

ADDENDUM

1. Assumption of Constant Pressure through the Flame.

It is stated, in section 3.3 (p 64, line 16), that the pressure associated with the momentum of the flow is negligible compared with the absolute pressure and that this will be demonstrated in Chapter 5. Explicit proof was omitted from the final version of the later chapter but the result is implicit in the momentum values listed in Table 2 (p 99). The maximum component of momentum generated across the flame is shown to be about 10^3 dyne/cm², that corresponding to atmospheric pressure is 10^6 dyne/cm². Thus the change of pressure is only .1% of the total.

2. Williams G.C., Hottel H.C. and Gurnitz R.N. Twelfth Symposium (International) on Combustion, p 1081, The Combustion Institute, 1969.

The above reference was overlooked in the preparation of the thesis. It is of interest on two counts. Firstly, it introduces a novel technique for the study of premixed, turbulent flames whereby the reactants are seeded with fine particles of magnesium oxide which are then photographed by scattered light. The instantaneous flame front is then marked by the change in density of illumination resulting from the change in particle density on acceleration through the flame.

One conclusion drawn from the study is that the flame turbulence was much greater than, and not simply related to, the turbulence in the burner stream - an interpretation that is in full accord with the present thesis.

E R R A T A

- p 25 line 6 ... advantages ...
- p 35 line 5 ... Ektar ...
- p 37 line 20 ... asymmetry of the geometry.
- p 40 line 27 ... 250 cm. focal length.
- p 44 line 7 ... point focus.
- p 48 line 32 ... (e.g. (31,32))
- p 50 line 14 ... to $\frac{c}{\mu}$ where ...
- p 56 Insert before equation for turbulent flame
"After averaging"
- p 57 line 15 ... 367 and 247 cm./s.
- p 74 line 10 ... sheathing ...
- p 76 line 1 ... consistent ...
- p 68 line 13 ... total saturation current, $J_{\underline{s}}$,
- p 93 line 4 In practice ...
line 22 Thus in practice ...
- p 103 line 14 ... (equation 4.1) is universal and ...

A STUDY OF PREMIXED TURBULENT FLAMES

by

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Submitted for the Degree of Ph. D.

ABSTRACT

An experimental study into the behaviour of premixed turbulent flames of hydrocarbon/air and hydrocarbon/oxygen mixtures, stabilized on burners, is reported. The state of the subject which led to the work is reviewed and the limitations of earlier investigations are discussed.

New optical methods are introduced to obtain relevant information. Particle tracks are combined with instantaneous schlieren contours to give various, but reproducible, definitions of local and average burning velocity. Ray deflection methods are developed to assess the comparative effectiveness of turbulence inducing devices and for measuring the time average distribution of products and reactants.

An electrical method for determining flame area, based on extracting all the ions generated in the flame and measuring the resultant current, is developed and tested. It is shown to be particularly suited to irregularly shaped and fluctuating flames where more usual methods of area measurement are difficult to apply.

The "wrinkled laminar" concept of turbulent flame propagation is checked by appropriate burning velocity results, and independently, by the above electrical method. Both tests show the model to fail, the failure being greater than can be explained by small scale turbulence in the burner flow.

The movement of the turbulent flame front is shown to be significant, compared with its thickness, during the transit of a pocket of gas. Part of this fluctuating motion is caused by the continuity of the perturbed flame front and part is explained by the interaction of flame generated momentum with the confined product flow. The turbulence 'seen' by the moving flame front accounts for the measured increase in burning velocity.

It is shown that the electrical measurements can be related to those of burning velocity if changes in flame structure are assumed to occur.

To my patient wife...

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FOREWORD

The study reported in this thesis was carried out in two distinct phases, separated by an interval of several years. The optical investigations took place between 1957 and 1961, whilst the electrical measurements and overall interpretation occurredⁱⁿ the latter part of 1969 and the early part of 1970.

The theory and measurements of the original optical study were published in Reference (1) and parts were subsequently incorporated into Reference (2). Thus, the early part of the work has become well known, and quoted in the literature before completion of the thesis. Several of the publications quoted in the survey of Chapter 1 are, in fact, pre-dated by the work of Chapters 2 and 3. The detailed analysis and combined interpretation of these results is reported, for the first time, in the present thesis, as are all the features of the electrical study.

ACKNOWLEDGEMENTS

It gives me great pleasure to express appreciation to some of the people and organisations whose help has enabled me to complete this Thesis.

Major acknowledgement and thanks are due to Professor F.J. Weinberg for his constant encouragement, help, and stimulation. It was he who suggested the original optical study and made it possible for me to return to Imperial College, considerably later, to follow it up with the electrical methods. In particular I value his constructive criticism and the patient way he has listened to some of the more far-fetched and ill-expressed ideas.

I owe a considerable debt to past and present members of the Combustion Physics Group, all of whom were willing to lend a helping hand and discuss problems, whenever needed. Specific mention must be made of Drs. W.S. Affleck, who collaborated in development of the flash source, A. Levy, who helped to prepare some of the photographic illustrations, and A. Jones for providing helpful suggestions about the summation of turbulence.

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SYMBOLS

A	- Flame area
c	- Velocity of light in vacuo
c'	- Velocity of light in a medium
D	- Optical path
E	- Electric field & Expansion ratio
f	- Fraction of hot products
G	- Flame speed (referred to reactants)
J	- Total current
j	- Current density per unit area of flame
k	- Ionic mobility
l	- Scale of turbulence
m	- Number of schlieren records
n	- Normal to direction of maximum refractive index gradient
r	- Radial position across burner (measured from axis)
r_0	- Burner radius
$S_{\text{subscript}}$	- Burning velocity
T	- Temperature
t	- Time
u & u'	- Intensity of turbulence
V	- Volumetric flow rate
v	- Velocity
X	- Length of optical test space
z	- Excursion of instantaneous flame front

SYMBOLS (Cont)

Δ_f	- Flame thickness
Δ_p	- Change in momentum
Δ_r	- Increment of burner radius
Δ_l	- Length of instantaneous flame surface corresponding to
μ	- Refractive index
δ	- $\mu - 1$
ν	- Kinematic viscosity
ϵ	- Eddy diffusivity
ρ	- Density
ϕ	- Angle between approach flow and flame surface
θ	- Angle of deflection of the incident ray
ψ	- Angle between flame front and (x,z) plane.

SUBSCRIPTS

av.	- Distance average across burner
b	- Limiting condition for electrical breakdown
f	- Flame
L	- Laminar
o	- Initial conditions (except for r_o)
p	- Products
r	- Reactants
s	- Saturation (electrical)
T	- Turbulent
$\perp$	- Perpendicular to flame
$\parallel$	- Parallel to flame

SUPERSCRIPTS

—	- Time average.
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CHAPTER 1 INTRODUCTION

Flames in turbulent, premixed reactants - henceforth referred to as 'turbulent flames' - are complex phenomena. Their study is made difficult by the large number of variables and the difficulties inherent in both controlling and measuring some of them.

Although Mallard and Le Chatelier⁽³⁾ noted the differences in appearance between laminar and turbulent flames as long ago as 1883, it is only within the past thirty-five years that attempts have been made to establish an understanding of the latter.

The first comprehensive investigation of flames in turbulent premixed gas streams was due to Damköhler,⁽⁴⁾ who realised that the difference between laminar and turbulent flames lies in their physical rather than their chemical properties. He also appreciated that there were differences between the regime where the scale of turbulence was small, compared with the flame thickness, as distinct from that where it was large. Theoretical models were established independently for each of these cases and experimental studies were performed on small burner-stabilized flames.

Damköhler's theory, for turbulence of small scale compared with the flame thickness, assumes the only difference between this and the laminar regime to lie in the transport properties. It can be shown that, for a laminar flame, the burning velocity, S_L , is related to the molecular diffusion coefficient, ν , in the following manner:-

$$S_L \propto \nu^{\frac{1}{2}} \quad (1.1) \quad (5)$$

Damköhler suggested that the corresponding burning velocity prevalent in a turbulent flame, S_T , would depend in a similar manner, upon the eddy diffusivity, $\mathcal{E}$, all else being equal. Thus the relation between laminar and turbulent burning velocities would be governed by the equation

$$\frac{S_T}{S_L} = \left(\frac{\mathcal{E}}{\nu} \right)^{\frac{1}{2}} \quad (1.2)$$

For large scale turbulence Damköhler assumed that the turbulent velocity fluctuations superimposed a number of small cones on the laminar surface, thus effectively increasing its instantaneous area. According to this picture the ratio of turbulent to laminar burning velocities would be equal to the ratio of instantaneous turbulent, A_T , to laminar, A_L , surface areas. Thus

$$\frac{S_T}{S_L} = \frac{A_T}{A_L} \quad (1.3)$$

This equation implies that, for regions where the flame thickness is small compared with the scale of turbulence, the concept of turbulent burning velocity arises solely from the increase in instantaneous area of flame surface. If this instantaneous area could in fact be considered instead of the area of some 'average' surface as seen by eye the laminar burning velocity would be obtained. By expressing perturbations in terms of pipe turbulence Damköhler showed that under these conditions

$$S_T \propto u' \quad (1.4)$$

where u' is the intensity of turbulence.

The experimental studies of Damköhler were on small flames stabilized on burners of circular cross section carrying flows of premixed propane/oxygen with fully developed pipe flow turbulence.

The experimental burning velocity was defined as the reactant volume flow rate divided by the surface area of the flame. This latter was obtained from a time-mean photograph of the flame's luminous zone. It was defined by rotating a line, formed by the innermost boundary of this zone, about the burner axis. The results obtained gave some measure of agreement with the theory and discrepancies were explained by Damköhler as being due to regimes of large and small scale turbulence occurring together. It has since been questioned by Karlovitz⁽⁶⁾ whether some of the agreement was not fortuitous.

Shchelkin⁽⁷⁾ extended Damköhler's theoretical considerations and modified the equation for turbulence of small scale compared with the flame thickness to

$$\frac{s_T}{s_L} = \left(\frac{\varepsilon + \nu}{\nu} \right)^{\frac{1}{2}} \quad (1.5)$$

to allow for the molecular transport properties in the turbulent regime.

Shchelkin also modified the Damköhler equation for large scale, small intensity turbulence. Once more Damköhler's model was used but the area of the superimposed cones was calculated more carefully, assuming fully developed pipe flow turbulence. The equation derived was:-

$$\frac{s_T}{s_L} = \left[1 + b \left(\frac{u'}{s_L} \right)^2 \right]^{\frac{1}{2}} \quad (1.6)$$

where b is a coefficient of order of magnitude unity.

A further regime was treated in Shchelkin's investigation. This was the case of high intensity, large scale turbulence. The flame was here conceived as a disrupted surface from which pockets of unburnt gas break away into the products and burn inwards as they are carried along by the exhaust gases. This

region will be specifically excluded from the present work and will be given no further attention.

Shchelkin's theory was considered rather surprising for appreciable scale turbulence in that, under certain conditions it predicted a turbulent burning velocity independent of, or only weakly dependent on, the laminar one. To test it Bollinger and Williams⁽⁸⁾ undertook an experimental investigation using Bunsen-type flames. As in Damköhler's case, the burning velocity was defined according to the equation

$$S_T = \frac{V}{A} \quad (1.7)$$

where V was the volume flow rate and A the surface area of the flame. The significant quantity everywhere is the surface area A . As in Damköhler's work it was derived from a time-mean photograph of the flame's luminous region. However, in this case the surface was constructed by rotation about the axis of a line drawn midway between the inner and outer boundaries of the luminous region. Fully developed pipe flow turbulence was assumed once more and the reactants were acetylene-air, ethylene-air and propane-air. The results showed that turbulent burning velocity increased with increasing turbulence intensity but not linearly, the rate of increase of turbulent burning velocity declining at higher intensities. Furthermore, the laminar burning velocity remained a controlling factor, even at high turbulence intensities, and the curves for different fuels showed no tendency to approach a common value. All this was in direct contradiction to the predictions of Shchelkin's theory.

Williams, Hottel and Scurlock⁽⁹⁾ worked on turbulent flames stabilized on baffles in confined channels. The apparatus used was such that the approach flow turbulence intensity could be controlled over a wide range and measured by means of a hot wire anemometer. It was shown that the approach flow turbulence had little effect on the turbulent burning velocity, which itself was

much higher than predicted by Shchelkin's theory. The conclusion drawn was that there was some mechanism producing turbulence which over-rode that present in the approach flow. This turbulence was accounted for in terms of the large velocity gradients induced by the flame in the confined channel. The particular investigation is of interest because, although it was not of flames stabilized on open burners, it was the first in which flame generated turbulence was detected experimentally and explained theoretically.

Markstein⁽¹⁰⁾ independently investigated the possibility of flame generated turbulence by introducing small perturbations at the base of a laminar flame and observing them as they travelled up it. From observations of the growth of the amplitude of the disturbance it was concluded that any turbulence in the unburnt gas could be considerably increased by the flame.

Pictorial evidence of the nature of turbulent flames came from Karlovitz⁽⁶⁾ and Wohl⁽¹¹⁾ as a result of instantaneous schlieren photographs which 'froze' the fluctuating turbulent flame. These instantaneous pictures showed the flames under consideration to have a continuous, sharply defined surface. They confirmed the earlier theories of Damköhler and Shchelkin in so far as these were based on a model of a distorted, fluctuating, laminar-type flame. Furthermore, these pictures showed the continuous surfaces to present sharp peaks to the burnt products, but much smoother facets to the unburnt reactants. Karlovitz attempted to explain this qualitatively by considering a laminar flame, arbitrarily distorted by large scale perturbations, propagating with its laminar burning velocity into quiescent reactants.

Karlovitz also introduced a model to explain flame generated turbulence. For this the acceleration undergone by a small volume of gas on passing through an element of flame front was considered.

It was known that this induced an excess velocity, normal to the flame front, whose magnitude could be expressed quantitatively in terms of the original and expended volumes of the gas and of the laminar burning velocity⁽¹²⁾. For a turbulent flame consisting of a fluctuating, laminar-type surface, the flame front and hence its normal would vary both with position and time. Thus it followed that the excess velocities induced in turbulent flames would appear as increased turbulent fluctuations superimposed on an increased mean flow velocity.

For his experimental investigations Karlovitz⁽⁶⁾ used flames similar to those investigated by Bollinger and Williams but the time-mean flame surface was derived by rotation about the axis of the line corresponding to the locus of maximum density on the photographic record. Karlovitz concluded that the large burning velocities measured could be accounted for if the sum of flame generated and approach flow turbulence were substituted for the approach flow turbulence.

Karlovitz's experimental work is also of interest in that it made use of the electrical conductivity of the flame. Fluctuations in the flame position were recorded by changes in current, on fixed position ionization probes, caused by passage of the ionizing part of the reaction zone.

Westenberg⁽¹³⁾ used sampling methods involving the diffusion of helium from a fine source in order to measure turbulent parameters in the flame region. He concluded that there was some evidence of flame generated turbulence.

Mickelsen and Ernstein⁽¹⁴⁾ studied freely propagating flames which were carried along by turbulent streams instead of stabilized on a burner and found their burning velocities to be substantially less than those recorded for burner stabilized flames.

Scurlock and Grover⁽¹⁵⁾ considered, theoretically, the effect of large scale turbulence on the flame front. They considered the interaction, on the instantaneous surface area, of three effects believed to be important in the propagation of flames. These are the eddy diffusion of reactants, which tends to increase the instantaneous flame area; the propagation of the flame, which tends to decrease the area; and the flame generated turbulence, which tends to increase the area. They concluded that whilst allowance could be made for the two former effects, there was insufficient experimental data to be able to assess the importance of the latter.

Spalding⁽¹⁶⁾ has indicated that under certain limited conditions the propagation of a turbulent flame may be controlled by the entrainment of stagnant gas surrounding the main flow.

Many later workers have studied turbulent flames, e.g. ⁽¹⁷⁻²¹⁾, but generally their work consisted of applying existing techniques towards accumulating more results to try and test the hypotheses already mentioned.

This, briefly was the state of the subject which led to the inception of the present work. Since then there have been more experimental investigations of the above type, e.g. ⁽²²⁻²³⁾. In addition there have recently been two novel approaches.

Hurle, Price, Sugden and Thomas⁽²⁴⁻²⁵⁾ have carried out a comprehensive investigation into noise generated by turbulent flames and suggest, incidentally, that their measurements on C_2^* emission support the "wrinkled laminar" hypothesis in describing the turbulent flame front.

Sokolik, Karpov and Semenov⁽²⁶⁾ have succeeded in generating turbulence within a bomb and have, independently of the present investigation, used the schlieren image (in conjunction with anemometer measurements of turbulent velocity) to check the above hypothesis. They find it to be incorrect in that the burning

velocity of the instantaneous flame front is considerably different from that for the normal laminar flame. Transient measurements of ionization currents were used to measure reaction times. The following comments on the inadequacies of previous burning velocity studies are not applicable to the work of Sokolik and collaborators, which will be ignored in this context, because the optical investigations in the present work considerably pre-dated their publication.

Any comprehensive study of the phenomenon so far undertaken can be subdivided into three sections. These comprise firstly, the physical theory where the effect of the turbulent velocity fluctuations on the flame front and its burning velocity are described. Secondly, a mathematical theory expressing the physical perturbations in terms of the relevant flow parameters. Finally, turbulent burning velocities must be measured experimentally and compared with predictions arising from the first two steps. This is a circular process involving hypothesis and verification and means that if a mistake is made at any particular point the whole argument is thrown off course and will not link up. Furthermore, it will not be possible to determine at what point, or points, the deficiencies occurred.

Perhaps the most obvious criticism of previous work lies in the definition of the experimental turbulent burning velocity. The investigations described have defined this turbulent burning velocity in terms of a volume flow rate divided by a time-mean surface area - equation 1.7.

It is desirable to consider how equation 1.7 arises and why it was used for the definition of turbulent burning velocity. The definition of laminar burning velocity conceives of the flame as propagating into stationary reactants. The burning velocity is then the component of the flame's velocity, perpendicular to the flame front, with respect to the cold gas. This can be applied to a burner stabilized flame since it does not matter whether the gas

or the element of flame front is stationary as long as the relative velocity of the two is known. In this case

$$S_L = v \sin \phi \quad (1.8)$$

where v is the local stream line velocity and ϕ the angle it makes with the flame front. If this equation is integrated over the burner mouth it gives rise to a mean laminar burning velocity, $S_{L,av.}$, over the burner mouth, so that

$$S_{L,av.} = \frac{\text{Volume flow rate}}{\text{Surface area}} \quad (1.9)$$

As far as the definition of turbulent burning velocity is concerned, the situation is rather different. The primary concept of a flame propagating into stationary reactants can no longer be realised experimentally since it is difficult to arrange for stationary reactants to be turbulent. Moreover, in the case of burner stabilized flames, equation 1.8 was not found to be of practical use due to the difficulty in measuring v locally. Thus, equation 1.7, which is the turbulent equivalent of equation 1.9, became the defining equation for turbulent burning velocity. It is the uncertainty and irreproducibility of the time-mean surface which has to be derived from the diffuse brush of the turbulent flame, that leads to trouble.

All the measurements of surface area have been derived from a time average 'picture' of the turbulent flame obtained by its own light. Furthermore, a photographic record of the type shown in Figure 1 was usually used for this purpose. This is unsatisfactory on three separate counts. Firstly, the turbulent flame brush occupies a large region so there are significant differences between the areas obtained from the incompatible definitions of time-mean surfaces that have been used by different workers. Secondly, the position of the diffuse boundaries of the luminous region, as indicated by this method, is subject to the photographic history of the plate rather than uniquely dependent on the flame. Thirdly, the apparent luminosity

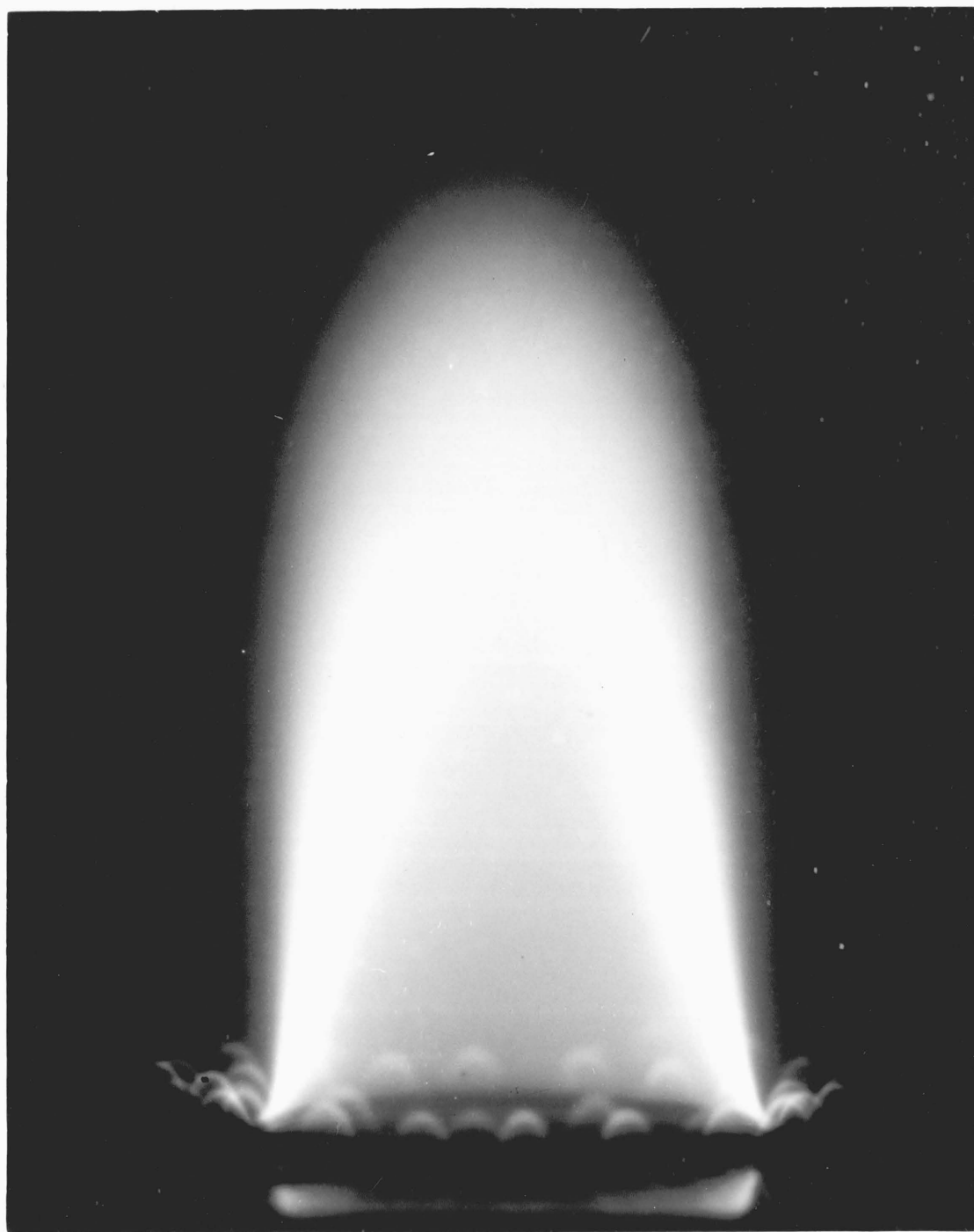


FIGURE 1 - TURBULENT FLAME BRUSH

falling on a measuring instrument from any element of flame front depends not only on the amount of light emitted by that element, but on its orientation to the direction of view. Thus, if similar elements are considered, those lying with their normal perpendicular to the viewing direction will appear very much brighter than those lying with their normal in any other direction. For an axially symmetrical, conical, laminar flame, the region of maximum intensity will sharply define the flame boundary on the axial plane perpendicular to the viewing direction. This occurs because the only elements of flame front with their normals lying perpendicular to the viewing direction lie on this boundary. With the disordered form of the turbulent flame this is no longer true and elements of flame front with their normals perpendicular to the viewing direction can lie anywhere over the flame surface. The latter consideration results in a weighting of the record of the time mean luminous surface and must certainly render suspect any definitions based upon the inner boundary of the luminous zone whether it be used for direct measurements or construction of an average surface. Similar criticism attaches to the method adopted by Bollinger and Williams who constructed their surface on a line midway between the inner and outer boundaries of the luminous zone. Even assuming this region does not suffer from the objections already mentioned, it is geometrically impossible to construct a line satisfying this definition without detailed knowledge of corresponding points on the inner and outer boundaries.

