velocity $V_{r}$ in the impingement zone ( 0.1 D ) is given by

$$
\begin{equation*}
V_{r}=\frac{r}{D} U \tag{3.1}
\end{equation*}
$$

where $U$ is the initial velocity of the gas stream in a jet of diameter D.

In view of the experimental results cited above, it would appear that the model can be borne out experimentally if the flat plate is assumed to have a finite thickness. Le Clerc's equation (3.1) was


Plate9. P.T. photograpt of the flame analyped.
also found to be applicable to a first approxination, (section 9.3) in so far as $V_{r}$ was seen to be directly proportional to $r$.

The important conclusion for present purposes is that the mapping of flow velocities in all regions is possible; but demands a flame which does not coincide with the stagnation point. To avoid further complications, e.g. incomplete combustion, pyrolysis etc:, it was decided to work with a flame in which the fucl-oxygen ratio was less than stoichiometric. Accordingly; the following flow rates were chosen :

$$
\begin{aligned}
& \text { Ethylene }=5.7 \text { ccs. }) \\
& \mathrm{N}_{2}(\text { Tt. side })=75 \text { cos } . \\
& \text { Oxygen }=22.4 \text { ccs. }) \\
& \left.\mathrm{N}_{2}\left(\mathrm{O}_{2} \text { side }\right)=60 \text { cos. }\right)
\end{aligned}
$$

A typical particle track photograph of such a flame is shown in Plate (9).
3.6. Mieasurement of gas velocities.

To obtain the local velocities from the particle track photographs, it was necessary to determine their scaling factor. The need for this is immediatrly apparent by reference to Fig. 10 . If the camera is focused on the diameter $A B$ of the flame, it sees a region bounded as in the chord $C D$. The factor was determined by taking the photograph of a metal scale placed at $A B$, immediately after the flame was put out, without disturbing the camera setting.


Fig.10. Correction for camera position

$$
52 .
$$

The particle tracks were then enlarged approximately eleven times with the help of a Zeiss enlarger. To avoid errors due to distortion, only a very small central region, about two millimetres in radius around the axis of the burner was plotted on a sheet of (white) paper. Along with the particle tracks, the two matrices together with a few characteristic features on the photographs were traced out. These points of reference were used for correlating several particle track photographs of the same flame and thus obtaining the local velocities at as large a number of points as possible. The exact value of magnification could be found with the help of the scale photograph at the same setting of the enlarger and paper.

Two rectangular axes, parallel and perpendicular to the matrices, were then drawn on this enlargement. For determining the gas velocities along these axes, it seemed reasonable to assume each individual track to be linear. This implies that the local curvature of the flow lines was disregarded over the distance travelled during one light flash. This seemed justifiable in view of the fact that the maximum gas velocities were of the order of $5 \mathrm{cms} / \mathrm{sec}$. and therefore the length of the corresponding tracks (distance travelled in ten milliseconds) was about $5 \times 10^{-2} \mathrm{~cm}$.

A piece of graph paper was pasted on each enlargement with its axes parallel to the constructed axes. Each track was then
geometrically projected on the graph paper. The distance between the pencil marks was measured with the help of a vernier of least count .01 cm . Since each component of velocity $V_{z}$ and $V_{r}$ varied from zero to a maximum value, it scemed advisable to take two or more tracks at a time in regions where these components were small. Assuming that the tracing of particle tracks is not in error, this method of measurement does not give an accuracy of more than $.02 \mathrm{cms} / \mathrm{sec}$. This was further reduced by the finite thickness of pencil lines and the inevitable errors associated with the geometrical projection of small lengths along certain directions. If the difficulty of locating the tips of the tracks due to grain size of the plates is also taken into account, it will be reasonable to expect a scatter in the results. Nevertheless, if a large number of points are available (from several photographs), a best fitting curve can be easily drawn. It was found that cortain tracks gave very low values of local velocities. These were rejected because they were obviously trajectories of heavier particles.

It was found that there were regions on the plate where the particle tracks were not clearly visible because of the masking effect of light scattered from the matrices and the light emitted from the flame itself. These naturally occurred in the immediate vicinity of the matrices and the flame. It was necessary, therefore, to interpolate the velocities in the region occupied by the flame and

to restrict the determination of heat release rate up to points well away from the matrices. This is further discussed in Chapter

## 9.

Since the bentonite particles were falling at their terminal velocities in the gas flow, the vertical component $V_{z}$ of the local velocity found from particle track measurements needed a correction. This was calculated on the basis of Stoke's law. If $\sigma$ is the density of particles of radius $r$, then their terminal velocity $V_{T}$ in a medium of viscosity $\eta$ is given by

$$
V_{T}=\frac{2}{9} \mathrm{~g} \sigma \mathrm{r}^{2} / \eta
$$

where $g$ is the acceleration due to gravity. The mean diameter of particles, as found from a random sample collected on a microscope slide, was 4 microns. The medium was assumed to be pure nitrogen and its viscosity at different temperatures was calculated (23). Knowing the density of bentonite $s=2.7 \mathrm{gms} / \mathrm{cc}$., a graph (Fig.11) of free fall velocity against temperature could be drawn. It was found that the magnitude of the local terminal velocity was of the order of the experimental scatter in $V_{z}$. No corrections for this were therefore necessary.
3.7. Results for a flame.

Fig. (12) shows a plot of $V_{z}$ and $V_{r}$ against $z$ for $r=0.27$ It is seen that on either side of the flame, $V_{z}$ increases to a


maximum and then steeply falls off to zero, the plunge being more steep on the oxygen side. Moreover, it will be noticed that on the fuel side the rate of fall of $V_{z}$ with $z$ decreases at a certain point. This lies in the region where heat release rate becomes appreciable and can, therefore, be attributed to the increased axial velocity of the hot products pushing against the oxidant jet.
$V_{r}$, on the other hand, increases from zero to a maximum value. This maximun again 1 ies in the zone where most of the heat release is taking place and the products are radially displaced by the oxidant jet.

## CHAPTER 4.

## MEASUREEET OP HLAME TEPPERAYURE.

### 4.1. Mearing of Temperature.

Before sumarizing the methods used for the determination of temperature and its distribution in diffusion flemes, the meaning of temperature in the context of the present work must be cosidered. Extreme conditions prevail in flames; in the case of pre-mixed flames, for instance, the rate of rise of temperature may be as high as 188,000 degrees $/ \mathrm{sec}$. for a burning velocity of only $8.56 \mathrm{cms} / \mathrm{sec}$. ( 24 ) a value which would be excuded by $2-3$ orders of magnitude at more normel burning velocities. Under such conditions it might be exnected that the energy of a molecule is not equally distributed among the various degrees of freedom. If auch is the case, a "temperature" has to be assigned to each degree of freedom and the structure of the flame can be described only by a set of temperature profiles corresponding to each of these. It has however been calculated that the "uncertainty" in temperature due to disequilibrium, in the case of veryslow flames such as that cited above, is of the order of only $10^{-2}$ degrees. Further, in diifusion flames of the type under investigation, the maximum rate of rise of temperature will be shown to be above $90,000^{\circ} \mathrm{C} / \mathrm{sec}$. and that too outside the region where heat release takes place. Moreover, in the region of the reaction zone


Fig. 13. Rate of rise of temperature normal to a diffusion flame
$d T / d t$ falls very steeply (Fig. 13). It is therefore obvious that the conditions are far less extreme in the region of interest in a counterflow diffusion flame. Outside this region the rate of rise of temperature is still less than in the premixed example quoted above. It is therefore safe to assume that any uncertainty in temperature due to disequilibrium will be negligible for the flemes investigated. 4.2. Methods for Measuring Temperature.

A large number of methods ( 12 ) are available for the measurement of high temperatures prevailing in flames. These can be subdivided into four groops.

1. Radiation methods. e.g. Spectrum line reversal, Doppler shift.
2. Methods using solid bodies. e.g. thermocouples, mrticle tracks, Suction pyrometry.
3. Optical methods. e.g. deflection meppine, interferometry.
4. Fiethods bosed on other gas properties e.g. velocity of sound measurements, renge of a particles.

Eech of these methods has its particuler merits and demerits. The choice therefore depends upon the range of temperatures and temperature gradients to be measured. Other considerations such as rapidity of measurement, magnitude of correotions involved have also to be taken into account. On the other hand, if the magnitudes of temperature and its gradient present in a flame are only roughly known, it is


Fig. 14 Line Reversal Set up.
always safer to use several methods with overlapping ranges of suitability. It was, therefore, thought desirable to determine the temperature and its distribution in a counter-flow diffusion flame by different methods which were complementary. The following discussion shell therefore be confined only to those methods which were used in this investigation.
4.3. Rediation Methods.

The most commonly used method belonging to this group is the spectrum line reversal method due to Fery (25). This is based on the assumption that, on introducing certain metal vapours, such as sodium, lithiur, chromium, into a flame, statistical equilibrium is established between the electronic degrees of frcedom of the metal atoms and the fleme gases. The metal atoms thus absorb and emit at their characteristic wave lengths as thermal radiators. If the intensity of these radiations is compared, locally, with that of the corresponding radiations derived from a celibrated background source, the local temperature of the fleme can be determined.

Light from a strip-filament tungsten lamp is focused by a lens $I_{1}$ to give an image of the filament in the flene (Fig. 14 ). The second lens $L_{2}$ forms an inage of the larap and the fleme on the slit of a direct vision spectroscope. The stop $S$ is adjusted such thet the solid angle of the pencil of light from the flame is the same as that of light from the source. The resolving power of the spectroscope
should be such that on introducing sodium into the flane, the two Na D lines arc seperately visible.

If the current passing through the tungsten filament is increased, the metallic lines are seen to disappear against the background continuum at a critical velue. On one side of this, the lines appoar more bright than the corresponding region of the continuum, while on the other side they look darker. According to Kirchhoff's law, the lines stend out against the continuum when the flane temperature is higher than the brightness temperature of the lamp and vice versa. At the critical point, therefore, the two temperatures are the same.

The great sensitivity of the method is due to the repid veriation of light intensity with temperature. The brightness B of a black body whose temperature $T$ is the same as that of a vapour enitting at wave length $\lambda$ is given (26) by

$$
B_{\lambda}=\frac{C_{1}}{\lambda^{5}} e^{-C_{2} / \lambda T}
$$

where $C_{1}=4.99 \times 10^{-15}$ erg.cm., and $C_{2}=1.44 \mathrm{~cm} \cdot\left({ }^{\circ} \mathrm{C}_{0}\right)$.
Thus the brightiess of the metal radiation emitted from a flame increases exponentielly with the temperature of the fleme and the accuracy of the method, therefore, also increases with temperature. The nethod is howover not suitable if large temperature gradients are present. For any two temperatures $T_{1}$ and $T_{2}$

$$
\frac{B_{1}}{B_{2}}=e \frac{C_{2}}{\lambda}\left(\frac{1}{T_{2}}-\frac{1}{T_{1}}\right)
$$

If $T_{1}-T_{2}=100^{\circ} \mathrm{K}$, say,

$$
\frac{B_{1}}{B_{2}}=e \frac{100 C_{2}}{\lambda} \frac{1}{T_{1} T_{2}}
$$

As temperature increases, the ratio $B_{1} / B_{2}$ falls exponentially and the "resolving power" of the method decreases rapidy with the rise of temperature. Moreover, the transluminating light cone contains a large range of temperatures in the flame, if the gradient is steep. The limitations of the spectral line reversal method can therefore be summarised as follows:

1. In the regions of its greatest applicability, the method is unsultable for measuring steep temperature gradients.
2. On account of the poor enission below $1500^{\circ} \mathrm{K}$, the reversal method is of little use for the purposes of temperature measurements below this value.
3. Difficulties also arise when the flame gases are not in equilibriun or when the flame contains solid particles. The first two disadvantages confine the nethod to certain recions of the flane, in which its inhorent adventages can be exploited. Thus, if the maximun temperature in a fleme is in the neighbourhood of say $1600^{\circ} \mathrm{K}$ with an associated temperature gredient of $100^{\circ} \mathrm{K}$ per min., the maximum error involved in its measurement by this method will be about $50^{\circ} \mathrm{K}$. This can be further reduced by taking a very narrow pencil from the backeround source and introducing the metal only in the regions where the temperature is to be measured.

The method therefore seemed to be well suited to determining maximum temperatures in certain counter-flow diffusion flames. In this type of flames, temperature falls steeply on either side of a maximum value (section 9.1. Also, in the region of maximum temperature, the beam of light emerging from the flame remains almost undeviated (section 5.4 ) from its original path. If, therefore, the maximum temperature is comparatively low ( $\alpha 1600^{\circ} \mathrm{K}$ ) the method can be safely used. This can provide a check for the values determined by other methods. However, in the present work, its main purpose was to establish a reference point in the high temperature region of the test space so as to improve the accuracy of the optical methods. (section 4.5). 4.4. Thermocouples.

Of all the methods used for flame temperature measurements, thermocouples are at first sight the most convenient. They have therefore been used by a large number of investigators. (27,28,29,30). However, great care is needed if it is desired to obtain rellable results. Thus Leah and Carpenter (27) recorded higher temperatures with uncoated Pt-Pt-Rh thermocouples, Friedman (28) using bare thermocouples observed a discontinuous jump of temperature in preflame gases and attributed this to catalysis. This was also observed by Kaskan (29). Both these workers have recommended the use of a thin protective coating of silica, which minimises the catalytic reactions on thermocouple wires.

Even when coated wires are used, the temperature measured by a thermocouple is still that of the junction. The gas temperature is higher by a certain amount $\Delta T$. The difference can be calculated by writing the heat balance (31) equation between flame gases and the thermocouple. The most significant factors in this equation are :
(i) heat transfer to the wire by convection;
(ii) heat lost by the wire by radiation.

The other factors in the heat balance equation are either negligible or canbe made negligible in laboratory scale experiments. (For example, thermal conduction along leads can be minimised by stretching the couple along an isotherm).

Thus

$$
\begin{equation*}
h \triangle T A=\sigma\left(T_{W}^{4}-T_{0}^{4}\right) A \tag{4.1}
\end{equation*}
$$

where

$$
h=\text { heat transfer coefficient }
$$

$$
\Leftrightarrow=\text { emissivity of the wire }
$$

$\overline{0}=$ Stefan's constant
$A=$ Area over which heat transfer takes place. $T_{0}=$ Temperature ( ${ }^{\circ} \mathrm{K}$ ) of the surface, which the thermocouple sees.

The values of emissivity given by Kaskan for a coated and uncoated ( $\mathrm{Pt}-\mathrm{Pt}-\mathrm{Rh}$ ) thermocouple are respectively 0.22 and 0.16 . The heat transfer coefficient can be obtained from a knowledge of the Nusselt number $N u$ and Reynold's number Re. Thus :

$$
\begin{equation*}
h=\frac{K}{D} \quad N u=\frac{K}{D} f(R e) \tag{4.2}
\end{equation*}
$$

The function $\mathrm{f}(\mathrm{Re})$ for obtaining the corresponding Nusselt's number has been plotted by McAdams (31). Thus, knowing the wire diameter, thermal conductivity of the flame gases and the Reynold's number of flow, $h$ can be calculated. Combining equation (4.1) and (4.2) :

$$
\Delta I=\frac{G \theta\left(T_{W}^{4}-T_{o}^{4}\right) D}{K f(\mathrm{Re})}
$$

To a first approximation, the magnitidue of the correction is therefore directly proportional to the wire diameter. To minimise this, very fine thermocouples have been used (29).

The flame temperature determined by a thermocouple even after applying this correction may be in error. These errors arise from factors such as conduction down leads, and "wake" effects. It is not difficult to take the necessary precautions to minimise these errors but they do make the method more cumbersome.

Thermocouples for this kind of work are usually made of extremely fine wires (one or two thou.) and are therefore extremely delicate and fragile. Their use for the determination of temperature distribution in flames tends to be an exercise in patience. On the other hand, they are ideal for determining temperatures at one or two placesespecially in the regions where the reaction has gone to completion so that catalysis becomes unimportant.

It was, therefore, decided to measure the final flame temperature by this method, to provide a check for the value determined by the spectrum line reversal method (Section 4.3).
4.5. Optical Methods

Every thermometer measures the temperature of its working substance. A group of methods for determining flame temperatures, in which no discrepancy between flame gases and working substance ean arise, is therefore based on measuring some property of the flame gases which themselves form the "working substance" of the "thermometer". One such property is density of the gases, which varies with temperature according to the law

$$
\begin{equation*}
\rho T=\text { constant } \tag{4.3}
\end{equation*}
$$

Optical methods utilise the dependence of refractive index $n$ of the flame-gases on their density and hence absolute temperature. Thus, Gladstone and Dale's law for a gas :

$$
\begin{equation*}
\frac{n-1}{\rho}=\text { constt. } \tag{4.4}
\end{equation*}
$$

can be combined with equation (4.3) to give :

$$
\begin{equation*}
n-1=\delta=\delta_{0} T_{0} / T \tag{4.5}
\end{equation*}
$$

where the subscript zero refers to standard conditions, say S.T.P. Equation (4.5)is, however, valid under conditions of constant pressure and, in the absence of any change in composition, dissociation and ionisation. If temperature is to be determined from measured refractive indices, such effects must be corrected for.

The determination of refractive index fields is usually carried out by transluminating the flame by a plane wavefront of monochromatic light. The magnitude of optical path gradient (which is the product of
refractive index gradient and geometric path length in the flame - if the latter is constant) determines the steepness of the perturbations induced in such a wavefront by the test space. Two kinds of approach are available for determining the topography of the $\quad$ merging wavefront. The methods of geometric optics - notably mapping the angles of deflection - are based on the concept of rays orthogonal to the emerging wavefront. They therefore record the slope of perturbations on the front and are most sensitive for large gradients, irrespective of the terminal values.

The methods of physical optics - notably interferometry -
"shear" the wavefront, usually with an unperturbed one, producing fringes at fixed phase increments. They therefore record the absolute heights of the perturbations in the form of contour maps and are less suited to measuring steep variations, both because of consequent crowding of fringes and because of deflection effects which here become aberrations. In the analysis of "flat" pre-mixed flames, deflection methods therefore become accurate. Interferometry has recently been successfully used for a flat flame whose flat portion was relatively small.

The great advantage of optical methods lies in their simplicity and versatility. Roreover one photograph is sufficient to provide full information regarding temperature distribution in a flame. The inevitable disadvantage in these methods is their decreased sensitivity at
high temperatures. Equation (4.5) on differentiation gives :

$$
\begin{equation*}
d \delta=-\delta_{0} T \circ \frac{d T}{T} \tag{4,6}
\end{equation*}
$$

The change in $\delta$ is therefore seen to be not only directly proportional to the change in temperature producing it but also inversely proportional to the square of the temperature. As temperature increases, the accompanying change in $\delta$ falls off rapidly and optical methods become less and less sensitive. Further analysis indicates that the fractional error in $\delta, \dot{E}_{\delta}$ is independent of temperature. Thus, dividing Equation ( 4.6 by Equation ( 4.5 :-

$$
\epsilon_{\delta}=\frac{d \delta}{\delta}=-\frac{d T}{T}=-\sigma_{T}
$$

In other words, the decreased accuracy at high temperatures is only due to smaller magnitudes of $\delta$ at these temperatures.

In deflection mapping studies, the experimentally determined quantity is the integral along the ray path of the refractive index gradient at right angles to it. To obtain the distribution of refractive index, a numerical integration has to be performed with respect to some known state. If this is at lower temperature, the values of $\delta$ at high temperatures are obtained by subtracting one large quantity from another. On the other hand, if the reference state is chosen at say the maximum temporature attained in the flame, (which is calculated or measured by another method) this disadvantage can be turned into an advantage and an extremely accurate temperature profile can be obtained.

In the case of interferometry, no such integration is involved. The principle, however, is the same in that $\delta$ determined at the high temperatures becomes excessively dependent on exact knowledge of the end corrections - an error of x in the cold distance being equivalent to $\frac{T}{T} \times$ in the flame. Pegging the distribution at the hot end amounts to using this large sensitivity to "cold distance" to effect corrections throughout the distribution. 4.6. Conclusions.

From the foregoing discussion it is apparent that optical methods furnish the most detailed and convenient way of finding the temperature distribution in flames. But, in view of their decreased sensitivity at high temperatures, it desirable to have a reference point in the region of maximum temperature.

The general line of approach was therefore to obtain the distribution of refractive index or its gradient in the test space and then to translate it into temperature distribution with the help of reference points (in the high temperature region) found by thermocouple andor spectrum line reversal method.

## CHAPTER 5.

## REFRACTIVE INDEX FISLD OF FLAT COUNTERCURPENY DIFFUSION FLANES.

5.1. Choice of Technique.

The theory of diffusion flames suggests thet so long as blow out conditions are not approached, relatively small refractice index gradients are to be expected. On the other hand, large geometrio path lengths are again advisable, to guard against pre-dominance of edge effects. It therefore seemed prudent to approach the problem without en "e priori" choice of only one method. The complenentary nature of the technques suggested, on the contrary, that one approach should be perfected from each, the deflection-mapping and the interferometric principles. This seemed desirable in view of the large range of conditions (e.g. flow velocities) that might be encountered and because it seemed quite possible that different approaches might be required even for different regions within the sane flame. 5.2. Deflection mapping
a) Principle:

In previous deflection mapping studies of pre-mixed flames (3) the distorted shadows or ineges of slits placed before and inclined at $45^{\circ}$ to the flame were recorded some distance beyond the fleme. This method is convenient and accurate for the large angles of deflection caused by the large optical path gradients across these flemes. The optical system is shown in Figure 15 . Light fron the mercury vapour


Fig. 16 Coordinate System
lamp is focused by the condenser $C$ on to a pin hole of diameter 'd' placed at the focus of the convex lens $I$ of long focal length $f$. The velues of 'd' and 'f' are so arranged that the angular departure from perallelism $d / f$ is small. (In the present work $d=.018$ cm. and $f=100 \mathrm{cms}$.$) . A grid, G$ of inclined slits is placed before the flame F while the shadow of these slite is recorded at $P$ et a distence $D$ from the flame.
b) Theory:

Whenever a ray of light trevels through a refrective indea field it is deviated from its peth and its locel radius of curvature is given by (19)

$$
\begin{equation*}
\frac{I}{\mathrm{R}}=-\frac{\operatorname{grad} n}{\mathrm{n}} \sin \phi \tag{5.1}
\end{equation*}
$$

where $n$ is the locel refractive index whose gradient makes an angle $\phi$ with the direction of the ray.

