

Wall Quenching of Flame Propagation

MPhil Thesis P F Thorne 1980

Corrigenda

- Page 2 Para 4 line 3 replace "bwing" by "being"
- Page 5 Item 7.6 insert 'of' after "relationship"
- Page 15 Last para line 1 "variations"
- Page 18 Last para line 4 replace "with" by "into"
- Page 19 bottom line "directly with"
- Page 22 line 13 "undergoes"
- Page 23 Para 4 line 3 insert ", momentum diffusivity" after "viscosity"
- Page 25 Replace subscript "j" by "i"
- Page 28 (T_f^a) 1800-2600K
- Page 30 Fig 2.1. . Ref 17
x Ref 17
□ Ref 18
Insert refs 17, 18 in title
- Page 31 Fig 2.2 Dainty and Brown⁽²¹⁾
Wolfhard and Brusjack⁽¹⁹⁾
Insert refs (19) (21) in title
- Page 33 Para 2 last line insert "the" after "of"
- Page 34 Para 4.1 Item III insert " T_i " after "temperature"
- Page 36 Equation 4.6 R.H.S. $-\Delta$
- Page 38 Eq'ns 4.9, 4.10 and following line. Replace A by C
- Page 39 Third line below eq'n 4.13 replace first "and" by "r"
- Page 40 Eqs 4.16 and 4.17 delete minus sign
- Page 42 Para 2 line 1 "quasi"
Eq'n 4.1. first term $\rho_u S_u C_p T_u$
- Page 43 Para 3 line 4 replace "Fig. 1" by "Fig. 4.2"
- Page 46 Replace λ by Δ
- Page 49 End of line 1 replace comma by "and"
- Page 52 Third line up Tables 6.1 and 6.2
- Page 56 (Facing) Key to Fig. 5.1 Item 9 insert "fig 5.2"
Item 10 delete "for piston ——"
Item 20 insert "figs 5.3 to 5.6"
- Page 75 Para 6.1.1 line 5 replace "-" after n-pentane by ","
- Page 104 Para 2 line 6 replace "rich" by "rich"
- Page 106 Para 2 line 6 insert " λ " after "The"
- Fig. 7.2 arrow alongside D to point in opposite direction
- Page 115 Para 8.4 line 4 replace " $(\phi = 1.2)$ " by " $(\phi) = 1.2$ "
last line replace "largest" by "longest"
- Page 117 α Lewis Semenov
- Page 118 α (K/GP)
- Page 123 Para 4 Table A.1.4
- Page 140 Para 2 line 1 "Danby"
- Page 142 Para 4 line 5 "Tufnol"
- Page 105 Line 2 insert "For upwards propagation" before "examination"

1

WALL QUENCHING OF LAMINAR

FLAME PROPAGATION

BY

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A THESIS SUBMITTED FOR THE DEGREE OF
MASTER OF PHILOSOPHY IN THE UNIVERSITY OF LONDON

DEPT OF CHEMICAL ENGINEERING

IMPERIAL COLLEGE

PRINCE CONSORT ROAD

LONDON SW7

MARCH 1980

ABSTRACT

Quenching distances of laminar flames in both quiescent and flowing mixtures of n-hexane in air have been measured at 100°C using a parallel plate flashback burner. The effect of increasing the gap length from 3mm to 25mm was to increase quenching distance for mixtures richer than stoichiometric by about 9 per cent: lean flames were unaffected. Inverting the burner resulted in a reduction in rich flame quenching distance of some 2 per cent. Horizontal flashback quenching distances were identical to vertically downward flashback quenching distances. Lean flames were not affected by direction of flame propagation. The effect of a superimposed flow of unburnt gas mixture in the same direction as flame travel was to decrease the quenching distance by a factor of about two at unburnt gas gap velocities of 10 ms⁻¹ and 20ms⁻¹ for 6mm and 25mm long gaps respectively.

Quenching distances have also been measured for the homologous series of n-alkanes C₅ - C₁₀ plus iso-octane using a 3mm long gap. Minimum quenching distances varied with molecular weight to the power -0.3.

On average the slot quenching Peclet number (Pe) in quiescent mixtures was found to be 35, which is equivalent to a Peclet number for a tube of 54.