If the circular argument is to link up, there is yet a further restriction on the definition of turbulent burning velocity. It should correspond to that used in the physical theory predicting the flame's behaviour. All the theories mentioned envisage the time average, diffuse boundaries of the turbulent flame being as mutually parallel. They base their predictions of turbulent burning velocity on a time average surface which is parallel to these boundaries. Reference to the photograph of Figure 1 shows the concept to be untenable for bunsen-type flames in so far as the diffuse boundaries themselves do not fulfil their specified conditions of parallelism.

The foregoing discussion has already shown how most of the approaches adopted in earlier studies attempted, at best, a circular argument of hypothesis and verification which bore inadequate relation to the actual physics of the problem. There is great need for investigations which short circuit this type of argument and provide step by step justification for the models employed. It is now time to outline, in some detail, the questions to be answered and the methods developed especially for that purpose.

The present investigation is into the combustion of flames of premixed gaseous reactants stabilized on burners and subjected to turbulent approach flows. The regime studied is one where large scale turbulence is present in the flow and where the instantaneous flame front, as seen in schlieren pictures, is a thin corrugated zone, fluctuating in position with time, within a fixed volume bounded by a time average brush.

The first, and most pressing, question is whether each element of the corrugated flame front behaves instantaneously as though it were a laminar flame occupying the same position. Whether its detailed structure and properties, such as the velocity of propagation, are the same as for a flat laminar flame. An affirmative answer would simplify the problem considerably. The interaction between turbulence and flame front would be explained in terms of Damköhler's model for turbulence of scale large compared with the thickness of the flame front, where macroscopic distortions of position do not affect the microscopic processes of propagation.

If the instantaneous, corrugated, fluctuating flame front is found to exhibit properties only slightly modified from those associated with the flat laminar flame, it may still be possible to explain the results in terms of Damköhler's hypothesis by including the effect of small scale turbulence. The model adopted for turbulence of scale small compared with the flame front thickness predicted an increase in burning velocity due to the increase in effective viscous transport caused by that arising from eddy diffusivity supplementing that already present. There is no reason

why the artificial separation between large and small scale turbulence, invoked by Damköhler as a matter of convenience for his models, should actually occur in real flows. It is much more likely that some spectrum of turbulence scale will exist. However, the intensity of small scale turbulence is limited by the available turbulent energy.

If the discrepancies between turbulent and flat laminar flame still remain unresolved, it is then necessary to decide whether they are due to geometrical peculiarities in the instantaneous, corrugated flame front rather than true turbulent, i.e. time variant, effects.

Any remaining anomalies between turbulent and laminar flames go beyond the original Damköhler theory and require additional concepts, e.g. flame generated turbulence, to explain them. Whilst this by no means excludes them from the scope of the present investigation, it is not thought profitable to anticipate them in detail now.

Burning velocity has, both in earlier studies and the foregoing discussion, implicitly been assumed to be the most important single characteristic property in assessing similarities, or otherwise, in the propagation of flames in constant composition mixtures of premixed reactants subjected to different flow conditions. Deficiencies in both definition and measurement of burning velocities in many previous investigations have already been pinpointed.

Whatever definition of burning velocity is chosen (the 3D form of equation 1.7 or the 2D form of equation 1.8) its actual measurement depends on defining and measuring the two, independent, features of approach flow and flame surface.

Approach flow velocities are of interest in terms of their local time-mean and fluctuation values. The tracks of particles, carried by the flow and illuminated by an interrupted Tyndall beam, have proved very successful for the measurement of approach velocities in laminar flames, e.g. ⁽²⁷⁾ but have not been widely used in turbulent

flames because of the low intensities of the recorded tracks at the high velocities involved. These difficulties can be alleviated by reducing flow velocities for a given level of turbulence and by increasing the intensity of illumination. Both have been attempted and the methods will be detailed in Chapter 2. In designing obstacles to intensify the turbulence, the advantage of generating it as uniformly and homogeneously as possible, across the burner mouth, have to be borne in mind.

Some method is needed of rapidly assessing the effectiveness of various devices in generating turbulence complying with the above conditions. The direction of deflection of a beam of parallel light by the refractive index gradient of a flame is characteristic of the orientation of the flame⁽²⁸⁾. This, in turn, is dependent on the turbulence present in the approach flow. Thus the possibility of an optical method based on the turbulence induced randomness of deflection of a beam of light suggests itself.

The great need for a method of delineating the instantaneous flame front has already been explained in considerable detail. Instantaneous schlieren photographs have already been shown to have provided qualitative confirmation of the hypothesis of a corrugated, fluctuating, laminar flame. Before this work no one had considered, in detail, what it is the schlieren pictures actually show. It is this analysis that reduces the problem to 2 dimensions and enables measurements of the schlieren image to be combined with measurements of approach flow, described above, to give adequate definitions of burning velocity and a direct test of the basic hypothesis. Furthermore, these measurements also lead to a reproducible definition of turbulent burning velocity.

The last two methods depend on the deflection of a beam of light by the flame's refractive index field. In practice they utilize only the direction of these deflections. Further information about the quantitative distribution of refractive index is contained in the magnitude and distribution of these deflections. In the case of a turbulent flame this can lead to a measure of the average

distribution of products and reactants. When applied to the case of some tracer, of different refractive index to the main flow, this aspect of the deflection is potentially capable of recording the effective transport properties governing the spread of that tracer and hence the parameters of turbulence.

Preference, so far, has been given to the use of optical techniques because they do not interfere materially with either the flow or the processes occurring within the flame. In addition, all discussed utilize an external light source and are, therefore, capable of sufficiently high time resolution to 'freeze' the fluctuating flame, where appropriate, and thus fulfil one requirement necessary for verification of the "wrinkled laminar" flame hypothesis.

A limitation of optical methods is that they reduce the problem to 2 dimensions. There remains a great need to measure flame areas directly. This cannot be done by schlieren so some alternative method is required. One such method depends on the electrical properties of the flame. Premixed hydrocarbon/air (or oxygen) flames are known to generate ions (e.g. Sugden⁽²⁹⁾). If all these ions can be extracted from the flame, by application of a D.C. field, and the current so produced, measured, one aspect of the "wrinkled laminar" hypothesis can be checked directly. Namely, that for a given combustible mixture the total saturation current, described above, depends only on the volumetric flow rate and not on whether the flow is laminar or turbulent. The "wrinkled laminar" concept requires flame area to be proportional to volume flow rate; the saturation current, for constant mixture, is proportional to flame area. Hence saturation current must be proportional to volumetric flow rate unless the flame structure is altered.

Detailed descriptions of the techniques developed follow; those of the optical methods and results in Chapters 2 and 3; those of the electrical method and results in Chapter 4.

CHAPTER 2 OPTICAL METHODS - DESCRIPTION

2.1 Particle Tracks

The first method to be discussed is the mapping of flow field by means of particle tracks illuminated by an interrupted Tyndall beam. The aim is to map the mean approach velocity and turbulent fluctuations upstream of the flame in an axial plane across the burner mouth. The method is to be used, in conjunction with delineation of the instantaneous flame front, to define burning velocities, so that it must operate under conditions compatible with the requirements of the latter. This consideration is important because it is necessary to tailor the flame to make it suitable for application of the technique.

The reasons why particle tracks have not been used for the investigation of turbulent flames have already been mentioned - lack of intensity due to the high velocities used and inertial effects due to the excess density of the particles over the carrier gas. Both of these difficulties result from the use of large flow velocities and so can be reduced by limiting these velocities. With ordinary pipe flow this results in the reduction of turbulence and so cannot be an acceptable solution to the problem. Introduction of some device for inducing turbulence upstream of the flame would seem to fulfil the requirement. At the same time it is obviously desirable that both the mean flow and parameters of turbulence should be as uniform as possible across the flame.

Since turbulence occurs as a result of shear stresses in a fluid, various ways of artificially inducing these stresses were investigated. They were limited by the need to produce the turbulence a short distance upstream of the flame.

An attempt was made to achieve stratified flow in a two dimensional model, designed to produce large shear stresses at the layer boundaries, by means of a device similar to an Amal flame trap matrix. The latter consists of successive layers of plain and crimped strips of metal laid upon one another, the crimpings being perpendicular to the long side of the strips. When these layers are tightly bound together the effect is similar to a bundle of thin walled, narrow tubes packed parallel to one another so that any fluid flow passing through them is aligned in the same direction. The projected turbulator differed from this in that the crimpings in successive layers were inclined alternately at plus or minus some angle, α , to the direction they would have had in the normal matrix. The result was that successive layers of flame trap material produced layers of gas, sliding over each other with equal speeds, but inclined to each other by 2α . The construction worked quite satisfactorily for a long, two dimensional burner mouth, but the matrix could not be wound in a form suitable for a small axially symmetrical burner.

The most satisfactory form of turbulator for axially symmetrical burners was made from perforated sheet, with hole diameters approximately the same size as their separation, which led to the production of fairly uniform flow and turbulence across the burner mouth. Experiments were performed moulding these turbulators to a shape approximating to the mean flame position to improve further the uniformity of turbulence. The attempt failed because of the tendency of the flame to flash back when in the immediate vicinity of the turbulator. An optical method of assessing the success of turbulators is to be described later.

With the more uniform turbulence affecting the normally laminar pilot region at the edges, it was found necessary to introduce some form of stabilization to prevent blow-off. This was achieved by diverting a small fraction of the main flow to form a pilot flame.

The pilot flow was fed to a series of closely packed, small holes with their centres based on a circle closely circumscribing the burner mouth. It was important that the pilot should be as small as possible to restrict its zone of influence and prevent it from obscuring deflections of the incident light by the main flame. To achieve this an annulus of fine gauze, of diameter slightly larger than the nozzle carrying the main flow was placed over the pilot. Its effect was to confine the pilot to a small annular ring surrounding the main flame. The burner itself is shown diagrammatically in Figure 2. A matrix of flame trap material was substituted for the turbulator to produce a laminar flame, under similar flow conditions, for direct comparison.

The flow system was designed with the requirements of the optical methods in mind. Versatility was aimed for, rather than extreme accuracy, because the use of turbulators made it difficult to predict flow rates necessary to attain desired turbulence levels.

Propane/air mixtures were chosen as representing a typical gaseous hydrocarbon/oxidant combustible system. The actual choice of fuel was largely dictated by availability, constancy of composition and cost. Air, rather than oxygen, was selected, for convenience and safety; stoichiometric proportions were used to avoid as many extraneous complications as possible. In view of the statistical nature of the phenomenon and its subsequent analysis, it was thought unnecessary to go to the extremes of purification and control employed in the more elaborate investigations of laminar flames.

Preliminary calculations and experiments showed that air flow rates of between .5 and 1.5 l./s. were to be expected together with fuel flow rates between 30 and 90 ml./s. to achieve stoichiometry.

Figure 3 shows a block diagram of the system used. Air was drawn from the laboratory by means of a Bullows 'Hydrovane' pump, and fed, via oil and water traps, into a calming reservoir of about 25 l. capacity. The oil trap was a tube loosely packed with felt whilst the water trap was a similar tube packed with silica gel.

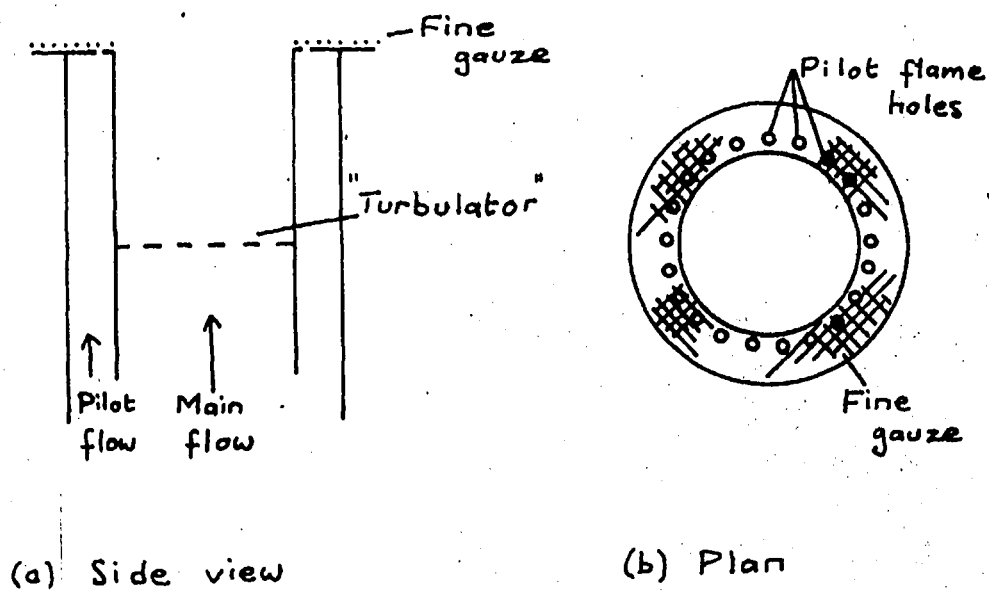


FIG. 2 BURNER MOUTH

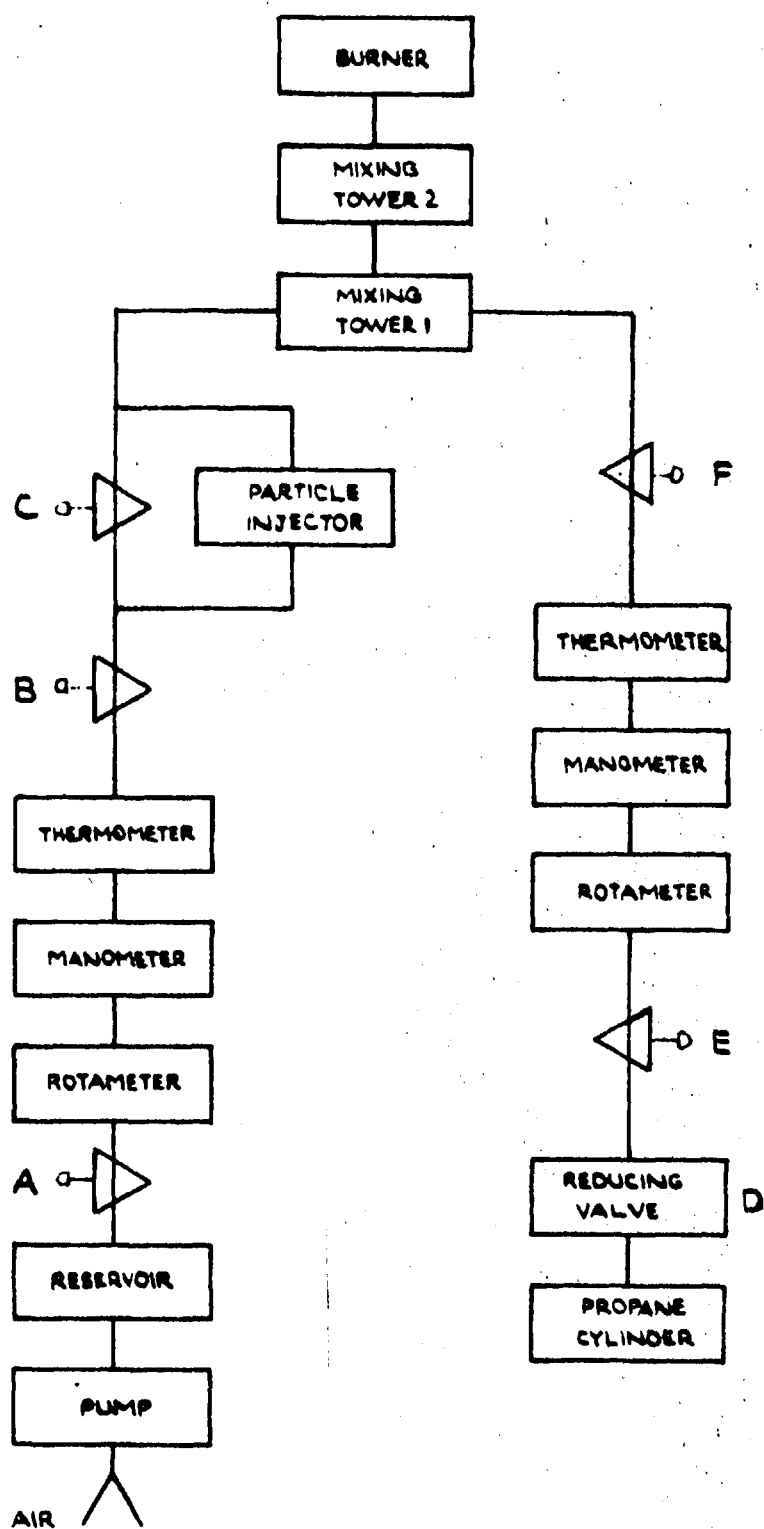


FIG. 3 FLOW SYSTEM

Downstream of the reservoir the first control valve, A, was followed by a calibrated Rotameter flow meter. The air then passed through a T junction, the third arm of which was connected to a mercury manometer; provision was also made in this junction for insertion of a mercury in glass thermometer to indicate the gas temperature. The flow next passed through a second control valve, B, after which it divided two ways, one portion passing through a third valve, C, before rejoining the other which passed through the particle injector. The latter comprised a fine nozzle through which the incoming air was directed on to a pile of elutriated Bentonite, some of which was picked up and carried along by the air stream. After recombination of the two flows the air was fed into the base of the first mixing tower from a device which resembled a small gas ring and was incorporated to aid mixing. The tower was made from a metal tube, of about 8 cm. diameter and 40 cm. length, packed about three quarters full with very short lengths of glass tubing. To ensure homogeneous mixing the reactants were then fed into the second tower which was similar to the first except that there was no gas ring at the bottom. The burner itself (Figure 2) was attached to the top of this tower.

The fuel line was somewhat simpler in that the propane was taken direct from a cylinder and was not passed through a particle injector. Fuel was taken from the cylinder, through the reducing valve, D, and controlling valve, E, to a flowmeter/manometer arrangement similar to that used for the air (except that the calibrated Rotameter was selected to cover the appropriate flow range). Fuel was then introduced into the first mixing tower by a smaller version of the gas ring arrangement used for the air.

Precautions were taken to avoid leaks in the flow lines and connections were made either by metal tubing or else by wired joints on rubber pressure tubing.

The air and fuel Rotameters were each calibrated, on the appropriate gas, at recorded pressure and temperature, by means of positive displacement meters (wet meter for air - bubble meter for fuel) placed in series. Corrections were made as necessary from calibrating to operating conditions by Manufacturer's formulae.

The other approach to improving particle tracks was to increase the intensity of illumination in the Tyndall beam.* One factor that had to be considered was the provision of sufficient illumination by the source to overcome masking by flame luminosity which was very much more serious when particles were injected into the flame than with a 'pure' flame. Fortunately most of the excess luminosity appeared to be due to sodium impurities in the particles, resulting in its confinement to a narrow wavelength region. Although it was extremely difficult to remove the impurities, their light could be blocked by suitable filters. Thus, the external source had either to be powerful enough to permit loss of some of its light in the sodium D line region, or have its radiation confined to wavelengths away from the sodium lines.

Line sources were deemed to have the most suitable geometry as the requirement is for illumination of a narrow axial section across the burner. Reference to available, continuous-running lamps of this type showed that none of them was nearly powerful enough for the purpose. The limitation was not serious as periodic interruption of the tracks was desired for a time base for velocity measurement.

The obvious alternative was some form of flash which could either take the form of several individual flashes produced at known time intervals, or of one long flash which effectively acts as a continuous source with separate time interruptions superimposed upon it. A difficulty arose in identification of the tracks of an individual particle in the presence of many others. It was severest where the duration of individual flashes was short enough to 'freeze' the image so that it appeared as a pinpoint which could then, by itself,

*Better forms of illumination, based on lasers, would be used nowadays but were not available at this phase of the work.

give no indication of the direction of motion. If, however, the particle travelled sufficient distance during its exposure to be recorded as a dash, the orientation of the latter would indicate where to expect the particle to be when the next flash occurred. Thus, it would be very much easier to follow the path of a single particle if the exposure time of an individual flash was of at least the same duration as the interval between successive flashes.

Preliminary experiments indicated that flow rates up to about 500 cm./s. were required. Hence the flash apparatus had to be designed to give reasonable spacing between successive exposures of one particle at this flow rate. Rough calculation showed that exposure times and intervals should be of the order of 0.2 ms.. This was rather long duration for any form of electronically controlled repetitive flash and a series of, say six, of these flashes, spaced at similar intervals, would require complicated and expensive circuitry. For this work it was decided to use a single, long duration flash which was subdivided by means of a mechanical shutter. The source itself consisted of a Siemen's S.F. 14 line flash tube which was supplied with power from a 3,000 μ F electrolytic condenser charged to 200v. It was energised by discharging a 0.25 μ F condenser, also charged to 200v, through the primary of a 6v car coil, the secondary of which was attached to the trigger electrode of the flash tube. Primary discharge was initiated by the opening of the shutter of the recording camera. Total flash duration thus obtained was of the order of 3 ms.. Periodic interruptions were obtained by means of a sector shutter rotating immediately in front of the flash tube. The shutter was constructed of a cardboard disc, of 33cm. diameter, divided into 90 equal sectors. Corresponding portions of alternate sectors were cut out to allow light from the source to reach the optical system. The disc was driven by an electric motor, controlled by a 'Variac' auto transformer, and was normally operated at 50 revolutions per second. An accurate measure of the rotation speed was obtained by means of a neon stroboscope.

The light from the source was focused by means of a condenser lens, using the method of no parallax, on to the burner axis and thus effectively illuminated a narrow plane through this axis.

Particle tracks were recorded by a camera placed perpendicular to the plane of illumination. A large aperture lens (Kodak Ekter F3.7 of 10.5 cm. focal length) was used to photograph the tracks in order to have a very small depth of field and obtain a two dimensional picture of the particle motion. Intense emission of sodium light which occurred when the particles were heated by the flame, was kept from the photographic emulsion by a filter of Chance ON 16 Didydium glass interposed between the flame and camera lens. Records were made on Ilford H.P.S. plates developed in Ilford Contrast FF developer. A typical record is shown in Figure 4.

2.2 Ray Deflection Methods - Principles

The first of the ray deflection methods was developed for the semi-quantitative assessment of the effectiveness of turbulators. The principles underlying the optical techniques will now be described.

A flame may be defined as a region in which a self-sustaining, exothermic reaction takes place. As this region is traversed the temperature rises from its initial value to a final one occurring towards the end of the reaction.