For expressine 'R' in tems of local co-ordinates, it is necessary to choose 2 freme of reference. A one dimensional refractive index field will be considered for the sake of simplicity. A three dinensionel cartesien system of co-ordinates Fig. (16) having the x-axis parallel to the incident beari end the Z-axis parallel to the dircction of grad $n$ is therefore assumed. The radius of curvature of the ray at any point, in this frome of reference, is

$$
\begin{equation*}
\mathrm{H}=-\sqrt{1}+\left(\frac{d z}{d x}\right)^{2} / \frac{d^{2} a}{d x^{2}} \tag{5.2}
\end{equation*}
$$

Also

$$
\operatorname{Erad} n=\frac{d n}{d z} \text { and } \phi=\frac{\pi}{2}
$$

Combining Equations (5.1) and (5.2) :

$$
\frac{d^{2} z}{d x^{2}}=\left[1+\left(\frac{d z}{z}\right)^{2}\right]^{\frac{1}{2}} \frac{1}{n} \frac{d n}{d z}
$$

In the case of flame gases $n \geq 1$ and the error involved in neglecting $\mathrm{dz} / \mathrm{dx}$ as compared to unity is insignificant (19). Thus

$$
\begin{equation*}
\frac{\partial^{2} z}{d x^{2}}=-\frac{d n}{d z} \tag{5.4}
\end{equation*}
$$

which on integration yields

$$
\left|\frac{d z}{d x}\right|_{1}^{2}=-\int_{1}^{2} \frac{d n}{d z} d x
$$

If the incident ray is parallel to surfaces of constant $n$,

$$
\left\lceil\left.\frac{d z}{d x}\right|_{1}=0\right.
$$

for the ray where it caters the flame say $2 i t z=z_{0}$ (Fig. 16 ).
Fence the deflection $\theta$ produced by the flame is

$$
\begin{equation*}
\theta=\tan \theta=\left(\frac{d z}{d x}\right)_{2}=-\int_{0}^{x} \frac{d n}{d z} d x . \tag{5.5}
\end{equation*}
$$

where ${ }^{\prime} \mathrm{x}$ ' is the distance over which the refractive index field extends and the integral is to be performed, along the ray. For a two dimensional ficld

$$
\left.\begin{array}{rl}
\theta_{y} & =-\int_{0}^{x} \frac{\partial n}{\partial y} d x \\
\theta_{z} & =-\int_{0}^{x} \frac{\partial n}{\partial z} d x  \tag{5.6}\\
\text { and } \quad \theta & =\left(\theta_{y}^{2}+\theta_{z}^{2}\right)^{\frac{1}{z}}
\end{array}\right\}
$$

c) Application:

For a determination of the local refractive indew gradients in a flame the only factors that need be know are its geometry and the corresponding deflections. If the distribution of refractive index in tho flame is requircd, it is also necessary to know a reference state in the test space for the purpose of integrating the grad $n$ curve, graphically or otherwise.

The deflections are obtained from the distorted shadows of inclined slits. If these are recorded at a distance $D$ from the test space

$$
\begin{equation*}
\theta=\frac{S}{D} \tag{5.7}
\end{equation*}
$$

where $S$ is the local displacoment produced by the flome perollel to the refractive index gradient being determined. This displecement is elways meesured with rospect to the undeviated shadow of the slits which therefore should also be know or construed. Thus, for a one dimensional fleme

$$
\begin{equation*}
\frac{S}{D}=-\int_{0}^{x} \frac{\ln }{d z} \mathrm{dx} \tag{5.8}
\end{equation*}
$$

If, to a first approximotion, the path of ray is assumed to be linear

$$
\frac{d n}{d z}=-\frac{S}{D} \cdot \frac{I}{x}
$$

This is however not strictly correct. The path of light will bend towerds the colder parts of the fleme and sheill not be linear.
d) Parobolic correction:

If this bending is taken into account, integration of Equation (5.8) is no longer a simple matter. The method followed is usually that of using successive approximetions. The first is based on the assumption that the rofractive index gradient $\mathrm{dn} / \mathrm{dz}$ along a ray path remains the same as its value, say $n^{\prime}$, at $x=0$ where the ray enters the flame. In this case

$$
\theta \leq \operatorname{sen} \theta=\frac{d z}{d z}=-\int_{0}^{x} n^{\prime} d x=-n^{\prime} x
$$

and the equation of the ray path becomes

$$
\begin{equation*}
z=-\frac{1}{2} n \cdot x^{2}+z_{0} \tag{5.9}
\end{equation*}
$$

This parabolic path can now be used for celculating the second approximation and the process continued till further approximations become inconsequential. The rapidity of convergence of the series (19) depends upon the phenomenon being andysod but generolly not more then two epproximations are needed.
e) Limitations:

The deflection mapping technique in this form suffers frem a seriovs limitation. If the method is to be extended to very much smaller opticai poth gredients, incecurcies orise beceuse of diffrection at the slits. Every critcrion on the diffraction pattern which could be used to read the record, such as the central diffraction maximum, is defined by a given angle subtended at the slit. Thus the sensitivity of the method cennot be incriased beyond a certain
amount by increesing the displacement on the record per unit ongle of deflection (e.e. by increasing the distence between test space and receptor). The widh of the central diffrection meximum, for instance, will increase proportionately and by remaining a constant fraction of the displacement, will plece an absolute linit on sensitivity. This difficulty is further aggroveted if not only sensitivity but also resolution in the test spece is to be increased. This can be cohieved only by decreasing slit wiath and thereby inoreasing the diffrection induced indeterminecy on the rocord.
5.3. Use of "helf wave steps"

If deflection mopping were to be extrapolated to opticol path cradients very much smaller than those occurring in flat premixed. flames, wn alternative method of "merking the wevefront" would be edvantageous. The principle of the helf-wave step (32) seemed readily edapteble to present requirements. Parallel strips of macnesium fluoride film, half a wave length thick, were evanorated onto an opticaliy flat glass plete. The distonces betweer adjecent strips werc equel to ecch other and to the width of the strips. The equidistont stops so produced were used in the some manner as inclined slits in the studics of premixed flemes. At every stop, the wavefront energing on ond siac of the edge is $\pi$ out of phasc with the wave adiacent/front. The destructive interference, which takos plece along the surface containing the step and perpendicular to the gless plate, results in a sharp ciark linc on a screen or yhotogrephic plate so long as the letter is not too for renoved from the halfweve step.


Plate 10. Half wave steps and slits



Plate il. Deflection mapping of Counter flow diffusion flame.


The "resolving power" of this device is compered with thet of slits in Plate 10. Both were placed in an cocurately parallel beem of light and the shedow rocorded at a distance of 165 ms. The wiath of the slits show lic between . 049 end .125 cms. and the wave longth of light was 5461 A. U. It will be seen that e very aonsideroble improvement in acourecy rosults from the use of a grid of half-wave stope.
5.4. Inferonces from deflection mapoine studies.

Piate 11 shows the distorted pottom of the half-wave grid after passage of the bean through the flat diffusion fleme. Large deflections are ouserved in the immediate vicinity of the burnor mouths. These are also responsible for the apparent incresse in the distance betweon the bumer nouths. This property of the deflection field of such diffusion flanes has two undesireble consequences. Firstly, the cangles of deflection are seen to fall to small magnitudes in the contrel zones winch sue likely to prove most interesting from the point of view of the flaw's mechenism. Secondly, becaise the refractive index grocionts extend right to the burner mouths, the undistorted shepe of the grid cemot be asccitaincd readily from the distortod pottern. In the pro-mixed flame, the refrective indox grodiont and hence deflection fells to zero on either side of the recction zone, weli before eny solid boundery obscures the Iight beam. Consequently, the undisturbed pattern on be construed (24) on the record by interpolation between
83.
the undeflected extremities , without recuiring a superimposed "blank". The difficulty is aggravated, in the case of diffusion flanes by the necessity of recording the direction, as well as the magnitude of deflection. The observed deflection pattern thus sugeests that an interferogram of the diffusion flame would be nore informative and in subsequent work interferograms were used for the main sequence of neasurements leading to temperature and heat release profiles.

## CHAPTER 6.

DEVELOPMINT OF INTERFEROMETRIC METHOD.

### 6.1. Choice of Interferometer

An interferometer for use in combustion research must have certain special features. Since the phenomena being studied are at high temperatures, the two beams should be appreciably separated. In the special case of flames suitable for optical analysis, the associated optical path gradients are steep and, therefore, the beam passing through the test space undergoes large deflections (Equation 5.8). It is on account of this that the layout of the interferometer must be such as to allow the beam to pass only once through the test space. If, in addition, the optical system allows the test space to be focused on a receptor, the effects of deflections can to a very large extent be minimised and sometimes eliminated. Furthermore, since it is necessary to have all rays parallel to a one-dimensional flame, the beams should be collimated in all directions (i.e, the effective source must approximate to a point, not a line).

These considerations narrow the field very considerably. The four mirror Mach-Zehnder ( 33 ) interferometer is the one most commonly used for this kind of work. Its disadvantages are its very high initial cost and the difficulty of its adjustment. The latter is inherent in any instrument based on beam reflection. Thus, for mirrors 15 cm . in extent and a wave length of $5 \times 10^{-5} \mathrm{~cm}$., one "involuntary" fringe will appear for an angular misalignment of
$8 \times 10^{-7}$ radians in each mirror.
An interferometer based on much the same geometrical layout but employing four diffraction gratings (34) instead of mirrors, is free from these objections; it is both insensitive to misalignment and remarkably inexpensive. It is, however, wasteful of light and has hitherto been used only for non-luminous phenomena. Although the counter-flow diffusion flame was steady enough to permit extended exposure times, it was thought that the range of interest might include flames of appreciable luminosity and this interferometer was therefore not used.

The interferometer which appeared most suitable is that discovered by Kraushaar (35) during his attempts to extend a "RonchiSchlieren" system to gratings of greater line frequency. It has been shown (19) that this interferometer is insensitive to misalignment. It is quite inexpensive if two long focus schlieren mirrors are already available. It is less wasteful of light than the four-grating interferometer though, of course, more so than the Mach-Zehnder interferometer.
6.2. Principle and Theory of Two-grating Interferometer

In this interferometer, the beam is split and recombined at points of focus of two schlieren mirrors by two fragments of a diffraction grating. The principle can best be illustrated by reference to lenses instead of mirrors 88 in Fig.(17), where $E$ is the effective point


Fig. 17 a. Cross-section of beams.
source. The lens $D$ focuses the cone of light at a diffraction grating B placed at the focus of lens $A$. This grating will diffract the light in various orders. It is arranged that all but two orders are lost to the system. If now a stop is placed so as to cut off the lower half of the pencil incident at $B$, the zero orders of the rays in the un-masked half cone will fill the lower half of $A$, while if the grating constant is chosen correctly, the first orders will fill the upper half. Thus the lens A shall produce two parallel beams derived from the same source. They are recombined by another identical combination of lens and grating and again several orders are obtained due to diffraction at the second grating B'. The optical system therefore produces two coherent beams and recombines them after the traversal of the medium on the right of $\mathrm{B}^{\prime}$, thereby producing interference fringes.

The choice of the grating is dictated by the f-number of the lens $A$ or the equivalent schlieren mirror. The fringes are only obtained if the first order of the ray 1 coincides with the zero order of the ray 2; if this is so, the first order of ray 2 follows the path of ray 3. In view of the fact that the grating is placed at the focus of $A$, the angle of diffraction $\theta$ for normal incidence is given by :

$$
\begin{equation*}
\theta=\sin ^{-1}\left(\frac{a}{f}\right) \tag{6.1}
\end{equation*}
$$

where $2 a$ is the aperture and $f$ the focal length of the lens:



Incident on. and emergent from $A$


After recombination by $A^{\prime}$ and $B^{\prime}$

Fig 18b. Cross-section of beams.


Fig. 19. Formation of fringes

If the wave length of light is $\lambda$, the grating spacing $d$ is given by :

$$
\begin{equation*}
\alpha=\lambda f / a \tag{6.2}
\end{equation*}
$$

Thus, for a schlieren mirror of focal length 8 ft . and aperture 8 inches, the grating constant $1 / \mathrm{d}$ should be about 1940 lines per inch if the green line of mercury $\lambda=5461 \mathrm{~A}^{\circ}$ is to be used. This of course allows the utilisation of all the available working space, which is as thown in Fig. (17a).

It is, however, not necessary to use the stop. Its purpose can be accomplished simply by turning the principal ray $E B$ through an angle $\sin ^{-1}(a / 2 f)$. Such a system has been shown in Fig. (18). The working space with this arrangement is circular, having a radius half that of the schlieren lens or mirror and has been shown in Fig. (18).

Under ideal conditions, the two grating interferometer is at infinite fringe condition. If the grating $B$ ' is displaced along the optic axis in its own plane, linear fringes are obtained (36). The fringe spacing $q$ for a displacement $\Delta x$ has been calculated (19), When the grating $B^{\prime}$ is at the focus of $A^{\prime}$ (Fig. 19) interference will tako place, within the half cone bounded by the rays 4 and 6 , between the first orders of rays bounded by 2 and 3 and the zero orders of rays bounded by 1 and 2. If it is displaced by a distance $A x$ to the position $\mathbf{B}^{\prime \prime}$, the latter remain unchanged but the bundle between 2 and 3 is displaced before it strikes the grating. Its first orders will now lie


Plate 12. Mount for gratung and mirror
between the rays 5 and 7 originating from a virtual focus displaced laterally through a distance $A$. This means that the two plane wavefront ahead of $A^{\prime}$ are no longer parallel but subtend an angle ( $\Delta \mathrm{y} / \mathrm{f}$ ) between them. This angle is given by

$$
\begin{equation*}
\frac{y}{f}=\frac{\lambda}{q} \tag{6.3}
\end{equation*}
$$

But

$$
\begin{equation*}
\Delta y=\Delta x \tan \theta \tag{6.4}
\end{equation*}
$$

Combining Equations (6.3), (6.4) and (6.1) the fringe spacing $q$ is seen to be

$$
\begin{equation*}
q=\frac{f a}{\alpha x}\left(1-\frac{\lambda^{2}}{d^{2}}\right)^{\frac{1}{2}} \tag{6.5}
\end{equation*}
$$

It is seen from this equation that, to a first approximation, the fringe spacing is independent of wave length. This is a unique property of 2-grating interferometer. On account of this, fringes will be obtained even with composite light, a fact which has been experimentally confirmed (36).

A closer examination of Equation (6.5) however shows that on account of chromatic aberration (only the lone focus components being lenses) $\Delta x$ itself is a function of wave length but this is only a second order effect, so long as ( $\mathrm{a} / \mathrm{f}$ ) is stall.
6.3. Sensitivity to misalignment.

As a first approximation Equation (6.5) can be written as

$$
\begin{equation*}
\mathrm{q}=\frac{\mathrm{fa}}{\mathrm{x}} \tag{6.6}
\end{equation*}
$$

which when combined with Equation (6.2) yields

$$
\begin{equation*}
q=\frac{f \lambda}{\Delta x} \frac{f}{a}=f^{2} \lambda / \varepsilon(\Delta x) \tag{6.7}
\end{equation*}
$$

Thus, for a given displacement of $\mathrm{B}^{\prime}$ from the infinite fringe condition, the fringe spacing $\mathbf{q}$ is seen to be proportional to $f^{2} / a$. Hence, the greater this ratio, the easier it is to set the interferometer at infinite fringe condition. Taking $f=8 \mathrm{ft} ., \mathrm{a}=4$ inch, $\Delta \mathrm{x}=1 \mathrm{~cm}$. and $\lambda=5461 A^{\circ}, q$ is seen to be about 3 millimetres and the number of fringes will therefore be approximately 3 per cm. It is, therefore, obvious that the greater the focel length of the schlieren mirrors, the easier it is to set the interferometer at infinite fringe condition.

### 6.4. Construction of the interferometer.

The optical system actually employed is shown in Fig. (20). $A$ and $A^{\prime}$ are two schlieren mirrors of 8 ft . focal length and 8 in. aperture. These were provided with tangent screws which could rotate them about a horizontal and a vertical axis. They were mounted on heavy steel plates provided with three levelling screws at a distance of about twenty-four feet from each other. The mirrors were front surface polished and the manufacturers claim an accuracy of $\lambda / 10$ across the whole field.

The optical system giving a focused image of the source at B consisted of a high pressure mercury vapour are, a condenser, a pin hole of about two millimetres diameter and another condenser $D$


Fug. 20 Layput of 2-grating interferemeter
G-M.V.arc.
F-Condenser
E=Pinhode
$C 8 C^{\prime}{ }^{D}$ - Variable aperture lins.
$B 8, B^{\prime}$ - Plane transmission grating 2000 l.p.i.
$A B A^{\prime}$ - Schlieren mirrors $f=243 \mathrm{cms}$. $2 a=20 \mathrm{cins}$
which was an aero-acta lens of variable aperture and focal length $\ddagger 78$ mms.

The gratings $b$ and $B^{\prime}$ were two pieces, each about $2 \mathrm{cms} . \times 3.5$ cms. cut from a comercial diffraction grating having 2000 lines per inch. These were mounted on a franework, shown in Plate ( 12 ), and each provided with two pairs of three levelling screws which could rotate the plane of the grating about a vertical and a horizontal axis. To prevent any demage to the gratings, the pieces were sandwiched between foam rubber rectangular frames and then slipped carefully in the rectangular recess between the front and the back pieces of the grating mounts. Each grating was thus held against one set of levelling screws by the spring action of foan rubber. In addition, each grating mount could be moved longitudinally along the path of light by a micrometer screw.

The plane mirror strips C and C' were front surface silvered and had roughly the same dimensions as the grating pieces. Their mounts, shown in Plate ( 12 ), had the same general construction as the grating mounts except that instead of holding the mirror in a rectangular recess, they were mounted permanently against a rectangular back. The camera $H$ was, during preliminary work, just a camera back with bellows.
6.5. Preliminary setting up of the interferometer.

The general scheme of aetting up is shown in Fig. (20). The mercury vapour lamp, the condenser $F$, the pin hole and condenser $D$
werc mounted on a separate optical bench, in that order. These were adjusted to obtain a focused image of the piri hole $E$ on the grating $B$ (via the plane mirror strip $C$ mounted on the same optical bench as $B$ ), which was approximately placed in the focal plane of mirror $A$ along the optic axis. The grating was then repleced by a pin hole and the mirror A was positioned so that the circular patch of light was fomed roughly in its centre and the steel plate on which the mirror was held was made horizontal using a spirit level. A plane mirror made vertical with the help of a plumb line was then placed in the path of the reflected light beyond the plane mirror strip C. A circular patoh of light with a shedow of the strip could be seen on the plane mirror. The tangent screws of A wore manipulated so as to obtain the shadow approximately in the middle of the circular patch of light. The pin hole (mounted in place of B) was moved slowly up and dow the opticel bench so that its focused image produced by the plane mirror and schlieren mirror combination was fomed in its plane. The condenser D was now moved so as to overlap the focal planes of the two halves of the optical system. Under these conditions, a focused imege of the original pin hole E wes formed in its own plane. This source and its image were made coincident by adjusting the levelling screws of the plane mirror strip. In this manner a horizontal collinated beam could be obtained.

The plane mirror was removed and the collimated bean whs allowed to fall on the mirror $A^{\prime}$ which was kept on a levelled stecl
plate so that the circular patch was again formed in its centre. It was then adjusted with the help of the two tangent screws in such a way that the image obtained by two reflections lay at the centre of the circular patch incident on $A^{\prime}$.

The plane mirror strip was tilted through a small angle so as to shift the patch incident on $A$ to one side of its centre. The aperture of $D$ was adjusted to give a circular patch of diameter equal to half the aperture of $A$. The grating $B$ was then replaced with the glass side away from the schlieren mirror and two orders occupying symmetrical halves of $A$ were at once obtained.

The other grating-mirror combination was then placed with the grating in the focal plane of $A^{\prime}$ and its glass side away from it. The mirror strip was tilted at a convenient angle to observe the fringes at a distance from the interferometer.

The fringes were not usually seen at the first attempt but a slight manipulation of the levelling screws of the grating $B^{\prime}$ brought them into existence. It was now just a question of improving their visibility which was maximum when the lines of $\mathrm{B}^{\prime}$ were made parallel with those of $B$. These fringes were obtained with composite light. A photograph of the fringes with a mercury green filter is shown in plate (13).

With practice, the entire optical system could be dismantled and set up again in less than half an hour. The visibility of the fringes was not significantly altered even after the pin hole E was removed.


Plate 13. Fringes witt 2-grating
interferometer

The adjustment for infinite fringe condition was fairly simple. The grating $B^{\prime}$ was first moved by hand to obtain about two to three fringes and then, using the micrometer screw, to reduce the number of fringes to a minimum which was one. This last fringe always floated around in the field of view and was attributed to convection currents, especially in view of the large separation between the mirrors $A$ and $A^{\prime}$. It might be mentioned that the grating displacement involved in going from 10 fringes $/ \mathrm{cm}$. to the infinite fringe condition was approximately 2.5 cms .
6.6. Interferogram of a diffusion flame.

The interferometer, having been adjusted for use, the burner was introduced in one of the beams at a distance of about four feet from $A$ (position I) in such a way that the order diverging from $B$ just cleared the burner. The fringe pattern when the flame was lit was not resolvable by the unaided eye unlike that in the absence of flame. An eyepiece was therefore used to view it. This was placed in the vicinity of the plane of the image of the burner formed by A'. It was observed that as the eye piece was moved up and down along the optic axis, the visibility of the fringes across the test space did not remain constant. The fringes in the centre, where the flame lay, remained equally visible over a certain distance about ten to fifteen centimetres. On one side of this range the fringes in one half of the combustion zone were more visible than
in the other. The condition was reversed on the other side of the midpoint. In addition to this, it was seen that as the eyepiece was moved, more and more fringes appeared till they became blurred in the immediate vicinity of the matrix.

This effect is obviously caused by the unequal deflections which the transluminating light beam experiences on the fuel and oxidant sides of the flame. It was noticed that in consequence of these deflections the "point" focus on $B$ ' spreads itself into a vertical line having its greatest intensity at the undeflected centre. When one half of this'line focus" was maked off, the fringes disappeared from the corresponding half of the interferogram. This effect is common to all test objects of steep refractive index gradients and is particularly noticeable for the flames under discussion where it occurs on either side of the reaction zone as was noticed already in the deflection mapping studies (Section 5.4 ) where on account of the large gradients near the two matrices the gap between them was apparently increased.

It can be shown (Appendix B) that all the rays deflected by the flame appear to come from its centre. In order to photograph the interferogram, it was therefore necessary to put the photographic plate in a plane conjugate with the axial plane of the burner, which was normal to the transluminating light. When this is arranged, the rays originating, or passing through, from the various points on this


Plate 14. Interferogram of diffusion flame


Plate 15. Effect of defocuoing


plane will terminate on their conjugate points in the image plane and the effects of deflection can thus be eliminated.

The procedure for taking a photograph of the interferogram was, therefore, as follows:

The fringes were received on a ground glass screen and viewed through an cyepiece. The screen was moved forwards and backwards till all the 'shadows" of the flame disappeared from the ficld of view. This was by no means an easy task on account of the large object range (37) of the mirror $A^{\prime}\left(\frac{a}{f}=\frac{1}{2^{4}}\right)$ and the disappearance of the shadow caused by deflection was the most sensitive criterion. Once the pasition of best focus was obtained a photograph could be taken. In preliminary work, H.P.S. plates were used. These were developed in promicrol developer. One such photograph is shown in Plate (14), while Plate (15) shows the effects of defocusing on either side of the position of focus.
6.7. Preliminary experiment.