A model for the progressive quenching of flames propagating along channels of quenching dimensions is discussed and the experimental results are seen as evidence for preferential diffusion being an important feature of the quenching mechanism for rich flames.

A comprehensive compilation of quenching distance data is also presented.

ACKNOWLEDGEMENTS

My thanks are due to J H Burgoyne, who suggested the topic, for helpful supervision; to D H Napier for his encouragement and supervision of the completion of the thesis, to K N Palmer for considerable encouragement in the writing of the thesis and to Mrs J Balcombe for typing.

The thesis is dedicated to my parents for whom the work was started and to my wife and daughters for whom it was completed.

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CHAPTER 1

INTRODUCTION

1.1. GENERAL

A quenching dimension (D) can be defined in the following manner. With the stoichiometry of a known gaseous fuel/oxidant mixture fixed, the cross-sectional area of a passage of defined shape is reduced to an extent at which a flame cannot propagate through that passage. The minimum dimension characteristic of the chosen shape at this condition is defined as the quenching dimension. Thus for a circular passage we have the "quenching diameter" (D_0) and for an infinite slot the "quenching distance" (D_{11}). Other quenching dimensions can be similarly defined eg for a triangle the height, for an ellipse the minor diameter, for a rectangle the shorter side etc. It is clear that, except for the circle and the infinite slot, an aspect ratio describing the proportions of the passage shape is also required to be known. It should be noted that this general definition, forms of which are well established historically, does not involve the depth of the quenching passage, or indeed its inclination which determines the direction of flame travel.

General but not invariable assumptions are normally implied; that the depth of passage is of the same order as the flame thickness and the inclination of the passage is vertical, the direction of flame propagation therefore being vertically downwards. However, it has been conventionally considered that the quenching dimension is not sensitive to the quenching passage depth or the direction of flame propagation. It can be argued that the quenching dimension, because it is dependent upon details of the apparatus on which it is measured, is not a fundamental property of a flame as are, for example, the adiabatic laminar flame speed (S_u) and adiabatic flame temperature (T_f^a). Nonetheless correlations of quenching dimension with other parameters, usually of engineering significance, of flame systems have been developed; notable have been correlations with minimum ignition energy.

Quenching dimension is regarded as significantly relevant to a number of important engineering methods for explosion protection.

The first and most direct of these was the development by Davy of his Miner's Safety Lamp in which flame propagation was prevented by a simple thin gauze, the mesh aperture dimensions of which were directly related to a quenching dimension for methane in air. The flames to be quenched were essentially stationary.

Flame arrester devices used in the chemical and process industries and in other applications are used to quench moving flames often in flammable gas mixtures which are themselves in motion. The use of flame arrester devices to prevent 'flashback' of stabilised flames is no less important. The geometry of practical flame arresting devices varies widely. It ranges from a single gauze providing an array of short rectangular apertures, through arrays of straight triangular and parallel passages of various depths to complex arrays of tortuous passages often of unknown length and varying characteristic dimensions formed for example by beds of pebbles or ball bearings, or by knitted wire meshes and porous metal sinters.

The sizes of the apertures in flame arresters are clearly related to a quenching dimension (D). Theoretical and experimental studies of the physico-chemical mechanism of flame arresters have correlated gross flame speed at the arrester with the dimensions of the arrester. Little attention has been paid to the rate of flow of unburnt gas ahead of the flame, particularly in studies of flame quenching in single gaps.

The method for protecting electrical equipment used in flammable atmospheres known as 'flame-proofing' involves knowledge of a parameter known as the "Maximum Experimental Safe Gap" (MESG). It is defined, in the UK, as "the widest gap which has been found to prevent ignition of the most easily ignited external mixture when the most incensive mixture of the same combustible is exploded inside the test vessel". Experimentally determined values of MESG relate to prescribed test conditions, the most important of which are the gap length, the volume of the test apparatus and the position of the ignition source relative to the flanged gap.