Gladstone and Dale's Law may be written as:

$$\frac{\mu - 1}{\rho} = \frac{\delta}{\rho} = \text{constant} \quad (2.1)$$

where μ is the refractive index and ρ is the density.

For a constant pressure, constant composition system this may be expressed in terms of the temperature, in which case

$$(\mu - 1)T = \text{constant} \quad (2.2)$$

where T is the absolute temperature.

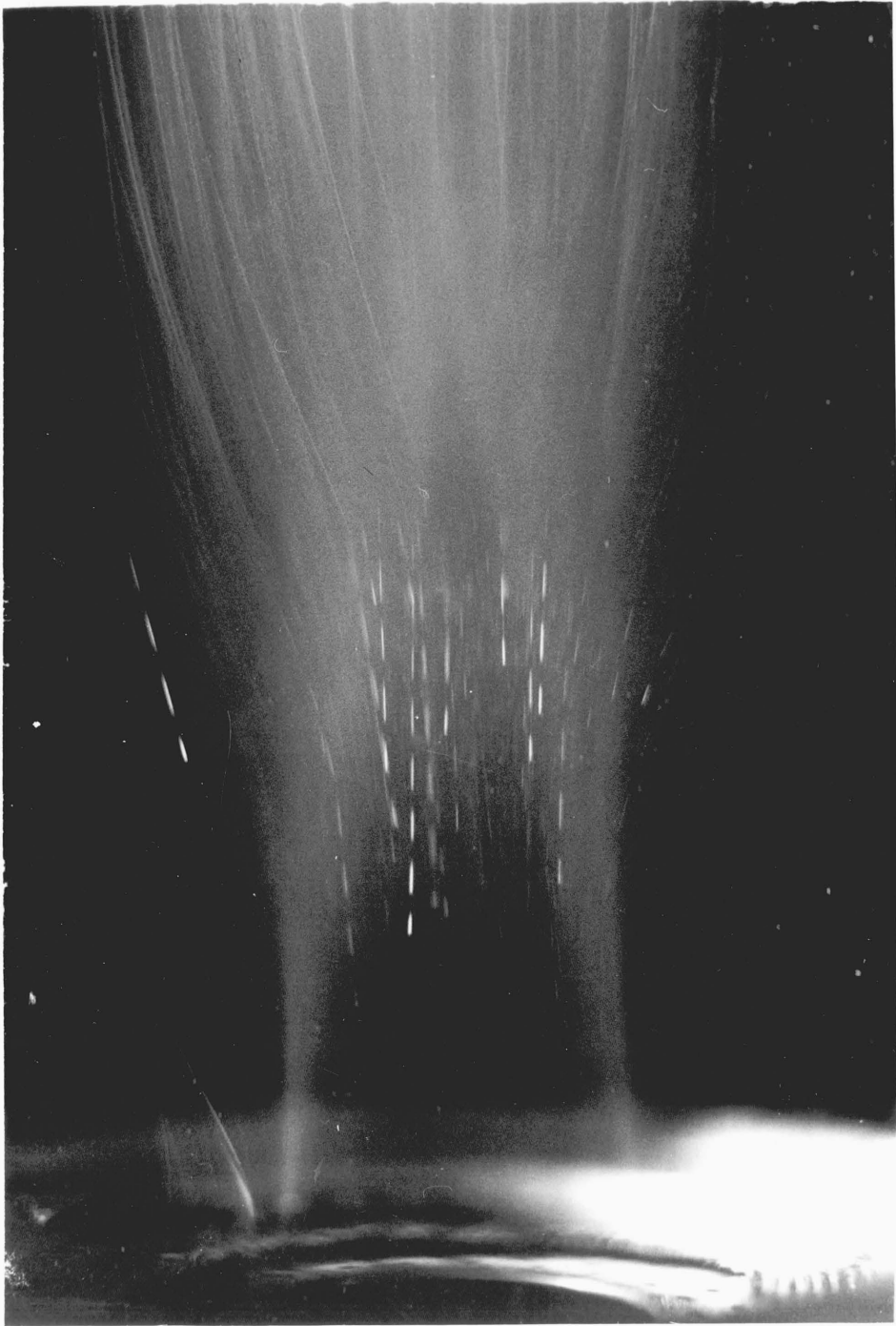


FIGURE 4 - PARTICLE TRACK RECORD

An element of flame front may be considered as a series of parallel constant refractive index planes, differing from the above condition only in so far as composition changes occur across it. The effect of these will be small compared with the temperature effects⁽²⁾ and are neglected in the subsequent analysis.

The deflection in the y plane, θ_y , of a light ray incident along x occurs in the (x,y) plane and is given by

$$\tan \theta_y = - \int_0^X \frac{1}{\mu} \frac{\partial \mu}{\partial y} dx \quad (2.3)$$

where X is the geometric path length.

For gases (where the refractive index, μ , approximates to unity and θ_y is small) this equation becomes

$$\theta_y = - \int_0^X \frac{\partial \mu}{\partial y} dx \quad (2.4)$$

In a two dimensional system the distribution of both X and θ_y are measurable, making possible calculation of the refractive index distribution in the flame. Since it is assumed that this distribution is due primarily to temperature variation, it has enabled the distribution of temperature to be deduced⁽²⁾.

As far as turbulent flames are concerned, the differential form of equation 2.4 is more important because of the instantaneous symmetry of the geometry. This may be written

$$d(\theta_y) = - \frac{\partial \mu}{\partial y} dx \quad (2.5)$$

If the element of flame front is inclined at an angle, ψ , to the (x,z) plane, equation 2.5 becomes

$$d(\theta_y) = -\frac{\partial \mu}{\partial n} \cot \psi dx \quad (2.6)$$

where n is the normal to the direction of maximum gradient.

It may be seen that for any given element the deflection will be maximum when the lines of constant refractive index lie parallel to the illuminating beam and will fall off rapidly with increasing inclination.

Differentiation of equation 2.2 yields a relation between refractive index and temperature gradients which may be substituted in equation 2.5 to yield

$$\frac{d}{dx}(\theta_y) = -\frac{(\mu_0 - 1) T_0}{T^2} \cdot \frac{dT}{dy} \quad (2.7)$$

In the early part of the flame (some times referred to as the preflame region) there is no heat release and heat flow is by conduction only. The heat balance in an element of streamtube, starting at temperature T_0 , flowing in the y direction, is given by:

$$k \frac{dT}{dy} = M C_p (T - T_0) \quad (2.8)$$

where k is the thermal conductivity, M the mass flux, and C_p the specific heat. At low temperatures

$$\frac{k}{M C_p} \neq f(T)$$

Substituting for $\frac{dT}{dy}$ equation 2.7 becomes:

$$\frac{d}{dx}(\theta_y) = \text{constant} \left(\frac{1}{T} - \frac{T_0}{T^2} \right) \quad (2.9)$$

Differentiating equation 2.9 w.r.t. T and equating the results to 0, shows maximum values of $\frac{d}{dx}(\theta_y)$ to occur when $T = 2 T_0$. Thus, if temperature effects only are considered, maximum deflections occur at twice the initial temperature.

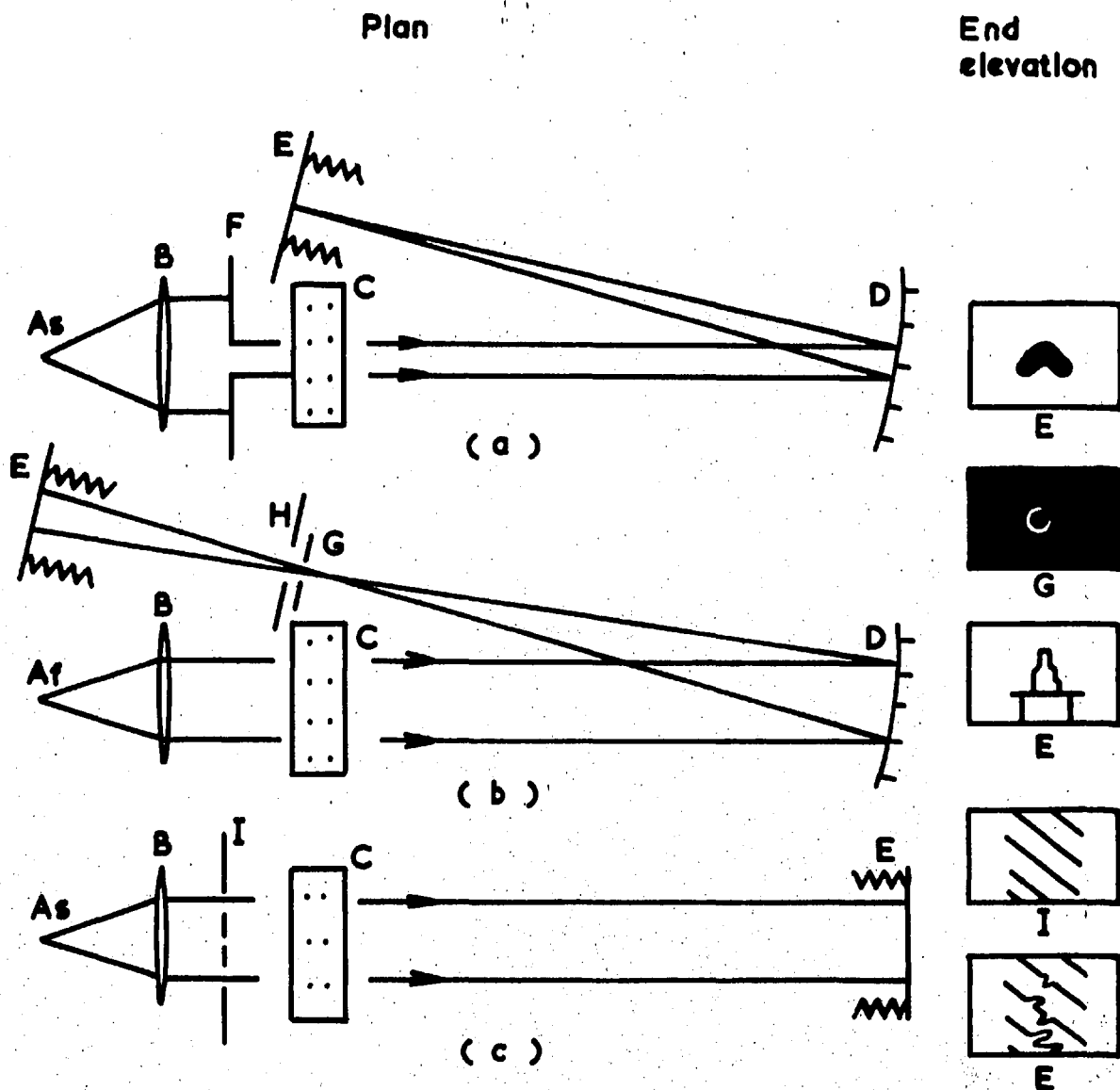
2.3 Polar Diagram Method

The particular method developed for a semi-quantitative comparison of the effectiveness of different turbulators depends on recording the randomness of orientation of the deflection producing elements of flame front. If parallel light is deflected by a geometrically simple, time-constant, laminar flame, its deflection will also be geometrically simple and time-constant. If, however, it is deflected by randomly oriented elements of flame front, it follows that its deflection will be random. Since the distortion of the flame front from laminar symmetry is caused directly by the turbulence, it further follows that a measure of the randomness of the deflection gives some measure of the turbulence. In order to make use of the effect it was necessary to confine the undeflected light in some way as to be able to display the distribution of randomness of deflections. The aim was achieved by focusing parallel light to a point. Any disturbance then occurring in a test region in the parallel section of the beam recorded as spread of some of the light from the point focus. The relevant property of the focused image is that it records angle, independent of position in the test space. A recording device placed in the focal plane showed a distribution of the angles of the deflection. The form assumed by this 'polar diagram' gave the desired measurement of turbulence. A record corresponding to the sides of a conical, laminar flame of apex half angle, α , appeared as two straight lines, each radiating downwards at an angle $(\frac{\pi}{2} - \alpha)$ to the vertical and meeting at the origin which contained the undeflected light. The opposite extreme is a section of flame front fluctuating so that it is randomly oriented. In that case the deflections exhibited corresponding randomness and the resulting polar diagram appeared as

a diffuse disc, surrounding the point focus corresponding to undeflected light. Intermediate turbulence levels resulted in a picture between the two extremes. The magnitude of the deflection recorded in the polar diagram due to a particular ray, was $F\theta$, where F is the focal length of the lens or mirror focusing the parallel beam and θ , the angular deflection suffered by that ray on passage through the test zone.

Since the randomness of orientation varies in different regions of the turbulent flame, it was desirable to make the method suitable for examining those regions separately. To do so it was necessary to confine the parallel beam by means of some form of aperture. Unfortunately, the aperture itself introduced diffraction effects which led to the production of a characteristic polar diagram even without any disturbance in the zone. The difficulty was overcome by designing apertures of such a shape that their own diffraction pattern was readily distinguished from the deflection pattern due to the flame. Both rectangular and triangular apertures were suited to this purpose.

A schematic diagram of the optical arrangement is shown in Figure 5(a). The light was provided by 250 watt, compact source, mercury vapour lamp which was focused, by means of a condenser lens of 4 cm. focal length, on to a pinhole. This pinhole was an effective source for the collimating lens which was an achromatic combination of 1m. focal length and was situated so that the pinhole was at its focus. The parallel beam was confined by a movable aperture and passed through the test zone. The undeflected light was focused to a point by means of a schlieren mirror of 250 cm. length, a photographic plate being placed at this focus. Figure 6 is a typical record of a wire stabilized flame with its apex facing downwards. The confining aperture was a horizontal slit, 0.35 cm. wide, and the individual exposures of (10 s. duration) correspond to the slit being moved vertically at 0.5 cm. intervals. Thus the



A - effective point source (pinhole; real source and condenser not shown), subscripts denote "steady" or "flash";
 B - collimating lens; C - refractive index field under investigation; D - schlieren mirror; E - photographic plate;
 F - movable slit; G - ring-shaped schlieren aperture;
 H - high speed shutter; I - screen of inclined slits.

FIG. 5. SCHEMATIC DIAGRAM OF OPTICAL SYSTEMS

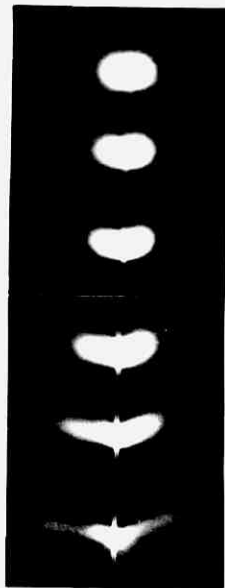


FIGURE 6 - POLAR DEFLECTION DIAGRAM

individual pictures commence in the near laminar region at the base and indicate the increase of turbulence on travelling upwards away from the stabilizing wire. The vertical line, at the centre of each exposure, is due to the diffraction pattern of the slit.

2.4 Location of Instantaneous Flame Front

The third of the optical methods is that for delineation of the instantaneous flame front necessary for a check of the fluctuating laminar flame hypothesis and a reproducible definition of turbulent burning velocity. For this method it is the distribution of certain deflection producing elements of flame front within the test zone that is of importance. The optical system for the polar diagram method, if considered without its confining aperture, provides the first section of a conventional schlieren system where the record is taken at the point conjugate with the test zone.

It has already been explained how the strongest qualitative evidence for the instantaneous structure of turbulent flames has come from the use of schlieren methods. They are, however, capable of much greater refinement both in use and interpretation. One property that makes them attractive in the present context is their ability to characterise and 'freeze' the turbulent flame surface. A further property, hitherto unexploited, is of fundamental importance here. The recorded contour of an instantaneous schlieren picture must always be due to elements of flame front whose radii of curvature lie in a plane perpendicular to the direction of illumination. The marking of any discontinuity depends on the angle of deflection of the light being sufficient to pass the schlieren stop. Thus the schlieren image is the locus of maximum deflection and is caused by elements of flame front parallel to the illuminating beam (equation 2.5). Elements aligned in other directions must lie within the outermost schlieren image and give rise to smaller deflections (equation 2.6). It is the use of such

contours in conjunction with mapping of the flow field by particle tracks, that enables the problem to be reduced to two dimensions because it permits the measurement of local approach flow angles, there being no component in other planes.

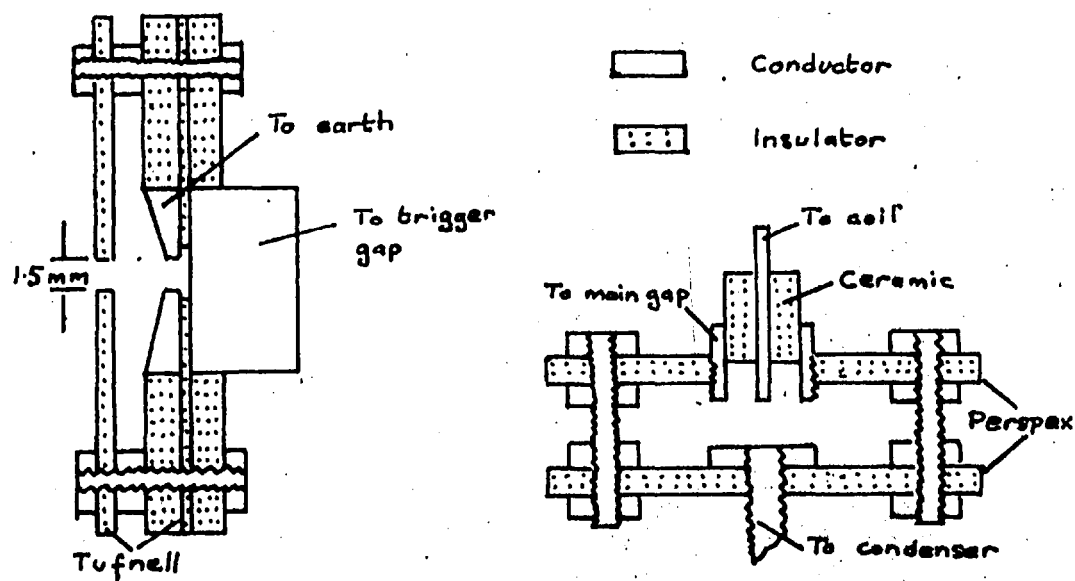
For conventional systems the schlieren stop itself usually takes the form of a knife edge. In the particular optical system described above this would be placed at the foint focus of the parallel light and would permit passage of light deflected in one particular direction. That is not a property desired for the particular application of the method envisaged here. The surfaces to be detected are those corresponding to the outermost continuous flame surface as opposed to those giving the maximum schlieren intensity. They can be aligned at any angle in a plane perpendicular to the direction of illumination and so are liable to cause deflections at any angle. Thus a schlieren stop is required which will detect deflections in any direction. The condition is satisfied by a small, opaque, circular disc, which, for maximum sensitivity, should be the same size as the image of the undeflected light. A further consideration is that it is the boundary corresponding to the outermost, continuous ridge that is of interest. It is quite feasible that the boundary might be marked by small deflections, giving rise to little illumination, and hence masked by large deflections, giving greater illumination, arising from elements of flame front other than those studied. To avoid this, the schlieren stop was further modified to consist of a small, clear ring on an opaque background. The central opaque portion corresponded to the stop described above, whilst the region outside the ring obstructed the passage of light deflected through large angles. Reference to Figure 5 shows that wherever the maximum deflection displaces rays beyond the outer boundary of the clear annulus, there are temperature regions, on either side of the one causing maximum deflection, which deflect the light through the correct angle to avoid the opaque parts of the stop. On simple, geometric, optical theory both these regions would be marked.

In practice, for the flames under consideration they are sufficiently close together to be masked by diffraction effects. It is these effects which limit the sensitivity of the method. The single diffracting discontinuity of the knife edge is replaced by the symmetrical annular ring which, for deflections in any particular direction, acts as a double slit system. As the width of the ring is decreased - corresponding to increased sensitivity - the diffraction effects become enhanced making it more difficult to identify the position of the flame's boundary.

As the method was designed to yield instantaneous contours of the flame surface the time exposure had to be short enough to freeze any fluctuations. Once again the source has to fulfil certain specific requirements; unfortunately these were not compatible with those for particle track illumination, so that an entirely separate source had to be developed.

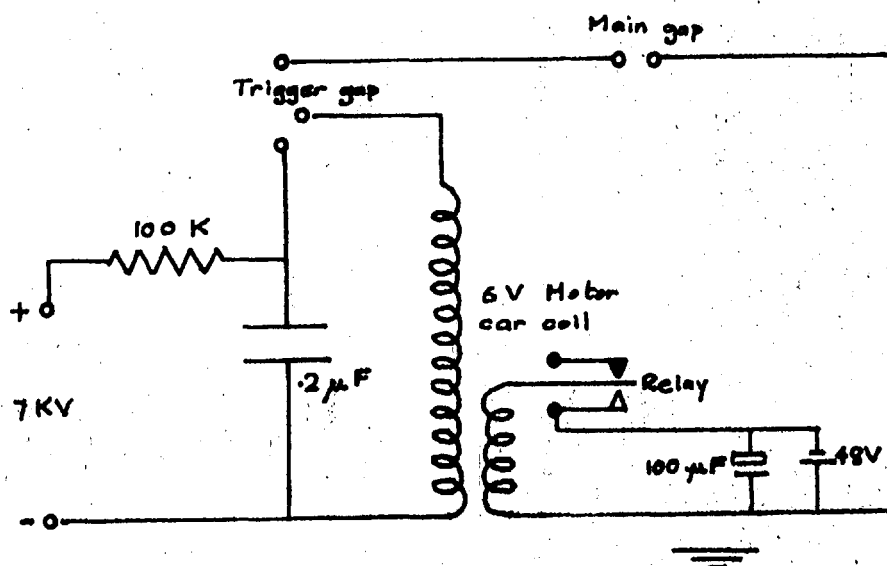
The exposure duration necessary to freeze the flame fluctuations was found to be of the order of tens of microseconds; moreover the effective part of the source had to be confined to a pinhole in order to produce parallel light. In addition, provision had to be made for some form of continuous running source for alignment purposes. The latter was provided by the high pressure mercury vapour lamp, already described, focused on to a fixed pinhole by means of a condenser lens, and was replaced by the flash source for the actual exposures.

The flash source itself was provided by means of a channelled air spark and is shown schematically in Figure 7. The principle of operation was to discharge a high voltage condenser through two spark gaps placed in series, one gap being the point source, the other a triggering gap which could be energised by some external source operated by the camera shutter. Details of the circuit are shown in Figure 7. The energy store was a $.2 \mu\text{F}$ condenser which was charged to 5 K.V. by means of a radio frequency oscillator.



(a) Horizontal section through main spark gap assembly.

(b) Vertical section through trigger gap.



(c) Circuit

FIG. 7 FLASH UNIT

Provision was made for coupling three similar condensers in parallel for applications where greater intensity was desired. A modified motor-car spark plug was mounted on perspex above the charged terminal of the condenser to provide the trigger gap, the outer case carrying the main discharge and the central electrode the triggering potential. The latter was provided by discharging a 100 μ F condenser charged to 48v. through the primary of a 6v. car coil, whose secondary was connected to the trigger electrode, and was initiated by opening the camera shutter. Triggering this gap caused the main condenser to discharge to earth through the main gap, providing the requisite flash. In order to minimise the flash duration, the length of wiring carrying the discharge current was kept as short as possible. The net result of this arrangement was a point flash of a few microseconds duration.