It is seen from these photographs that the refractive index field of such diffusion flames extends far beyond the outer matrices. In the position where the burner was located so far there was a chance of the light incident on A passing through this field even before collimation. It was, therefore, thought advisable to place the burner at a different position along the collimated beam. Aecordingly, the burner was located midway between the two mirrors in the position II (Fig. 20). Since the object distance from $A^{\prime}$ was now reduced
it was found necessary to introduce a large focus lens, in fact a telecope objective $f=100 \mathrm{cms}$. between the plane mirror strip $C^{\prime}$ and the photographic plate. In this position, however, another difficulty was encountered, the reason for which was not immediately apparent. It was seen that the complete interferogram could not be obtained in one order. The fringes formed between the burner matrices were sharp in one order while those due to the edge effect were sharp in the complementary order. It was therefore decided to photograph the two orders simultaneously and then combine the two for the purposes of mapping the temperature distribution in a flame.

It was also found, after a number of photographic platedeveloper combinations had been tried, that Kodak 0.250 plates developed in D.19b gave the best results with mercury green light.

The flame portrayed in the interferogram in Plate ( 16 ) was of ethylene, oxygen and nitrogen in stoichiometric proportions. The approach folume flow rates were equal to each other and to $82.5 \mathrm{ccs} / \mathrm{sec}$. at S.T.P. Thus the approach molar compositions were $\mathrm{C}_{2} \mathrm{H}_{4}+10 \mathrm{~N}_{2}$ and $30_{2}+8 N_{2}$. The mean approach tomperatures were $75.6^{\circ} \mathrm{C}$. (top matrix) and $82.5^{\circ} \mathrm{C}$. (bottom matrix).
6.8. Analysis of the interferogram.

The analysis of this interferogram was carried out, more as an exercise, to obtain some indication of the general nature of the

Plate 16. Interferogram analysed for prelimmary work

temperature distribution and to find the relative importance of the various terms involved. For this purpose the flame was assumed to be axi-symmetric and circular. The test space was first divided into ten "slices" by planes parallel to the burner mouths. Each slice was then divided into twenty-five annular rings (Fig21 ) thus giving 250 elements within each of which the refractive index was, in the first instance, assumed to be constant. The outermost annulus was so constructed that the outermost fringe lay in its middle. Each slice was now treated independently by a method of numerical analysis: the optical path difference was deduced using a tenfold magnification of the interferogram, the magnification itself being determined from a knowledge of the radius of the brass tube whose edge was visible on the interferogram. The optical path difference which in the present case was the fringe order (because the interferometer was set for the infinite fringe condition) was taken as a weighted mean of the fringe arder in each annular slice. The optical path difference deduced from the interferogram for the outernost annulus was used to deduce the mean refractive index of that element. Considering next the beam which traverses the first and second, but not the third zone, the now calculable optical path due to the first zone was subtracted from the value recorded by the interferogram, to yield the optical path and hence the refractive index within the second annulus. This process was continued until the axis was reached.


Fug 21. Construction of zones

Thus, if $p_{n}$ represents the fringe order in the $n t h$ zone, the geometrical path lengh $x j$ which a bean traverses in the $j$ th zone is given by

$$
\begin{equation*}
x \delta_{c}-\sum_{j=1}^{n-1} x j \delta j-x_{n} \delta_{n}=\lambda p_{n} \tag{6.8}
\end{equation*}
$$

where $X=\sum_{j=1}^{n} x j$ and the subscript $c$ stands for the cold condition or the reference beam. With the knowledge of room temperature and atmosheric pressure at the time of the experiment, the value of $\delta_{c}$ for $\lambda=5461 \mathrm{~A}^{\circ}$ could be found (38). The first two terms on the left hand side of Equation (6.8) are known and hence $\delta_{n}=\mu_{n}-1$ in the $n$th zone can be calculated from a knowledge of $p_{n}$ as determined from the interferogram.

This method of analysis can give reliable results only if the zones are so chosen that the refractive index does not vary very steeply in going from one zone to the next. This was the case at the boundary between hot and cold and therefore the edge effects had to be accurately determined. In this region the zone width was so chosen that the shift in fringe order involved in going from one zone to the next did not amount to more than one.
6.9. Precautions and sources of error.

1. Since the boundary between hot and cold was not well defined, it was necessary to evaluate the "edge effects" carefully. It is seen from Equation (6.8) that the fringe order $p_{n}$ is given by

$$
x \delta_{c}-\int_{0}^{n} \delta d x=\lambda p_{n}
$$

which can also be written as

$$
\begin{equation*}
\left.X \delta_{c}-\delta_{o} T_{0}\right\}_{0}^{n} \frac{d x}{T}=\lambda p_{n} \tag{6.9}
\end{equation*}
$$

The change in optical path due to the presence of the flame is thus seen to be inversely proportional to the temperature of the zone through which the test beam passes. The effect of this is to exaggerate the edge effects where the temperature is lower than in the flame. Furthermore in this region where the hot effluent mixes with cold air, there is a steep variation of temperature in going from one zone to another. This was the reason for constructing the zones on the basis of unit change in order, as mentioned above. 2. The accuracy of the analysis depends upon the least detectable change in fringe order. In the high temperature regions the fringes were very thick and therefore, when plotting the enlarged fringes, the locus of maximum intensity on a black fringe could be determined only approximately. Moreover, in the regions where the fringes were very close together even a slight error in the direction of fringes would introduce a large error in $\delta$. Over and above this, in the regions where the change in direction of the fringes was very gradual, it was difficult to deduce the change in fringe order in going from one zone to another. This could, however, be avoided by taking the annular slices of greater width in these regions. As a result, the minimum change in order that could be
measured by the method followed was only about a quarter of a fringe, on the assumption that fringes could be traced correctly.

Each analysis was carried out twice with each flame, the first result being used to construct a subdivision into elemonts better suited to the particular refractive index field.
6.10. Translation of refractive index distribution into temperature profile.

The next step was the translation of the refractive index into a temperature distribution. This could be done with the help of Equation (4.5). The test space was divided into two halves by the "slice" giving the minimum value of $\delta$ near the axis of the burner. This, to a first approximation corresponded to the section at which temperature was the highest and therefore the regions where the composition corresponded to the products of combustion. In one half of the test space towards the fuel side, the value of $\delta_{0}$ was taken, to a first approximation, to be that of a mixture of 7.5 ccs. of $\mathrm{C}_{2} \mathrm{H}_{4}$ and 75 ecs. of nitrogen at S.T.P. Since $\delta$ is additive by volume (19) this can be easily calculated if the refractive indices of the gases for $\lambda=5461 \mathrm{~A}^{\circ}$ are known (38). Knowing the constant $\delta_{0} T_{o}$ and $\delta$, temperature could be calculated at the corresponding points of this half of the test space. In the other half on the oxygen side the approximate procedure was the same except that $\delta_{0}$ now corresponded to a mixture of 22.5 ccs . of oxygen and 60 ccs . of nitrogen (both at S.T.P.). This gave the temperature distribution to a first approximation:

### 6.11. Correction for diffusion induced composition cifects.

Whilst temperature is the main variable, the diffusion induced variation in composition was also taken into account. As discussed in Chapter 1, this secondary dependence was calculated on the assumptions underlying the theories of diffusion flame structure viz. the equality of diffusion coefficients with the thermal diffusivity. Under these conditions the fraction of reaction completed is equal to that of temperature rise, $f$

$$
\begin{equation*}
f=\frac{\tau-1}{\tau_{b}-1} \tag{6.10}
\end{equation*}
$$

where $\tau$ denotes the ratio of temperature ( ${ }^{\circ} \mathrm{K}$ ) to its initial value and the suffix ' $b$ ' indicates the burnt statc. One method of solution is the use of successive approximations. In this, the entire refractive index distribution is assumed, as a first approxination, to be due to temperature variation alone. The resulting temperature distribution determined, as discussed above, is used to compute the composition distribution, according to the above equation. The approximate temperature distribution is next corrocted and the entire process is repeated until further variation is negligible.

Since, using the ebove relationship, the composition distribution can be expressed uniquely in terms of temperature, it is equally valid and more rapid to express the dual dependence analytically. Thus in the law relating refractive index $(1+\delta)$ to temperature :

$$
\begin{equation*}
\delta=\frac{\delta_{u}}{\tau} \tag{6.11}
\end{equation*}
$$

$\delta$ refers to the mixture composition corresponding to $\tau$ and the suffix
'u' denotes initial temperature. Adding the contributions of reactants (suffix r) and products (suffix p)

$$
\begin{equation*}
\delta_{u}=(1-f) \delta_{r}, u+f \delta_{p, u} \tag{6.12}
\end{equation*}
$$

which when combined with Equation (6.10) gives :

$$
\left(\tau_{b}-1\right) \delta_{u}=\left(\tau_{b}-\tau\right) \delta_{r, u^{+}}(\tau-1) \delta_{p, u}
$$

$\delta_{u}$ can be eliminated with the help of Equation (6.11). Thus,

$$
\begin{equation*}
\left(\tau_{b}-1\right) \tau \delta=\left(\tau_{b}-\tau\right) \delta_{r, u}+(\tau-1) \delta_{p, u} \tag{6.13}
\end{equation*}
$$

which on simplification gives

$$
\begin{equation*}
\tau=\frac{\delta_{r, u}+x}{\delta+x} \tag{6.14}
\end{equation*}
$$

where $x=\frac{\delta_{r, u}-\delta_{p, u}}{\tau_{b}-1}$
Equation (6.14) was therefore used for determining the temperature distribution from the knowledge of the local values of $\delta$ in the test space. Since the temperature distribution across the faces of the two matrices was known, $\delta_{r, u}$ could be calculated in both the halves of the test space. Thus,

$$
\delta_{r, u}=\frac{7.5 \delta_{E t, u}+758 N_{2,} u}{82.5} \text { on the ethylene side }
$$

and

$$
\delta_{r, u}=\frac{22.5 \delta 0_{2, u}+608 N_{2, u}}{82.5} \text { on the oxidant side. }
$$

Furthermore, if the reaction proceeds to completion

$$
7.5 \mathrm{C}_{2} \mathrm{H}_{4}+22.5 \mathrm{O}_{2}+135 \mathrm{~N}_{2}=15 \mathrm{CO}_{2}+15 \mathrm{H}_{2} \mathrm{O}+135 \mathrm{~N}_{2}
$$

Therefore

$$
\delta_{p, u}=15\left(\delta_{\mathrm{CO}_{2}, u}+\delta \mathrm{H}_{2} \mathrm{O}, \mathrm{u}\right)+135 \delta \mathrm{~N}_{2, \mathrm{u}}
$$

For this case, $\delta_{r, u}-\delta_{p, u}=25 \times 10^{-7}$.

### 6.12Final flame temperature

The value of $T_{b}$ ras taken to be the adiabatic flame temperature ( 39) which would have been attained if the two reactant mixtures concerned had been pre-mixed in such a proportion that the $\mathrm{C}_{2} \mathrm{H}_{4}: \mathrm{O}_{2}$ ratio was stoichiometric and burnt.

The temperature was assumed to be low enough to neglect dissociation. For the purpose of this calculation, the volumes of reactants were dalculated as follows:

Since it was supposed that the maximum temperature was attained at a surface where the ethylene and oxygen concentrations were in stoichiometric proportions, for a reaction proceeding to carbon dioxide and water, the volumes of $\mathrm{C}_{2} \mathrm{H}_{4}$ and $\mathrm{O}_{2}$ would be respectively $7.5 \mathrm{ccs} / \mathrm{sec}$. and $22.5 \mathrm{ccs} / \mathrm{sec}$. However, if the reaction proceeded to CO and $\mathrm{H}_{2} \mathrm{O}$, the volumos of $\mathrm{C}_{2} \mathrm{H}_{4}$ and $\mathrm{O}_{2}$ would respectively be $7.5 \mathrm{ccs} /$ sec, and 15: ces/sec. The volume of nitrogen fron either jet arriving at the stoichiometric surface was taken to be the fraction of the total volume of nitrogen in the corresponding gas stream associated with the volume of the reactant taking part in the reaction. Thus for the reaction proceeding to $\mathrm{CO}_{2}$ and $\mathrm{H}_{2} \mathrm{O}$

$$
\begin{aligned}
& \mathrm{N}_{2}(\text { Ethylene side })=\frac{75 \times 7.5}{7.5}=75 \mathrm{ccs} / \mathrm{sec} \\
& \mathrm{~N}_{2} \text { (Oxygen side) }=\frac{60 \times 22.5=60 \mathrm{ccs} / \mathrm{sec}}{22.5}
\end{aligned}
$$

For the flame under distussion, $T_{b}$ was approximately $1950^{\circ} \mathrm{K}$ for the reaction proceeding to completion while for the reaction proceeding to carbon monoxide and water, it was approximately $1850^{\circ} \mathrm{K}$.



Fig.22. Approximate Temperature Distribution in an Opposed Jet Diffusion Flame.

## CHAPTIR 7.

## PRBLIMINARY RESULHS

7.1. Temperature distribution

The approximate distribution of temperature in the flame analysed is shown in Fig. 2,2. . Three features are apparent from this graph.
(i) There is a considerable random variation in temperature distribution in the main combustion zone. As remarked earlier, this is due to the difficulty in finding the fringe shift in regions where the direction of fringes changes very gradually,
(ii) The maximum temperature in the main flame is well below the theoretically calculated value.
(iii) Outside the main flame, the temperature is seen to attain the theoretically calculated value in the effluent.

It was therefore thought necessary to check the last two points with the help of sodium line reversal method and thermocouple.
7.2. Measurement of maximum temperature
a) Sodium line reversal method.

For a determination of the maximum temperature in the flame by sodium line reversal method the optical system was the same as in Fig. 14 . The source of sodium was a fine bead of sodium chloride at the end of a platinum wire. In consequence of the aerodynamics of the flame, the sodium vapour spread all over the flame if the bead was introduced near the axis of the burners. In fact the region over which sodium vapour spread was determined by the position of the bead with
respect to the burner axis. It was therefore arranged that the vapour spread over only a triangular sector of the flame with the bead located at the apex of this sector. This could be easily attained by putting the bead away from the axis, the distance being governed by the desirability of providing the light from the background source with an optical path in the sodium vapour small enough to avoid the errors due to complex flame structure but large enough to produce equilibriun radiation.

With the flow rates remaining unchanged, reversal was obtained over a range of temperatures, the maximum variation being $50^{\circ} \mathrm{K}$. This was presumably due to the range of temperatures within the light cone of the transluminating beam and also to the difficulty of introducing the sodium bead at the same place everytime. The reproducibility of the results was poor for the same reason. Since a gradient was present on either side of the flame and only the maximum temperature was relevant the highest value out of a set of ten readings was taken. This was $1700^{\circ} \mathrm{K}$ near the edge.
b) Pt/Pt-Rh thermocouple.

Immediately after this the temperature was determined by a coated Pt-Pt-Ph (13\%) thermocouple.

The thermocouple was made from .001" thick wires. Small lengths of the metal and the alloy were spot welded on to thicker wires of the same material by means of a low temperature flame. Long leads of thick copper wire were soldered to the free ends of
the thick wires.
The free ends of the finer wires were then brought together so as to make a cross and were similarly spot welded. The superfluous lengths protruding from the junction were clipped off.

A thin layer of $\mathrm{Si}_{2}$ was deposited on the thernocouple by the following simple process. A low temperature flame of town gas was stabilised on a Meker burner. Part of the gas supply was then by-passed through an alcoholic solution of hoxamethyl-disiloxanc. The flome at once acquired a dull grey colour. The thermocouple was coated by moving it quickly across this flame so that it just lost its metallic Iustre.

In view of the steep temperature gradient in the flame the thermocouple was mounted on a stand so that it could be moved along the vertical and horizontal directions by micrometer screws. The e.m.f. was read by a millivoltmeter which, in the preliminary experiments, was not calibrated.

It was found that the temperature in the main flame was higher at the edges. In the effluent however the thermocouple melted suddenly while probing for the maximum temperature region. This was sufficient proof that the temperature in the effluent was above the melting point of platinum.

### 7.3. Inferences.

It is perhaps worth mentioning that the melting of platinum at one point in the effluant could not be reproduced when attempts were made to stabilise a similar flame several months later. This may be
due to the fact that the temperature rose and fell steeply in the effluent so that the location of the maximum temperature regions was not easy.

A possible source of errors occurred in matching the two orders of the interferogram to yield a composite picture. At the same time, the experiments confirmed the need for determining the highest temperature by at least two independent methods. This cross-check was expected to provide a rcliable reference point, in the high temperature region, for "pegging"the interferogram. The advantages of this have already been mentioned.

Attempts were, therefore, made to improve the setting of the interferometer. An investigation into the fractional errors, some conclusions of which are summarised in Appendix $C$, caused in $\delta$ due to various factors occurring in Fquation (6.8) was also undertaken. 7.4. Improvements in interferometer setting.

The relationship (Equation 6.2 ) between grating constant and f-number of the schlieren mirrors implicitly assumes normal incidence at the gratings. In fact the angle of incidence varies from zero to $\sin ^{-1}(a / f)$ for the system shown in Fig. 20 . In view of this, Equation 6.2 will be strictly valid only for the mean ray whose angle of incidence $I$ on the grating is $\sin ^{-1}(a / 2 f)$. The angle of diffraction for the first order is therefore given by

$$
d(\sin \theta+\sin I)=\lambda \text { where } \sin I=a / 2 f \ldots(7.1)
$$

and the deviation $D$ suffered by the diffracted ray is

$$
\begin{equation*}
D=I-\theta \tag{7.2}
\end{equation*}
$$

Combining Equations (7.1) and (7.2) the condition for minimum deviation is found to be

$$
\begin{equation*}
\theta= \pm I \tag{7.3}
\end{equation*}
$$

The solution $\theta=+I$ gives the zero order of the mean ray while $\theta=-I$ is valid for the first order diffraction maximum. This condition should be satisfied if the zero and first orders corresponding to the mean ray are to fall symmetrically on opposite sides of the pole of $A$. When this happens, the two orders (for all the rays in the incident cone) incident on $A$ will, to a first approximation, be circles of diameter equal to the radius of $A$ and two collimated coherent beams result.

Substitution of Equation (7.3) in Equation (7.1)gives $2 d \sin I=\lambda$
or $\quad d=\frac{\lambda_{f}}{a}$
While through this analysis the grating constant is still found to be the same as in Equation (6.2) an important condition for an accurate setting of the interferometer is obtained, viz. the gratings $B$ and $B^{\prime}$ should be set for minimum deviation.

This setting up was quite simple. Without altering any other elements in the optical system, each grating was slowly rotated.
119.

This alters the separation between the orders on account of the changing deviations of the first orders of the incident cone. When the separation becomes a minimum, the zero and first orders lie on A in such a way that they touch each other at the pole of the schlieren mirror. If the grating is further rotated in the same direction the orders begin to move further apart once again.

This refinement led to a much improved visibility of fringes giving at the same time the complete interferogram of the diffusion flame in a single order. The intensity of the interferogram in the zero and first orders of $\mathrm{B}^{\prime}$ were significantly different ( 36 ).

To avoid errors due to vibrations of the interferometer, subsequent work was done at right.

### 8.1. Observations

The flow rates of the reactants for the flame considered here have been mentioned in Section (3.6). These flow rates remained constant for well over fifteen minutes while the experiment took only five minutes. The sequence of operations was as follows:
(i) to note the barometric pressure and room temperature;
(ii) to adjust the flow rates and light the flame;
(iii) to wait till the matrix temperatures attained steady values. This usually took about forty minutes. During this time the flow rates had to be adjusted from time to time.
(iv) to take four photographs of the interference pattem. Bach plate was exposed for about five to ten seconds;
(v) to check that the flow rates remained unchanged;
(vi) to take eight particle track photographs;
(vii) to record the thermocouple readings;
(viii) to re-check the flow rates, atmospheric priessure and room temperature.

The second half of the experiment consisted of determining the maximum temperature at a particular position in the flame by sodium line reversal method and by thermocouple. For the sake of convenience this place was chosen just above the burner rim.

The position of the thermocouple junction was varied in a vertical direction by means of a micrometer screw, till the millivoltmeter

showed a maximum deflection. When the axial position of the thermocouple was altered, it was found necessary to wait for about five to ten seconds before the millivoltmeter showed a steady deflection. The resistance of the thermocouple at the maximum temperature was also measured in order that a correction term to the reading of the calibrated millivoltmeter could be applied.

The correction $\Delta T$ for the difference between the wire temperature $T_{w}$ and that of the gas could be determined with the help of particle track photographs which gave the local velocity in the region occupied by the thermocouple. For the purpose of calculating the Reynold's number of flow, the diameter of the junction, assumed to be spherical, was taken to be equal to the wire diamoter and the flame gases were treated as nitrogen.

An interferogram of the flame analysed is shown in Plate 17 and a typical particle track photograph in Plate 9 . The values of the maximum temperature as found by thermocouple and sodium line reversal method were respectivcly $1600^{\circ} \mathrm{K}$ and $1585^{\circ} \mathrm{K}$. It will be shown later that these were not the highest temperatures in the system. The theoretically calculated valuc for completion of reaction to $\mathrm{CO}_{2}$ and $\mathrm{H}_{2} \mathrm{O}$ was $1850^{\circ} \mathrm{K}$ approximately. The temperature for reaction to CO and $\mathrm{H}_{2} \mathrm{O}$ was $1750^{\circ} \mathrm{K}$ but, in this instance, this was found irrelevant in view of the fincings of sampling followed by gas chromatographic analysis whel is further discussed below.
8.2. Gas chromatographic analysis.

A simple apperatus was used for taking gas samples from the test space. A sample tube was connected in series with a cenco hyvac pump and a syringe with a hypodemic needle was located in the test space. The sample tube was evacuated and samples were then aspirated in from the different regions of a fleme, stabilised using the same flow rates of reactants. The hypodermic needle was located at (i) the edge of the burner; (ii) on the ethylene side immediately under the luminous zone and (iii) on the oxygen side immediately above the luminous zone. No exact measurements of the location of the needle were taken.

The analysis was carried out with the help of a gas chromatography column. It was fourd that :
(i) At the edge, traces of ethylene along with a high concentretion of carbon dioxide and oxygen, a small amount of carbon monoxide and, possibly, hydrogen were present. The concentration of carbon monoxide was not thought to be more than two percent of that of carbon dioxide.
(ii) On the "fuel side"the very small amount of ethylene present revealed that the probe must have been closer to the central reaction surface than was originelly supposed. In addition to large amounts of oxygen and carbon dioxides hydrogen, carbon monoxide and ethylene, as well as amoints of ethane of the same order as those of ethylene could be detected.
(iii) The species detected on the oxygen side were principally oxygen ond carbon dioxidc, together with smeller amounts of ethene and hydrogen. The amounts of thene and hydrogen did not appear to be much different from the previous case but no ethylene could be detected.