Much has been written about the physico-chemical mechanisms involved in the transmission of flame through such gaps, which are generally of the order of half the quenching distance (D_{11}). Because other properties of flame

systems, such as minimum ignition energy (E_{Im}) and quenching distance (D_{11}) are often easier to measure, there have been many attempts to show that MESGs can be estimated from knowledge of those properties. Both theoretical and experimental correlations have been produced which appear to be quite successful, but as will be discussed later, there is no fundamental significance to them.

The work described in this thesis was carried out in order to establish and evaluate the relative importance for flame quenching in gaps of factors which had not been examined in detail in previous studies, ie quenching gap depth, direction of flame propagation, modest (laminar) superimposed flow of unburnt gas through a quenching gap. In addition the relationship between quenching distance (D_{11}) and MESG was studied using an homologous series of fuels. The scope of the work carried out is described in more detail in Section 1.2 .

1.2 SCOPE OF THE PROBLEM EXAMINED

As discussed above, quenching distance is a property of a flame system which is of practical importance in the field of explosion protection. However, a number of potentially significant factors upon which the quenching distance (dimension) could be expected to depend have not hitherto been investigated systematically. The lack of such basic information is the more apparent because many of these factors have been the subject of investigation in connection with explosion protection methods which either depend directly upon the principle of flame quenching by solid surfaces or upon closely related phenomena.

In particular the effect of quenching gap length, unburnt gas flow and fuel type have been examined in relation to either the performance of flame arresters or the measurement of MESGs.

The following factors have been investigated in the work reported here:

- 1) The effect of fuel structure within the homologous series of paraffin C_6 to C_{10}
- 2) The effect of quenching passage length over the range 3.2mm ($\frac{1}{8}$ in) to 25.4mm (1 inch)
- 3) The effect of quenching passage orientation (direction of flame propagation) from 0° (propagation vertically downwards) to 180° (propagation vertically upwards)
- 4) The effect of the flow of unburnt gas in the quenching gap ahead of and in the same direction as the flame.

The work as a whole is distinguished by the fact that it has been carried out using one basic apparatus, and methodology the principle of which is closely related to the practical applications, and at a constant temperature and ambient pressure.

The four aspects to the work were chosen for the following reasons, briefly

1) Quenching distances have been measured most commonly for flames of gaseous fuels which are gases at ambient temperature, on account of the ease with which gases can be handled experimentally. There is little systematically determined data on the quenching distances of liquid hydrocarbon fuels. On the other hand MESGs have been measured for many liquid fuels. Systematic variations with molecular weight of several flame properties have been variously reported. The homologous series of normal paraffins C_6 to C_{10} was therefore chosen as being a family of liquid fuels of practical interest and significance which had not been intensively investigated. Iso-octane was included to show the effect of a branched chain structure. Values for MESG were available for most of the normal series.

2) Flameproof electrical equipment is protected essentially by narrow flanged gaps 25.4mm (1 inch) long. For many fuels gap dimensions for flanges 12.7mm ($\frac{1}{2}$ in) long are specified. Most determinations of quenching distance have been made using gaps about 3 or 4mm long or shorter (see Appendix 1).

Flame arrester elements are of variable length. Some arresters of the 'crimped ribbon' type are up to 100mm (4 inches) long whilst for light duties gauzes of only 1 to 2mm thickness are used. It was decided that a quenching gap length of 25.4mm (1 inch) was of significant practical interest, and because accurate measurements would be difficult to acquire for gap lengths significantly longer than this with the chosen experimental methodology, this gap length was set as the maximum. Shorter lengths were investigated, reducing the gap length by a half in steps down to a length of 3.2mm ($\frac{1}{8}$ in).

3) It is well known that limits of flammability as measured in tubes wide enough for wall quenching effects to be negligible, are influenced significantly by the direction of flame travel. The limits for upwards propagation can be some 100 per cent wider than for downwards propagation; the rich limit experiencing most of the effect.

Only one

rather unsuccessful attempt to investigate directly the effect of the direction of flame propagation having been reported, the effect of gap orientation was successfully investigated for the 3.2mm ($\frac{1}{8}$ in) and 25.4mm (1 inch) long gaps at orientations of 0° , 90° , 135° and 180° .

- 4) For the most part flame arresters are required to quench flames which approach them at a velocity greater than S_u .