The optical system from the pinhole onwards, as explained at the beginning of this section, was identical to that used for the polar diagram method up to the focus of the schlieren mirror. The photographic plate was then replaced by the schlieren stop and the plate itself placed conjugate with the test zone. This is the system shown in Figure 5(c) which was the original experimental arrangement. Two improvements were subsequently incorporated. The first was to discard the collimating lens since it was found, in practice, that the focal length of the schlieren mirror was such that light from the pinhole itself falling on the mirror could be regarded as parallel. The second was to reduce the overall length of the optical path to make the method less inconvenient for use in the limited laboratory space available, and enable 35mm. film to be used for the large number of records desired. This was facilitated by the use of two similar microscope objective lenses of 2.5cm. focal length subsequent to the schlieren stop. The first of these formed a small image of the test zone, near its focal plane, which acted as an aerial object for the second lens, whose position was adjusted, until it gave an image of the test zone of the desired magnification. This image was focused on to the screen of a Pentacon 35mm. reflex camera from which the lens had been removed. The flash source was synchronised to the

focal plane shutter of the camera which was set to a speed of .1s. to enable the complete picture area to be exposed when the shutter was fired. About fifty records of each individual flame were made on Adox KB 17 film developed in "Beutler" high resolution developer for 12 mins. at 20°C. The final alignment of the system, before exposure, was made using the continuous source and with a flame present in the test region, so that allowance could be made for deflections due to the hot products surrounding the main flame. A typical record is shown in Figure 8.

2.5 Time-mean Distributions of Refractive Index

The last of the optical parallel light methods is for the measurement of time-mean distributions of substances of different refractive indices. Westenberg⁽¹³⁾ has used helium as a tracer and has measured its concentration by means of probes, downstream of the injection point, and in so doing has deduced the turbulence present. Unfortunately the method suffers from all the disadvantages of a probe technique in that the geometry of the original flow is liable to be disturbed by the presence of the probes themselves. If quantitative optical measurements of deflections can be used to deduce the concentrations, one source of uncertainty is removed. To do this it is necessary to introduce some refractive index different to that of the main flow. Also, for quantitative measurements, it is desirable to assume a two dimensional model with no variation of optical path along the axis of the illuminating beam. Thus the techniques here described will be best suited to conditions prevailing on long, slot burners. A natural subdivision of the use of the method suggests itself here; between regimes where refractive index differences are already present and those where they have to be induced artificially (e.g. a stabilized flame and cold flow). The former is the most promising as regards the present work. Deflection mapping techniques have proved a very potent tool in the investigation of flat laminar flames (e.g. ^(30,31)) and may be regarded as the quantitative version of the polar diagram method in so far as they indicate magnitude and distribution of the deflections over the test zone. In this case the undeflected light is confined by a series of



FIGURE 8 - INSTANTANEOUS SCHLIEREN CONTOUR OF TURBULENT FLAME

parallel, inclined slits so that deflections show up as distortions of the regular slit pattern. The magnitude and direction of the time average pattern can be used, in conjunction with knowledge of some mean flame position, to deduce the distribution of refractive index. If it is assumed, on the basic concept of the instantaneous flame surface, that the flame front is thin compared with the amplitude of the corrugations the method will lead to a measure of the time-mean distribution of products and reactants. The flame may be considered as a surface of discontinuity separating products, of refractive index, μ_p , from reactants of refractive index, μ_r .

Equation 2.3 may be written as

$$\tan \theta_y = \int_0^X \frac{1}{c'} \frac{\partial c}{\partial y} dx \quad (2.10)$$

where c' is the velocity of light within the medium and is equal to $\underline{c}$ where c is the velocity of light in vacuo.

In the turbulent case, c' is replaced by its mean value, $\bar{c}'$,

$$\text{where} \quad c' = \frac{X}{\int dt} \quad (2.11)$$

and the concept of the optical path

$$D = \int_0^X \mu dx = \int_0^X \frac{c}{\bar{c}'} dx \quad (2.12a)$$

becomes useful. Integrating

$$\bar{c}' = \frac{cX}{D} \quad (2.12b)$$

Substitution in equation 2.10 gives

$$\tan \theta_y = \frac{X}{D} \frac{\partial D}{\partial y} \quad (2.13a)$$

which may be simplified to

$$\theta_y \approx \frac{\partial D}{\partial y} \quad (2.13b)$$

which is virtually exact since even in the worst possible case, (i.e. for cold gas) μ differs from unity (or D from X) by less

than 3 parts in 10^4 . Expressing D in terms of the volume fraction, f , of hot products at any height

$$D = -X [\mu_r - f(\mu_r - \mu_p)] \quad (2.14)$$

substitution from equation 2.13b gives

$$\theta = -X [\mu_r - \mu_p] \frac{df}{dy} \quad (2.15a)$$

or, numerically, considering all deflections towards the cold gas

$$f = \frac{1}{X(\mu_r - \mu_p)} \int_{-\infty}^y \theta dy \quad (2.15b)$$

In the work on laminar flames, to which reference has already been made, distributions of ray deflections were mapped by recording the images or shadows of inclined slits, through which a parallel beam of light was passed. The beam was also parallel to the plane of the flat flame which it traversed, and the confining slits were inclined at an angle of 45° to that plane. The simplest optical system is shown in Figure 5(c) and corresponds to that used in the present investigation. The displacement of any part of the slit from its undeflected position, determined by reference to the undisturbed portions of the slit image, was simply $(x\theta)$, where x was the distance between test zone and photographic plate. The optical arrangement Figure 5(c) was the same as that adopted for the polar diagram method as far as the test region. The latter contained a wedge-shaped turbulent flame, the long side of which measured 3.0 cm. and was parallel to the illuminating beam. The record shown in Figure 9 was obtained on an Ilford N40 Process Plate placed 1m. from the test zone. The photograph was exposed for 1 min. and developed in Ilford PQ Universal Developer.



FIGURE 9 - INCLINED SLIT RECORD OF TURBULENT FLAME

The distribution of f and in particular its approach to its two extremities of zero and unity, will be shown later to be of fundamental importance in estimating the shape of the mean corrugations. Such information can be deduced, as shown in the preceding theory, from the shape of the deflection profile.

Figure 10 shows the record obtained with a similar optical arrangement (except that the distance between test space and plate was 3m.) applied to the spread of heat from a coil of length 1 cm., diameter 1mm., wound from wire of 0.2mm. diameter placed in the cold flow stream. The coil was heated electrically to about 600°C. Time-mean distribution of heat, and hence transport properties, are calculable from the record. The method was not developed further because the length of coil necessary to achieve adequate sensitivity made it unsuitable for use in conjunction with the relatively small burners employed in the rest of the study.

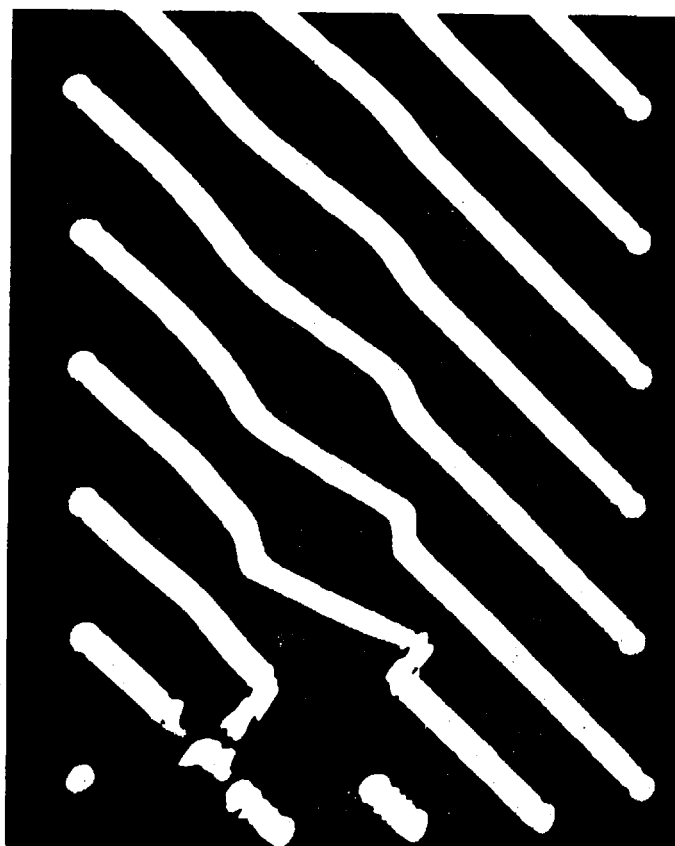


FIGURE 10 - INCLINED SLIT RECORD OF HEATED COIL

CHAPTER 3 OPTICAL METHODS - RESULTS

3.1 Burning Velocity of the Instantaneous Flame Front

The time average, local burning velocity, $\bar{S}_L$, of the instantaneous, corrugated, fluctuating flame front was obtained by combination of the particle track records of section 2.1 and the frozen flame contours of section 2.4.

The definition of $\bar{S}_L$ is derived from that for the local burning velocity in laminar flames and is expressed by the turbulent form of equation 1.8.

$$\bar{S}_L = \bar{v} \overline{\sin \phi} \quad (3.1)$$

where $\bar{v}$ is the local mean approach velocity and $\overline{\sin \phi}$ the local mean value of the sine of the angle, ϕ , between approach flow and flame surface. (N.B. — is taken throughout as representing time, not distance, mean). The equation in its above form, is unsuited to direct measurement because of the rapidity and randomness of local changes in ϕ , both from record to record and across a burner diameter (e.g. Figure 8). Reference to Figure 11 shows how equation 3.1 may be re-written in the form:

$$[\bar{S}_L] = \bar{v} \left(\frac{\Delta r}{\Delta l} \right) \quad (3.2a)$$

where $\bar{S}_L$ represents $\bar{S}$ averaged over a particular increment of radius, Δr , and Δl is the corresponding length of flame surface, as delineated by the outermost schlieren contour. For a constant value of Δr , averaged over m records, the equation becomes:

$$[\bar{S}_L] = \bar{v} \frac{\Delta r}{m} \sum \frac{1}{\Delta l} \quad (3.2b)$$

where all terms on the right hand of the equation can be measured directly.

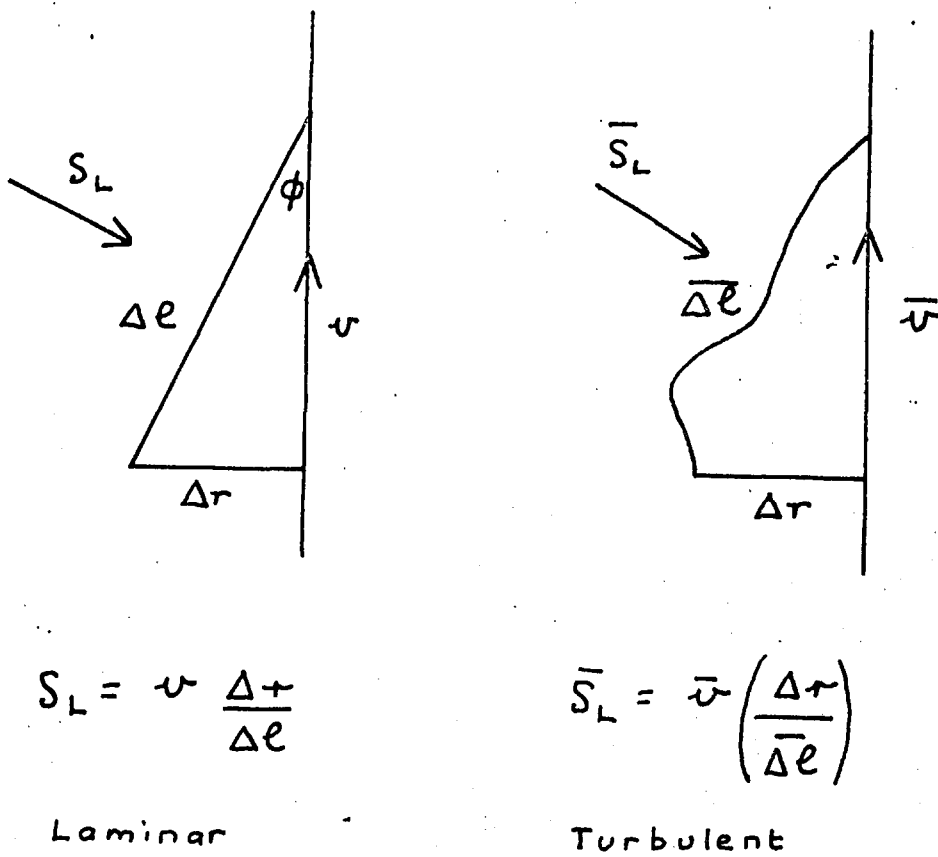


FIG. 11 DEFINITION OF BURNING VELOCITY
FOR LAMINAR AND TURBULENT FLAMES.

For purposes of analysis the radial section across the burner mouth was subdivided into six equidistant zones, for each of which mean velocities were determined from particle tracks and mean lengths of flame surface from instantaneous contours. The number of contours necessary to give a reasonable statistical average of length, in a particular zone, was found by increasing the number of samples until further increase yielded no significant change in the average. 40 - 50 records were found to be adequate. Actual measurements were carried out on enlarged, projected, images of the original records.

Because of the large number of records involved, detailed analysis was restricted to two flames. They were of the same reactant composition - stoichiometric propane/air. Both had fairly uniform distribution of mean velocity over the burner mouth - the values being 367 and 147 cm./s., respectively. Intensities of turbulence, measured by particle track deviations, near the axis, were 18 and 12 cm./s., about 5% of mean approach velocities. The effective scale of turbulence was assumed to be 1.8 mm., the spacing of the turbulent grid.

The same type of burning velocity measurement was carried out on laminar flames of similar composition and mean flow, 379 and 252 cm./s., respectively, to the turbulent flames. Laminar flow was attained by replacing the turbulator with a conventional, flow straightening, flame trap matrix. Analysis was far less arduous because the time constancy of the system meant that only one flame contour had to be measured.

Results for the higher flow velocity are shown in Figure 12; for the lower velocity in Figure 13. In each case curve 1 represents the apparent local burning velocity of the laminar flame S_L , curve 3 the equivalent burning velocity for the instantaneous corrugated surface of the turbulent flame, $S_{L'}$.

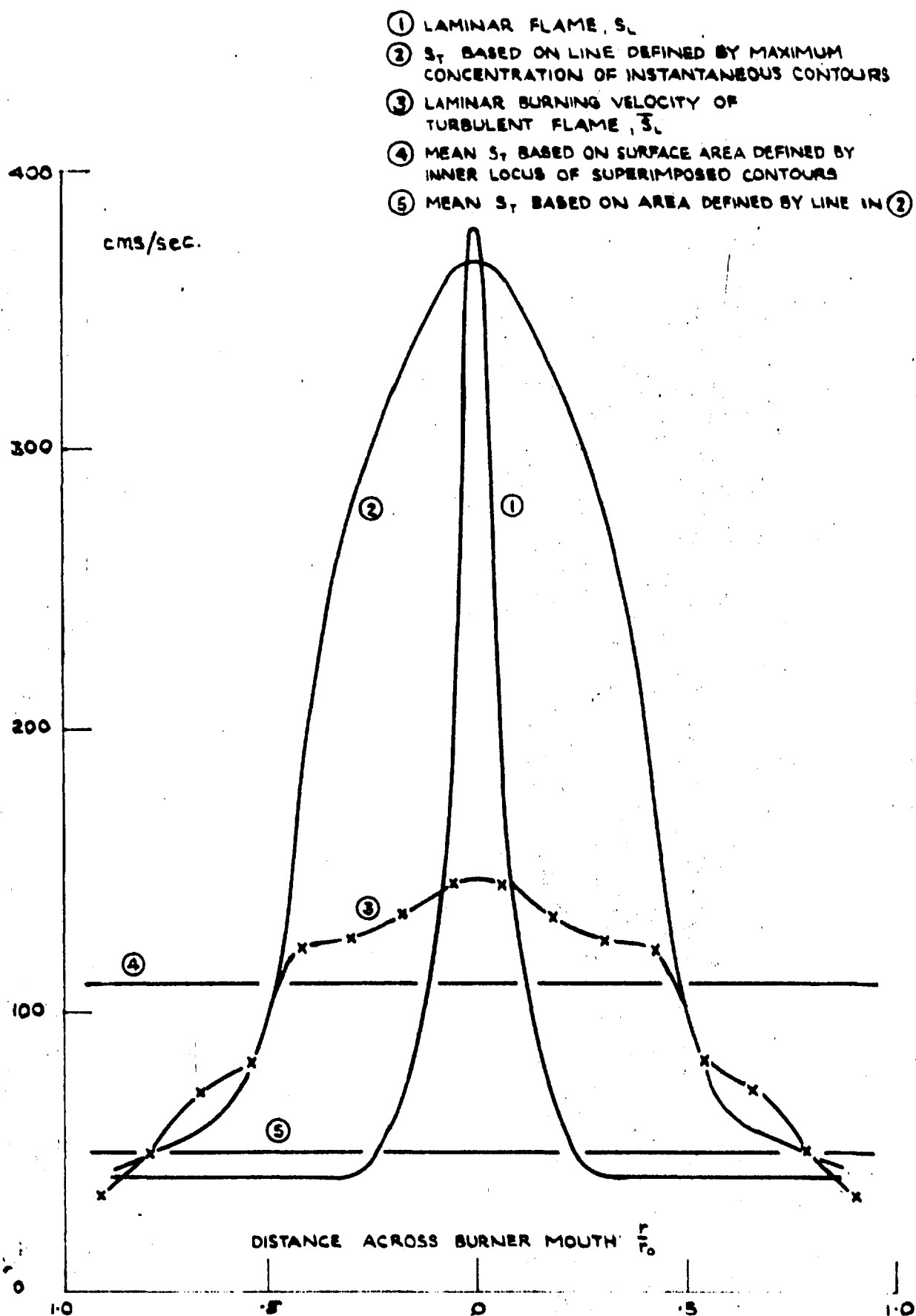


**FIG. 12 BURNING VELOCITIES OF LAMINAR AND TURBULENT FLAMES
 BASED ON SCHLIEREN CONTOURS**

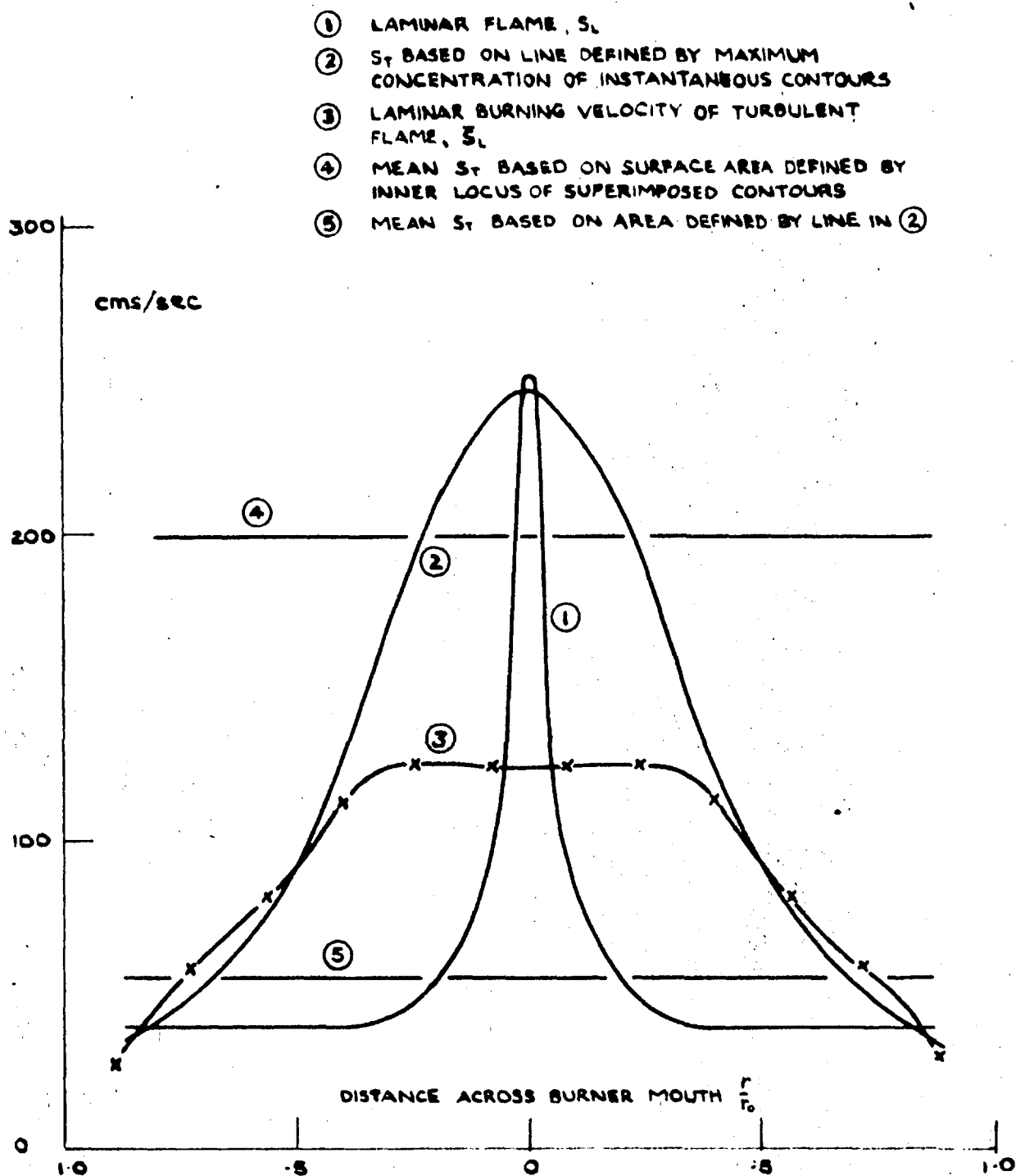


FIG. 13 BURNING VELOCITIES OF LAMINAR AND TURBULENT FLAMES BASED ON SCHLIEREN CONTOURS

3.2 Turbulent Burning Velocity

The fundamental nature, in terms of real flame surfaces, of the instantaneous schlieren contours, enable them to be used in the construction of artificial, but reproducible surfaces for use in definitions of turbulent burning velocity, S_{T} . Its definition may either be in terms of an average value across the burner mouth, in which case the turbulent form of equation 1.9

$$S_{T,av.} = \frac{V}{A} \quad (3.3)$$

holds true, where V represents the volumetric flow rate and A the artificial surface area; or a distribution across a burner diameter, in which case equation 3.1 applies and the arbitrary flame surface is used to define ϕ .

Individual schlieren contours were superimposed (e.g. Figure 14) and used to construct regular smooth surfaces at the maximum concentration and innermost loci. The surfaces were used, in turn, to define average turbulent burning velocities (lines 4 and 5 in Figures 12 and 13). The locus of maximum concentration of instantaneous contours was also used, in conjunction with particle tracks, to derive a distribution of S_{T} across the burner mouth (curve 2 in Figures 12 and 13).

3.3 Interpretation of Laminar Burning Velocity

The "wrinkled laminar" flame hypothesis, in its simplest form, likens each element of instantaneous turbulent flame front to an element of a freely propagating, infinite, plane, laminar wave. Even laminar flames stabilized on laboratory burners depart from this idealised model and an understanding of relevant departures provides an essential basis for interpreting turbulent flame results.