The significance of these findings will be discussed in the next chepter. 8.3. Caiculations.

The distribution of refractive index in the test space was determined by the method outlined in section 6.8 . The magnification 1 of the interferogram was determined, in the first instance, ky dividing the separation of the images of the matrices in the enlargement by the cotual separation, determined by means of $a$ cathetometer when the burner was cold. This measurement was carried out along the exis, which was assumed to be exactly coincident with both the line of symmetry and the "eye" of the interferogram. This velue of proved unreliable, lergely because of the opticel distortion induced by the ray defiections near the matrix (Plate ll). The observation that the scparation of the images on the enlergement varied somewhat along the radius of the metrices confirmed thet focusing did not entirely eliminate this effect of refractive index gradient. Accordingly, the value of the magnification was based on perts of the
inage unaffected by these optical effects - the distance between the "eye" of the interferogram and the edge of the outer matrix, as well as the width of the outer matrix. Both measuiements indicated $M=12.55$. The question of the accuracy of this geometry is in fact rather important. If $p$ is the fringe order for the first annular strip the optical peth gradient $\lambda p$ is given by

$$
\begin{equation*}
X\left(\delta_{c}-\delta\right)=\lambda p \tag{8.1}
\end{equation*}
$$

Thus, if the interferogram was enlarged M times

$$
\begin{equation*}
X_{E_{i}}=M X \tag{8.2}
\end{equation*}
$$

where $X_{i}$ was the distance actually found graphically. Therefore Equation (8.1) becomes

$$
\begin{equation*}
X_{\mathrm{E}}\left(\delta_{\mathrm{c}}-\delta\right)=M \lambda_{p} \tag{8.3}
\end{equation*}
$$

The error in $\delta$ due to an error $d \mathbb{N}$ in M is, therefore,

$$
\begin{equation*}
d \delta=-\frac{\partial M}{M}\left(\delta_{c}-\delta\right) \tag{8.4}
\end{equation*}
$$

This result will be used below.
The values of $\delta=\delta_{a}$ for $\mathrm{H}=12.55$ are shown in column 2 (Tablo I). The next step was the pegging of this distribution to the temperature : as recorded by Na I) line reversal and thermocouple. The minimum $\delta$ calculated on the basis of these measurements was $53 \times 10^{-6}$ as compared with $61 \times 10^{-6}$ obtained from the interferogran. The reasons for correcting the letter value to the former heve been set out in a previous chapter. The remaining question was how to adjust the distribution. The method devised is equivalent to essuming an error in magnification - (Equation 8.4) - for the following reasons.

First, an error of only $4 \%$ in M suffices to account for the difference. This is equivalent to a misaligmment of 1.6 mms . between the axis of the jets and the minor axis of the "eye". Since, as nentioned before, no scaling marks were available on the interferogram, an error of 1.6 mms. does not seem improbable if the method of finding the axis of the jets is taken into account.

Second, the correction is linear and therefore, easy to apply. The third and main point is, however, that the cause of the discrepancy is not very important - the initial and final values are fixed and the deviation in between is unlikely to be appreciable, even if the error does not follow a first order law. The corrected values $\delta=\delta_{\text {b }}$ are shown in column 3 (pable I). These were then converted to temperatures allowing for diffusion induced chenges in composition. 8.4. Diffusion-induced changes in refractive index.

The effects of composition-induced chenges were determined according to Equation (6.14). For the flame, under discussion, the values of $\delta_{\text {mixture }}$ at $273^{\circ} \mathrm{F}$ and 77.28 cms . of Hg. are :

$$
\begin{aligned}
& \delta_{\mathrm{r}, \mathrm{u}}=330.77 \times 10^{-6} \text { on the fuel side } \\
& \delta_{\mathrm{r}, \mathrm{u}}=297 \times 10^{-6} \quad \text { on the oxygen side. }
\end{aligned}
$$

The products being carbon dioxide, water vapour, excess oxygen end nitrogen,

$$
\delta_{\mathrm{p}, \mathrm{u}}=311.25 \times 10^{-6}
$$



Therefore

$$
\begin{gathered}
\delta_{r_{, u} u^{-} \delta_{p, u}}=19.52 \times 10^{-6}\left\{\begin{array}{c}
\text { on the fuel side. } \\
x=4.02
\end{array}\right. \\
\delta_{r_{,} u^{-\delta} \delta_{p, u}}=-14.24 \\
x=2.93 \\
\tau_{\mathrm{x}}=1=4.86
\end{gathered}
$$

In the regions occupied by the products of the reaction,

$$
\begin{aligned}
5.7 \mathrm{C}_{2} \mathrm{H}_{4}+ & 22.4 \mathrm{O}_{2}+135 \mathrm{H}_{2}=11.4 \mathrm{CO}_{2}+11.4 \mathrm{H}_{2} \mathrm{O}+5.3 \mathrm{O}_{2}+1.35 \mathrm{~N}_{2} \\
\delta \mathrm{r}_{\mathrm{s}} u^{-\delta} \mathrm{p}, \mathrm{u}= & 2.4 \times 10^{-6}
\end{aligned}
$$

and

$$
x=0.49
$$

The values $\delta_{c}$ obtained after applyine this correction are show in column 4 (Table I) and are plotted in Fig. (23). 8.5. Parabolic correction.

The analysis so far has been based on the assumption that any transluminating rey travels undeviated through the fleme. This is implicit in using Equation (6.8) in place of the more correct Equation ( 6.9 ) where $x$ inside the integral has to be measured elong the ray. For a more accurate anslysis, the path of light inside the flame should therefore be known. The osrtesian equation of this path Fig. ( 24 ) has been seen to be (Section 5.2 )

$$
z-z_{0}=+\frac{1}{2}\left(\frac{d \delta}{d z}\right)^{x^{2}}
$$

The approach in the present investigetion was to find the magnitude $z-z_{0}$ of the axial displecement expexienced by the rays


Fig 24. Parabolic Correction
due to the wertical component of the refractive index gradient. (It will be seen - section 8.6 - that the redial component, in the region of interest, is negligible within experimentel errors): In view of the complex refractive index field (Fig. 23 ) only the relatively flat portion of the flame was considered for the purpose of this calculation.

The deflection mapoing studies showed (section 5.4 ) that the refrective index gradient is a maximum in the imediate vicinity of the two matrices. This observation is confirmed by the graph (Fig. 25 ) of $\delta$ against $z$. It is seen thet $\delta$ chenges most steeply near the matrices. In the rogions of heat release, grad $\delta$ is quite small.

In view of this, it was decided to find $z-z_{0}$ near the two matrices and see if the displecement was more then the "depth" of each annular slice over which the average fringe order had been determined for evaluating the interferogram. Thus on the fuel side

$$
\begin{gathered}
\frac{d \delta}{d z}=439.25 \times 10^{-6} \text { at } z=15.0(\div 12.55) \\
x=\frac{30}{12.55} \times \frac{4}{3} \\
\therefore z-z_{0}=-\frac{1}{2}\left(\frac{d \delta}{d z}\right) x^{2}=-.00 \not 2 \mathrm{cms} .
\end{gathered}
$$

Similarly on the oxident side

$$
\frac{d \delta}{d z}=375.5 \times 10^{-\epsilon} \text { at } z=0.5(\div 12.55)
$$

and using the same vaiue of $x$

$$
z-z_{0}=-.0019 \mathrm{cms} .
$$



The "depth" (along the axis) of each slice was about .032 cms . whioh is one order of magnitude greater than the ray displacement. It, therefore, follows that the method of analysis of the interferogram was such that the inaccurecies introduced by using Equetion (6.8) instead of Lquation (6.9) were negligible.

### 8.6. Temperature profiles.

The temperature profiles were derived from the graph of refractive index distribution (Fig. 23). Since the method essentielly gave the average value of $\delta$ in cech annular strip the curve (for each siice) was drawn through the means of successive s's. It was found that the $\delta$ profile was sensibly flat in the contral region. This smoothed $\delta$ - profile wes used for calculating the temperature distribution according to Equation (6.11). The approximate isotherms thus obtained are shown in Fig. (26). The gradiont in the effluent was so steep that it was found difficult to follow through ell the isothems in this region.

It will be noted that the meximum temperature ( $0.1650{ }^{\circ} \mathrm{K}$ ) is not reached till in the periphercl zones of the flame. Comparison of this result with theoreticci value will be included in the discussion. 8.7. Correlation of the interferogram anc particle track photoscaphs.

In view of the opticel distortion induced by ray deflection near the ratrices, it seened advisable to seek another refurence plane for correlating the interferogram and particle track photographs. The middle section of the test space where the ray deflection was very small was well suited for this purpose. This could be found by bisecting the distance between the images of the ratrices on the interferogram and on the particle track photographs.

Oxidant side matrix


The distences were accordingly measured from this central plane. Since the ray deflections near the two matrices were of the sane order of magnitude, the error in location of the middle-section of the test space on the interferogram could not be appreciablo even if the axial seperation was distorted.
8.8. Gomponents of locel velocity.

Teble II gives the verticel and redial components of local ges velocities as deterained from eight perticle track photographs of the sane flame. Vithin the accurccy of measurement, the axial component $V_{z}$ was found to exhibit the same variation with $z$ for three velues of $r$. Accordingly one best fitting curve was drawn through ell these points. (Fig. 27 ).
$V_{r}$ on the other hand increased with $r$. Its values are plotted in Fig. ( 28 ).

On account of the light scattered by the matrices, the particle trecks conid not be followed up to the upstream origin of each jet. hs a result of this, the determination of heat release rate was limited to only those ragions where the flow velocity could be determined. Since the temperature in the incecessible regions wes too low for mprecieble reaction, this wes not of much conscquence for the purpose of the investigation (Soction 9.5).

reperence plane $\quad . \quad 28$ vig. 34 Variation of radial velocty.
with axial distance.

## CHAPTER 9.

## ANALYSIS OF THE STRUCTURE OF A FLAT DIETUSION FLAME

9.1. Temperature and derived profilos.

Over the flat central region the variation of temperature with the axiol co-ordinate was found to be as shown in Fig. (29). Tho parameters (section 1.6 ) needed for the determination of the distribution of heat release rate were found with the help of this profile.
$d r / d z$ was determined graphically at various points across the test space. It was found (Fig. 30) to increase at first and then start decreasing. The general form of the varintion was the same on both the fuel and oxidant sides, but the fall was more rapid on the oxidant side.

Tho values of the local thermal conductivity were necded for a detormination of $\frac{d}{d z}\left(K \frac{d T}{d z}\right)$. While there are many sources $(23,40,41)$ for thermal conductivity data of individual gases at high temperatures these do not usually give values up to the temperatures attained in this flame. The required values were ultimately found in a text book (42) but their source was not given. The thermal conductivity of the relevant mixtures was estimated (43) by taking an average of the arithmetic mean by volume of the component conductivities and of the hermonic volume weighted mean.

The procedure was to find the thermal conductivities of the two reactant mixtures of (i) 5.7 ccs. cthylene and 75 ccs . of nitrogen; (ii) 22.4 ccs . of oxygen and 60 ccs . of nitrogen at temperatures up to $373^{\circ} \mathrm{K}$. The thermal conductivity of the products was then similarly


calculated at temperatures in the neighbourhood of $1600^{\circ} \mathrm{K}$. Dach intermediate tomperature occurs along two surfaces, one on either side of the zone of maximum temperature. The compositions differ on the two sides but on each side can be related uniquely to temporature by the law used already in the conversion of $\delta$ to $\mathbb{T}$. Since the fractional change in composition corresponds to that in temperature, the following procedure was employed. Two graphs were plotted of conductivity against temperature, each including the composition variation on one side of the flame. Three points for each of the cold reactont streams (at temp. up to $373^{\circ} \mathrm{K}$ ) and for the hot products (around $1600^{\circ} \mathrm{K}$ ) were used to define the position and slope of the terminal curves, to which the roquired graph must become asymptotic. From these the two relationships were then determined by interpolation (Fig. 31 ). It was found that only one curve was needed for both the oxidant and fuel sides.

From a plot of $K \frac{d T}{d z}$ against $z$, the values of $\frac{d}{d z}\left(K \frac{d T}{d z}\right)$ could then be determined at verious axial distances.

### 9.2. Thermodynamic properties.

While a knowledge of tomperature distribution in the test space is sufficient for calculating the local density and enthelpy, to a first approximation, the effect of diffusion induced changes in composition on these themodynamic properties was again taken into account.


Fig. 31 Thermal Conductivity in the test space

The approach was similar to thet outline in section 6.11. The basic equation used was also similar. Thus the relations used were

$$
\begin{equation*}
\frac{\text { mix } \left.\left.^{-\mathrm{E}} \text { react }\right]_{\text {prod }}{ }^{-H}{ }_{\text {react }}\right]_{\tau}}{\mathrm{E}_{\mathrm{b}}-1} \tag{9.1}
\end{equation*}
$$

for enthalpy in cals/gm.
and

$$
\begin{equation*}
\frac{(\rho T)_{\operatorname{mix}}-(\rho T)_{\text {react }} \tau}{(\rho T)_{\left.\operatorname{prod}^{-(\rho T}\right)_{\text {react }}}^{\tau}}=f=\frac{\tau-1}{\tau_{\mathrm{b}}-1} \tag{9.2}
\end{equation*}
$$

for density in gms./cc.
The values of $\rho$ and $H$, for the mixtures, at different temperatures could be calculated from a knowledge of $\rho$ and if for the component gases at these temperatures (44).

The local density and enthalpy of the flame gases thus deter ined . were plotted and the values of $d \rho / d T$ and dII/dT found graphically fron these curves. 9.3. Gradients of velocity

The method of deriving the gredient of axial velocity was also graphical. Its variation with $z$ is shown in Fig. ( 32 ).

Before finding $\frac{d V_{r}}{d r}$.graphically it was decided to check the applicability to these flames of Le clerc's basic result, viz. the postulate that the radial velocity in the impinement zone is directly proportional to the radius. The radial velocity at different axial distances was plotted against $r$ in Fig. ( 33 ). It was found that away from the region of heat release, ' $V_{r}$ varied linearly with $r$. In the



Enlargement 11.05 times


Fuel side
Fig. 33 Variation of $V_{r}$ with $r$


Fig. 34 Variation of $\frac{d V_{r}}{d r}$ with $z$
combustion zone the rate of change of $V_{r}$ with $r$ remained linear for small values of $r$ but tended to a.ttain a constant value at bigger radii. A11 graphs between $V_{r}$ and $r$ passed through the origin. Since it was decided to confine the determination of heat release rate to the central region of the flame the values of $V_{r}$ for lerger r's were not relevant here and a straight line was drawn through the first three points for each $z$. The slope of these lines cgave $d V_{r} / d r$ at different z's. The graph is shown in Fig. (34 ).
9.4. Determination of heat release rate.

The heat balance equation (section 1.6 ) is

$$
\begin{equation*}
\frac{1}{r} \frac{\partial}{\partial r}\left[-r K \frac{\partial T}{\partial r}+r \rho V_{r}\right]+\frac{\partial}{\partial z}\left[\left.-K \frac{\partial T}{\partial z}+\rho V_{z} H \right\rvert\,-w Q=0\right. \tag{9.3}
\end{equation*}
$$

It has been shown that
and

$$
\left.\begin{array}{l}
\frac{\partial T}{\partial r}=0  \tag{9.4}\\
V_{r} \alpha r
\end{array}\right\}
$$

With these conditions Equation 9.3 on differentiation becomes

$$
\begin{equation*}
\frac{\partial}{\partial z}\left(-K \frac{\partial T}{\partial z}\right)+V_{z} \frac{\partial T}{\partial z}\left(\rho \frac{\partial H}{\partial T}+H \frac{\partial \rho}{\partial T}\right)+\rho H \frac{\partial V_{z}}{\partial z}+\frac{2 V_{r}(\rho H)}{r}=w Q \tag{9.5}
\end{equation*}
$$

This equation was therefore used for the celculation of heat release rete. The different terms of this equation heve been tabulated in Table III, whle the calculations have been summarised in Table IV. The profile of heat heat release rate is shown in Fig. (35).


Fig.35. Heat release rate profile
9.5. iscussion of results.

The heat release rate is seen to increase gradually at first but its variation with axial distance becomes very steep near the middle. The profile is somewhat wider on the fuel side and shows a negative heat release rate on both the oxidant and fuel sides. The thickness of the reaction zone does not seem to be less than five millimetros.

The totol heat release rate per unit area was found by a graphical integration of the heat release rate profile. For this the negative heat release obteined on the fuel end oxidant sides was also taken into account. This was compared with the theoretical value obtained by dividing the heat of reaction with the area of the flame.

The area of the flane was calculated from the particle track photographs. The flame was assumed to be a circular disc and the skirts on the periphery were neglected. The radius of the cylinder whose section appeared as skirts on the photograph was taken as the radius of the circular disc (Plate 9). The area of the flame thus detcrmined was 49 sq . cms. The heat of reaction (44) liberated when 5.7 cos. of ethylene at S.T.D. burnt to cerbon dioxide and weter was

$$
\frac{316.195 \times 5.7}{22400} \mathrm{cals} .
$$

and the heat relcased per second per unit area of the flane would therefore bo

$$
\frac{316.195 \times 5.7}{49 \times 22400}=1.64 \frac{\mathrm{cals}}{\mathrm{~cm}^{2} . \mathrm{sec}}
$$

The value found by integration of the heat release rate was 1. $59 \mathrm{cals} / \mathrm{cm}^{2} / \mathrm{sec}$. The agreement between the two values suggests that the analysis is reasonably accurate. However, the appearance of negative heat release rate on either side of the flame was the reason for further investigation. While it did not seem impossible that the presence of pyrolysis would give rise to a negative heat release rate on the fuel side, no good explanation for its appearance on the oxidant side could at first be thought of. It was, therefore, desirable to look into the uncertainties of the terms in Equation (9.5) which add up to give wQ.

The two terms involving the variation of thermodynamic properties with temperature were, to a first approximation, equal and opposite in the regions where negative wQ was obtained. Only the terms involving themal conductivity and axial and radial gradients of velocity made up the major portion of wQ.

> In view of the interpolation of thermel conductivity at intermediate temperatures (section 9.1) the conductive term seemed the one most likely to be in error. To investigate this, the negative heat release rate was subtrected from the conductive term so as to yield the value of $\frac{d}{d z}\left(\frac{d T}{d z}\right)$ which would reduce the negative heat release to zero at different $z^{\prime}$ s, and a graph of this function we.s plotted. Graphical intergration of this curve gave $K \frac{d T}{d z}$ and hence the $K$ for various temperatures which would eliminate the anomaly.

These points have been marked with crosses on the thermal conductivity curve (Fig. 31 ). It is apparent that the variation of thermal conductivity suggested by these points is not very likely.

Next, the negative heat release rate was subtracted from the term involving $V_{r}$ and the value of $V_{r}$ for no heat release in the region was found. These values have been plotted as crosses on Fig. 34

Similariy, the change in the remaining term needed to eliminate the negative heat release rate was found. The values of $\partial V_{z} / \partial_{z}$ needed for this purpose have also been plotted on Fig. ( 32 ).

While it is true that the particle track method of finding the gas velocity is aproximate (Appendix A), the large magnitude of corrections needed in $V_{I}$ and $d V_{Z} / \partial_{Z}$ did not seem very probable either. 9.6. Sampling and gas-chronatography.

The reasons for examining the gas composition by the method outlined in the preceding chapter were twofold. First, it seemed desirable to compare the CO with the $\mathrm{CO}_{2}$ concentration in the products, in order to assess the extent of completion of reaction. In the flamc used during preliminary work, the increase in temperature in going from the axis to the edge of the burner suggested that only the first stage might be going to completion in the centre, the $\mathrm{CO}_{2}$ stage being blown off towards the edge. Wo analyses were carried out under these conditions and, in view of the proliminary neture of the measurements on that flame, the question must remair unresolved, for the present. The current experiments provide no proof to the contrary because
reactant compositions as well as flow velocities were different in the second sequence of exporiments. The two temperatures calculated for the second system $\left(1750^{\circ} \mathrm{K}\right.$ to $\mathrm{CO}+\mathrm{H}_{2} \mathrm{O}$ and $1850^{\circ} \mathrm{K}$ to $\left.\mathrm{CO}_{2}+\mathrm{H}_{2} \mathrm{O}\right)$ however are also compatible with either reaction scheme. The relatively small difference betwoen the two temperaturos is due to the assumption that the maximum temperature always occurs at the surface of stoichiometric composition and the oxyeen (with diluent) requircment is different in the two cases.

The results of gas chromatography were therefore first oxamined for CO content. The sample taken near the centre of the fleme did, in fact, contain some $C O$, but the CO concentration was such a small fraction of thet of $\mathrm{CO}_{2}$ as to leave no doubt that the reaction could be regarded as going to completion. This result is in excellent agreement with the comperison between the integrated heat release and that celculated from the fuel flow on the assumption of complete oxidation.

The second conclusion of the sampling study was no less interesting. It was found thet a sample taken well on the oxidant side of the centre of the flame containcd some ethane, in regions far enough fron the flame for the ethylene content to have fallen to undetectably small valucs. There seems little doubt that $\mathrm{C}_{2} \mathrm{~F}_{1} 6$ will be formed as a result of attack on $\mathrm{C}_{2} \mathrm{iH}_{4}$ by E and $\mathrm{H}_{2}$ and molecular hydrogen was found present in the samples analysed. In vicw of the
very high diffusion coefficient of hydrogen, it would be expected to permeate large distances from the reaction zone. The main conclusion of this analysis, however, was to destroy the conviction that nothing could be presert on the oxidant side which would be capable of nggative heat release. The initicting steps in the oidation of $\mathrm{C}_{2} \mathrm{H}_{6}$, for instance, are undoubtediy endothermic. Such an explanation would also account for the good agreement between measured and calculated total heat release.

The evidence is not sufficiently quantitative to attribute the negative heat release rate to any such definite step. There is, however, enough room for speculation to make any further search for an error in the measured quantities which would be responsible for the observation unprofitable. The negative heat release is in any caseonly a small fraction of the total heat release and does not affect the conclusions of the work. 9.7. Reaction rate laws.

It is possible in principle to detemine overall effective reaction kinetics with the help of the type of results under discussion even without sampling studios. Such a determination ( 4 ) can be based upon the equivalence of the heat and mass conservation equations for any species $j$ whose diffusion coefficient, $D_{j}$ bears a lnown relationship to thermal diffusivity. Thus fron Fiquation (I.I), the conservation of mass can be writteii es (15)

$$
\begin{equation*}
\text { div } \left.\square_{j} \quad \operatorname{grad} m_{j}+\operatorname{Hn}_{j}\right]-\dot{m}_{j}^{\prime \prime}=0 \tag{9.6}
\end{equation*}
$$

where $m_{j}$ is the mass fraction of the $j$ th species whose rate of generation per unit volume is $m_{j}$ and $M$ is the mass flow rate of the mixture per unit area.