Expansion of hot burnt gas behind the flame exerts a force on the unburnt gas ahead of the flame. Provided that it is free to do so the unburnt gas will flow through the arrester as the flame approaches it. On interacting with the arrester, therefore, the flame will be propagating through a moving rather than a stationary gas mixture.

An essential feature of 'flameproof' electrical equipment is that flame inside the equipment, on reaching the protective gap is propagating through a gas mixture which is flowing, often at sonic velocity, through that gap.

The effect of the movement of unburnt gas mixture ahead of a flame through a single quenching gap in order to correlate the velocity with any change in quenching distance has not previously been reported. The work on gas flow reported here is limited to laminar flow (based on Reynolds number for air) in the quenching gap. Experiments have been made with 25.4mm (1 inch) and the 6.4mm ($\frac{1}{4}$ in) long gaps.

CHAPTER 2

SUMMARY OF PREVIOUS WORK

2.1. Experimental studies

The bulk of the reported experimental work available at the time on the measurements of quenching dimensions using a variety of methods under a range of conditions has been reviewed comprehensively by Potter⁽¹⁾. A useful review of the more practical aspects has been made by Massey and Lindley⁽²⁾. Relevant work published since these reviews will be summarised here.

Potter⁽¹⁾ distinguished four principal methods for measuring quenching distances, viz:

- 1) The burner method; determination of whether a flame stabilised on a burner will flashback or be quenched when flow to the burner is interrupted.
- 2) The tube method; determination of the critical tube diameter for the propagation of a flame in a quiescent mixture.
- 3) The flanged electrode method.
- 4) Extrapolation of blowoff - flashback stability diagrams to the quenching point.

Potter also reviewed work on the effect of fuel type and concentration, pressure, temperature, quenching gap geometry, wall coatings, turbulence, buoyancy and pressure gradient. It will be convenient to discuss the later work under one or more of these headings.

With regard to experimental techniques variation on the burner and tube methods have been published⁽³⁾⁽⁴⁾. Their apparent advantage is reduction in the work involved in making a determination. The essential feature is that flame propagates through a quiescent mixture into either a conical tube⁽³⁾ or a wedge-shaped channel⁽⁴⁾. The point at which the flame is quenched is determined photographically. A variation of this approach entails shrouding a longitudinal burner by a wedge-shaped

water cooled collar, the distance along the collar that flame propagates being noted⁽⁵⁾. The conical tube gives a result for methane in line with other methods and is included in Appendix 1. The wedge-shaped channel⁽⁴⁾ has been described in connection with very reactive systems at low pressures: for acetylene/oxygen a wedge gap of 1.68mm at a pressure 11mm Hg was reported. The wedge-shaped burner⁽⁵⁾ gave a result for propane which is in agreement with other results and is included in Appendix 1.

There has been interest in wall quenching of flames in combustion chambers; incompletely reacted fuel being a potential pollution problem. Some interesting experimental techniques have been used to examine wall quenching simulated in actual piston engine combustion chambers⁽⁶⁾ and in constant volume bombs⁽⁷⁾ ⁽⁸⁾. The interesting feature of these experiments is that they have enabled quenching distance measurements to be made at pressures up to 60 atmospheres, although the pressure has often not been constant, ie has steadily increased, during an experiment.

Goolsby and Haskell⁽⁶⁾ report results for iso-octane at peak pressures between 10 and 30 atmospheres which, for $\phi > 1$, agree with Friedman and Johnston's⁽⁹⁾ correlation of low pressure data for iso-octane, $D_{11} \propto P^{-0.91}$. They also report limited data for n-propane at about 30 atmospheres which is close to Friedman and Johnston's⁽¹⁰⁾ correlation for n-propane, again $D_{11} \propto P^{-0.91}$.

Green and Agnew⁽⁷⁾ found the pressure dependence of $D_{11}(\text{min})$ for propane at pressures between 2 and 60 atmospheres to be some 30 per cent lower in terms of the exponent than Friedman and Johnston⁽¹⁰⁾.