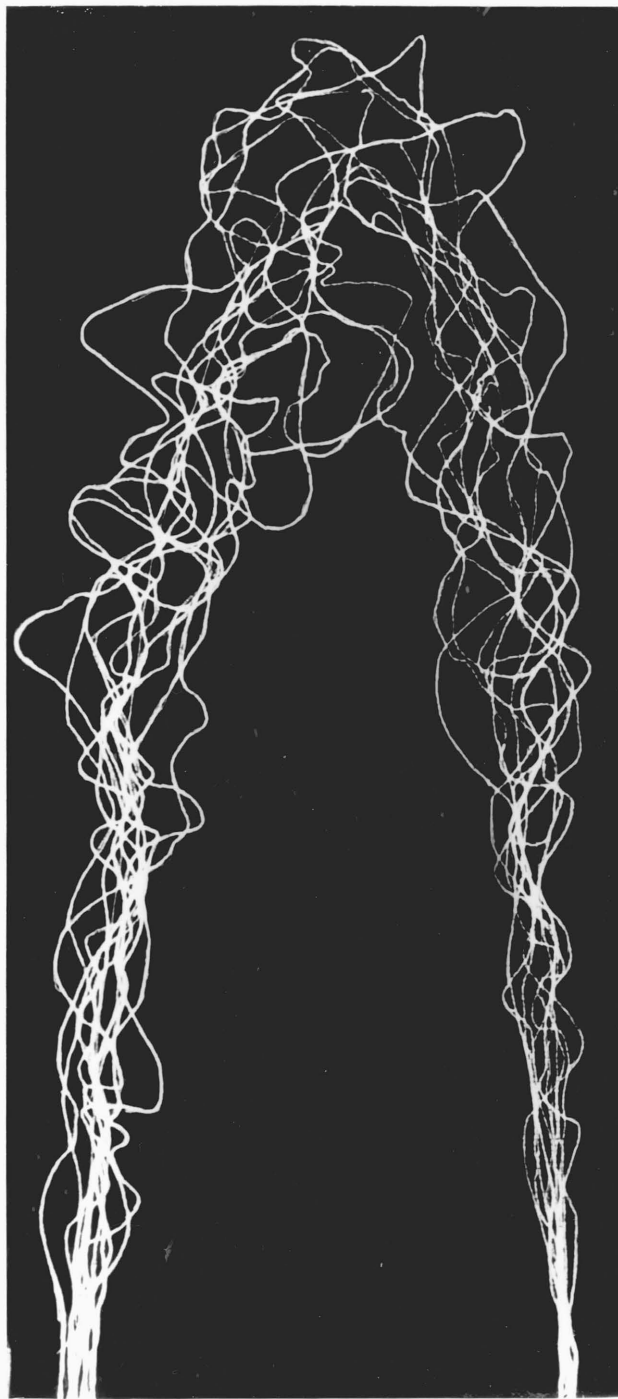


FIGURE 14 - SUPERIMPOSITION OF INSTANTANEOUS SCHLIEREN CONTOURS

Burning velocity distributions obtained with laminar flames (curve 1 in Figures 12 and 13) show three distinct regions. Starting from the burner rim the burning velocity rises (region 1) to a plateau (2) at a value of 40.4 cm./s. - which represents good agreement with similar measurements by other workers⁽³⁸⁾ - and then peaks to the mean axial flow velocity. Region 2, away from extraneous boundaries and regions of high flame curvature, approximates closely to the modelling conditions described above. In region 1 the burning velocity is reduced (as discussed in Chapter 4) by entrainment of surrounding atmosphere and by quenching at the burner rim. Neither effect need concern us in detail here as we can confine interpretations of burning velocity to central regions of the turbulent flame remote from such boundary layer phenomena. The apparent increase in burning velocity at the axis must be fully understood as it is associated with flame curvature, an effect which is common to, although different in, the frozen turbulent flame.

Figure 15 illustrates the relation between flow field and flame position for a conical laminar flame. In the absence of buoyancy and viscosity effects the conservation of momentum requires flow lines and constant pressure surfaces to form an orthogonal system. The flame is characterised by a series of constant temperature surfaces which, in the reaction zone, are coincident with constant composition surfaces. Flame area may be defined by any one of these constant temperature surfaces.

A uniform approach flow can, far upstream of the flame, be divided into a series of similar parallel flame tubes. Conservation of mass can be applied to all of these flame tubes between stations far upstream, as described, and the point where they cross any, arbitrarily defined, flame surface.

$$\text{Thus,} \quad \rho_0 v_0 dA_0 = \rho' v' dA' \quad (3.4)$$

where ρ is density, v velocity and dA area of the streamtube and subscripts $_0$ and $'$ apply to conditions far upstream and at the flame.

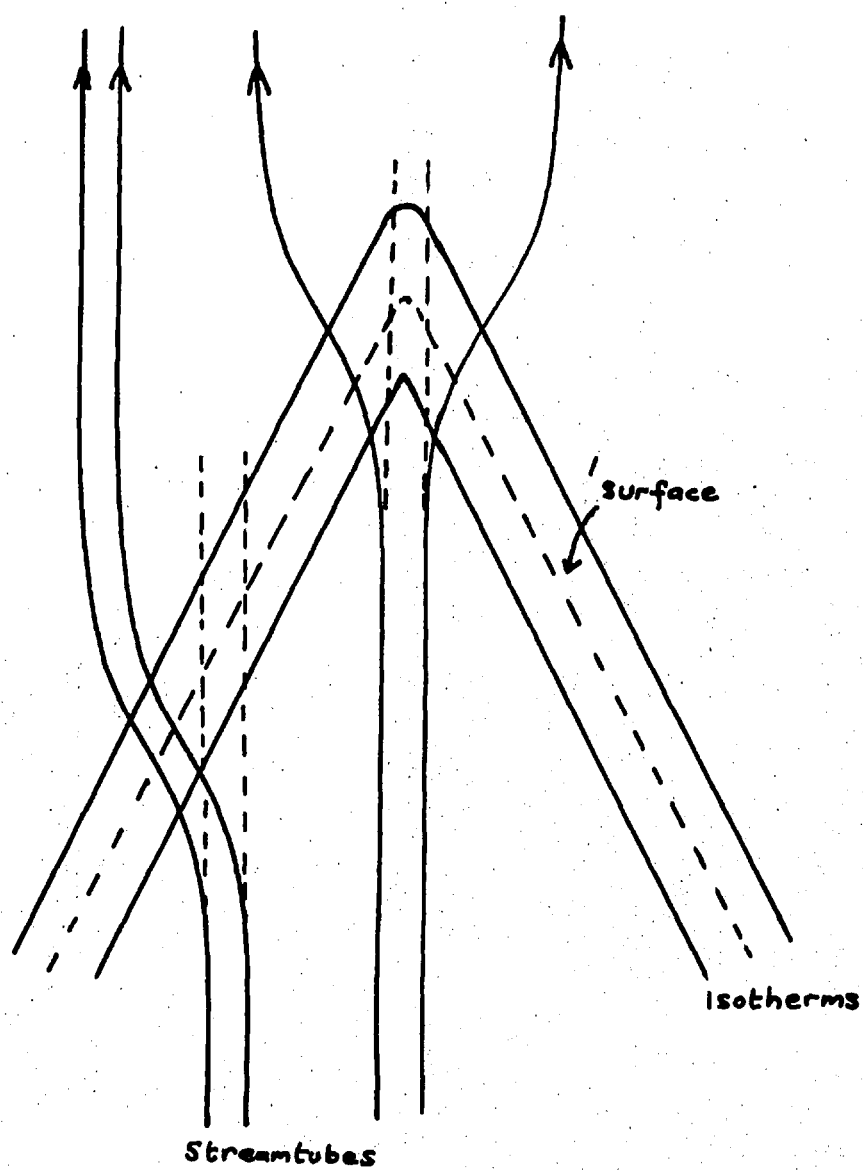


FIG. 15 FLOW FIELD IN A CONICAL
LAMINAR FLAME

The fundamental definition of laminar burning velocity, S_L , is of volume flow, far upstream, divided by flame area. Applying this definition to the general stream tube gives:

$$S_L = \frac{v_0 dR_0}{dA'} \quad (3.5)$$

Reference to Figure 15 shows that, away from regions of strong flame curvature, the sides of the stream tubes remain very nearly parallel on passing through the flame, so that all definitions of flame surface give rise to similar areas, dA' . The result is no longer true for stream tubes passing through regions of strong flame curvature, in particular, the stream tube passing through the apex. Here the flame area, dA' , and hence the burning velocity will be critically dependent on the flame surface chosen.

Solving equations 3.4 and 3.5 simultaneously yields

$$v' = \frac{p_0}{p'} S_L \quad (3.6)$$

It will be shown, in Chapter 5, that for the flames studied, the pressure associated with the momentum of the flow is quite negligible compared with the absolute pressure. This result will be anticipated for the present in that a constant pressure system will be assumed. Under such conditions, and for a fixed reaction scheme, density may be expressed as a function of temperature alone.

Thus equation 3.6 becomes

$$v' = \frac{S_L}{T_0} f(T') \quad (3.6a)$$

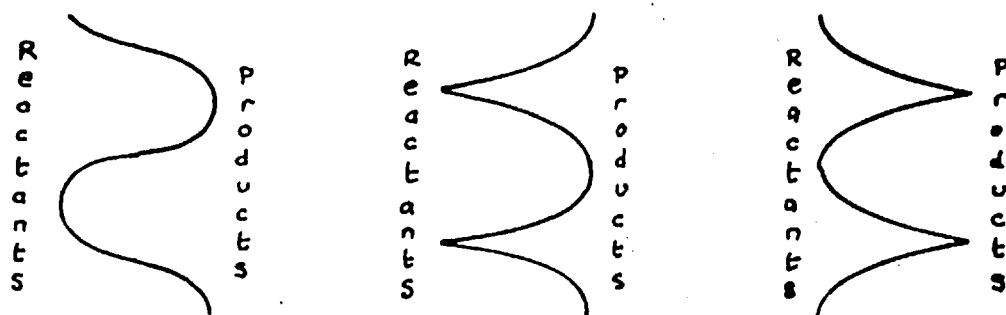
If the laminar burning velocity, S_L , is a fundamental property of the reactant mixture, equation 3.6a defines, uniquely, the correct surface to be used in area measurements for burning velocity.

Fristrom and Westenberg⁽³³⁾ have shown, by very careful use of particle tracks with sub-atmospheric flames, that this surface corresponds to that marked by the onset of luminous reaction.

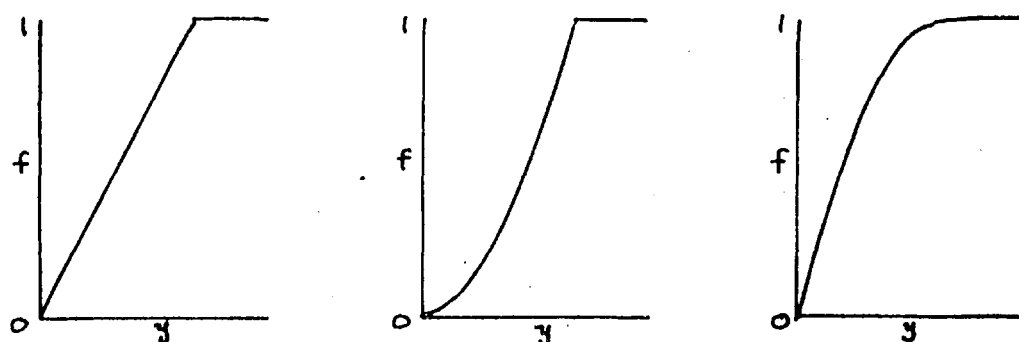
Figure 15 also illustrates the deflection of the flow lines that occurs immediately upstream of the flame because of pressure redistribution caused by the momentum generated by the expansion across the flame. Particles cannot follow this reorientation of flowline exactly, because of their inertia. Nor can their tracks measure accurately velocity changes in the direction of flow that take place within the scale of those tracks. However, away from regions of strong flame curvature, the use of both particle tracks and the schlieren image for measuring burning velocity represent a good approximation. The particle tracks measure the far approach velocity, as defined in equation 3.4, whilst the schlieren image, although in the wrong position, yields the correct area, and hence marks the correct angle, for use in the 2D definition of burning velocity of equation 1.8. Results obtained near the apex of the flame are in error because of the strong divergence of central stream tubes.

3.4 Shape of Instantaneous Flame

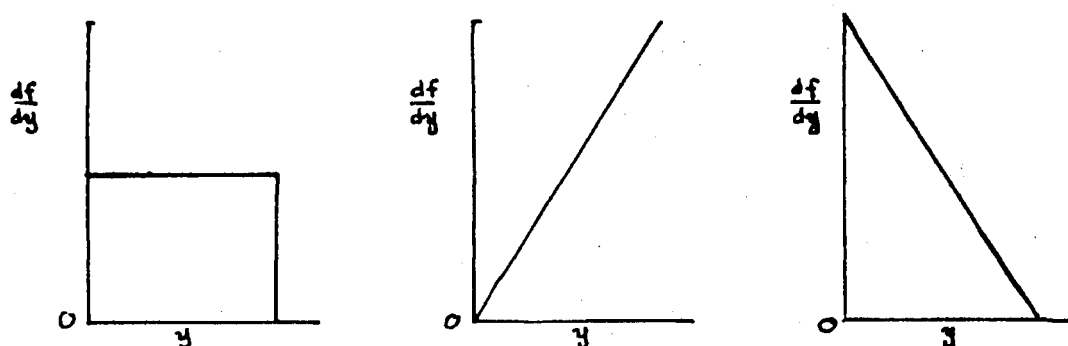
It was explained in section 2.5, how time mean deflections of inclined slit patterns, of the type shown in Figure 9, can be used to determine the average distribution of products and reactants. If the flame be regarded as a continuous surface, marking their boundary, it is possible to deduce the average shape of this boundary from the above distribution. Figure 16 illustrates the reverse process - deflections are predicted from knowledge of flame shape. Each of the three columns corresponds to the flame shape shown at its head. Records, like Figure 9, obtained with turbulent flames



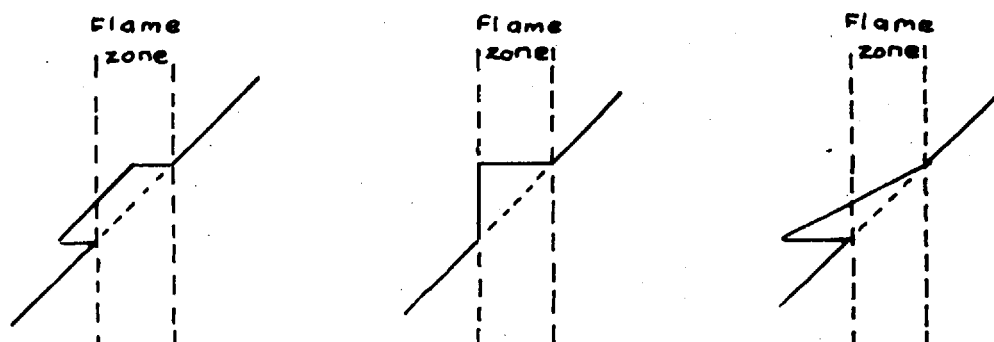
Average flame shape.



Time mean distribution of products across flame.



Fractional gradients corresponding to above distributions.



Inclined slit deflections corresponding to above gradients.

FIG. 16 INCLINED SLIT DEFLECTIONS FOR CONSTANT GEOMETRICAL PATH THROUGH THE FLAME REGION AND VARIOUS AVERAGE FLAME SHAPES

on 2D slot burners, show the form of the last column. Thus the mean flame surface is asymmetric. When viewed from reactants, the concave surfaces have much greater curvature than the convex ones.

CHAPTER 4 ELECTRICAL METHOD AND RESULTS

4.1 Description of Method

When a flame which is a sufficiently weak ion source, is placed between two electrodes and a graph of current versus applied voltage is plotted, an extended plateau occurs at that current which corresponds to the total rate of generation charge. The condition is one where charged particles, formed in the combustion reactions, are removed faster than they are able to re-combine. Measurement of the plateau current has been used to determine rates of ion generation in a variety of premixed laminar flames^(35, 36, 37). It has been established, for an adiabatic flame, that the current drawn per unit area of front, j_s , is a combustion property of the reactant mixture and is related to the total saturation current, J_s , and flame area within the electric field, A , by the simple expression:

$$J_s = Aj_s \quad (4.1)$$

Equation 4.1 represents the basis of powerful analytical methods for use in flames of premixed reactants. If j_s be known, measurement of J_s gives immediate access to A . Even if j_s is not known explicitly, measurements of J_s at different flow rates, for the same mixture, give area ratios. The method is particularly valuable for irregularly shaped or fluctuating flames where the more usual means of measuring area can no longer be applied.

In addition j_s is strongly dependent on temperature so that, under appropriate conditions, measurements of J_s can be used to determine, monitor or control temperature, or its causative parameter, mixture ratio.

4.2 Relevance to Problem

Measurements of flame area via saturation current have two further characteristics which make them potentially attractive to the study of premixed turbulent flames. Firstly, the time response is rapid (ionic drift velocities are up to 10^5 cm./s., electronic drift velocities are much greater); secondly, the measurement of flame area is independent of its spatial orientation, providing the basic propagation process remains unchanged.

For constant reactant composition and approach conditions, in an adiabatic laminar flame, the volumetric flow, V , is related to the burning velocity, S_L , by the laminar version of equation 1.9

$$V = AS_L$$

when combined with equation 4.1 this gives

$$\frac{J_s}{V} = \frac{j_s}{S_L} \quad (4.2)$$

If it can be shown, for laminar flames, that j_s is proportional to V , independent of geometry, then the "wrinkled laminar" flame front hypothesis demands that the same proportionality should hold true for turbulent flames. Maintenance of the relation is an essential condition for, but not final proof of, the hypothesis.

4.3 Conditions for Method to Work

Several independent requirements remain to be satisfied before saturation currents can be obtained and used to interpret flame processes. The most important will now be considered.

Flames must be set up which can, at constant mixture, be stabilized over a range of flows wide enough to include laminar, transitional and turbulent flow and to enable trends to be detected.

Saturation plateaux must be obtainable at all flow rates. The main limitation to the measurement of saturation current is due to the onset of secondary ionization at the electrode surface and is caused by the field locally exceeding its critical value. The growth of field strength towards the electrodes due to space charge has been analysed in detail. (30, 35).

Gauss's Law states that the flux of induction across any closed surface is equal to 4π times the charge contained within that surface,

$$\text{or} \quad \oint E_p dA = 4\pi \Sigma q \quad (4.3)$$

where E_p is the field perpendicular to the element of area dA and Σq is the charge within the closed area.

For a 1D system with field components in the x direction only, equation 4.3 becomes:

$$\frac{dE}{dx} = 4\pi (n_+ - n_-)e \quad (4.4)$$

where $n_{\pm}$ are the number of + ive and - ive ions, each carrying charge e .

The current, j , at any point is given by

$$j = j_+ + j_- = (K_+ n_+ - K_- n_-)Ee \quad (4.5)$$

where the K 's are the ionic mobilities.

Outside of the reaction zone of the flame there is no charge generation and the charge, in any given volume, is monopolar. Combining equation 4.4 with equation 4.5 gives

$$\frac{dE}{dx} = \frac{4\pi j}{KE} \quad (4.6)$$

$$\text{Integrating} \quad E^2 = E_0^2 + \frac{8\pi jx}{K} \quad (4.7)$$

where E is the field at any point in the electrode space outside the reaction zone.

If the electrode space is filled with products the negative charge carriers stay as electrons with much greater mobilities (by a factor of $10^2 - 10^3$) than the heavy positive ions. As long as the applied electrode potential is less than, or equal to, that required to extract saturation currents from the flame, E_0 may be taken as zero at the reaction boundary facing the anode. (The assumption here is that the electron mobility is infinite compared with that of the positive ions).

Maximum field strengths occur, due to the build up of space charge, at the anode. If E_b is the breakdown field, (the maximum that can be supported by the charge carrying medium without leading to secondary ionization), the limiting saturation current density, j_b , which avoids breakdown, is given by substituting $E_0 = 0$ in equation 4.7.

$$\text{Thus} \quad j_b = \frac{E_b^2 K}{8\pi x} \quad (4.8)$$

where x is now the distance of the electrode from the ion source.

It follows that some flames could be too rich in ions, particularly where small electrode separations are impracticable, to yield legible saturation plateaux. As a numerical guide, a breakdown field strength of 30 KV/cm., corresponding to dry air at S.T.P., with an electrode 5mm. away from the flame surface, gives a maximum current density of approximately $250 \mu\text{A}/\text{cm}^2$. for the mobility of the H_3O^+ ion.

If saturation currents are to be explained in terms of flame processes other potential sources of ionization (i.e. products) must be negligible. Direct experimental check of this assumption will be presented later.

Accurate control of mixture strength is essential over the whole flow regime. It has been found that 60°C rise in final flame temperature, for some mixtures, corresponds to doubling the saturation current. As 60°C rise is equivalent to increasing the fuel flow by only 15%, the need for care is obvious.

Figure 17 shows some typical saturation current densities plotted against equivalence ratio. These were obtained⁽³⁵⁾ using flat flames on a porous plug burner and extrapolating the results to zero heat loss. They give some guidance towards the choice of most suitable fuel/oxidant combinations in the light of the foregoing discussions.

Early tests on laminar flames gave satisfactory saturation currents with methane/air mixtures. The increased volumetric flow rates necessary for turbulent flames did not allow the plateaux to establish before the onset of secondary ionization. The bulk of the work was therefore carried out with, the more weakly ionizing, mixtures of methane/oxygen.