On the assumption of an overall reaction scheme, the rate of formation of the jth species cen be linked with the volumetric heat release ret. $w \in \dot{d}=\dot{q}^{\prime \prime \prime}$. Thus if Fistands for the amount of hoet liberated per unit mass of the mixture which is associated with tho mess fraction $m_{j}$, and if $D_{j}=\frac{k}{\rho_{c}}$,

$$
\begin{equation*}
\frac{m_{j}-m_{j, 0}}{m_{j, f}-m_{j, 0}}=\frac{H-E_{0}}{\mathrm{E}_{\mathrm{f}}-\mathrm{E}_{0}} \tag{9.7}
\end{equation*}
$$

where 0 and $f$, respectively, stand for the initial and final values.
Thus the concentration of each major species is calculable at every point. This, together with the knowledge of local temperature and reaction rate everywhero, makes it possible to deduce effective rate lews, activation energies and reaction orders. Such an approach has been used to establish the validity of the "global" reaction concept in yre-mixea flames (4).

In view of the preliminary nature of the present work, such an analysis was not attempted. The negative heat release rate is due either to an individucl reaction step, which could not be accounted for on the above overall model or to an unaccounted lack of accuracy in measurement, in which case such an analysis was also not thought to be justified.

### 9.8. Comparison with pre-mixed flames.

The raison d'etre of the present work was not only to study the flat diffusion flame as such, but also to develop a method for analysing the kinetics of "faster" reactants. Bosidos the fact that it is not very safe to premix such reactants, there are two reasons why it is not easy to study their kinctics with the help of pre-mixed flames. Taking the case of the flame analysed ( $I_{b}=1850^{\circ} \mathrm{K}$ ) the burning velocity $(24,4.5)$ of the equivalent pre-mixed flame would be of the order of $25 \mathrm{cms} / \mathrm{sec}$. Such fast burning mixtures cannot be stabilised on a flat flame burmer at atmosphiric pressures. Fioreover, the thickness of the reaction zonc would be so small that the flame would not be analysable by any existing methods. The thickness $A$ of the reaction zone of a flame, of burning velocity ( $s_{u}$ ) $5 \mathrm{cms} / \mathrm{sec}$., stabilised on a flat flame burner is always less than 3 mms. Assuming that $\Delta$ is inversely proportional to $S_{u}$

$$
\begin{equation*}
\Delta<\frac{5 \times 0.3}{S_{u}} \mathrm{~cm} . \tag{9.8}
\end{equation*}
$$

and for the equivalent flame of the example cited above

$$
\begin{equation*}
\Delta<\frac{5 \times 0.3}{25} \tag{9.9}
\end{equation*}
$$

Thus the thickness of the reaction zone of the equivalent pre-mixed flame would be expected to be smaller than 0.6 ms. It will be seen that the counter-flow diffusion flane in which the thickness of the roaction zone is about 5 mms . therefore provides a much moro convenient tool for the study of fast burning mixtures.

## CHAPTER 10.

## CONCLUSIONS APD RGCOMMENATIONS FOR FURIHER VORK

### 10.1. Conclusions.

The main conclusions of this research are:

1. The counter-flow bumer is capable of yielding a flat fleme of reectants which cannot be burnt in equivelent mixture strengths on a flat flame burner.
2. The aerodynamics of counter-flow jets is altered when the flame is lit. The theory which supposes the flow pattern to be identical with that of two jets impinging on the opposite sides of an infinitely thin plate is only approxinately correct.
3. The refractive index field of these flames is such that deflection mapping is not very suited to it.s measurement in the centre of this flame.
4. The distribution of refrective index and hence of temperature in the conbustion zone ceari be determined with the help of an interferometer. 5. For improving the accuracy of the detemination of the refroctive index ficld, it is desirable to heve reference points in the high temperature region of the fleme. These can be determined by sodium line reversal method or themocouple.
5. For laminar flows, the position of the fleme is determined by the stoichiometric locus of fuel and oxident.
6. It is possible to use this flame to stuay the kinctics of highly reactive fuel-oxygen combinations. This is so because the present investigation reveals that such flames are not only stabiliseble as flat reaction zones on the opposed jet burner but also heve a thick enough reaction zono which onebles the analysis to be carried out. 8. As distinct from premixed flemos, the lack of transport deta at higi tomperatures may not bo such a major hindronce in such a study because the axiol gradient of temperature is constant over large regions and where it is not, the tomperature range is snall. 10.2. Kecommendetions.

While the possibility of using opticel techniques to the in situ determination of heat rolcase rate in diffusion flanc has been demonstrated in principle, there is room for further improvements. If the method is to be uscd for kinctic studies, in perticular, its acourscy should be improved. A major souree of inaccuracy in the present work has been the spocial refractive index field of such a flame, involving large gradients noar the matrices due to which some residual distortion appears to occur even on the focused record. Some attention should, therefore, be paid to the aberrations which affect the imeging of tho diemetral plane of the flame on a flet photographic platc. Parabolic schlieren mirrors may be worth considering in this context. In any case, it seems adviseblo to incorporete some scaling marks on the interferogram plate in order to determine the magnification accuratcly and thereby eliminate the major
157.
uncertainty due to distortion. Noreover, the use of some optical device for correlating the interferogram and particle track photogrephs is highly recommended.

Attempts should be made to deduce the fringe order from the interferogrem more accurately. A micro-densitometric record of the same would therefore be very valuable.

The use of particles having a thermal conductivity greater than bentonite would reduce the themal forces acting on the tracer particles when they move throngh steep temperature gradients. This would increase the reliability of flow velocity measurements. At the same time it may be better to work in curvilinear co-ordinates (along the streamlines) to prevent the inaccuracies thet are introduced when the particle tracks are resolved along a cartesian system of axes. Ultimately, the only absolute method of obtaining more accurate flow velocities is to make the irreducible errors a smaller fraction of the total by working at flow rates higher than the very small values employed in the present investicetion. This implies. larger fiamo diameters, unless either the bumer dianeters are reduced (which seems feasible) or the mixtures are made leaner (in which case blow-out may be approacled). Larger flame dianeter would tend to aggravate the above-nentioned ontical problems.

Another suggestion is the use of shortor focus schlieren mirrors for the type of interferometer used in this investigation. The main argument against their use has been the difficulty of
alignment. Since the technique of alignment has been established this should no longer be regarded as a major consideration. The smaller object range of such mirrors would facilitate precise focusing of the tost space. Moreover the distance between such mirrors could be reduced, thereby avoiding the need for a big room and the associated problem of eliminating convection currents across the optical path. The aberrations due to the deviation from fletness of conjugate planes would, however, be aggravated and suitably corrected surfaces might well prove rather expensive.

The burner and the flame devcloped can be put to many other uses. It can be used for the study of reaction intermediates, pyrolysis and the effect of inhibitors. The very interesting results of the preliminary study involving sampling followed by chromatographic analysis, suggest alreedy that a full kinetic investigation should not be undertaken without detailed analysis for the species present.

The flame has already found application in a study of the electrical properties of flemes in which the matrices have also become high tension electrodes.

A very important potential application cen be the determinction of thermel conauctivitios of mixtures at high temporatures. The additional advantege in using this burncr for this purpose is thet, since the heat release is confined to only a narrow centrel zone, the mixture composition is affected only by diffusion up to quite high temperatures before reaction sets in. One method of climineting all composition variation would be to substitute a heated plate for the flame
159.
whilst retaining the optical and flow tracing methods used in the prosent work.

## Appendix A

## Accuracy of flow velocity measurements

There are two important potential sources of error (46) in the determination of velocity of flame gases by the particle track method. The first is the themomechanical effect which could be important because of the steep temperature gradients present in flames. This is supposed to be due to "slippage" of gas molecules along the unequally heated surface of the tracer particles. As a result of this, a force is brought into play which pushes the particle towards the colder regions. The velocity which the particle acquires has becn calculated (47) and the relations experimentally verified (48) (49). This velocity depends upon the ratio of mean free path I and particle radius a. For the purposes of present investigation, the relevant formulae are :

$$
\begin{aligned}
& v=-17.9 \frac{K_{a}}{2 K_{a}+K_{i}} \quad p \frac{L^{2}}{T} \frac{d T}{d z} \frac{1+\frac{L}{z_{i}} A}{6 \pi r} \underset{\operatorname{La} \operatorname{Mesenblatt}}{\operatorname{Ra}}(48) . \\
& v=-1.5\left(1+\frac{A L}{a}\right) \frac{r^{t}}{\rho^{T}} \frac{d T}{d z} \frac{K_{a}}{2 K_{a}+K_{i}} \\
& \text { Saxton and Ranz (49). } \\
& v=0.14 \frac{\mathrm{~K}}{\mathrm{p}} \frac{d T}{d z} \quad \text { Waldman (47). }
\end{aligned}
$$

where $p=$ atmospheric pressure

$$
\begin{aligned}
& K_{a}=\text { thermal conductivity of flame gases } \\
& K_{i}=\text { thermal conductivity of tracer particles } \\
& A=1.25
\end{aligned}
$$

The magnitude of this effect can thus be calculated at any


Fig. 36 Useful range of tracer particles
162.
point from the measured $d T / d z$ and a correction applied, if necessary. However, it is doubtful, if the equations developed for the less extreme conditions can be extended to the case of steep and rapidly varying gradients and the effects of convection prevailing in flames. The extent of error introduced in flow velocity measurements due to thermomechanical forces on tracer particles in flames has been investigated by Fristrom (46). The vertical lines in Fig. (36) show the limit imposed to quantitative applicability of particle track studies in an atmospheric flame, for an error of less than $3 \%$. It appears from this figure that the size of particles used in the present investigation (4 $\mu$ ) lies well within this range.

The other source of error is the velocity lag of particles in accelerated or decelerated gas flow. This has been investigated (50) theoretically for linear rates of change of velocity. It has been shown that the velocity lag $\Delta$ is given by

$$
\begin{equation*}
\Delta \equiv \frac{V-U}{V}=\frac{\emptyset(1+\lambda)-1+(1-\phi) \sqrt{1+2)} \operatorname{Coth} \tau \sqrt{1+2 \lambda}}{1+\lambda \phi+\sqrt{1+2 \lambda} \operatorname{Coth} \tau \sqrt{1+2 \lambda}} \tag{A.I}
\end{equation*}
$$

where

$$
\begin{aligned}
& V=\text { fluid speed } \\
& U=\text { particle speed } \\
& \lambda=2\left(\frac{d v}{d z}\right) \text { actual } \frac{2 \rho a^{2}}{9!}=\frac{4 \mathrm{ca}^{2}}{9 \mathrm{~s}} \mathrm{x} \text { vel. gradient } \\
& \emptyset=\frac{\text { Particle speed }}{\text { Fluid speed }} \text { initial } \\
& \tau=\frac{9 \eta}{4 \rho a^{2}}, t=\text { time, } \rho=\text { particle density }
\end{aligned}
$$

For large values of $\tau$ equation (AC) simplifies to

$$
\begin{equation*}
\Delta_{C O}=\frac{1+x-\sqrt{1+2 \lambda}}{\lambda} \tag{A,Z}
\end{equation*}
$$

The values of $\lambda$ and $\tau$ for the present investigation are

$$
\begin{aligned}
& \tau \approx 10^{4} t \\
& \lambda=10^{-4}\left(\frac{\mathrm{dv}}{\mathrm{dz}}\right)_{\mathrm{actual}}
\end{aligned}
$$

The maximum value of the velocity gradients observed from particle track studies was of the order of $10 \mathrm{sec}^{-1}$ and therefore $\lambda$ was negligible as compared to one. The velocity $\operatorname{lag} \Delta_{\infty}$ according to Equation (A.2) was also negligible.

While the theory is not rigorous, it nevertheless points to the conclusion that the velocity lag of particles in the type of flame studied will not introduce a serious error in particle track studies.

This effect has again been considered by Fristrom and the corresponding limit is indicated by the inclined line in Fig. (36). The crosshatched region indicates the satisfactory range of particle size and burning velocity for an error of less than $3 \%$. It will be seen that the size of particles used in the present study lies near the centre of a very large range of permissible values.

## Appendix B

## Virtual Origin of the deflectod beam

The path of a ray initially parallel to a one dimensional flame to a close approximation has been shown to be (Section 5.2).

$$
\begin{equation*}
z-z_{0}=+\frac{1}{2} \frac{d \delta}{d z} x^{2} \tag{3,1}
\end{equation*}
$$

If the ray leaves the flame at $\mathrm{x}=\mathrm{D}$, the corresponding value $\mathrm{z}^{\prime}$ (Fig. 24) is given by

$$
z^{\prime}=z_{0}+\frac{1}{2} \frac{d \delta}{d z} D^{2}
$$

The intersection of the tangents drawn to this parabola at the points $z=z_{0}, x=0$ and $z=z^{\prime}, x=D$ gives the virtual origin of the deflected rays. This can be obtained by solving simultaneously the equations of incident ray

$$
z=z_{0}
$$

and the emergent ray

$$
\begin{equation*}
\frac{z+z^{\prime}}{2}-z_{0}=+\frac{1}{2} \frac{d \delta}{d z} \quad x D \tag{B.3}
\end{equation*}
$$

where $z^{\prime}$ is given by Equation (B.2).
The solution is $z=z_{0}, x=\frac{D}{2}$ which are the co-ordinates of the contre of the flame. This solution being independent of $d \delta / d z$, it follows that the virtual origin of all deflected rays, to a close approximation is the centre of the flame.

## Appendix $C$.

## Calculation of fractional errors

The Equation (6.8) used for the analysis of interferogram can be written as

$$
\begin{equation*}
\delta_{c} \sum_{j=1}^{n} x j-\sum_{j=1}^{n-1} x j \delta_{j}-x_{n} \delta_{n}=\lambda p_{n} \tag{C.1}
\end{equation*}
$$

Out of the factors involved in this expression, it will be assumed that the geometrical distances can be read off very accurately from Fig. (21). The fractional error introduced due to small crrors in x's will be insignificant. Attention will therefore be confined only to the two important variables $\delta_{c}$ and $p_{n}$.
(i) Brrors in $\delta_{c}$

Since the R.H.S. of Equation (C.1) is the optical path difference between the reference and the test beams for each annular strip, an error in the reference temperature and hence $\delta_{c}$ will introduce an error in the $\delta$ 's for all these strips. Whus for the first strip
and

$$
\delta_{1}=\delta_{c}-\frac{\lambda p_{1}}{X_{1}}
$$

$$
\begin{equation*}
d \delta_{1}=d \delta_{c} \tag{C.2}
\end{equation*}
$$

For the second strip

$$
\begin{equation*}
\delta_{c} x_{2}-\delta_{1} x_{1}-\delta_{2} x_{2}=\delta_{2} \tag{c.3}
\end{equation*}
$$

where $X_{2}=x_{1}+x_{2}$ and $p_{2}$ is the local fringe order. In Equation (c.3) since $\delta_{c}$ is in error, both $\delta_{1}$ and $\delta_{2}$ will be wrone by a certain amount.

Thus differentiating Equation (C. 3).

$$
\begin{array}{ll} 
& x_{2} d \delta_{c}-x_{1} d \delta_{1}-x_{2} d \delta_{2}=0 \\
\text { or } \quad & x_{1}\left(d \delta_{c}-d \delta_{1}\right)+x_{2}\left(d \delta_{c}-d \delta_{2}\right)=0
\end{array}
$$

which on combining with Equation (C.2) gives

$$
d \delta_{c}=d \delta_{2}
$$

In general

$$
d \delta_{c}=d \delta_{1}=d \delta_{2}=d i_{n}
$$

Hence the fractional error $=\delta_{n}$ in $\delta_{n}$ is given by

$$
\begin{equation*}
\therefore \delta_{n}=\frac{d \delta_{n}}{\delta_{n}}=\frac{d \delta_{c}}{\delta_{c}} \cdot \frac{\delta_{c}}{\delta_{n}}=\frac{\delta_{c}}{\delta_{n}} \varepsilon \delta_{c} \tag{C.4}
\end{equation*}
$$

Since $\delta$ " $\frac{1}{T}$, the fractional error introduced in the calculated temperature of the nth strip will be

$$
\begin{equation*}
\dot{\therefore} T_{n}=\frac{T_{n}}{T_{c}} \in_{T_{c}} \tag{c.5}
\end{equation*}
$$

A small error in $T_{c}$ is therefore magnified by a factor $T_{n} / T_{c}$. The room temperature should therefore be very accurately known.
(ii) Errors in local fringe order $P_{n}$

If there has been an error $d_{n}$ in finding the local fringe order, the corresponding $\delta$ will also be in error. This can be determined by differentiating Iquation (C.1) for the two variables $\delta_{n}$ and $p_{n}$. Thus

$$
\begin{aligned}
\therefore & \because x_{n} d \delta_{n}=-\lambda d p_{n} \\
& \varepsilon \delta_{n}=\frac{d \delta_{n}}{\delta_{n}}=-\frac{d}{x_{n}} \frac{d p_{n}}{p_{n}} \frac{p_{n}}{\delta_{n}}
\end{aligned}
$$

$$
\epsilon_{\delta_{n}}=-\frac{\lambda p_{n}}{x_{n} \delta_{n}} \epsilon p_{n}
$$

The fractional error $\subseteq_{\delta_{n}}$ is seen to be directly proportional to the local fringe order and inversely proportional to $\delta_{n}$. The negative sign indicates that a positive error in $p_{n}$ causes a negative error in $\delta_{n}$ and vice versa.

Refractive index distribution $S_{=}(n-1) 10^{6}$.
Temp. in ${ }^{\circ} \mathrm{K} . \quad r=$ radial distance $\times 9.41 \mathrm{cms}$. $z=$ Axial distance $x 12.55$ cms.

| $z=0.5$ |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: |
| $r$ | $\delta_{\text {a }}$ | 5 | $\delta_{\mathrm{c}}$ | Temperature |
| 0.00 | 195.79 | 192.79 | 189.86 | 423 |
| 6.00 | 187.66 | 184.36 | 181.43 | 443 |
| 9.00 | 190.20 | 187.00 | 184.07 | 436 |
| 12.00 | 196.24 | 193.24 | 190.31 | 422 |
| 15.00 | 195.45 | 192.45 | 189.52 | 424 |
| 18.00 | 194.13 | 191.08 | 188.15 | 427 |
| 21.00 | 192.26 | 189.11 | 186.18 | 431 |
| 23.25 | 188.00 | 185.10 | 182.17 | 441 |
| 24.75 | 197.80 | 194.90 | 192.00 | 418 |
| 26.25 | 193.95 | 190.90 | 188.00 | 427 |
| . 27.75 | 188.81 | 185.56 | 182.63 | 440 |
| 29.10 | 185.21 | 182.17 | 179.24 | 448 |
| 30.30 | 171.29 | 167.39 | 164.46 | 488 |
| 31.50 | 151.84 | 147.34 | 144.41 | 556 |
| 32.70 | 134.58 | 129.33 | 126.40 | 635 |
| 33.75 | 132.15 | 126.80 | 123.87 | 648 |
| 34.65 | 120.26 | 114.51 | 111.58 | 720 |
| 35.55 | 114.04 | 108.00 | 105.07 | 764 |
| 36.45 | 111.63 | 105.53 | 102.60 | 782 |
| 37.20 | 104.43 | 98.00 | 95.07 | 844 |
| 37.80 | 103.13 | 96.69 | 93.75 | 856 |
| 38.40 | 98.91 | 92.31 | 89.38 | 898 |
| 39.00 | 99.00 | 92.40 | 89.47 | 897 |
| 39.60 | 96.45 | 89.75 | 86.82 | 925 |
| 40.05 | 95.69 | 89.00 | 86.07 | 934 |
| 40.35 | 95.00 | 88.25 | 85.32 | 941 |
| 40.65 | 88.43 | 81.43 | 78.50 | 1023 |
| 40.95 | 92.70 | 85.90 | 83.00 | 967 |
| 41.25 | 83.70 | 76.50 | 73.57 | 1091 |
| 41.55 | 83.95 | 76.85 | 73.92 | 1086 |
| 41.85 | 82.32 | 75.12 | 72.19 | 1112 |
| 42.15 | 89.62 | 81.62 | 78.69 | 1020 |
| 42.45 | 83.58 | 76.48 | 73.55 | 1092 |
| 42.75 | 80.33 | 73.03 | 70.10 | 1145 |
| 43.05 | 81.26 | 74.00 | 71.07 | 1130 |
| 43.35 | 87.31 | 80.31 | 77.38 | 1038 |
| 43.65 | 87.41 | 80.41 | 77.48 | 1036 |
| 43.95 | 85.58 | 78.08 | 75.15 | 1068 |
| 44.25 | 93.45 | 86.65 | 85.72 | 937 |
| 44.55 | 96.10 | 89.40 | 86.47 | 928 |

Table I - conta.

| $z=0.5$ |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: |
| $r$ | 8 a | $\delta_{b}$ | $\delta_{\mathrm{c}}$ | Temperature |
| 44.85 | 110.17 | 104.00 | 101.07 | 793 |
| 45.15 | 118.38 | 112.48 | 109.55 | 733 |
| 45.45 | 139.81 | 134.81 | 131.88 | 609 |
| 45.75 | 153.84 | 149.34 | 146.41 | 548 |
| 46.05 | 175.72 | 172.00 | 169.07 | 475 |
| 46.35 | 188.17 | 184.87 | 181.94 | 441 |
| 46.65 | 226.09 | 224.19 | 221.26 | 363 |
| 46.95 | 239.09 | 237.69 | 234.76 | 342 |
| 47.25 | 243.58 | 242.38 | 239.45 | 335 |
| $z=1.5$ |  |  |  |  |
| 0.00 | 160.58 | 156.28 | 153.65 | 523 |
| 6.00 | 167.57 | 163.52 | 160.59 | 500 |
| 9.00 | 160.73 | 156.43 | 153.50 | 523 |
| 12.00 | 169.81 | 165.86 | 162.93 | 493 |
| 15.00 | 162.70 | 158.50 | 155.57 | 516 |
| 18.00 | 162.53 | 158.28 | 155.35 | 517 |
| 21.00 | 158.52 | 154.12 | 151.19 | 531 |
| 23.25 | 155.90 | 151.40 | 148.47 | 541 |
| 24.75 | 158.38 | 154.00 | 151.07 | 531 |
| 26.25 | 156.95 | 152.50 | 149.57 | 537 |
| 27.75 | 150.16 | 145.46 | 142.53 | 563 |
| 29.10 | 149.26 | 144.15 | 141.22 | 569 |
| 30.30 | 138.00 | 132.85 | 129.92 | 618 |
| 31.50 | 129.26 | 123.81 | 120.88 | 664 |
| 32.70 | 115.73 | 109.73 | 106.80 | 752 |
| 33.75 | 108.00 | 101.75 | 98.82 | 812 |
| 34.65 35.55 | 101.31 96.14 | 94.81 89.44 | 91.88 86.51 | 874 928 |
| 36.45 | 91.00 | 84.10 | 81.17 | 989 |
| 37.20 | 88.18 | 81.18 | 78.15 | 1027 |
| 37.80 | 84.86 | 77.76 | 74.83 | 1073 |
| 38.40 | 84.93 | 77.83 | 74.90 | 1072 |
| 39.00 | 83.06 | 75.86 | 72.93 | 1101 |
| 39.60 | 77.64 | 70.24 | 67.31 | 1193 |
| 40.05 | 81.85 | 74.65 | 71.72 | 1119 |
| 40.35 | 78.80 | 71.45 | 68.52 | 1172 |
| 40.65 | 80.58 | 73.33 | 70.40 | 1140 |
| 40.95 | 79.51 | 72.21 | 69.28 | 1159 |
| 41.25 | 74.19 | 66.69 | 63.76 | 1259 |
| 41.55 | 77.68 | 70.28 | 67.35 | 1192 |
| 41.85 | 76.71 | 69.31 | 66.38 | 1209 |
| 42.15 | 80.73 | 73.43 | 70.50 | 1139 |