Nair and Gupta⁽⁸⁾ investigated 'commercial' butane at pressures between 5 and 30 atmospheres finding a pressure exponent of -0.78 for stoichiometric mixtures. Extrapolation to atmospheric pressure gives a value for D_{11} of 0.78mm, considerably less than the expected value. The experimental method was, however, dynamic in that it depended upon the passage of flame through a slit only 1mm deep into a small secondary chamber. Although this chamber was situated in the wall of the 280mm spherical bomb some residual flow pattern, probably turbulent, can be expected to have existed in the vicinity of the quenching gap.

The work of Ishikawa and Branch⁽¹¹⁾ using the electrode method in a constant volume bomb has led to values for D_{11} for methane, methanol and methanol/iso-octane blends. The pressure dependence exponent for the latter being -0.61 for stoichiometric mixtures for pressures between 0.2 and 1 atmosphere. Their results are included in Appendix 1.

With regard to work on fuel type, Grove⁽¹²⁾ (13) using the burner method has measured quenching diameters (D_0) for materials covering a range of chemical structure including carbon monoxide containing different amounts of water vapour. His results are summarised in Appendix 1. The objective of the work was to explore any relationship there might be between D_0 and MESG. A reasonably good empirical relationship was found, viz

$$\ln (\text{MESG}) = 0.5484 \ln (D_0 - 0.027) - 1.8934 \quad 2.1$$

Where MESG and D_0 were both expressed in inches.

Ryason and Hirsch⁽¹⁴⁾ have reported some measurements of quenching diameter for cool flames. These results, summarised in Appendix 1, table A.1.2 confirm Palmer's⁽¹⁵⁾ finding in his work with flame arresters that 'cool' flames are more easily quenched than 'hot' flames of the same fuel/air system.

Sturmon⁽¹⁶⁾ working with methane, propane and butane in air flames has investigated the effect of burner orientation on quenching distances using the burner method. Quenching distances were unaltered for horizontal propagation (90° inclination) as compared with downward propagation (0° inclination). From 90° to 165° quenching distances were slightly smaller than for 0° to 90° . In this region (90° to 165°) a zone existed below the quenching distance curve in which flashback sometimes occurred. This zone was limited by a flashback curve below which it never occurred. The flashback and quenching distance curves coincided at the stoichiometric mixture but separated on either side. From 165° to 180° unsteady flames were encountered, and the flashback and quenching distance curve separated markedly but the quenching distance curve was still but little changed as compared with the 0° to 90° range.

Payman and Wheeler⁽¹⁷⁾ and Singer and von Elbe⁽¹⁸⁾ propagated methane/air

flames ($\phi = 1.05$) through tubes up to 300mm long. For downwards propagation Singer and von Elbe⁽¹⁸⁾ found the diameter that just allowed full propagation to be 3.99 mm whilst propagation extended for less than a quarter of the tube length at 3.52mm diameter. Payman and Wheeler⁽¹⁷⁾ found an initially linear increase of critical diameter with tube length. Both found that linear flame speeds in tubes of diameter approaching quenching dimensions approached the standard burning velocity. The results are summarised in Fig 2.1.

Friedman and Johnston found no difference in quenching distance for gaps of 3mm and 10mm length.

There has been much interest in the effect of flow through single and multiple gaps on their ability to prevent the propagation of explosions. The interest is related to the phenomenon of the MESG and its application to flameproof electrical equipment although, clearly, the performance of flame arresters is also of related interest.

The physico-chemical mechanisms involved in flameproofing and flame arresting are sufficiently different, in detail, for it to be necessary to consider them as separate phenomena.

In the case of the MESG, or its tube equivalent, three distinct scenarios, following Wolfhard and Bruszak⁽¹⁹⁾, are possible. They are (1) A laminar or turbulent flame is carried through the channel and propagates without discontinuity with the outer mixture. (2) The channel extinguishes the flame only gradually. In some cases elements of flame may just reach the channel exit, in others the flame front may be extinguished at or near the entrance to the channel. (3) If the flame front is essentially extinguished within the channel, hot burnt gases from the inner mixture, having undergone a cooling process in the channel itself, form a jet in the outer mixture and ignition of the outer mixture may occur in the boundary between the hot burnt gas and the cold explosive mixture. The burnt gases may be hot enough to be luminous and in some instances small elements of flame may be ejected from the channel exit without ignition taking place. Wolfhard and Bruszak⁽¹⁹⁾ and Phillips⁽²⁰⁾ have both published high speed schlieren cine-photographs illustrating this process.