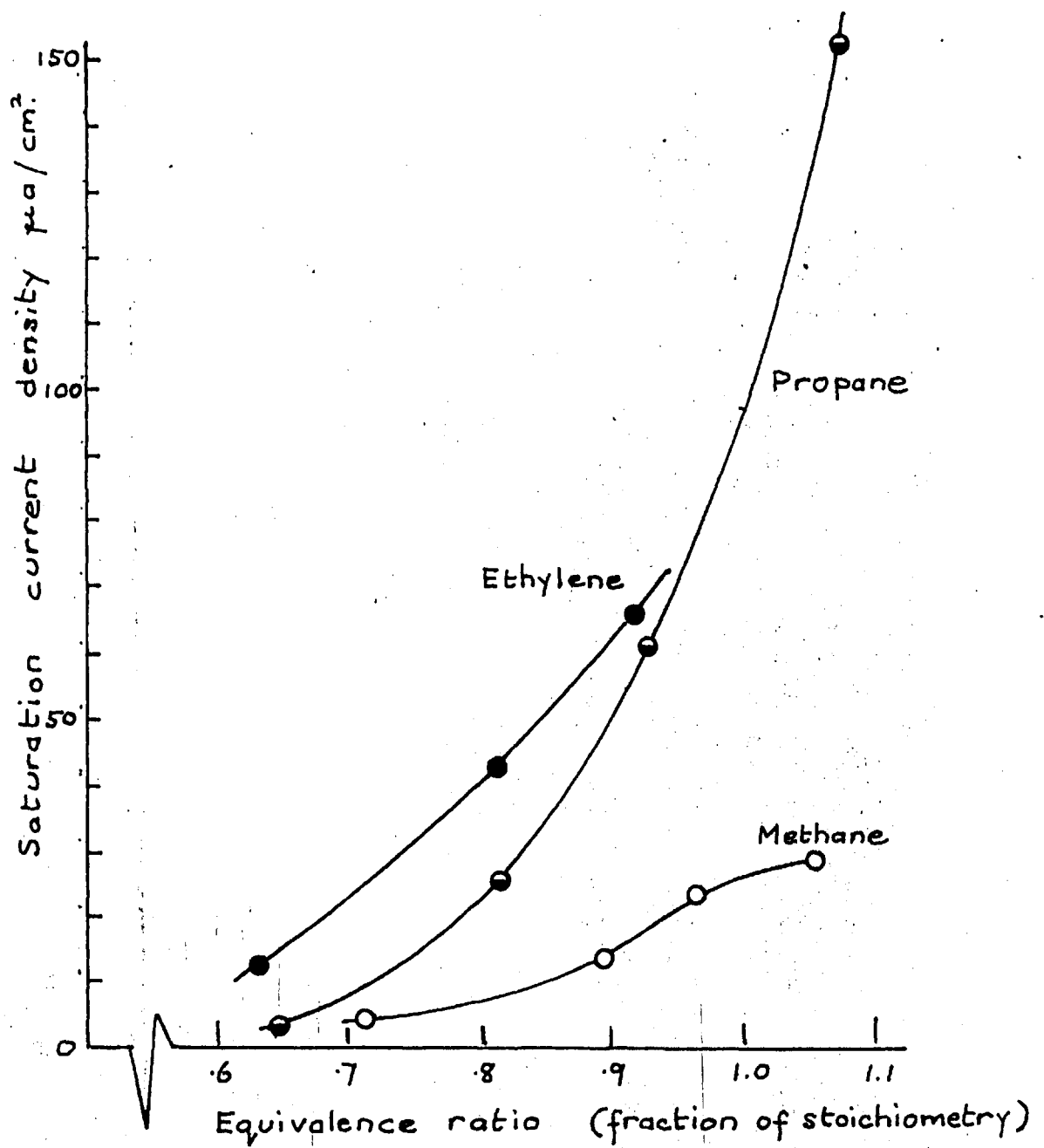


FIG. 17

SATURATION CURRENT DENSITIES
FOR HYDROCARBON-AIR FLAMES

4.4 Burners

Various forms of piloting and grids were used, at the burner mouth, to prevent flash back, at the lower laminar, and blow off, at the higher turbulent, flows.

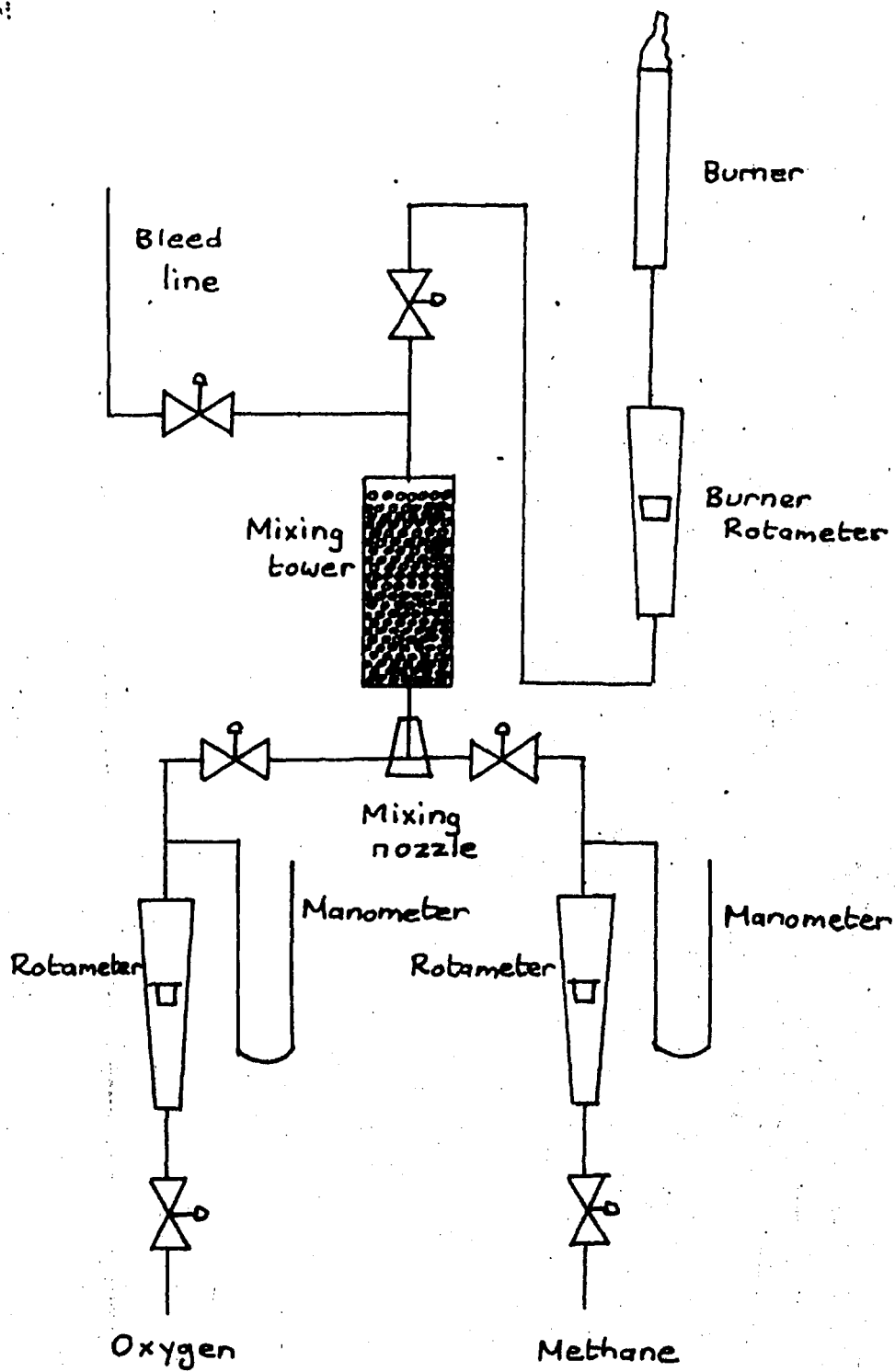
The main burners were made from glass tubes, ranging from 0.57 to 1.6 cms. internal diameter. Each was long enough to allow pipe flow to become fully established within the turbulent regime. All incorporated a flame trap at the input end.

Flames were stabilized on the smallest burner by passing a fraction of the total flow through a surrounding annular pilot, set up by shething the burner tube in a metal tube that was both longer and had internal diameter slightly greater than the external diameter of the burner tube itself. The latter was centralized by a layer of crimped flame trap material and the pilot flow was restricted by winding Sellotape around the burner tube - the optimum thickness being found by trial and error.

Stabilizing grids replaced the annular pilot for the larger diameter burner tubes. These were made of clusters of parallel quartz tubes, 0.3 to 0.4 mm. external diameter, laid on the burner mouth and spaced equidistantly across it. The grids served both to prevent flash back, at lower flows, and to provide stabilizing wakes at the higher flows.

4.5 Flow System

The flow system is shown diagrammatically in Figure 18. Methane and oxygen were drawn from separate cylinders and metered independently by Rotameter/manometer combinations before mixing in a sealed Bunsen burner nozzle and passing through a mixing tower packed with glass beads. The flow was then split two ways - part passing through a calibrated Rotameter, to the burner, the remainder through a bleed line for discharge outside the laboratory.

FIG. 18FLOW SYSTEM

To maintain consistent fuel/oxidant ratios throughout and between the tests, the fuel and air Rotameters and manometers were set and adjusted to maintain constant flow and pressure readings, as the burner flow was altered. Allowance was made for atmospheric pressure variation in setting the fuel/oxidant readings. Pressure drop across the burner itself was found to be small and was ignored. Burner flows are quoted in terms of volumetric flow rates at N.T.P.

4.6 Electrical System

The electrical system is shown in Figure 19. Its purpose was to provide a variable voltage across, and measure the resulting current drawn from, the flame. A neon safety device, which discharged to earth when subjected to excessive potential difference, was wired in parallel with the current meter (a Pye Scalamp mirror galvanometer) to protect the latter from serious overload by erratic and sudden increases in current, caused by breakdown at high voltage departure from the saturation plateau. Driving potential was provided by a 0-30 KV D.C. Brandenburg generator, type S.0530/10, and was measured on an integral voltmeter. Transient records were displayed, when required, on a Telequipment oscilloscope, type D53, connected between points A and B of the circuit.

Three, alternative, flame electrode systems were used, the choice between them being dictated, in some part, by the particular test of interest at a given time. The first set of electrodes comprised a pair of parallel, circular brass discs, of 15 cm. diameter, set vertically, with the burner mouth and flame between them. The second electrode system consisted of a metal tube (or thick wire) surrounding the burner mouth and a stainless steel gauze, mounted on a brass annulus with a 10 cm. diameter hole cut out of its centre, placed horizontally and centrally to the burner axis, above the flame. During the study it was realised that secondary emission from the red hot gauze was causing incorrect readings of saturation current.

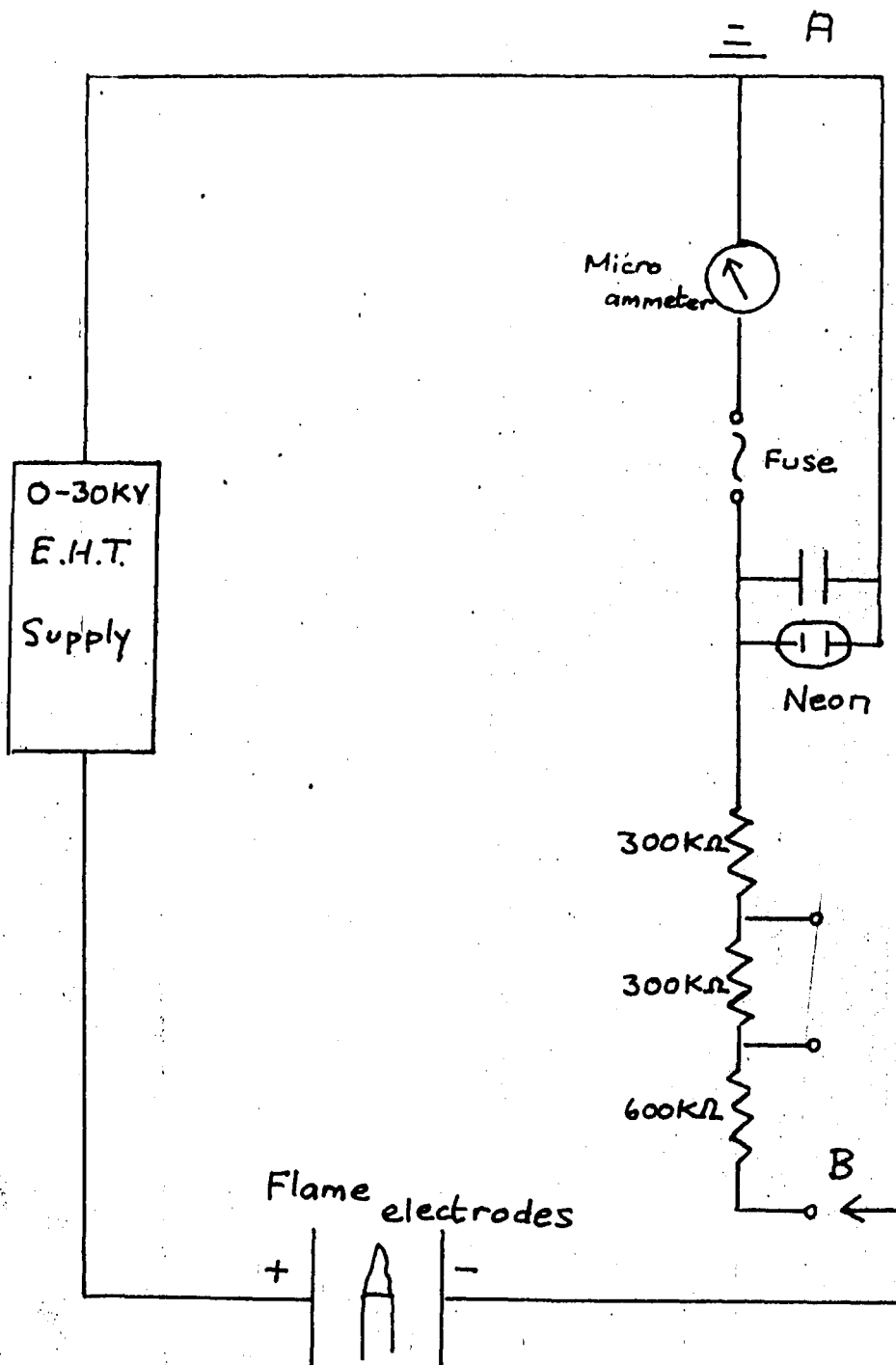


FIG. 19

ELECTRICAL CIRCUIT FOR
FLAME CURRENT MEASUREMENTS.

The third electrode system was a compromise between the first two which overcame this difficulty and consisted of one of the vertical disc electrodes, above and slightly to one side of the burner, used in conjunction with a conducting burner rim.

Wherever the burner was used as an electrode it was maintained negative to maximise breakdown voltages.

4.7 Laminar Flames

Several sets of preliminary tests were carried out on simple laminar flames in advance of the main tests. Their objective was to establish the method and interpret its results under well behaved and comparatively well understood, flame situations. The specific features tested, experiments and conclusions drawn, are enumerated below.

The earliest experiments were aimed at checking the predictions of laminar flame behaviour made in equation 4.2, i.e. verifying that saturation current was proportional to volumetric flow rate. Methane/air mixtures were used for these tests which were carried out on both regular and irregular shaped flames with no detectable difference. Well defined saturation plateaux were obtained and saturation currents are plotted versus volumetric flow in Figure 20. Equivalence ratio was allowed to vary as indicated in the table. That the graph still turned out to be a straight line, passing through the origin, is of great importance in interpreting later results.

The remaining experiments were carried out on methane/oxygen mixtures to reduce ionization densities and accommodate the potentially higher saturation currents brought about by the increased flow in turbulent flames. It was found, with the flames and geometries of interest, that clearly defined saturation plateaux were obtained with total saturation currents of 10 μ A or less. This is more than adequate for the method as applied to the present investigation.

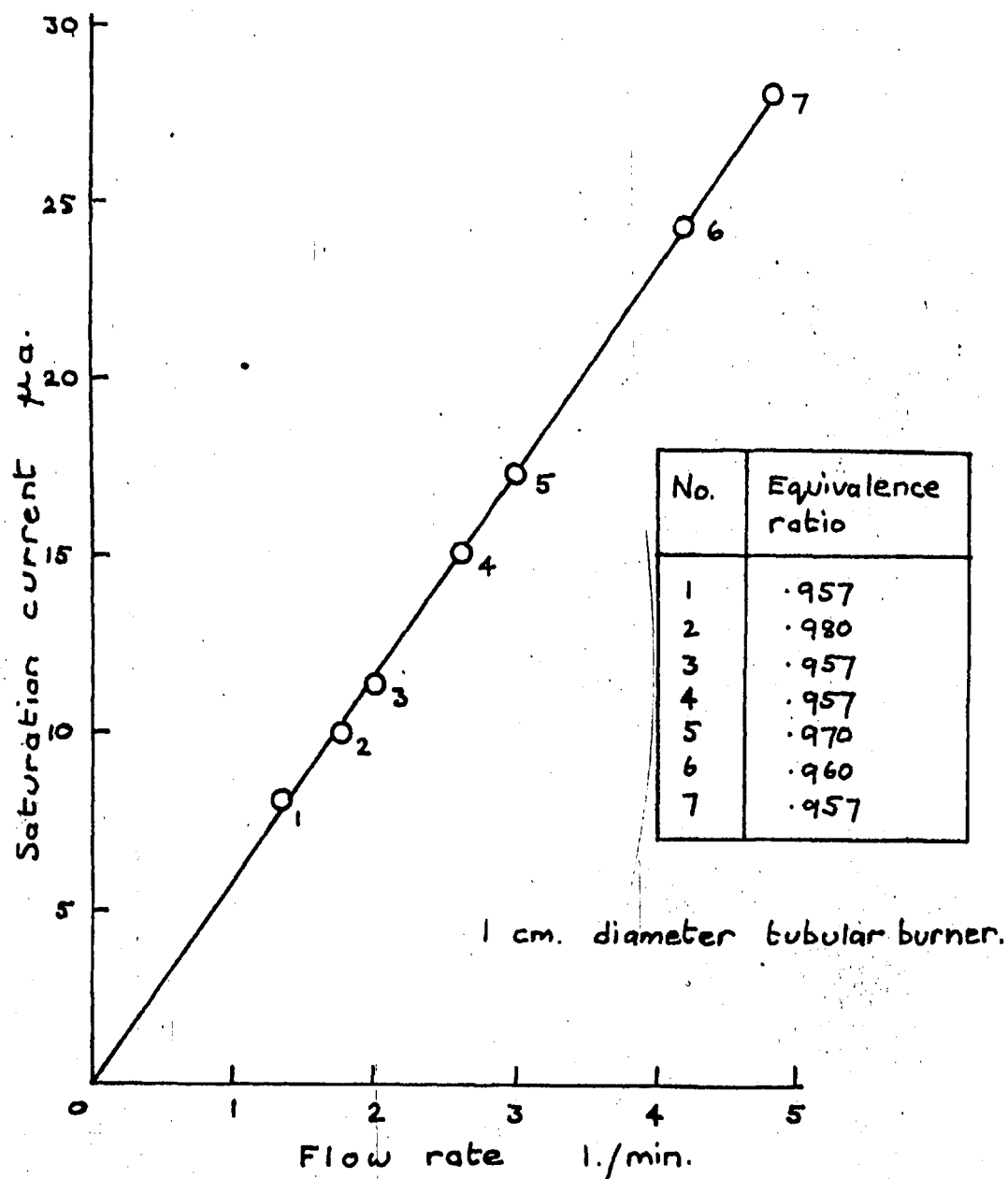


FIG. 20

METHANE-AIR FLAMES— SATURATION CURRENTS.

Previous measurements of saturation currents have usually been under conditions where positive ions and electrons, once separated by electric fields, remain physically separated, without any possibility of undergoing collisions leading to recombination. The present situation is different in that a given line of force may be cut by several flame surfaces and that both positive ions and electrons can populate the region between the bounding surfaces, leading to the possibility of recombinative collisions. The effect was checked experimentally by use of two similar small conical flames. In the first test they were placed side by side between the vertical (first) electrode system described in section 4.6, so that current from the two flames reached the electrodes without mutual interference; in the second test the flames were placed 'in line' so that charge from one flame traversed the other. No difference in saturation current was detected, and it was concluded that there was no detectable recombination in the region of coexistence.

To interpret saturation current measurements it must be assumed that product ionization is negligible. The assumption was tested experimentally, using the horizontal (second) electrode arrangement of section 4.6, by varying the electrode separation, i.e. the height of the positive electrode above the burner mouth, in the presence of a standard flame. The constancy of the saturation current thus obtained demonstrated the unimportance of product ionization and the validity of the original assumption.

Experiments were carried out to check the influence of the flame stabilizing grids (section 4.4) on the saturation current. The reactant mixture and flow rate chosen for this test were such as to enable a conical laminar flame to be stabilized on the unobstructed burner, without grids, as well as on the grids themselves.

The results are shown in Figure 21, and are included, rather than just mentioned, because of their dual importance in both the present context and in later interpretations of flame processes. Conical flame results are represented by circles, grid stabilized, multi-peak flames by squares. There is no detectable difference in saturation current although the shape of the current/voltage characteristics differ slightly because of the different flame geometry. The similarity in saturation current for the two cases is taken to indicate unchanged local flame processes. The possible, but less probable, explanation that compensating changes in local current density occur at base and peak in the grid system is not favoured, because of the elaborate chain of balancing arguments required to explain the observed result.

4.8 Saturation Current Variation with Flow Rate

Results of saturation current plotted against volumetric flow rate are shown in Figure 22. All the points are taken with a methane/oxygen mixture at a constant equivalence ratio of .191 of stoichiometric. The different curves correspond to fully developed pipe flow in burners of .57 and 1.15 cm. internal diameter respectively; the curves are related to the applicable burner in the legend. The plots were reproducible and several sets, each exhibiting similar characteristics, were obtained at slightly different mixture ratios.

The lines corresponding to each of the burners shows the same pattern of near linearity followed by a sudden discontinuity of slope to a curve of lower gradient than the original line but one in which the gradient is steadily increasing. Over the flow range tested, with the accuracy of result obtained, it is not possible to see whether the gradient of the curved portion of the graph eventually achieves that of the straight line. For each burner the discontinuity was observed, audibly, visually and by calculation of transitional Reynolds number, to coincide exactly with departure from steady laminar flow.