Table I - contd.

| $z=1.5$ |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: |
| r | $\varepsilon_{a}$ | $\delta_{b}$ | $\mathrm{E}_{6}$ | Temperature |
| 42.45 | 79.85 | 72.55 | 69.62 | 1153 |
| 42.75 | 80.49 | 73.24 | 70.31 | 1142 |
| 43.05 | 83.74 | 76.60 | 73.67 | 1090 |
| 43.35 | 81.00 | 73.75 | 70.82 | 1134 |
| 43.65 | 85.12 | 78.02 | 75.09 | 1069 |
| 43.95 | 94.54 | 87.80 | 84.87 | 946 |
| 44.25 | 93.71 | 86.90 | 83.97 | 956 |
| 44.55 | 110.00 | 103.80 | 100.87 | 796 |
| 44.85 | 119.66 | 113.86 | 110.93 | 724 |
| 45.15 | 138.93 | 133.83 | 130.90 | 613 |
| 45.45 | 157.61 | 153.21 | 150.28 | 534 |
| 45.75 | 177.00 | 173.30 | 170.37 | 471 |
| 46.05 | 193.52 | 190.42 | 187.49 | 428 |
| 46.35 | 231.33 | 230.60 | 227.67 | 353 |
| 46.65 | 235.79 | 234.29 | 231.36 | 347 |
| 47.025 | 248.87 | 247.87 | 244.94 | 328 |
| $z=2.5$ |  |  |  |  |
| 0.00 | 126.35 | 120.75 | 117.82 | 681 |
| 6.00 | 133.53 | 128.23 | 125.30 | 641 |
| 9.00 | 138.97 | 133.87 | 130.94 | 613 |
| 12.00 | 140.53 | 135.50 | 132.57 | 606 |
| 15.00 | 139.45 | 134.35 | 131.42 | 611 |
| 18.00 | 123.53 | 117.83 | 114.90 | 699 |
| 21.00 | 123.78 | 118.13 | 115.20 | 697 |
| 23.25 | 127.72 | 122.22 | 119.30 | 673 |
| 24.75 | 123.74 | 118.10 | 115.17 | 697 |
| 26.25 | 127.25 | 121.75 | 118.82 | 676 |
| 27.75 | 122.86 | 117.16 | 114.23 | 703 |
| 29.10 | 120.08 | 114.30 | 111.37 | 721 |
| 30.30 | 110.92 | 104.77 | 101.84 | 788 |
| 31.50 | 107.08 | 100.78 | 97.85 | 820 |
| 32.70 | 95.33 | 88.60 | 85.67 | 937 |
| 33.75 | 85.68 | 89.00 | 86.07 | 933 |
| 34.65 | 87.00 | 80.00 | 77.07 | 1042 |
| 35.55 | 82.76 | 75.56 | 72.63 | 1105 |
| 36.45 37.20 | 79.00 77.79 | 71.70 70.44 | 68.77 67.51 | 1167 1189 |
| 37.20 37.80 | 77.79 73.34 | 70.44 65.79 | 67.51 62.86 | 1277 |
| 37.80 38.40 | 73.37 | 65.82 | 62.89 | 1277 |
| 39.00 | 72.89 | 65.34 | 62.41 | 1286 |
| 39.60 | 70.85 | 63.25 | 60.32 | 1331 |
| 40.05 | 72.54 | 65.00 | 62.07 | 1293 |

Table I - contd.

| $z=2.5$ |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: |
| r | F.a | $\mathrm{E}_{0}$ | $E_{c}$ | Temperature |
| 40.35 | 74.86 | 67.36 | 64.43 | 1246 |
| 40.65 | 75.23 | 67.73 | 64.80 | 1239 |
| 40.95 | 78.89 | 71.49 | 68.56 | 1171 |
| 41.25 | 71.62 | 64.02 | 61.09 | 1314 |
| 41.55 | 73.79 | 66.29 | 63.36 | 1267 |
| 41.85 | 76.26 | 68.86 | 65.93 | 1218 |
| 42.15 | 74.29 | 66.79 | 63.86 | 1257 |
| 42.45 | 78.00 | 70.60 | 67.67 | 1186 |
| 42.75 | 84.14 | 77.04 | 74.11 | 1083 |
| 43.05 | 79.54 | 72.24 | 69.31 | 1158 |
| 43.35 | 87.00 | 80.00 | 77.07 | 1042 |
| 43.65 | 88.28 | 81.28 | 78.35 | 1025 |
| 43.95 | 101.24 | 94.74 | 91.81 | 874 |
| 44.25 | 111.88 | 105.68 | 102.75 | 781 |
| 44.55 | 125.57 | 120.00 | 117.07 | 686 |
| 44.85 | 138.95 | 133.75 | 130.82 | 614 |
| 45.15 | 157.69 | 153.29 | 150.36 | 534 |
| 45.45 | 177.27 | 173.57 | 170.64 | 470 |
| 45.75 | 204.84 | 202.14 | 199.21 | 403 |
| 46.05 | 234.00 | 232.40 | 229.47 | 350 |
| 46.35 | 234.66 | 233.06 | 230.13 | 349 |
| 46.725 | 248.60 | 247.60 | 244.67 | 328 |
| $z=3.5$ |  |  |  |  |
| 0.00 | 112.10 | 106.00 | 103.07 | 780 |
| 6.00 | 104.13 | 97.73 | 94.80 | 847 |
| 9.0 | 116.78 | 110.90 | 108.00 | 743 |
| 12.00 | 120.69 | 114.89 | 112.00 | 717 |
| 15.00 | 112.60 | 106.50 | 103.57 | 775 |
| 18.00 | 108.47 | 102.22 | 99.29 | 809 |
| 21.00 | 106.38 | 100.10 | 97.17 | 826 |
| 23.25 | 108.00 | 101.75 | 98.82 | 812 |
| 24.75 | 106.40 | 100.10 | 97.17 | 826 |
| 26.25 | 104.00 | 97.60 | 94.67 | 848 |
| 27.75 | 100.39 | 94.00 | 91.07 | 882 |
| 29.10 | 95.93 | 89.23 | 86.30 | 930 |
| 30.30 | 91.14 | 84.30 | 81.37 | , 987 |
| 31.50 | 89.04 | 82.10 | 79.17 | 1014 |
| 32.70 | 82.00 | 74.80 | 71.87 | 1117 |
| 33.75 | 82.89 | 75.70 | 72.77 | 1103 |
| 34.65 | 75.80 | 68.35 | 65.42 | 1227 |
| 35.55 | 72.27 | 64.67 | 61.74 | 1300 |
| 36.45 | 72.70 | 65.15 | 62.22 | 1290 |

Table I - contd.

| $z=3.5$ |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: |
| $r$ | $\delta_{a}$ | $\delta_{b}$ | $\delta_{0}$ | Temperature |
| 37.20 | 68.35 | 60.65 | 57.72 | 1391 |
| 37.80 | 68.57 | 60.87 | 57.94 | 1385 |
| 38.40 | 66.40 | 58.60 | 55.67 | 1442 |
| 39.00 | 67.88 | 60.13 | 57.20 | 1404 |
| 39.60 | 68.57 | 60.87 | 57.94 | 1385 |
| 40.05 | 71.20 | 63.60 | 60.67 | 1323 |
| 40.35 | 68.60 | 60.90 | 57.97 | 1385 |
| 40.65 | 69.84 | 62.20 | 59.27 | 1355 |
| 40.95 | 70.60 | 63.00 | 60.07 | 1337 |
| 41.25 | 71.45 | 63.85 | 60.92 | 1318 |
| 41.55 | 78.23 | 70.83 | 67.90 | 1182 |
| 41.85 | 74.68 | 67.18 | 64.25 | 1250 |
| 42.15 | 80.46 | 73.16 | 70.23 | 1143 |
| 42.45 | 83.66 | 76.56 | 73.63 | 1090 |
| 42.75 | 78.67 | 71.27 | 68.34 | 1175 |
| 43.05 | 87.90 | 80.90 | 77.97 | 1030 |
| 43.35 | 95.81 | 89.11 | 86.18 | 932 |
| 43.65 | 99.49 | 93.00 | 90.07 | 891 |
| 43.95 | 118.05 | 112.15 | 109.22 | 735 |
| 44.25 | 129.39 | 123.89 | 120.96 | 664 |
| 44.55 | 146.27 | 141.47 | 138.54 | 579 |
| 44.85 | 159.86 | 155.56 | 152.63 | 526 |
| 45.15 | 188.66 | 185.46 | 182.53 | 440 |
| 45.45 | 216.98 | 214.78 | 211.35 | 379 |
| 45.75 | 229.35 | 227.55 | 224.62 | 357 |
| 46.35 | 256.44 | 255.64 | 252.71 | 318 |
| $z=4.5$ |  |  |  |  |
| 0.00 | 92.83 | 86.03 | 83.10 | 966 |
| 6.00 | 96.84 | 90.14 | 87.21 | 921 |
| 9.00 | 94.14 | 87.40 | 84.47 | 950 |
| 12.00 | 97.99 | 91.39 | 88.46 | 908 |
| 15.00 | 91.77 | 84.92 | 82.00 | 979 |
| 18.00 | 94.09 | 87.29 | 84.36 | 952 |
| 21.00 | 90.86 | 84.00 | 81.07 | 990 |
| 23.25 | 87.33 | 80.30 | 77.37 | 1038 |
| 24.75 | 86.15 | 79.10 | 76.17 | 1054 |
| 26.25 | 87.98 | 80.98 | 78.05 | 1029 |
| 27.75 | 84.81 | 77.71 | 74.78 | 1074 |
| 29.10 | 82.09 | 74.89 | 71.96 | 1116 |
| 30.30 | 79.90 | 72.60 | 69.67 | 1152 |
| 31.50 | 77.33 | 69.93 | 67.00 | 1198 |

```
Table I - contd.
```

| $z=4.5$ |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: |
| $r$ | Sa | sb | $5_{0}$ | Temperature |
| 32.70 | 73.19 | 65.64 | 62.71 | 1280 |
| 33.75 | 73.09 | 65.54 | 62.61 | 1282 |
| 34.65 | 69.00 | 61.30 | 58.37 | 1375 |
| 35.55 | 66.70 | 58.90 | 56.00 | 1434 |
| 36.45 | 63.72 | 55.82 | 52.89 | 1518 |
| 37.20 | 65.20 | 57.35 | 54.42 | 14 '75 |
| 37.80 | 63.66 | 55.76 | 52.83 | 1520 |
| 38.40 | 64.69 | 56.80 | 53.87 | 1490 |
| 39.00 | 62.37 | 54.42 | 51.49 | 1559 |
| 39.60 | 69.79 | 62.14 | 59.21 | 1356 |
| 40.05 | 64.47 | 56.60 | 53.67 | 1496 |
| 40.35 | 66.25 | 58.45 | 55.52 | 1446 |
| 40.65 | 65.82 | 58.00 | 55.07 | 1458 |
| 40.95 | 73.27 | 65.72 | 62.79 | 1279 |
| 41.25 | 74.27 | 66.77 | 63.84 | 1258 |
| 41.55 | 75.68 | 68.23 | 65.30 | 1229 |
| 41.85 | 81.36 | 74.11 | 71.18 | 1128 |
| 42.15 | 79.50 | 72.20 | 69.27 | 1159 |
| 42.45 | 81.31 | 74.10 | 71.07 | 1130 |
| 42.75 | 93.65 | 86.85 | 83.92 | 957 |
| 43.05 | 95.34 | 88.64 | 85.71 | 937 |
| 43.35 | 111.05 | 104.95 | 102.02 | 787 |
| 43.65 | 119.03 | 113.18 | 110.25 | 728 |
| 43.95 | 145.60 | 140.75 | 137.82 | 583 |
| 44.25 | 153.02 | 148.42 | 145.49 | 552 |
| 44.55 | 178.32 | 174.67 | 171.74 | 467 |
| 44.85 | 197.45 | 194.50 | 191.57 | 419 |
| 45.15 | 225.54 | 223.64 | 220.71 | 364 |
| 45.45 | 247.52 256.81 | 246.42 | 243.49 | 330 |
| 46.05 | 256.81 | 256.11 | 253.18 | 317 |
| $z=6$ |  |  |  |  |
| 0.00 | 76.05 | 68.60 | 65.67 | 1222 |
| 6.00 | 76.75 | 69.30 | 66.37 | 1209 |
| 9.00 | 81.40 | 74.18 | 71.25 | 1127 |
| 12.00 | 80.50 | 73.25 | 70.32 | 1142 |
| 15.00 | 80.65 | 73.40 | 70.47 | 1139 |
| 18.00 | 79.17 | 71.87 | 68.94 | 1146 |
| 21.00 | 71.47 | 63.87 | 60.94 | 1317 |
| 23.25 | 71.28 | 63.68 | 60.75 | 1322 |
| 24.75 | 72.27 | 64.67 | 61.74 | 1300 |
| 26.25 | 69.29 | 62.59 | 59.66 | 1346 |
| 27.75 | 67.92 | 60.17 | 57.24 | 1403 |
| 29.10 | 70.79 | 63.15 | 60.22 | 1333 |

Table I - conta.

| $z=6$ |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: |
| $r$ | $5_{a}$ | $S_{b}$ | $\varepsilon_{C}$ | Temperature |
| 30.30 | 66.52 | 58.72 | 55.79 | 1439 |
| 31.50 | 66.84 | 59.04 | 56.11 | 1431 |
| 32.70 | 62.98 | 55.05 | 52.12 | 1540 |
| 33.75 | 62.73 | 54.80 | 51.87 | 1548 |
| 34.65 | 63.58 | 56.68 | 53.75 | 1494 |
| 35.55 | 60.95 | 52.95 | 50.02 | 1605 |
| 36.45 | 62.80 | 54.87 | 51.94 | 1546 |
| 37.20 | 52.12 | 43.82 | 41.89 | 1917 |
| 37.80 | 71.29 | 63.69 | 60.76 | 1321 |
| 38.40 | 60.94 | 52.94 | 50.01 | 1605 |
| 39.00 | 66.34 | 58.54 | 55.61 | 1444 |
| 39.60 | 64.34 | 56.44 | 53.51 | 1500 |
| 40.05 | 66.00 | 58.20 | 55.27 | 1453 |
| 40.35 | 76.23 | 68.80 | 65.87 | 1219 |
| 40.65 | 70.10 | 62.40 | 59.47 | 1350 |
| 40.95 | 76.06 | 68.60 | 65.67 | 1222 |
| 41.25 | 77.33 | 69.93 | 67.00 | 1198 |
| 41.55 | 79.54 | 72.24 | 68.31 | 1175 |
| 41.85 | 86.18 | 79.13 | 77.20 | 1040 |
| 42.15 | 101.87 | 95.37 | 94.44 | 850 |
| 42.45 | 89.84 | 83.00 | 80.07 | 1003 |
| 42.75 | 112.09 | 106.00 | 103.07 | 779 |
| 43.05 | 129.45 | 124.00 | 101.07 | 794 |
| 43.35 | 147.14 | 142.34 | 139.41 | 576 |
| 43.65 | 176.73 | 173.03 | 170.10 | 472 |
| 43.95 | 179.09 | 175.49 | 172.56 | 465 |
| 44.25 | 214.03 | 211.73 | 208.80 | 384 |
| 44.55 | 248.11 | 247.06 | 244.13 | 329 |
| 45.45 | 254.82 | 254.02 | 251.19 | 320 |
| $z=7$ |  |  |  |  |
| 0.00 | 69.38 | 61.68 | 62.18 |  |
| 6.00 | 67.85 | 60.10 | 60.60 | 1415 |
| 9.00 | 70.00 | 62.30 | 62.80 | 1366 |
| 12.00 | 73.11 | 65.56 | 66.06 | 1298 |
| 15.00 | 72.30 | 64.70 | 65.20 | 1316 |
| 18.00 | 69.44 | 61.74 | 62.24 | 1378 |
| 21.00 | 66.00 | 58.20 | 58.70 | 14.61 |
| 23.25 | 63.75 | 56.85 | 57.30 | 1497 |
| 24.75 | 66.55 | 58.75 | 59.25 | 1448 |
| 26.25 | 65.55 | 57.86 | 58.36 | 1470 |
| 27.75 | 61.41 | 53.41 | 53.91 | 1591 |
| 29.10 | 62.96 | 55.06 | 55.56 | 1544 |

Table $I$ - conta.

| $z=7$ |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: |
| r | $\mathrm{C}_{2}$ | 50 | $\varepsilon_{0}$ | Temperature |
| 30.30 | 59.05 | 50.95 | 51.45 | 1667 |
| 31.50 | 62.37 | 54.40 | 54.90 | 1562 |
| 32.70 | 59.00 | 50.95 | 51.45 | 1667 |
| 33.75 | 59.74 | 51.74 | 52.24 | 1642 |
| 34.65 | 63.58 | 55.68 | 56.18 | 1527 |
| 35.55 | 61.21 | 53.21 | 53.71 | 1597 |
| 36.45 | 63.10 | 55.20 | 55.70 | 1540 |
| 37.20 | 60.74 | 52.74 | 53.24 | 1611 |
| 37.80 | 64.65 | 56.70 | 57.20 | 1500 |
| 38.40 | 64.81 | 56.86 | 57.36 | 1495 |
| 39.00 | 61.74 | 53.74 | 54.24 | 1581 |
| 39.60 | 67.70 | 60.00 | 60.50 | 1418 |
| 40.05 | 64.31 | 56.36 | 56.86 | 1509 |
| 40.35 | 77.97 | 70.60 | 71.10 | 1206 |
| 40.65 | 72.79 | 65.24 | 65.74 | 1305 |
| 40.95 | 74.67 | 67.17 | 67.67 | 1268 |
| 41.25 | 90.03 | 83.13 | 83.63 | 1026 |
| 41.55 | 88.90 | 82.00 | 82.50 | 1040 |
| 41.85 | 93.12 | 86.32 | 86.82 | 988 |
| 42.15 | 111.55 | 105.45 | 105.95 | 810 |
| 42.45 | 111.68 | 105.00 | 105.50 | 813 |
| 42.75 | 142.89 | 137.94 | 138.44 | 620 |
| 43.05 | 148.66 | 143.91 | 144.41 | 594 |
| 43.35 | 176.00 | 172.30 | 172.80 | 496 |
| 43.65 | 207.61 | 205.06 | 205.56 | 417 |
| 43.95 | 232.12 | 230.47 | 230.97 | 377 |
| 44.25 | 252.20 | 251.30 | 251.80 | 341 |
| 45.15 | 260.74 | 260.14 | 1260.64 | 329 |
|  |  | $z=8$ |  |  |
| 0.00 | 64.095 | 56.00 | 56.50 | 1518 |
| 6.00 | 57.50 | 49.40 | 49.90 | 1719 |
| 9.00 | 68.79 | 60.79 | 61.29 | 1400 |
| 12.00 | 66.55 | 58.75 | 59.25 | 1448 |
| 15.00 | 65.90 | 53.10 | 58.60 | 1464 |
| 18.00 | 66.00 | 58.20 | 58.70 | 1461 |
| 21.00 | 62.96 | 55.04 | 55.54 | 1544 |
| 23.25 | 64.37 | 56.47 | 56.97 | 1506 |
| 24.75 | 59.65 | 51.60 | 52.10 | 1646 |
| 26.25 | 62.23 | 54.28 | 54.78 | 1566 |
| 27.75 | 61.74 | 53.74 | 54.24 | 1581 |
| 29.10 | 60.00 | 51.95 | 52.45 | 1635 |
| 30.30 | 60.94 | 53.00 | 53.50 | 1603 |

Table I - conta.

| $z=8$ |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: |
| r | Sa | $\varepsilon_{b}$ | $\delta_{0}$ | Temperature |
| 31.50 | 60.00 | 51.95 | 52.45 | 1635 |
| 32.70 | 58.10 | 50.00 | 50.50 | 1699 |
| 33.75 | 60.18 | 53.00 | 53.50 | 1603 |
| 34.65 | 64.44 | 56.54 | 57.04 | 1504 |
| 35.55 | 63.45 | 55.55 | 56.05 | 1530 |
| 36.45 | 66.36 | 58.56 | 59.06 | 1452 |
| 37.20 | 66.36 | 58.56 | 59.06 | 1452 |
| 37.80 | 64.44 | 56.54 | 57.04 | 1504 |
| 38.40 | 67.80 | 60.05 | 60.55 | 1417 |
| 39.00 | 67.80 | 60.05 | 60.55 | 1417 |
| 39.60 | 69.82 | 62.12 | 62.62 | 1370 |
| 40.05 | 68.40 | 60.70 | 61.20 | 1402 |
| 40.35 | 79.23 | 71.93 | 72.43 | 1184 |
| 40.65 | 77.68 | 70.28 | 70.78 | 1212 |
| 40.95 | 85.12 | 78.00 | 78.50 | 1093 |
| 41.25 | 92.00 | 85.15 | 85.65 | 1001 |
| 41.55 | 100.67 | 94.17 | 94.67 | 906 |
| 41.85 | 106.78 | 100.48 | 100.98 | 849 |
| 42.15 | 129.00 | 123.50 | 124.00 | 692 |
| 42.45 | 145.61 | 140.76 | 141.26 | 607 |
| 42.75 | 170.15 | 166.15 | 166.65 | 515 |
| 43.05 | 179.77 | 176.17 | 176.67 | 486 |
| 43.35 | 230.09 | 228.39 | 228.89 | 375 |
| 43.80 | 249.55 | 248.55 | 249.05 | 344 |
| 44.85 | 260.68 | 260.08 | 260.58 | 329 |
|  |  | $z=9.0$ |  |  |
| 0.00 | 63.48 | 55.58 | 59.60 | 1534 |
| 4.20 | 61.73 | 53.73 | 57.75 | 1583 |
| 7.20 | 64.41 | 56.51 | 60.53 | 1510 |
| 10.20 | 64.68 | 56.83 | 60.85 | 1502 |
| 13.20 | 66.29 | 58.49 | 62.51 | 1462 |
| 16.20 | 65.95 | 58.15 | 62.17 | 1470 |
| 19.20 | 62.40 | 54.45 | 58.47 | 1563 |
| 22.20 | 65.20 | 57.35 | 61.37 | 1489 |
| 25.20 | 61.58 | 53.58 | 57.60 | 1587 |
| 27.30 | 61.10 | 53.10 | 57.12 | 1600 |
| 28.50 | 61.30 | 53.30 | 57.32 | 1596 |
| 29.70 | 61.33 | 53.33 | 57.35 | 1594 |
| 30.90 | 62.10 | 54.15 | 58.17 | 1571 |
| 31.95 | 62.91 | 55.00 | 59.02 | 1549 |
| 32.85 | 63.33 | 56.43 | 60.45 | 1512 |
| 33.75 | 70.13 | 62.48 | 66.50 | 1374 |
| 34.65 | 66.62 | 58.82 | 62.84 | 1454 |