Wolfhard and Bruszak⁽¹⁹⁾ determined the oxygen index (OI) of primary mixtures of ethane in oxygen/nitrogen atmospheres which would just ignite a stoichiometric ethane/air secondary mixture when the primary mixture was ignited and the explosion was communicated to the secondary mixture via a tube of known length and internal diameter. They argued that the OI was a measure of the ignitibility of the secondary mixture. Their results for ethane, have been replotted in a new form in Fig 2.2. For a constant oxygen index of 0.5 the diameter of a tube permitting ignition has been plotted against its length. As tube length is increased, other conditions remaining constant, the critical diameter is reduced to a minimum of about 0.5mm at a length of 5mm; thereafter the critical diameter gradually increases with tube length.

This correlation is of the same general shape as that presented by Dainty and Brown⁽²¹⁾ for similar experiments with methane. Their results are reproduced in Fig 2.2 for comparison. In both cases actual gas velocities were not measured.

Dainty and Brown⁽²¹⁾ argued that entrance effects in the tube followed by the subsequent development of a boundary layer would influence the fluid dynamics of the jet of burnt gas emerging from the tube sufficiently to be a significant feature of the mechanism of explosion propagation. The arguments are too involved to discuss in detail at this point and are, in any case, complicated by the fact that for a given primary explosion pressure the velocity distributions at the tube exit will vary with tube length. However the essential feature of the arguments is that the minimum critical diameter for ignition will occur at a tube length corresponding to that at which initial entrance effects have dissipated and a boundary layer is just beginning to develop.

Maekawa et al⁽²²⁻²⁴⁾ have determined the dimensions of single and multiple gaps which will permit the propagation of an explosion between a primary and a secondary chamber, using stoichiometric methane/air mixtures. The work is of limited usefulness because gas velocities were not measured⁽²²⁾⁽²⁴⁾. Where velocity was calculated for a circular quenching orifice from a knowledge of the inlet pressure this was not correlated with directly orifice diameter⁽²³⁾. The most important

result of this work was that gap distance had to be reduced as the number of multiple and adjacent gaps was increased from one to four. The greatest reduction in gap distance was required for two gaps compared with a single gap (about a 50 per cent reduction from a gap distance of 7.5mm). The work with the quenching orifice led to the result that the diameter which prevented propagation of the explosion was approximately proportional to the ejected velocity, which is qualitatively at variance with some of the authors' other conclusions.

Palmer and Tonkin have investigated the effect of the type of construction and dimensions of flame arresters on their ability to quench flames of different fuels. They investigated wire gauzes using propane, ethylene and 'town' gas⁽²⁵⁾ perforated sheets and blocks using propane⁽²⁶⁾ also various liquid fuels and ethylene⁽¹⁵⁾ and crimped ribbon arresters using propane⁽²⁷⁾. Davies, Palmer and Rogowski⁽²⁸⁾ also examined the performance of a metal foam.

The performance of single gauzes could be correlated by

$$V_F = C m^{-n} \quad 2.2.$$

Where, for the various combinations of fuel gas and gauze material and C took values in the range 12.8 to 30 and n 1.0 to 1.27 compared with theoretically predicted values of 21.6 and 0.9 respectively.

The results were broadly similar for all the combinations examined but there are two significant overall results. For low approach velocities (less than 0.4 or 0.5 ms^{-1}) brass and phosphor bronze gauzes performed better than steel gauzes; also brass or phosphor bronze gauzes more readily quenched flames propagating upwards than those propagating downwards. This second result is especially interesting because the flammability limits for flames propagating upwards in similar sized tubes to those used in the gauze experiments are wider than for flames propagating downwards⁽²⁹⁾. In both situations ignition was at the open end of a tube which was closed at the opposite end. Upwards propagation is the more favourable condition for flame stability. The explanation of the apparant contradiction is found in the respective flame shape for laminar flames. Flames propagating upwards are roughly parabolic whilst those propagating downwards are essentially flat. The underlying mechanisms have been discussed by Levy⁽³⁰⁾. For a given flame speed the rate at

which a gauze is required to extract heat from a flame propagating upwards is less than from the corresponding downward propagating flame.