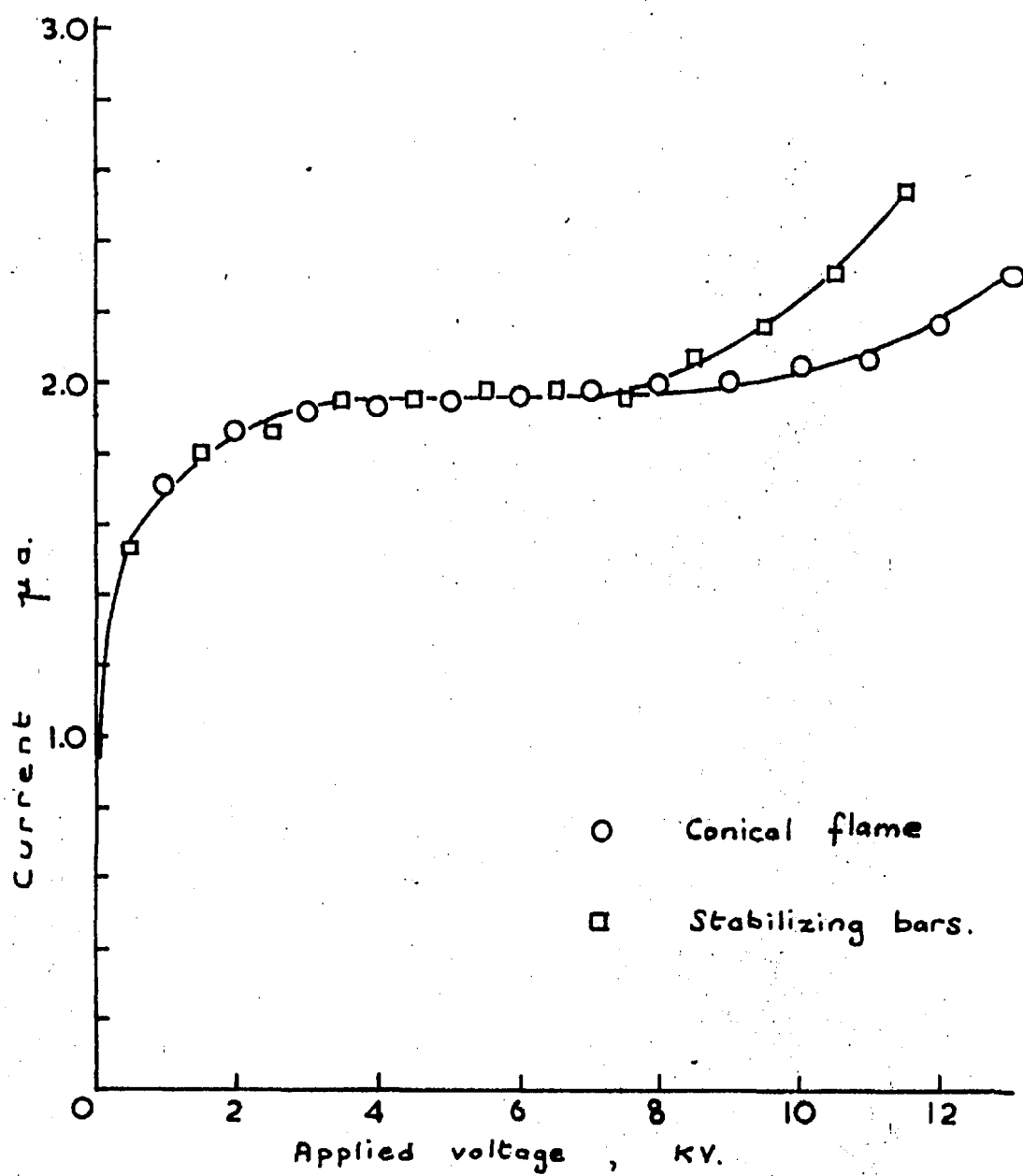


FIG 21 CURRENT VERSUS VOLTAGE,
LAMINAR FLAMES

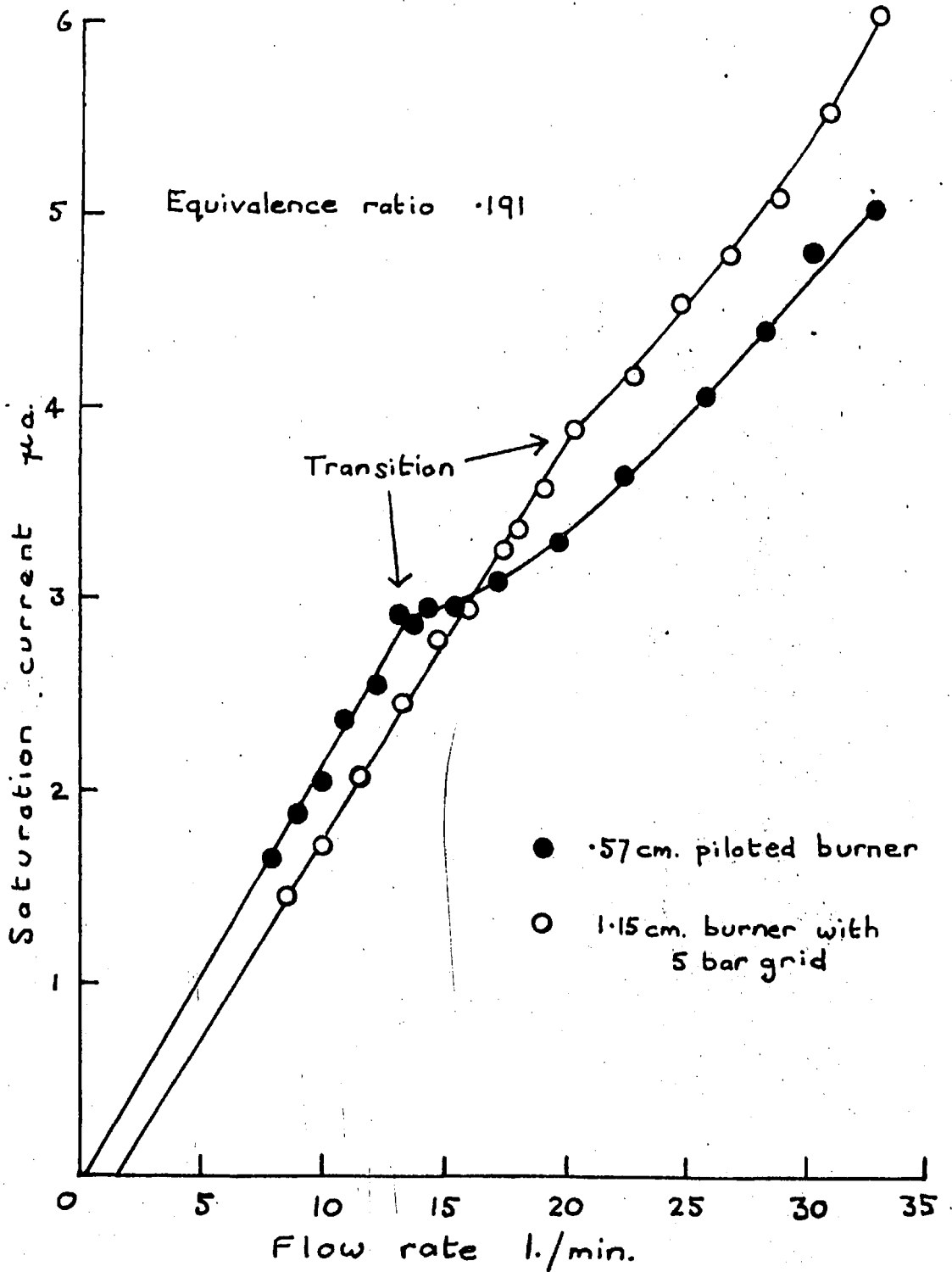


FIG. 22

METHANE-OXYGEN FLAMES

— SATURATION CURRENTS.

Breakdown always appeared to originate at the centre of the flow and was recognised by a rough spitting which coincided with the apex of the flame flashing back from its stable, laminar position towards the burner mouth. At the onset of turbulence the frequency of the effect was 2 - 5 Hz, which increased with the increasing flow. Concurrent with the increase in frequency the flame appeared more stable and the rough spitting changed to a smoother roar.

Displacement of the straight line (laminar) portions of the curves for 1.15cm. burner results, from a line passing through the origin, was first attributed to quenching at the outer rim of the burner, with the intercept on the abscissa indicating the effective volume flow lost by that quenching. However, two sets of experimental results, already described, are inconsistent with such an explanation.

The saturation current against volumetric flow plots for methane/air (described in section 4.7 and illustrated in Figure 20) were obtained at similar volume concentrations of methane (and hence overall heat release) on similar main burners to the present results, yet pass through the origin. Were quenching the reason for the displacement from the origin in Figure 22, similar displacement should occur on the earlier graph.

The other, apparently anomalous, result is that of section 4.7 where introduction of flame stabilizing grids (i.e. comparatively cool, solid surfaces at the base of the flame) failed to affect the measured saturation current.

The discrepancies are explained in terms of entrainment around the burner rim. Recent results of sampling around the periphery of premixed flames on such burners, followed by mass spectrometric analysis ⁽³⁸⁾ have suggested that the effect may be important. The main difference between the results in Figures 20 and 22 lies in the composition and flow rates. More specifically, nitrogen present in the former is replaced by oxygen in the latter. Reference to

Figure 17 shows a peculiarity of the methane/air system in that saturation current densities are insensitive to equivalence ratios around stoichiometric. This is not true at similar fuel air ratios in the methane/oxygen system. Further confirmation comes from the linearity of the results of Figure 20 despite the variation of equivalence ratio previously highlighted. Introduction of the flame stabilizing grids would not be expected to alter appreciably entrainment from the surrounding atmosphere around the burner rim.

The foregoing explanation predicts that the saturation current volumetric flow curve should pass through the origin - in the limit zero flow would correspond to zero entrainment. If the results of Figure 22 for the lowest flow rates on the 1.15cm. burner are carefully re-examined in the light of the present interpretation it can be seen that they equally well lie on a smooth curve passing through the origin. Deviation from linearity, in the laminar region, brought about by this effect is small, when compared with the discontinuity occurring on transition to turbulence, and does not detract from the validity of the method.

The more fundamental question that has now to be answered is whether the discontinuity corresponding to transition could be explained in terms of alteration in entrainment from the surrounding atmosphere. It is important to differentiate between entrainment of the ambient atmosphere, which is a function of burner geometry, and that of products, which need not be. The former is likely to be a boundary layer effect which achieves greatest importance on small, laboratory burners; the latter a more fundamental aspect of turbulent flame propagation. The available evidence suggests that entrainment of ambient atmosphere does not explain deviation from the extrapolated laminar line. In Figure 22 the greatest deviation occurs for the piloted flame which is not subject to entrainment. The main, turbulent flame is protected from the ambient atmosphere by the laminar piloting sheath and so should experience least interaction. In addition, the flow first breaks down away from the boundary layer, which retains its laminar character during the early stages of transition, yet the discontinuity is sharp and always coincides with the first departure from steady conditions.

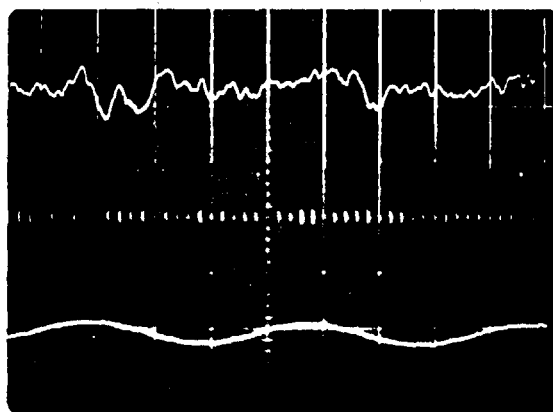
4.9 Steadily Oscillating Flames

In an attempt to see if the discontinuity of the previous section was caused purely by the flame's motion, saturation currents of 'singing' flames were compared with those of laminar flames at similar flow rates. Oscillations, of 1300 Hz, were introduced into the reactant flow by passing it through a small mouth organ upstream of the burner mouth. Thickening of the flame brush was just visible to the naked eye. However, no change in saturation current was detected.

4.10 Time Variance of Saturation Current

Time variation of the saturation current of turbulent flames was recorded by placing an oscilloscope across the resistance chain of Figure 19 and photographing the resultant trace using a Polaroid camera. A typical record, including both turbulent flame and blank trace, is shown in Figure 23. The horizontal time scale represents 5ms./cm., whilst the vertical scale corresponds to 1V/cm, and is measured across 1.2 M Ω . Strictly speaking the steady, 50 Hz, mains hum, recorded on the blank trace should be subtracted from the record of the turbulent flame. Nonetheless, it is clear that there can be a 20% variation in saturation current over a time interval of 3ms.

In terms of the original theory, as expressed in equation 4.1, the above variation would correspond to turbulence induced fluctuations in instantaneous area, A . When coupled with the results of section 4.8 it could represent fluctuations in both A and the saturation current density, j_s . Either way it is a measure of temporal inhomogeneity averaged spatially over the flame.



12

$y = 1V/\text{division}$ $x = 5ms/\text{division}$

FIGURE 23 - OSCILLOGRAM RECORD OF TURBULENT FLAME SATURATION CURRENTS

CHAPTER 5 DISCUSSION

5.1 Comparison with Laminar Flames

A constant theme running throughout the present, and all previous investigations in similar regimes of turbulence, has been the comparison between the burner stabilized, pre-mixed, turbulent flame and its better understood (because of its time constant properties) laminar counterpart.

Visual differences between laminar and turbulent flames, stabilized at similar mixture ratios, on the same burner, are qualitatively understood. On tubular burners, with edge stabilization, the laminar flame is conical and symmetrical with a well defined luminous zone, whilst the turbulent flame is characterised by the familiar, diffuse flame brush. Instantaneous photographs of short enough duration to 'freeze' the turbulent flame cannot be taken by its own light. Records taken using an external light source by schlieren (e.g. Figure 8), shadowgraphy or light scattered from smoke which disappears in the flame front, all show it to consist of a convoluted flame front fluctuating in a manner depending on the parameters of turbulence, within the envelope defined by the diffuse zone.

It was therefore natural to conclude that what the eye (and the camera at normal shutter speeds) sees, of a turbulent flame, is a time exposure of the fluctuating front and almost as reasonable to assume that every element of the instantaneous front behaves (at all times) as if it were part of a freely propagating, laminar combustion wave. The latter, however, does not follow inevitably and the main question, posed at the outset of this work, was whether this 'wrinkled laminar' hypothesis, would be supported by detailed experimental studies of fundamental flame parameters, such as burning velocity or saturation current density. Both series of tests applied - the burning velocity results, described in Chapter 3, and the saturation current results of Chapter 4 - independently show the model to fail. Neither the laminar burning

velocity of the turbulent flame, nor the saturation current per unit volumetric flow, equal the laminar values. It is worth noting that the extent of this failure is by no means the same for all flames. For those analysed in Chapter 3 the maximum local "laminar" burning velocities exceeded the normal burning velocity of laminar flames by up to 350% - a result which is in qualitative agreement with those obtained by Sokolik and collaborators⁽²⁶⁾. The deviation in the saturation current - volumetric flow rate characteristic never exceeded 40% and, in the case of the "5 bar grid" burner mouth, was less than 10%. Had this been the only flame analysed and had the method been only marginally less sensitive, it might have been concluded that the 'wrinkled laminar' flame front concept always applies. Other workers, using different methods, e.g. Sugden and his collaborators⁽²⁴⁾, found no appreciable deviations for their flames. The reason for the different conclusions will become apparent later.

Thus the turbulent flame, though it consists of a fluctuating, laminar like, corrugated flame surface, can exhibit quite different properties to those of the corresponding laminar flame. The only difference in input to the two flames is that, for the one, the approach flow is turbulent, whilst, for the other, it is laminar. The turbulence may, although it need not, result from higher flow rates.

Experiments have been contrived to check the two component attributes of turbulent burning separately. The effect of flame corrugations was tested, independently of fluctuations, by stabilizing the flame on a grid of parallel quartz rods, placed on top of the burner in laminar flow (Section 4.7). Saturation current measurements taken at similar flow rates, with and without the rods (Figure 21), show no detectable change. Hence it is concluded that flame corrugations, by themselves, are not responsible for changes in flame behaviour.

Regular, controlled oscillations were introduced into the flow by allowing the pre-mixed reactants to pass through a miniature mouth organ before entering the burner tube. Small oscillations were generated at a frequency of approximately 1300 hz. and caused the flame to 'sing' at this frequency (Section 4.9). Once again there was no detectable change in saturation current (however, the amplitude of flame oscillation obtained in this way was small compared with the excursions of the turbulent flame front).

The conclusion to be drawn from the comparison with laminar flames, whether stationary, corrugated, or fluctuating, is that turbulence can induce changes in the parameters of the flame front which regular convolutions or oscillations on their own do not.

5.2 Effect of Small Scale Turbulence in the Burner Stream

One reason for some discrepancy between the laminar burning velocity S_L , and the instantaneous burning velocity of the turbulent flame, $\bar{S}_L$, already mentioned in Chapter 1, is the influence of any small scale turbulence present in the reactant flow. To account for the entire difference $\bar{S}_L$ would have to be altered to $\bar{S}_L$ by the additional diffusivity arising from turbulence with scale smaller than the flame thickness. The additional diffusivity required, ϵ' , may be calculated. Equation 1.5 may be re-arranged to give:

$$\frac{\epsilon'}{\nu} = \left(\frac{\bar{S}_L}{S_L} \right)^2 - 1 \quad (5.1)$$

The following analysis is based on measured burning velocities for the two turbulent flames, for which the largest deviations from the corresponding laminar flames were obtained. The turbulent flames are represented by lines 3; the laminar by lines 1 in Figures 12 and 13. Additional data for the two flames is presented

in Table 1. The scale of turbulence in the burner flow was determined by the dimensions of the perforated grid in the burner mouth; the intensity was measured from lateral displacement of particle tracks in the approach flow.

T A B L E 1
REACTANT FLOW CHARACTERISTICS
AND MEASURED BURNING VELOCITIES

QUANTITY	SYMBOL	UNITS	LAMINAR		TURBULENT	
			1	2	1	2
Kinematic Viscosity	ν	cm^2/s	.14	.14	.14	.14
Density	ρ	g/l	1.3	1.3	1.3	1.3
Expansion Ratio	E		7	7	7	7
Approach Velocity	u	cm/s	379	252	367	247
Scale	ℓ	cm	-	-	.18	.18
Intensity	u	cm/s	-	-	18	12
Eddy Diffusivity	ϵ	cm^2/s	-	-	.32	.22
Burning Velocity	S_L	cm/s	40.4	40.4	146	126

Inserting these quantities into equation 5.1 ϵ' would have to be approximately 1.7 and 1.3 cm^2/s for the two flames.

The thickness of a laminar flame with burning velocity of order 40 cm/s is of the order of .2 mm. Since turbulence relevant here must be of scale small compared with the flame thickness, it follows that its intensity would have to be well in excess of 85 and 65 cm/s (or 20% of the mean flow velocity) for the two flames.

As the small scale turbulence can only be a small fraction of the total, comparison of the above values of turbulence with those measured and tabulated shows the effect to be quite inadequate. Whilst small scale turbulence must modify the burning velocity to some extent, it cannot, at its level in the burner stream, explain an appreciable part of the discrepancy between S_L and S_L .

5.3 Effect of Flame Movement

So far the parameters of turbulence have always been defined with respect to a stationary observer. Thus, the usual definition of turbulence intensity is in terms of the root mean square value of the perturbation to the mean flow velocity. However, the flame front itself is in violent random motion so that an observer travelling with it would see far greater fluctuation in approach velocity. It is this fluctuation that is pertinent to the propagation process. This important feature seems to have been overlooked in previous work, possibly because flame fluctuation is caused by that in the flow and at first sight it seems improbable that the relative motion could be increased.

One mechanism whereby the flame's motion is enhanced occurs because local changes in flow rate alter the flame shape and hence affect all positions downstream. Figure 24 illustrates the effect of a local increase in flow rate, δv , extending over distance δx at x . If δv represented a turbulent fluctuation and turbulence were confined to this element, the flame elements downstream of that point would "see" the laminar approach stream as turbulent due to their own movement. If the approach stream outside δx is also turbulent, the velocity fluctuations of the approach stream, u , add to those of the flame, u_f . The square of the relative intensity, u_r , is given by

$$u_r^2 = (u_f \pm u)^2 = (u_f)^2 + (u)^2 \pm 2(u_f)(u) \quad (5.2)$$

If u_f is not dependent on the local u and both are random, the time mean $u_f \cdot u = 0$ and

$$u_r^2 = u_f^2 + u^2 \quad (5.2a)$$

In practise the local flame position and its movement are both influenced by all the events taking place upstream. Referring the flame shape to cylindrical co-ordinates, h and r , equation 1.8 ($S_L = v \sin \phi$) implies that:

$$\begin{aligned} \frac{dh}{dr} &= \pm \sqrt{\left(\frac{v}{S_L}\right)^2 - 1} \\ \text{or } h &= \pm \int \sqrt{\left(\frac{v}{S_L}\right)^2 - 1} \, dr \end{aligned} \quad (5.3)$$

It is apparent that large changes in h can occur around the apex due to the cumulative effect of changes in v across the radius. Nor is the scale of the flame perturbations necessarily the same as that of the approach flow. This discrepancy is determined by the time scale of turbulence, if that is zero - i.e. if the flow perturbation is of infinitesimal duration - the indentation merely travels up the flame without increasing in size. For an infinite time scale, on the other hand, the situation portrayed by Figure 24 applies: the flow perturbation introduces at step, not an indentation, into the flame. Under these conditions the "flame scale" would be given by the mean distance to the nearest turbule whose velocity is in the opposite direction. Thus in practise there is always some magnification.

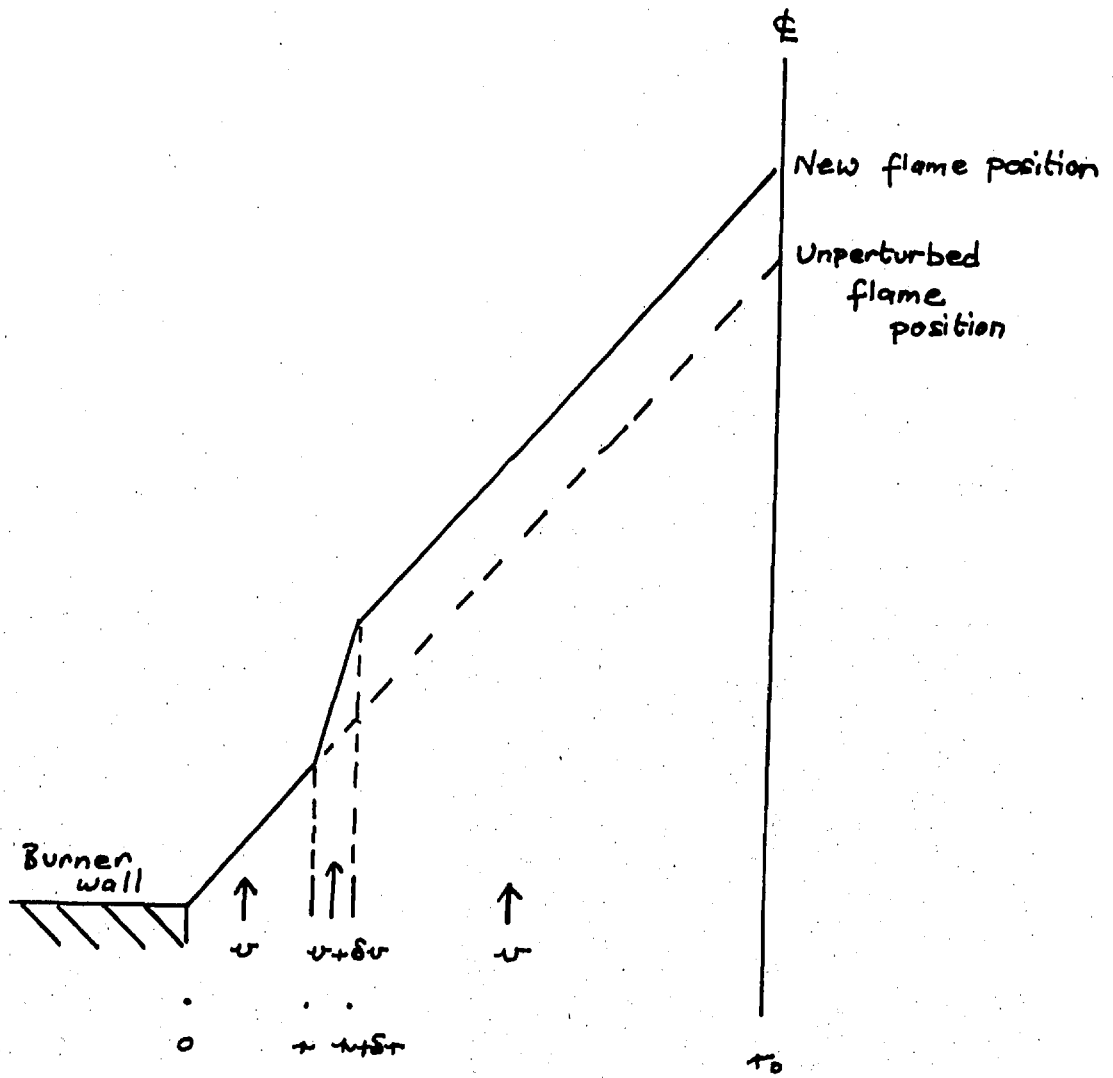


FIG 24 DISPLACEMENT OF FLAME
FRONT BY VELOCITY
PERTURBATION

The rate of propagation of any disturbance travelling along the front is $v \cos \phi$. Hence both ends of the indentation travel up the flame at $v \sqrt{1 - \left(\frac{S_L}{v}\right)^2}$. The trailing edge, however, sets out later, after the time interval for which the turbulence perturbs the flow. This is $\left(\frac{l}{S_L}\right)$ where l is the scale of the approach flow turbulence. The scale along the front is therefore:

$$l + \frac{lv}{S_L} \cos \phi = l (1 + \cot \phi) = l \left(1 + \sqrt{1 - \left(\frac{S_L}{v}\right)^2}\right) \quad (5.4)$$

which tends to twice the gas stream scale at high flow rates.