Table I - contd.

| $z=9.0$ |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: |
| $r$ | $S_{a}$ | $\delta_{b}$ | $\mathrm{Sc}_{\mathrm{c}}$ | Temperature |
| 35.55 | 73.57 | 66.00 | 70.02 | 1305 |
| 36.30 | 73.37 | 65.80 | 69.82 | 1309 |
| 36.90 | 73.66 | 66.00 | 70.02 | 1305 |
| 37.50 | 69.18 | 61.48 | 65.50 | 1395 |
| 38.10 | 65.28 | 57.43 | 61.45 | 1487 |
| 38.70 | 66.58 | 58.78 | 62.80 | 1455 |
| 39.15 | 68.80 | 61.10 | 65.12 | 1404 |
| 39.45 | 69.84 | 62.20 | 66.22 | 1380 |
| 39.75 | 72.22 | 64.62 | 68.64 | 1332 |
| 40.05 | 74.38 | 66.88 | 70.90 | 1289 |
| 40.35 | 81.68 | 74.43 | 78.45 | 1165 |
| 40.65 | 83.69 | 76.49 | 80.51 | 1135 |
| 40.95 | 96.38 | 89.68 | 93.70 | 975 |
| 41.25 | 106.26 | 100.00 | 104.02 | 879 |
| 41.55 | 126.55 | 121.00 | 125.02 | 731 |
| 41.85 | 138.31 | 133.21 | 137.23 | 666 |
| 42.15 | 156.29 | 151.79 | 155.81 | 587 |
| 42.45 | 193.79 | 190.69 | 194.71 | 469 |
| 42.75 | 211.73 | 209.33 | 213.35 | 428 |
| 43.05 | 246.57 | 245.47 | 249.49 | 366 |
| 43.35 | 246.80 | 246.70 | 250.72 | 365 |
| 43.80 | 248.77 | 247.77 | 251.79 | 363 |
|  |  | $z=10.0$ |  |  |
| 0.00 | 69.20 |  |  | 1395 |
| 5.50 | 66.40 | 58.50 | 62.52 | 1462 |
| 11.10 | 63.00 | 55.10 | 59.12 | 1546 |
| 15.60 | 68.60 | 60.90 | 64.92 | 1409 |
| 18.60 | 67.70 | 59.95 | 63.97 | 1429 |
| 21.60 | 69.14 | 61.44 | 65.46 | 1396 |
| 23.85 | 64.20 | 56.30 | 60.32 | 1515 |
| 25.35 | 63.76 | 55.86 | 59.88 | 1526 |
| 26.70 | 54.57 | 46.32 | 50.34 | 1815 |
| 27.90 | 85.11 | 78.00 | 82.02 | 1114 |
| 29.10 | 67.81 | 60.00 | 64.02 | 1428 |
| 30.30 | 73.91 | 66.41 | 70.43 | 1298 |
| 31.50 | 71.36 | 63.76 | 67.78 | 1348 |
| 32.70 | 72.37 | 64.77 | 68.79 | 1329 |
| 33.75 | 80.50 | 73.25 | 77.27 | 1183 |
| 34.80 | 81.80 | 74.60 | 78.62 | 1163 |
| 35.40 | 77.10 | 69.70 | 73.72 | 1240 |
| 36.00 | 86.40 | 79.35 | 83.37 | 1096 |
| 36.60 | 81.13 | 73.88 | 77.90 | 1173 |

Table I - contd.
$z=10.0$

| $r$ | $S_{a}$ | $8_{b}$ | $S_{0}$ | Temperature |
| :---: | :---: | :---: | :---: | :---: |
| 37.20 | 76.48 | 72.00 | 76.02 | 1202 |
| 37.80 | 70.57 | 62.92 | 66.94 | 1365 |
| 38.40 | 67.24 | 59.49 | 63.51 | 1439 |
| 38.85 | 74.15 | 66.65 | 70.67 | 1293 |
| 39.15 | 68.36 | 60.60 | 64.62 | 1414 |
| 39.45 | 70.77 | 63.17 | 67.19 | 1360 |
| 39.75 | 74.60 | 67.00 | 71.02 | 1287 |
| 40.05 | 87.72 | 80.72 | 84.74 | 1079 |
| 40.35 | 87.00 | 80.00 | 84.02 | 1088 |
| 40.65 | 93.81 | 87.00 | 91.02 | 1004 |
| 41.25 | 127.73 | 122.23 | 126.25 | 724 |
| 41.55 | 146.93 | 142.13 | 146.15 | 625 |
| 41.85 | 182.74 | 179.24 | 183.26 | 499 |
| 42.15 | 198.14 | 195.24 | 199.26 | 459 |
| 42.45 | 218.59 | 216.49 | 220.51 | 414 |
| 43.20 | 255.56 | 254.76 | 258.78 | 353 |
| 44.70 | 262.57 | 262.07 | 266.09 | 343 |
|  |  | $z=11.5$ |  |  |
| 0.00 | 86.27 | 79.22 | 83.24 | 1098 |
| 4.26 | 88.07 | 81.07 | 85.09 | 1074 |
| 7.20 | 78.59 | 71.24 | 75.26 | 1214 |
| 10.20 | 73.56 | 66.00 | 70.02 | 1305 |
| 13.20 | 83.13 | 75.93 | 79.95 | 1143 |
| 16.20 | 82.87 | 75.67 | 79.69 | 1147 |
| 19.20 | 85.25 | 78.15 | 82.17 | 1112 |
| 22.20 | 88.60 | 81.60 | 85.62 | 1067 |
| 25.20 | 89.71 | 82.81 | 86.83 | 1053 |
| 27.30 | 86.44 | 79.39 | 83.41 | 1096 |
| 28.50 | 91.26 | 84.36 | 88.38 | 1034 |
| 29.70 | 90.40 | 83.50 | 87.52 | 1044 |
| 30.90 | 91.12 | 85.00 | 89.02 | 1027 |
| 31.95 | 91.95 | 85.10 | 89.12 | 1026 |
| 32.85 | 92.41 | 85.61 | 89.63 | 1020 |
| 33.75 | 93.71 | 86.91 | 90.93 | 1005 |
| 34.65 | 98.35 | 91.75 | 95.77 | 954 |
| 35.55 | 103.00 | 96.55 | 100.57 | 909 |
| 36.30 | 104.43 | 98.00 | 102.02 | 896 |
| 36.90 | . 96.44 | 89.74 | 93.76 | 975 |
| 37.50 | . 91.48 | 84.63 | 83.65 | 1031 |
| 38.10 | 78.61 | 71.25 | 75.27 | 1214 |
| 38.70 | 72.34 | 64.74 | 68.76 | 1329 |
| 39.15 | 79.36 | 72.00 | 76.02 | 1202 |

Table I - contd.

| $z=11.5$ |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: |
| $r$ | $b_{a}$ | $S_{6}$ | $\delta_{c}$ | Temperature |
| $\begin{aligned} & 39.45 \\ & 39.75 \\ & 40.05 \\ & 40.35 \\ & 40.65 \\ & 40.95 \\ & 41.25 \\ & 41.55 \\ & 41.85 \\ & 42.15 \\ & 43.20 \\ & 44.70 \end{aligned}$ | $\begin{array}{r} 88.54 \\ 87.35 \\ 97.29 \\ 116.37 \\ 128.12 \\ 160.84 \\ 172.74 \\ 204.56 \\ 230.26 \\ 244.42 \\ 255.32 \\ 258.81 \end{array}$ | $\begin{array}{r} 81.54 \\ 80.35 \\ 90.69 \\ 110.42 \\ 122.62 \\ 156.54 \\ 168.84 \\ 201.86 \\ 228.56 \\ 243.22 \\ 254.52 \\ 258.16 \end{array}$ | $\begin{array}{r} 85.56 \\ 84.37 \\ 94.71 \\ 114.44 \\ 126.64 \\ 160.56 \\ 172.86 \\ 205.88 \\ 232.58 \\ 247.24 \\ 258.54 \\ 262.18 \end{array}$ | $\begin{array}{r} 1068 \\ 1083 \\ 965 \\ 798 \\ 722 \\ 569 \\ 529 \\ 444 \\ 393 \\ 370 \\ 354 \\ 349 \end{array}$ |
|  |  | $z=12.5$ |  |  |
| $\begin{array}{r} 0.00 \\ 4.20 \\ 7.20 \\ 10.20 \\ 13.20 \\ 16.20 \\ 19.20 \\ 22.20 \\ 25.20 \\ 27.30 \\ 28.50 \\ 29.70 \\ 30.90 \\ 31.95 \\ 32.85 \\ 33.75 \\ 34.65 \\ 35.55 \\ 36.30 \\ 36.90 \\ 37.50 \\ 38.10 \\ 38.70 \\ 39.15 \\ 39.45 \\ 39.75 \\ 40.05 \\ 40.35 \\ 40.65 \end{array}$ | $\begin{array}{r} 96.82 \\ 94.11 \\ 92.54 \\ 97.96 \\ 94.73 \\ 101.02 \\ 102.00 \\ 106.61 \\ 107.89 \\ 104.17 \\ 108.92 \\ 107.29 \\ 108.07 \\ 109.80 \\ 108.52 \\ 109.55 \\ 113.11 \\ 114.06 \\ 112.00 \\ 117.64 \\ 101.58 \\ 103.17 \\ 100.97 \\ 100.92 \\ 107.51 \\ 127.00 \\ 129.80 \\ 145.52 \\ 160.06 \end{array}$ | 90.12 87.31 85.74 91.36 88.00 94.50 95.50 100.30 101.64 97.77 102.72 101.00 101.82 103.60 102.27 103.25 107.06 108.06 105.90 111.74 95.10 96.77 94.47 94.42 101.20 121.45 126.40 140.67 155.76 | $\begin{array}{r} 94.14 \\ 91.33 \\ 89.76 \\ 95.38 \\ 92.02 \\ 98.52 \\ 99.52 \\ 104.32 \\ 105.66 \\ 101.79 \\ 106.74 \\ 105.02 \\ 105.84 \\ 107.62 \\ 106.29 \\ 107.27 \\ 111.08 \\ 112.08 \\ 109.92 \\ 115.76 \\ 99.12 \\ 100.79 \\ 98.49 \\ 98.44 \\ 105.22 \\ 125.47 \\ 130.42 \\ 144.69 \\ 159.78 \end{array}$ | $\begin{array}{r} 971 \\ 1001 \\ 1018 \\ 958 \\ 993 \\ 928 \\ 918 \\ 876 \\ 865 \\ 898 \\ 856 \\ 870 \\ 864 \\ 849 \\ 860 \\ 852 \\ 823 \\ 815 \\ 831 \\ 790 \\ 922 \\ 907 \\ 928 \\ 928 \\ 869 \\ 728 \\ 701 \\ 632 \\ 572 \end{array}$ |

Table $I-\operatorname{conta}$.
$z=12.5$

| $r$ | $\varepsilon_{a}$ | $\delta_{0}$ | $6_{C}$ | Temperature |
| :---: | :---: | :---: | :---: | :---: |
| 40.95 | 191.31 | 188.11 | 192.13 | 476 |
| 41.25 | 221.20 | 219.20 | 223.22 | 409 |
| 41.55 | 230.41 | 228.71 | 232.73 | 393 |
| 41.85 | 252.00 | 251.10 | 255.12 | 358 |
| 42.15 | 249.38 | 248.00 | 252.02 | 363 |
| 43.20 | 255.45 | 254.65 | 258.67 | 353 |
| 44.70 | 258.81 | 258.11 | 262.13 | 349 |
|  |  | 13.5 |  |  |
| 0.00 | 105.77 | 99.42 | 103.44 | 884 |
| 4.20 | 107.13 | 100.83 | 104.85 | 872 |
| 7.20 | 111.68 | 105.53 | 109.55 | 834 |
| 10.20 | 118.12 | 112.22 | 116.24 | 786 |
| 13.20 | 122.07 | 116.32 | 120.34 | 760 |
| 16.20 | 122.96 | 117.22 | 121.24 | 754 |
| 19.20 | 132.45 | 127.10 | 131.12 | 697 |
| 22.20 | 126.30 | 120.70 | 124.72 | 733 |
| 25.20 | 130.82 | 125.42 | 129.44 | 706 |
| 27.30 | 134.66 | 129.41 | 133.43 | 685 |
| 28.50 | 134.96 | 129.71 | 133.73 | 683 |
| 29.70 | 133.00 | 127.70 | 131.72 | 694 |
| 30.90 | 131.23 | 125.83 | 129.85 | 704 |
| 31.95 | 128.27 | 122.77 | 126.79 | 721 |
| 32.85 | 129.16 | 123.66 | 127.68 | 716 |
| 33.75 | 120.37 | 114.57 | 118.59 | 771 |
| 34.65 | 131.13 | 125.73 | 129.75 | 704 |
| 35.55 | 129.00 | 123.50 | 127.52 | 717 |
| 36.30 | 131.73 | 126.38 | 130.40 | 701 |
| 36.90 | 133.00 | 127.70 | 131.72 | 694 |
| 37.50 | 129.10 | 123.60 | 127.62 | 716 |
| 38.10 | 132.93 | 127.63 | 131.65 | 694 |
| 38.70 | 132.17 | 126.82 | 130.84 | 699 |
| 39.15 | 142.59 | 137.59 | 141.61 | 645.41 |
| 39.45 | 141.74 | 136.74 | 140.76 | 649 |
| 39.75 | 154.44 | 150.00 | 154.02 | 593 |
| 40.05 | 165.58 | 161.48 | 165.50 | 552 |
| 40.35 | 174.19 | 170.39 | 174.41 | 524 |
| 40.65 | 205.33 | 202.68 | 206.70 | 442 |
| 40.95 | 226.33 | 224.43 | 228.45 | 400 |
| 41.25 | 232.11 | 230.46 | 234.48 | 390 |
| 41.55 | 236.78 | 235.28 | 239.30 | 382 |
| 41.85 | 251.06 | 250.00 | 254.02 | 360 |
| 42.15 | 248.87 | 249.87 | 253.89 | 360 |
| 43.20 | 255.74 | 255.00 | 259.02 | 353 |
| 44.75 | 260.17 | 259.57 | 263.59 | 347 |

```
Table I - contd.
```

$z=14.5$

| $r$ | 1 a | ${ }^{5}$ | $\delta_{c}$ | Temperature |
| :---: | :---: | :---: | :---: | :---: |
| 0.00 | 151.58 | 146.93 | 150.95 | 605 |
| 4.20 | 148.53 | 143.78 | 147.80 | 618 |
| 7.20 | 142.30 | 137.30 | 141.32 | 647 |
| 10.20 | 138.36 | 133.26 | 137.28 | 666 |
| 13.20 | 151.61 | 147.00 | 151.02 | 605 |
| 16.20 | 155.40 | 150.90 | 154.92 | 590 |
| 19.20 | 157.38 | 153.00 | 157.02 | 584 |
| 22.20 | 164.00 | 159.80 | 163.82 | 558 |
| 25.20 | 168.60 | 164.60 | 168.62 | 542 |
| 27.30 | 168.36 | 164.36 | 168.38 | 543 |
| 28.50 | 171.19 | 167.29 | 171.31 | 533 |
| 29.70 | 163.20 | 159.00 | 163.02 | 561 |
| 30.90 | 159.00 | 154.65 | 158.67 | 576 |
| 31.95 | 149.53 | 144.83 | 148.85 | 614 |
| 32.85 | 150.45 | 146.00 | 150.82 | 609 |
| 33.75 | 148.14 | 143.39 | 147.41 | 620 |
| 34.65 | 153.00 | 148.40 | 152.42 | 600 |
| 35.55 | 153.00 | 148.40 | 152.42 | 600 |
| 36.30 | 151.75 | 147.10 | 151.12 | 605 |
| 36.90 | 152.51 | 147.90 | 151.92 | 602 |
| 37.50 | 158.60 | 154.20 | 158.22 | 578 |
| 38.10 | 159.67 | 155.37 | 159.39 | 573 |
| 38.70 | 158.46 | 154.11 | 158.13 | 578 |
| 39.15 | 178.87 | 175.27 | 179.29 | 510 |
| 39.45 | 183.02 | 179.57 | 183.59 | 498 |
| 39.75 | 187.00 | 183.70 | 187.72 | 487 |
| 40.05 | 200.60 | 197.75 | 201.77 | 453 |
| 40.35 | 812.00 | 209.60 | 213.62 | 428 |
| 40.65 | 231.00 | 229.30 | 233.32 | 392 |
| 40.95 | 235.67 | 234.17 | 238.19 | 384 |
| 41.25 | 235.67 | 234.17 | 238.19 | 384 |
| 41.55 | 241.68 | 240.38 | 244.40 | 374 |
| 41.85 | 249.87 | 248.87 | 252.89 | 361 |
| 42.15 | 246.00 | 244.85 | 248.87 | 367 |
| 43.20 | 258.11 | 257.41 | 261.43 | 350 |
| 44.85 | 257.30 | 256.55 | 260.57 | 351 |
|  | $z=15.5$ |  |  |  |
| 0.00 | 188.38 | 185.10 |  | 483 |
| 4.20 | 164.00 | 159.80 | 163.82 | 558 |
| 7.20 | 193.38 | 190.33 | 194.35 | 470 |
| 10.20 | 171.49 | 167.59 | 171.61 | 532 |

Table $I-$ contd.
$z=15.5$

| $r$ | $\delta_{a}$ | $\delta_{b}$ | $\delta_{c}$ | Temperature |
| :---: | :---: | :---: | :---: | :---: |
| 13.20 | 192.35 | 189.20 | 193.22 | 473 |
| 16.20 | 189.69 | 186.44 | 190.46 | 480 |
| 19.20 | 194.11 | 191.00 | 195.02 | 467 |
| 22.20 | 205.57 | 202.92 | 206.94 | 442 |
| 25.20 | 207.58 | 205.00 | 209.02 | 437 |
| 27.30 | 207.28 | 204.73 | 208.75 | 438 |
| 28.50 | 210.87 | 208.42 | 212.44 | 430 |
| 29.70 | 206.10 | 203.50 | 207.52 | 440 |
| 30.90 | 196.92 | 193.92 | 197.94 | 462 |
| 31.95 | 179.60 | 176.00 | 180.02 | 508 |
| 32.85 | 182.78 | 179.28 | 183.30 | 499 |
| 33.75 | 174.02 | 170.22 | 174.24 | 525 |
| 34.65 | 174.77 | 171.00 | 175.02 | 522 |
| 35.55 | 181.26 | 178.26 | 182.28 | 501 |
| 36.30 | 183.75 | 180.35 | 184.37 | 496 |
| 36.90 | 181.49 | 178.00 | 182.02 | 502 |
| 37.50 | 185.00 | 181.60 | 185.62 | 492 |
| 38.10 | 184.00 | 180.60 | 184.62 | 495 |
| 38.70 | 192.71 | 189.60 | 193.62 | 472 |
| 39.15 | 207.69 | 205.14 | 209.16 | 437 |
| 39.45 | 202.00 | 199.25 | 203.27 | 450 |
| 39.75 | $214 . .38$ | 212.10 | 216.12 | 423 |
| 40.05 | 219.15 | 217.00 | 221.02 | 414 |
| 40.35 | 230.10 | 228.35 | 232.37 | 393 |
| 40.65 | 234.27 | 232.67 | 236.69 | 386 |
| 40.95 | 237.10 | 235.60 | 239.62 | 381 |
| 41.25 | 239.68 | 238.28 | 242.30 | 377 |
| 41.55 | 242.16 | 240.86 | 244.88 | 373 |
| 41.85 | 247.56 | 246.46 | 250.48 | 365 |
| 42.15 | 248.61 | 247.61 | 251.63 | 363 |
| 43.20 | 255.11 | 254.31 | 258.33 | 354 |
| 45.00 | 262.86 | 262.36 | 266.38 | 343 |

Table II.
All distances in cms., velocity in $\mathrm{cms} / \mathrm{sec}$.
$z$ measured from oxidant side. ( $7.55 \div 11.05 \mathrm{cms}$. ) from the mid-section Plate $1-r=3.0 \times .0905$ of the test space.

| z $\times 11.05$ | $\mathrm{V}_{\mathrm{z}} \times 11.05$ | z $\times 11.05$ | $\mathrm{V}_{\mathrm{z}} \times 11.05$ |
| :---: | :---: | :---: | :---: |
| 1.0 | 40.5 | 0.85 | 48.0 |
| 1.80 | 39.0 | 2.50 | 42.0 |
| 2.95 | 47.0 | 2.95 | 32.0 |
| 3.50 | 46.0 | 3.90 | 35.0 |
| 4.00 | 23.0 | 5.30 | 20.0 |
| 5.20 | 23.0 | 6.50 | 3.0 |
| 5.40 | 19.0 | 8.55 | 2.0 |
| 5.90 | 14.0 | 10.10 | 10.10 |
| 6.40 | 5.0 | 10.90 | 30.0 |
| 6.75 | 4.5 | 12.20 | 34.0 |
| 9.70 | 15.0 | 12.75 | 41.0 |
| 10.30 | 40.0 | 74.20 | 39.0 |
| 10.50 | 28.0 |  |  |
| 10.70 | 29.0 |  |  |
| 10.90 | 24.0 |  |  |
| 11.20 | 31.0 |  |  |
| 11.10 | 29.0 |  |  |
| 11.60 | 39.0 |  |  |
| 12.10 | 38.0 |  |  |
| 12.40 | 38.0 |  |  |
| 13.20 | 45.0 |  |  |
| 13.70 | 40.0 |  |  |
| 13.90 | 42.0 |  |  |
| Flate $2-r=3.0 \times .0905$ |  |  |  |
| 1.50 | 30.0 | 4.65 | 29.0 |
| 1.80 | 38.0 | 4.85 | 31.5 |
| 3.30 | 40.0 | 5.15 | 22.0 |
| 3.80 | 40.0 | 5.20 | 24.0 |
| 4.30 | 34.0 | 6.20 | 14.5 |
| 4.50 | 29.0 | 6.30 | 9.0 |
| 5.25 | 16.0 | 6.85 | 3.5 |
| 5.70 | 14.0 | 6.95 | 3.0 |
| 6.00 | 10.5 | 8.35 | 16.0 |
| 6.50 | 5.0 | 10.95 | 27.0 |
| 7.00 | 3.5 | 13.00 | 26.0 |
| 3.30 | 30.0 |  |  |

Table 2-contd.

| Plate $1-r=4.5 \times .0905$ |  |  |  |
| :---: | :---: | :---: | :---: |
| z $\times 11.05$ | $V_{z} \times 11.05$ | $z \times 11.05$ | $\mathrm{V}_{\mathrm{z}} \times 11.05$ |
| 0.4 | 35.0 | 3.65 | 37.5 |
| 1.2 | 40.5 | 3.80 | 39.0 |
| 2.70 | 45.0 | 4.85 | 38.0 |
| 3.80 | 37.0 | 4.15 | 39.5 |
| 5.30 | 16.0 | 5.85 | 13.0 |
| 4.85 | 19.0 | 6.15 | 4.0 |
| Plate 2. $r=4.5 \times .0905$ |  |  |  |
| 1.40 | 40.0 | 3.15 | 42.0 |
| 2.0 | 43.0 | 4.15 | 35.0 |
| 2.90 | 37.0 | 4.35 | 32.0 |
| 3.30 | 36.0 | 4.85 | 24.0 |
| 3.90 | 34.0 | 5.30 | 20.0 |
| 5.00 | 25.0 | 5.55 | 13.0 |
| 5.25 | 22.5 | 5.95 | 12.0 |
| 5.45 | 17.0 | 6.80 | 3.0 |
| 5.95 | 12.0 | 10.05 | 23.0 |
| 6.15 | 4.5 | 10.20 | 23.0 |
| 6.60 | 4.0 | 10.80 | 27.0 |
| 7.95 | 16.0 | 10.45 | 21.5 |
| 7.70 | 5.0 | 11.70 | 35.5 |
| 11.05 | 31.0 | 10.65 | 29.5 |
| 10.15 | 20.0 |  |  |
| Plate 3. $\mathrm{r}=3.0 \times .0905$ |  |  |  |
| 3.65 | 36.0 | 10.20 | 24.0 |
| 5.20 | 19.5 | 10.60 | 29.0 |
| 5.95 | 10.0 | 11.45 | 34.0 |
| 6.30 | 9.0 | 11.60 | 38.0 |
| 9.40 | 14.0 | 13.10 | 41.5 |
| 9.90 | 21.5 | 14.60 | 36.0 |


| Plate 3. $\mathrm{r}=4.5 \times .0905$ |  |  |  |
| :---: | :---: | :---: | :---: |
| z x 11.05 | $V_{z} \times 11.05$ | z $\times 11.05$ | $V_{z} \times 11.05$ |
| 3.55 | 32.0 | 3.50 | 26.0 |
| 3.60 | 36.0 | 3.90 | 30.0 |
| 3.75 | 33.0 | 4.00 | 35.0 |
| 4.00 | 37.0 | 4.90 | 27.0 |
| 5.05 | 23.0 | 5.95 | 9.0 |
| 5.85 | 10.5 | 6.05 | 15.0 |
| 6.60 | 3.0 | 6.30 | 3.0 |
| 9.00 | 15.0 | 6.35 | 7.0 |
| 9.85 | 19.0 | 6.45 | 6.0 |
| 9.90 | 16.6 | 10.70 | 21.0 |
| 11.10 | 39.5 | 11.00 | 31.5 |
| 12.00 | 36.0 | 12.10 | 38.5 |
| 12.20 | 36.75 | 12.55 | 42.0 |
| 12.45 | 44.00 | 12.70 | 39.5 |
| 12.70 | 42.5 | 13.10 | 41.5 |
| 13.10 | 34.0 | 13.20 | 42.5 |
| 13.30 | 39.0 | 13.80 | 41.0 |
| 2.65 | 30.0 | 13.90 | 40.0 |
| 3.45 | 38.0 | 14.15 | 47.0 |
| Plate 1. $\mathrm{r}=6 \mathrm{x} .0905$ |  |  |  |
| 0.45 | 38.0 | 2.70 | 38.0 |
| 2.50 | 33.0 | 2.90 | 41.7 |
| 2.65 | 35.0 | 3.20 | 39.5 |
| 3.20 | 30.0 | 4.45 | 28.5 |
| 3.35 | 27.0 | 5.10 | 30.0 |
| 3.50 | 26.0 | 5.50 | 22.5 |
| 3.65 | 33.0 | 6.20 | 9.5 |
| 4.05 | 30.0 | 7.50 | 5.0 |
| 4.40 | 22.5 | 7.65 | 12.0 |
| 4.65 | 27.0 | 9.50 | 19.0 |
| 5.10 | 17.5 | 10.00 | 20.0 |
| 5.30 | 18.0 | 10.40 | 24.0 |
| 5.35 | 16.5 | 12.25 | 39.0 |
| 5.50 | 14.0 | 12.55 | 37.0 |
| 5.60 | 20.5 | 13.05 | 33.0 |
| 5.85 | 10.0 | 13.40 | 41.0 |
| 6.30 | 6.5 | 14.00 | 38.5 |
| 6.50 | 3.5 | 14.05 | 35.0 |
| 1.0 1.10 | 40.0 | 14.15 | 35.5 |
| 1.10 | 38.5 |  |  |

Table 2-contd.

| Blate 2. $\mathrm{r}=6 \mathrm{x} .0905$ |  |  |  |
| :---: | :---: | :---: | :---: |
| z $\times 11.05$ | $V_{z} \times 11.05$ | z $\times 11.05$ | $V_{z} \times 11.05$ |
| 0.90 | 42.0 | 3.20 |  |
| 1.00 | 40.0 |  |  |
| 1.30 | 45.0 |  | 34.0 |
| 1.40 | 4 | 3.55 | 38.0 |
| 1.90 |  | 4.55 | 32.5 |
| 1.90 | 38.0 | 5.30 | 25.0 |
| 2.00 | 40.0 | 5.50 | 24.0 |
| 2.25 | 40.0 | 5.80 | 13.5 |
| 3.50 | 33.5 | 9.15 | 13.5 |
| 3.80 | 31.0 | 9.85 | 18.0 |
| 3.80 | 34.0 | 9.70 | 15.0 |
| 3.65 | 39.0 | 9.90 | 17.0 |
| 4.30 | 21.0 | 10.40 | 25.0 |
| 4.50 | 17.0 | 11.00 | 31.5 |
| 5.05 | 21.5 | 11.40 | 33.0 |
| 5.30 | 20.0 | 11.80 | 51.5 |
| 2.75 | 39.5 | 12.10 | 39.5 |
| 2.95 | 40.0 | 13.30 | 59.0 |
| 3.10 | 38.0 |  |  |
|  |  |  |  |
| z $\times 11.05$ |  |  |  |
| 1.50 | 5.5 | 4.60 | 20.0 |
| 2.00 | 4.0 | 5.10 | 21.5 |
| 3.30 | 15.0 | 6.35 | 40.0 |
| 4.00 | 23.0 | 9.70 | 35.0 |
| 4.25 | 17.0 | 10.50 | 36.0 |
| 4.35 | 15.0 | 10.65 | 30.0 |
| 5.40 | 31.0 | 11.00 | 20.0 |
| 5.70 | 28.5 | 11.50 | 19.0 |
| 5.90 | 27.5 | 12.20 | 17.0 |
| 5.95 | 29.0 | 12.50 | 10.0 |
| 6.50 | 38.0 | 13.10 | 17.0 |
| 6.85 | 32.0 | 13.25 | 7.75 |
| 2.05 | 12.0 | 3.25 | 17.0 |
| 2.40 | 15.0 | 3.70 | 22.5 |
| 3.00 | 17.0 | 5.20 | 25.0 |

Table 2 - contd.
Plate 1. $r=3 \times .0905$ (Contd.)

| z $\times 11.05$ | $V_{r} \times 11.05$ | z $\times 11.05$ | $\mathrm{V}_{\mathrm{r}} \mathrm{x} 11.05$ |
| :---: | :---: | :---: | :---: |
| 5.00 | 30.5 | 5.95 | 30.0 |
| 6.15 | 30.0 | 6.15 | 27.5 |
| 9.85 | 29.0 | 6.20 | 30.0 |
| 10.15 | 28.0 | 12.50 | 22.0 |
| 10.50 | 22.0 | 12.45 | 19.0 |
| 11.50 | 21.0 | 13.15 | 10.0 |
| 12.45 | 14.0 |  |  |
| 12.10 | 17.0 |  |  |
| Plate 3. $\mathrm{r}=3 \mathrm{x} .0905$ |  |  |  |
| 1.85 | 6.50 | 2.10 | 10.0 |
| 2.70 | 10.50 | 2.90 | 11.0 |
| 3.40 | 16.00 | 5.20 | 24.0 |
| 4.20 | 20.00 | 6.50 | 28.0 |
| 5.15 | 24.50 | 9.70 | 28.5 |
| 5.25 | 25.50 | 9.90 | 26.5 |
| 5.70 | 27.00 | 11.35 | 20.0 |
| 5.40 | 23.00 | 11.40 | 18.5 |
| 6.40 | 30.00 | 12.00 | 19.0 |
| 6.55 | 32.50 |  |  |
| 10.00 | 27.00 |  |  |
| 10.90 | 22.00 |  |  |
| 11.20 | 24.00 |  |  |
| 12.85 | 10.00 |  |  |
| 13.65 | 10.50 |  |  |
| Plate 1. $\mathrm{r}=4.5 \times .0905$ |  |  |  |
| 3.80 | 38.0 | 1.20 | 10.0 |
| 3.90 | 26.6 | 3.90 | 29.0 |
| 4.20 | 31.2 | 4.30 | 40.0 |
| 4.65 | 46.5 | 5.80 | 45.0 |
| 5.10 | 42.0 | 6.10 | 47.0 |
| 5.30 | 50.0 | 6.90 | 49.0 |
| 6.40 | 40.0 | 10.30 | 41.0 |
| 9.40 | 44.0 | 10.50 | 39.3 |
| 9.50 | 43.0 | 10.85 | 35.0 |
| 10.10 | 42.0 | 12.10 | 32.0 |
| 11.30 | 36.5 | 12.60 | 32.5 |
| 12.75 | 21.5 | 13.30 | 15.0 |
| 13.80 | 13.0 | 13.75 | 17.5 |

Plate 2. $r=4.5 \times .0905$

| z $\times 11.05$ | $\mathrm{V}_{\mathrm{r}} \mathrm{x} 11.05$ | z $\times 11.05$ | $V_{r} \times 11.05$ |
| :---: | :---: | :---: | :---: |
| 3.60 | 27.0 | 3.55 | 28.0 |
| 3.90 | 28.5 | 5.05 | 39.0 |
| 4.40 | 28.0 | 5.85 | 44.5 |
| 5.0 | 23.0 | 6.35 | 43.0 |
| 6.35 | 43.0 | 6.80 | 50.0 |
| 10.05 | 40.0 | 11.80 | 30.5 |
| 12.20 | 26.5 | 12.60 | 24.5 |
| 13.30 | 15.0 | 13.10 | 16.0 |
| Platc 3. $r=4.5 \times .0905$ |  |  |  |
| 1.10 | 4.0 | 1.85 | 10.2 |
| 1.40 | 6.0 | 2.85 | 19.5 |
| 2.30 | 14.0 | 3.05 | 29.0 |
| 3.10 | 22.5 | 3.15 | 28.5 |
| 3.45 | 23.0 | 4.20 | 32.0 |
| 4.40 | 34.5 | 4.30 | 34.0 |
| 5.25 | 35.0 | 4.75 | 29.0 |
| 5.45 | 27.0 | 5.20 | 41.0 |
| 6.05 | 35.0 | 5.35 | 36.0 |
| 6.20 | 38.5 | 5.50 | 42.0 |
| 6.60 | 43.5 | 5.45 | 34.0 |
| 6.90 | 50.0 | 10.05 | 40.0 |
| 7.90 | 50.5 | 10.30 | 37.7 |
| 10.20 | 44.5 | 10.50 | 33.5 |
| 10.70 | 44.0 | 10.80 | 34.0 |
| 11.10 | 37.0 | 11.60 | 34.0 |
| 11.65 | 32.5 |  |  |
| 12.15 | 29.5 |  |  |
| Plate 1. $r=6 \times .0905$ |  |  |  |
| 1.05 | 12.2 | 0.50 | 7.5 |
| 2.70 | 31.0 | 2.70 | 19.5 |
| 2.95 | 33.5 | 3.50 | 32.2 |
| 3.25 | 33.5 | 3.65 | 35.0 |
| 4.45 | 42.5 | 4.05 | 39.0 |
| 5.25 | 45.0 | 4.30 | 39.0 |
| 5.10 | 45.5 | 4.40 | 39.5 |
| 5.45 | 46.0 | 4.60 | 47.0 |
| 5.60 | 40.0 | 4.95 | 45.0 |
| 6.10 | 49.5 | 5.10 | 49.5 |
| 6.70 | 53.5 | 5.20 | 49.0 |
| 7.50 | 57.5 | 5.30 | 57.0 |
| 9.50 | 52.5 | 5.45 | 40.0 |
| 10.00 | 45.0 | 5.60 | 56.0 |
| 11.30 | 36.0 | 5.80 | 42.0 |
| 12.40 | 30.0 | 6.20 | 51.0 |

Table 2-contd.
189.

| Plate 1. $\mathrm{r}=6 \times 0905$ |  |  |  |
| :---: | :---: | :---: | :---: |
| z $\times 11.05$ | $V_{r} \times 11.05$ | z $\times 11.05$ | $\mathrm{V}_{\mathrm{r}} \times 11.05$ |
| 13.20 | 25.5 | 6.50 | 51.0 |
| 13.80 | 15.0 | 6.60 | 55.0 |
| 13.85 | 17.0 | 6.80 | 58.0 |
| 13.90 | 18.0 | 7.55 | 53.0 |
| 14.00 | 15.0 | 9.40 | 55.5 |
|  |  | 9.95 | 52.0 |
|  |  | 10.30 | 52.0 |
|  |  | 13.00 | 22.0 |
| Plate 2. $r=6 \times .0905$ |  |  |  |
| 2.25 | 10.0 | 5.05 | 50.0 |
| 2.40 | 22.0 | 5.45 | 47.0 |
| 2.80 | 20.0 | 6.05 | 49.5 |
| 4.50 | 44.0 | 6.15 | 55.0 |
| 4.70 | 45.0 | 6.40 | 57.0 |
| 5.20 | 44.5 | 8.45 | 56.0 |
| 5.70 | 50.0 | 9.85 | 53.0 |
| 5.90 | 50.0 | 10.65 | 51.0 |
| 6.15 | 55.0 | 10.80 | 47.0 |
| 6.80 | 58.0 | 11.25 | 42.2 |
| 8.05 | 49.0 | 13.35 | 23.0 |
| 9.60 | 44.0 | 13.55 | 23.0 |
| 10.10 | 50.0 | 13.90 | 19.0 |
| 10.65 | 47.5 | 14.10 | 18.5 |
| 12.50 | 30.0 | 14.40 | 18.0 |
| 13.20 | 29.0 |  |  |
| 13.75 | 20.0 |  |  |
| Plate 3. $\mathrm{r}=6 \times .0905$ |  |  |  |
| 1.70 | 10.0 | 1.05 | 11.0 |
| 2.25 | 24.0 | 3.00 | 24.0 |
| 3.75 | 38.0 | 3.15 | 29.0 |
| 4.15 | 45.0 | 3.35 | 29.0 |
| 4.40 | 42.0 | 3.55 | 31.0 |
| 5.10 | 51.0 | 4.60 | 42.5 |
| 5.30 | 50.0 | 5.85 | 53.0 |
| 6.30 | 52.0 | 9.20 | 54.0 |
| 10.60 | 50.0 | 9.75 | 47.0 |
| 11.30 | 40.0 | 11.10 | 45.0 |
| 12.30 | 29.0 | 11.90 | 40.0 |
| 13.10 | 21.0 | 12.40 | 38.0 |
|  |  | 13.45 | 24.0 |

TABLE III.
190.


| $z$ | T | $(\rho H) T$ | $\underline{z V}_{\underline{r}}(\mathrm{\rho H})_{T}$ | $V_{z} \frac{\partial T}{\partial z}$ | $\mathrm{H} \frac{\partial \rho}{\partial T}$ | $V_{z} \frac{\partial T}{\partial z}\left(H \frac{\partial \rho}{\partial T}\right)$ | $\rho\left(\frac{\partial H}{\partial T}\right)$ | $V_{z} \frac{\partial T}{\partial z}\left(\rho \frac{\partial}{\partial T}\right.$ | $\mathrm{pH} \frac{\partial V_{z}}{\partial z}$ | $\frac{\partial}{\partial}$ \% $\left(-K \frac{\partial T}{\partial z}\right)$ | WQ | Remarks |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| $\begin{array}{r} 7.968 x \\ 10^{-2} \\ \hline \end{array}$ |  | $10^{-4}$ |  | $\begin{aligned} & 113 \cdot 58 x \\ & 10^{-1} \end{aligned}$ | $\begin{aligned} & 2.5 \mathrm{x} \\ & 10^{-7} \end{aligned}$ | $\begin{gathered} 283.95 x \\ 10^{-3} \end{gathered}$ | $10^{-4}$ | $\begin{gathered} 113.58 \mathrm{x} \\ 10^{-5} . \end{gathered}$ | $5 \times 10^{-4}$ | 65.08 | $\begin{gathered} \text { cals/cc } \\ \text { sec. } \end{gathered}$ | $\begin{gathered} \text { Multiply } \\ \text { by } \end{gathered}$ |
| 6.0 | 560 | 840 | . 4872 | 457.42 | 612 | 2.80 | 1.678 | 767.55 | 168.00 | . 00035 | -. 08 |  |
| 5.5 | 625 | 866.4 | . 6411 | 494.33 | 566.2 | 2.80 | 1.5641 | 773.13 | 649.8 | $\because .0095$ | -0.21 |  |
| 5.0 | 690 | 853.45 | . 7766 | 508.00 | 519.67 | 2.64 | 1.3958 | 709.17 | 1066.8 | . .0115 | -0.45 |  |
| 4.5 | 760 | 883.57 | . 9719 | 500.00 | 465.00 | 2.33 | 1.2949 | 647.50 | 1546.24 | . 0125 | -0.54 |  |
| 4.0 | 825 | 890.10 | 1.1571 | 474.07 | 424.20 | 2.01 | 1.2031 | 568.88 | 1859.2 | . 015 | -0.68 |  |
| 3.5 | 910 | 897.00 | 1.3275 | 423.90 | 379.50 | 1.61 | 1.1045 | 466.29 | 2107.9 | . . 0165 | -0.73 |  |
| 3.0 | 1000 | 915.56 | 1. 3015 | 375.75 | 353.37 | 1.33 | 1.02 | 383.26 | 2197.3 | . 0165 | - . 61 |  |
| 2.5 | 1080 | 927.30 | 1. 5877 | 301.87 | 330.17 | 0.9967 | . 952 | 287.38 | 2179.15 | . 0150 | - . 34 |  |
| 2.0 | 1170 | 939.40 | 1.3600 | 212.09 | 308.00 | 0.6532 | . 885 | 187.69 | 1972.74 | . 0125 | - . . 09 |  |
| 1.5 | 1260 | 949.20 | 1.7933 | 123.53 | 285.60 | 0.3528 | . 829 | 102.41 | 1518.72 | . 0075 | + 0.76 |  |
| 1.0 | 1355 | 971.25 | 2.1367 | $\because 44.50$ | 286.75 | 0.1276 | . 780 | 34.71 | 679.87 | p | + 1.80 |  |
| 0.5 | 1440 | 976.38 | 2.2066 | 16.40 | 287.46 | 0.0471 | . 739 | 12.11 | 195.28 | . 0.2 | + 3.41 |  |
| 0.0 | 1515 | 981.75 | 2.2187 | 48.00 | 294.00 | 0.1411 | . 701 | 33.65 | 932.66 | . 045 | + 4.68 |  |
| 0.5 | 1560 | 983.06 | $2.182^{4}$ | 14.4 | 304.15 | 0.044 | . 701 | 10.09 | 1081.36 | . 2175 | +15.79 |  |
| 1.0 | 1550 | 978.25 | 2.1130 | 34.65 107.80 | 301.00 | 0.1043 | . 705 | 24.43 | 1271.73 | . 065 | +5.70 |  |
| 1.5 | 1515 | 981.75 | 2.062 | 107.80 | 294.00 | 0.3169 | . 686 | 73.95 | 1374.45 | . 045 | + 4.30 |  |
| 2.0 | 1460 | 984.55 | 1.9888 | 210.00 | 294.35 | 0.6181 | . 714 | 149.94 | 1575.28 | . 039 | + 3.08 |  |
| 2.5 | 1375 | 985.84 | 1.9027 | 322.00 | 285.75 | 0.9201 | . 764 | 246.00 | 1675.92 | . 016 | +2.12 |  |
| 3.0 | 1285 | 975.16 | 1.765 | 430.00 | 291.23 | 1.2523 | . 818 | 351.74 | 1755.29 | . 01066 | +1.36 |  |
| 3.5 | 1190 | 969.85 | 1.5905 | 527.5 | 317.85 | 1.6766 | . 882 | 465.25 | 1745.73 | 0 | +0.77 |  |
| 4.0 | 1100 | 956.80 | 1.4352 | 623.5 | 336.37 | 2.0973 | . 946 | 589.83 | 1625.56 | . 01175 | - . 04 |  |
| 4.5 5.0 | 990 890 | 940.97 | 1.2609 | 691.0 | 372.40 | 2.5733 | 1.0 .372 | 716.71 | 1505.55 | .0ヶ\% | --0.55 |  |
| 5.0 5.5 | 890 790 | 930.22 815.20 | 1.1163 | 733.65 741.15 | 414.75 478.40 | 3.0428 | 1.138 | 834.89 | 1302.31 |  | -0.85 |  |
| 5.5 6.0 | 790 | 915.20 911.62 | 0.8518 $C .8113$ | 741.15 680.4 | 478.40 537.63 | 3.5457 | 1.2544 | 929.69 | 1098.24 | . 0250 | - 1.17 |  |
| 6.0 | 640 | 911.62 900.55 | C. 8113 $C .6664$ | 680.4 578.00 | 537.63 593.45 | 3.6580 3.4301 | 1.3714 1.5048 | 933.10 869.77 | 729.29 0. | $.0225$ | -1.00 -0.7 |  |

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