There would be very little point in numerical estimates of these parameters, because l and u are not the values corresponding to the turbulence leaving the burner tube. The flame generated turbulence considerably modifies that present in the approach stream.

5.4 Flame Generated Modification of Approach Stream Turbulence

As Karlovitz⁽⁶⁾ has already recognised, the expansion process that takes place across the flame front greatly increases turbulence. As an illustration, the principles of mass and momentum conservation will be applied across the element of instantaneous flame front shown in Figure 25. Although the flow is idealised for analytical purposes, the flame front is assumed to behave as observed experimentally. Buoyancy and viscosity effects are neglected; the element of flame is assumed to be parallel sided and the flow to be incompressible. Reactant flow is assumed to approach the flame front with velocity v at angle ϕ .

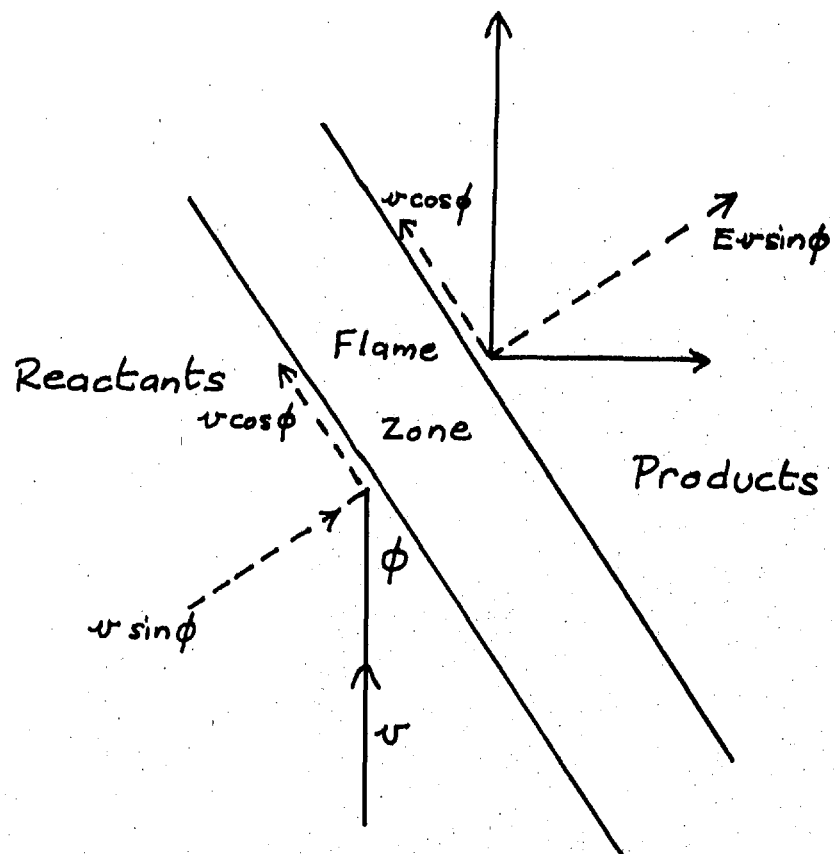


FIG 25 FLOW ACCELERATION ACROSS
THE FLAME FRONT

The expansion ratio across the flame, E , is given by:

$$E = \frac{\rho_r}{\rho_p} \quad (5.5)$$

where ρ_r is reactant density and ρ_p product density.

The component of velocity, perpendicular to the initial flow, after expansion, is:

$$\begin{aligned} v_{\perp} &= E v \sin \phi \cos \phi - v \sin \phi \cos \phi \\ &= \frac{v}{2} (E - 1) \sin 2\phi \end{aligned} \quad (5.6)$$

The component of velocity, parallel to the initial flow, after expansion, is:

$$\begin{aligned} v_{\parallel} &= E v \sin^2 \phi + v \cos^2 \phi \\ &= v (E - 1) \sin^2 \phi + 1 \end{aligned} \quad (5.7)$$

These velocities correspond to momentum generated across the flame front as follows:

Perpendicular to initial flow

$$\begin{aligned} \Delta p_{\perp} &= (\rho v_{\perp}^2) \text{ products} \\ &= \frac{\rho_r}{E} \frac{v^2}{4} (E - 1)^2 \sin^2 2\phi \end{aligned} \quad (5.8)$$

Parallel to initial flow

$$\begin{aligned} \Delta p_{\parallel} &= (\rho v_{\parallel}^2) \text{ products} - (v^2) \text{ reactants} \\ &= \frac{\rho_r}{E} v^2 (E - 1) \sin^2 \phi + 1^2 - \rho_r v^2 \\ &= \frac{\rho_r}{E} v^2 \left\{ \frac{[(E - 1) \sin^2 \phi + 1]^2}{E} - 1 \right\} \end{aligned} \quad (5.9)$$

So far the analysis is quite general. For laminar flames there is the additional constraint set by the constant burning velocity.

$$S_L = v \sin \phi \quad (1.8)$$

Using equation 1.8 to eliminate ϕ from equations 5.6 - 5.9 gives:

$$v_{\perp} = S_L (E - 1) \sqrt{1 - \left(\frac{S_L}{v}\right)^2} \quad (5.6a)$$

$$v_{\parallel} = v \left[(E - 1) \left(\frac{S_L}{v}\right)^2 + 1 \right] \quad (5.7a)$$

$$\Delta p_{\perp} = \frac{\rho_r}{E} S_L^2 (E - 1)^2 \left[1 - \left(\frac{S_L}{v}\right)^2 \right] \quad (5.8a)$$

$$\Delta p_{\parallel} = \rho_r v^2 \left\{ \frac{\left[(E - 1) \left(\frac{S_L}{v}\right)^2 + 1 \right]^2}{E} - 1 \right\} \quad (5.9a)$$

All quantities on the right hand sides of the equations are explicitly known so that the velocity and momentum components can be evaluated for specific flames.

For turbulent flames, the more general, equations 5.6 - 5.9 apply directly. Examination of schlieren contours, like Figure 8, show the ~~near~~ randomness of the flame front orientation - denoted in the present context by the angle, ϕ . Transverse components of velocity and momentum are maximum when $\phi = 45^\circ$; those in the direction of approach flow when $\phi = 90^\circ$.

Table 2 shows the results of the foregoing analysis applied to the flames listed in Table 1.

T A B L E 2

FLAME GENERATED VELOCITY AND MOMENTUM

QUANTITY	SYMBOL	UNITS	LAMINAR		TURBULENT	
			1	2	1	2
Velocity Parallel to Flow	$v_{ }$	cm/s	392	286	2569	1739
Velocity Parallel to Flow	$v_{\perp}$	cm/s	240	240	1100	740
Momentum Generated $ $ to Flow	$\Delta p_{ }$ max.	dyne/cm ²	-157	-66	1075	480
Momentum Generated $\perp$ to Flow	$\Delta p_{\perp}$ max.	dyne/cm ²	10	10	225	104

The Table shows that, in the direction of mean approach flow, momentum is lost across the laminar flames but can be generated across the turbulent flames. Both types of flame generate momentum in a direction perpendicular to the mean cold flow, a direction in which, on average, there was previously none. The effect can be an order of magnitude greater for the turbulent flames than for the laminar ones.

Ignoring mixing with ambient surroundings, both cold and flame bearing flows will be parallel to the burner axis. For the former this will be true everywhere; for the latter it will be true far upstream and far downstream of the flame region. Reconciliation of these boundary conditions with the presence of, flame generated, transverse momentum, mentioned above, requires different pressure distributions to occur within cold and reacting flows. The pressure field is further modified because the surrounding atmosphere does not permit free expansion of the product flow, but confines it, thus imposing an additional boundary constraint.

With a laminar flame, all the pressure redistribution takes place, in such a way as to provide a time constant flow field, by distortion of the original streamline flow pattern. In the presence of turbulence the pressure field is no longer time constant and manifests itself as fluctuations in flame position. Reference to Table 2 shows the considerable momentum that can be generated locally across the instantaneous flame front. If the products flow away freely the gases carrying the flame front are unaffected by this momentum. If the products are totally constrained, the momentum is fed back, driving the interface back into the reactants. In practice the situation varies locally; transient fluctuations occur and the prevailing condition lies between the limiting extremes described.

Viscous effects tend to increase the feed-back by adding to the confinement of the products, which, by virtue of their temperature, have viscosity some three times as great as the reactants. This tends to restrict the product flow and causes expansion to be taken up by readjustment in the approach flow rather than by dissipation in the products.

5.5 Measured Flame-Turbulence Interaction and its Effect on Flame Structure

The first sections of this Chapter showed that the properties of the turbulent flame front can differ from those of the corresponding laminar flame and that these deviations from the "wrinkled front" concept were too large to be accounted for in terms of the small scale end of the spectrum of turbulence emerging from the burner. Each of the following two sections presented a distinct reason for not considering the burner turbulence as relevant: firstly, the increase in "relative" turbulence caused by the movement of the front and, secondly, the actual increase in approach stream turbulence due to feed-back of flame generated turbulence. One reason for the extensive discussion of the latter was to show not only that the effect was large, but also, unlike

the former, that there was little prospect of calculating it. The computation of the effective product "confinement" due to time varying orientation and temperature dependent viscosity presents a most intractable problem.

The detailed optical analyses, however, once more make possible the deduction of the relevant parameters directly from the flame behaviour. Thus it is possible to combine records of superimposed schlieren contours, of the type shown in Figure 14, with relevant approach flow parameters to give an average value of flame speed, G , where G is defined by the relation

$$G = \frac{\text{Average distance travelled by flame front}}{\text{Average time of fluctuation}} \quad (5.10)$$

Both the mean excursion, $\bar{Z}$, and the average flame front position, are measured directly from records like Figure 14. Combining the average flame position with particle tracks enables the mean flow velocity, normal to the average surface, v_n , to be obtained by the relation

$$v_n = \bar{v} \sin \phi \quad (5.11)$$

where $\bar{v}$ is the mean approach velocity and ϕ the angle of approach to the mean flame surface. Each flame movement is caused by encounter with a turbule in the approach flow and the time scale is, therefore, given by the time of passage of that turbule. If the scale of turbulence (as defined in Section 5.2) is 1, the transit time of turbule through flame (or flame through turbule) is given by $\frac{1}{v_n}$.

Substitution into equation 5.10 gives:

$$G = \frac{\bar{Z}}{\frac{1}{v_n}} = \bar{Z} \bar{v} \sin \phi \quad (5.12)$$

Measured values of $\bar{Z}$ and $\sin \phi$ for the central portions of the two flames are, very approximately, 0.14 cm. and 0.5. When combined with the values of $\bar{v}$ and l (defined by the burner grid dimensions), given in Table 1, G becomes 140 and 96 cm/s for the two flames.

If the altered burning velocity, for the central portions of the flames whose properties have been tabulated, is due to this cause, the movement of the instantaneous flame front, during the gas residence time, must be significant compared with its thickness. The time taken for molecular transit of a flame .2 mm. thick is of order 10^{-4} s., during which time the flame surfaces above will have travelled .14 and .10 mm. Thus it is demonstrated, by direct experimental measurement, that the fluctuation of the flame is sufficient to account for changes in structure, and hence in burning velocity.

There are two levels on which the structure can be modified. At the lower level only the physical transport properties are altered whereas a sufficiently large perturbation could affect the reaction rate also. This subdivision cannot be made absolutely rigorous because reaction rates depend, inter alia on radical concentrations which are affected by diffusion. However, Fristrom and Westenberg⁽³⁴⁾ have shown that the thickness of the zone which pilots the main reaction is exceedingly small - a minute fraction of the thickness of the preheat zone - so small indeed that there is no detectable affect of curvature on burning velocity, if the latter is measured in the reaction zone. This justifies the model proposed by Damköhler⁽⁴⁾ - see P.12 - in which small scale turbulence can modify diffusivity and hence the structure of the pre-reaction zone, as well as burning velocity, without affecting the reaction rate. Now the time intervals calculated above are just about comparable with the residence time in the entire flame

(defined, say, as the zone of varying temperature). They are very large by comparison with the crucial reaction times. Let us therefore hypothesize that the regime postulated by Damköhler applies here. This is speculation - unlike the rest of the thesis.

There are at least two reasons for testing such a hypothesis: firstly, it allows the comparison of measured burning velocities with those predicted from measured parameters of turbulence and, secondly, it permits further information to be extracted from the electrical measurements. The latter arises because it is reasonable to assume that the fundamental saturation current density, j_s , is unchanged if the reaction is the same, so that the observed change in the total saturation current J_s , is due to the changed area, A . Thus, $J_s = j_s A$ (equation 4.1) universal

$$\frac{\bar{S}_L}{S_L} = \frac{V/\bar{A}_L}{V/A_L} = \frac{A_L}{\bar{A}_L} = \frac{J_L}{\bar{J}_L} \quad (5.13)$$

for each volume flow rate V where the subscripts L apply to laminar and $\bar{L}$ to average values of turbulent.

Figure 26 illustrates the ratio of burning velocities calculated on this basis for the results of Figure 22 (here plotted downwards). These results demonstrate strikingly how the deviation of S_L from $\bar{S}_L$ increases with distance from a burner wall - a result that was anticipated by the theory of Section 5.3 and was apparent already from the optical analysis (curves 3 of Figure 12 and 13). The 350% increase in burning velocity, described in Section 5.1, was, of course, the local value, on the axis of the flow, .65 cm. from the wall. The average value for this burner is 85% and compares with the 37% maximum of the .57 cm. diameter burner deduced from saturation

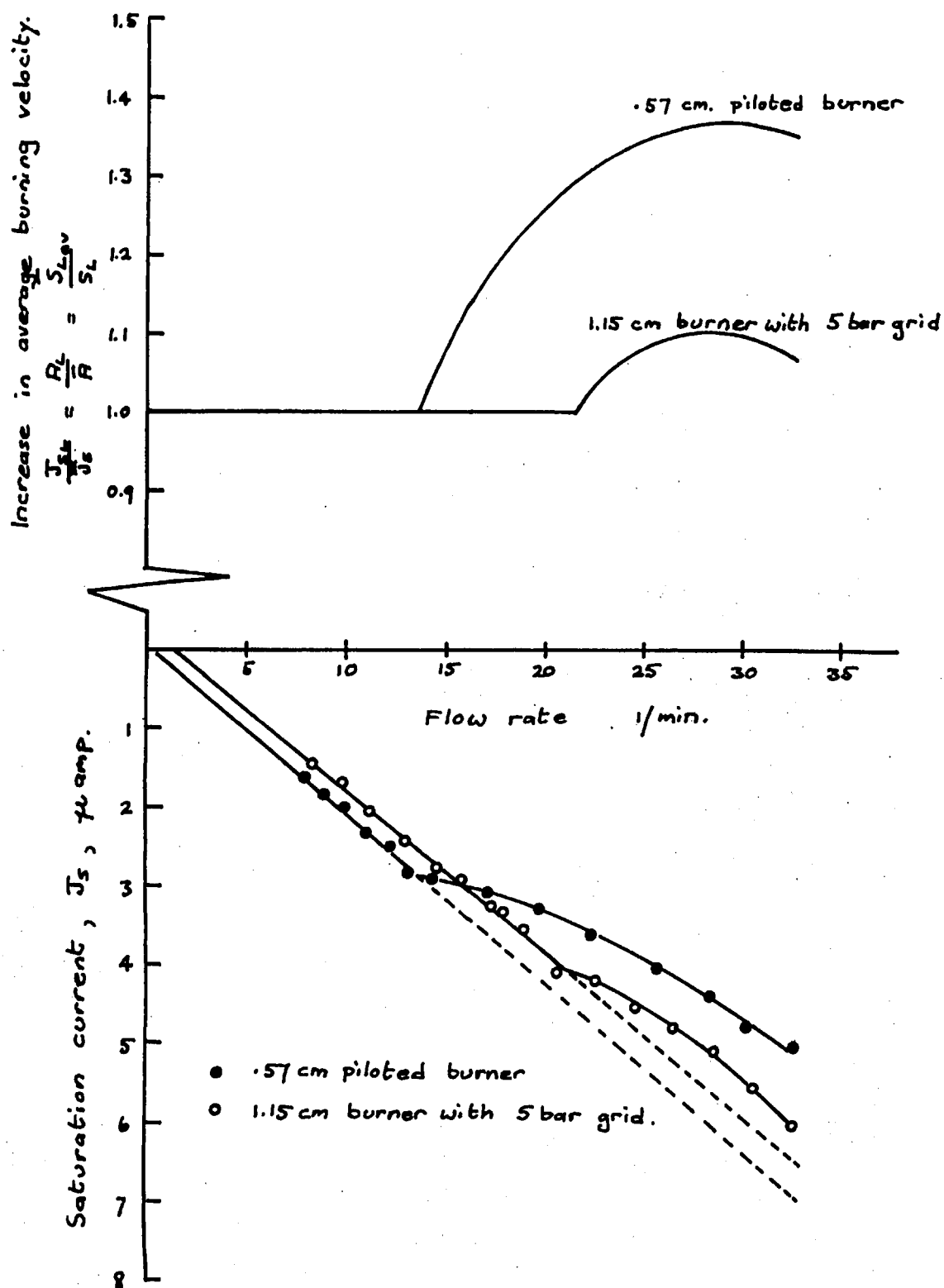


FIG. 26

AVERAGE BURNING VELOCITY CALCULATED
FROM SATURATION CURRENT RESULTS

current. For the flame stabilized on bars 2 mm. apart, the difference is 10% and, as mentioned previously, might have been overlooked had it been measured by a less sensitive method. The parallel increase in the excursions of the flame front and hence in its contribution to the turbulent fluctuation, is immediately obvious by inspection of Figure 14.

If the hypothesis is correct, then the "modified laminar" burning velocity, S_L , should be predictable by Damköhler's theory (equation 5.1) provided the eddy diffusivity - or rather that part of it due to scales smaller than the flame thickness - is based not on the approach stream turbulence but on that actually experienced by the flame. Once again this is best worked out from the flame fluctuations.

It has already been shown, by equation 5.1, that the eddy diffusivities required from the largest discrepancies - on the axes of the two flames - are 1.7 and 1.3 cm²/s. The mean fluctuating flame speed, G , has been defined in terms of total distance travelled in the period of a fluctuation (equation 5.10) without any allowance being made for direction of motion. When considered in terms of a perturbation on a mean approach velocity between flame and reactants, it has all the characteristics of turbulence. Its intensity, u_f , is the root mean square of the fluctuating velocity. Since its calculation requires more elaborate statistical analysis of the results than seems worthwhile, let u_f be equal to some fraction $\mathcal{L}$ of G . The eddy diffusivity, $\mathcal{E}_f$, corresponding to the scale of the flame front thickness, Δ_f , is given by

$$\mathcal{E}_f = \mathcal{L} G \Delta_f \quad (5.14)$$

This expression is equated to the required value of eddy diffusivity, mentioned above, and solved for $\mathcal{L}$. As before, Δ_f is assumed to be .2 mm. - a value thought to be appropriate for the flame studied. For the two flames, the resulting $\mathcal{L}$ is .61 and .68. All the results applicable to the centre of the flames are summarised in Table 3.

TABLE 3
FLOW PROPERTIES ON THE FLAME AXES

QUANTITY		SYMBOL	UNITS	LAMINAR		TURBULENT	
				1	2	1	2
A	Kinematic viscosity	ν	cm ² /s	.14	.14	.14	.14
P	Density	ρ	g/l	1.3	1.3	1.3	1.3
P F	Expansion Ratio	E		7	7	7	7
R L	Approach Velocity	v	cm/s	379	252	367	247
O O	Scale	ℓ	cm	-	-	.18	.18
A W	Intensity	u	cm/s	-	-	18	12
C H	Eddy Diffusivity	ϵ	cm ² /s	-	-	.32	.22
	Burning Velocity	S_L	cm/s	40.4	40.4	146	126
	Mean Excursion	$\bar{z}$	cm	-	-	.14	.14
	Sin of Mean Approach Angle	$\sin \phi$		.106	.160	.5	.5
	Flame Speed	G	cm/s	-	-	140	96
	Velocity Parallel to Flow	$v_{ }$	cm/s	392	286	2569	1739
	Velocity Normal to Flow	$v_{\perp}$	cm/s	240	240	1100	740
	Momentum Generated // to Flow	$\Delta p_{ \max}$	dyne/cm ²	-157	-66	1075	480
	Momentum Generated $\perp$ to Flow	$\Delta p_{\perp \max}$	dyne/cm ²	10	10	225	104
	Eddy Diffusivity to Account for measured increase in S_L	ϵ'	cm ² /s	-	-	1.7	1.3
	Flame Thickness	Δ_f	cm	-	-	.02	.02
	Flame Speed			-	-		
	Effective Intensity	$\mathcal{L}$		-	-	.61	.68

Even without a more detailed analysis of the fluctuating forms the values obtained certainly appear to be reasonable. If, for instance, the motion were sinusoidal, $\mathcal{L}$ would be

$\frac{1}{\sqrt{2}} = .71$. The explanation of burning velocity increase in terms of turbulence seen by the moving flame front thus appears to be plausible on a qualitative basis.

It will be noted that the contribution of the burner stream intensity, u , was not even included above and would not, in fact, have made any appreciable contribution!

CHAPTER 6 CONCLUSIONS

A new optical method has been established for recording burning velocities of turbulent flames. These have been measured according to variously defined, but reproducible, flame surfaces, both as averages over the flame and distributions across the burner mouth.

Other optical methods have been introduced to compare the effectiveness of turbulence inducing devices and the average distribution of products and reactants in the presence of a flame, or as a measure of mixing of jets of gases of dissimilar refractive indices.

An electrical method has been developed as a means of measuring flame area under steadily propagating conditions. It is of particular value for irregularly shaped flames where alternative methods are difficult to apply and has, in the present instance, been used in the study of transition from laminar to turbulent flames.

The hypothesis that each element of a turbulent flame's surface propagates, instantaneously, at the normal laminar burning velocity, has been checked and, contrary to current belief, found to be an inadequate approximation for most flames. Measurements of burning velocity show that the discrepancy is far too great to be accounted for by small scale turbulence in the burner flow.

Changes in saturation current per unit volume of flow have been observed to occur on transition from laminar to turbulent flames. They have been interpreted as independent confirmation of differences in the propagation of the two flames.

The burner flow turbulence, which proves to be quite inadequate to account for these effects, is shown to fall far short of the real effective value because of two neglected contributions. One is that due to the extensive fluctuation of the front, which is not caused locally, and greatly adds to the "relative" value. The other is explained in terms of the fluctuating feed-back of momentum from the products, which manifests itself as flame generated turbulence. This feed-back depends on the extent of produce confinement and, although it is difficult to calculate, the effective flame turbulence could be deduced from measurements on the fluctuations of the front.

The movement of the flame front during reactant transit time was found to be comparable with flame thickness, implying a change in flame structure. It is suggested that this change is likely to correspond to changed transport properties and not large enough to modify the reaction. On this basis, the electrical measurements are correlated with optical burning velocity determinations. Using turbulence parameters deduced from measured flame fluctuations, it is shown that the changes in burning velocity can indeed be accounted for in terms of the eddy diffusivity of scale smaller than flame thickness.

Thus, the Damköhler theory is upheld, provided it is not used with the eddy diffusivity corresponding to burner turbulence - the contribution of which is, indeed, quite insignificant.

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