The results of similar experiments with sheets and blocks perforated by circular holes and a wide range of fuels were correlated by equations of the form⁽¹⁵⁾⁽²⁶⁾

$$V_F = A \frac{k \Delta T}{\mu} \cdot \frac{y}{d^2} \quad 2.3.$$

Cool flames of acetaldehyde and diethyl ether were for the most part quenched by apertures 5.6mm diameter compared with the aperture diameter of 1.75mm and less required for hot flames of the same and other fuels.

The crimped ribbon type of arrester were characterised by the parameter ny where n is the number of apertures per unit area of arrester face and y is the length of the quenching aperture (thickness of arrester). The equation developed to correlate the results was of the form

$$V_F = A \frac{k \Delta T}{\mu} \cdot ny \left(\frac{P_o}{P} \right) \quad 2.4.$$

where (P_o/P) is a correction for pressure required when bends and/or obstructions are present in the pipe.

The performance of metal foams was also shown to be correlated reasonably by this equation.⁽²⁸⁾

Ballal and Lefebvre⁽³¹⁻³³⁾ attempted to ignite flowing mixtures of methane and propane with air or oxygen mixed with nitrogen, argon, helium and carbon dioxide in various proportions. The mixtures were arranged to flow at various levels of pressure, turbulence and velocity. Quenching distance, as measured by the electrode method, increased with turbulence intensity, decrease in pressure and departure of mixture strength from stoichiometric ($\phi = 1$).

Tewari and Weinberg⁽³⁴⁾ have made a fundamental study of the structure of a lean ethylene/air flame under the quenching influence of a cold surface. Using particle track visualisation and by gas sampling, a flame structure was deduced in terms of burning velocity, flow pattern and diffusion of selected species. It was found that flame was always

convex to, with the reactants adjacent to, the cold surface. Only very strong suction into a slit in the surface could induce flame to sit normal to it. Burning velocity decreased as the surface was approached but the amount of decrease appeared to depend upon the orientation of the flame front to the surface in a manner which the authors could not account for solely by variations in heat loss. It was concluded that diffusion of active species, particularly hydrogen atoms, towards the surface in the vicinity of the reaction zone was a dominant factor. As a result of the study Tewari and Weinberg took the view that the wall quenching "phenomenon is likely to prove even more intractable than has hitherto been supposed". The reason behind this conclusion is the deduced mechanism that hydrogen atoms diffuse to the solid surface, there undergoes the reaction $H^{\bullet} + O_2 \rightarrow \bullet OOH$, the radical so formed, subsequently, diffuses into the preheat region of the flame there enhancing the rate of reaction. Any "comprehensive theory would not only have to take into account the effect on reaction rate of small concentrations of species rapidly diffusing from the flame; the active species originates not in the flame, but on the wall"

2.2 Theoretical Studies

In addition to reviewing the experimental flame quenching studies available to him, Potter⁽¹⁾ also reviewed many of the theoretical models which were available at the time. They were of two types.

- 1) Simplified models, based mainly on heat transfer considerations, in which heat losses to walls and/or unburnt gas were considered in various geometries (35,36,37)
- 2) Attempts at comprehensive treatments, mostly involving conservation equations (of energy and mass) (38-41)

Theoretical models which have appeared subsequently are also of one or other of these types.

Many of the studies then and since have utilised a dimensionless Peclet number (Pe) in their correlations.

A short explanation of the Peclet number is in order. There are, in fact, two Peclet numbers; for heat transfer and for mass transfer. For heat transfer $Pe(H) = Re.Pr$ when Re is the Reynolds number (ratio of inertia to viscous forces) and Pr is the Prandtl number (ratio of momentum diffusivity to thermal diffusivity).

$$Pe(H) = \frac{\rho d u}{\mu} \cdot \frac{C_p \mu}{k} = d.u. \frac{\rho C_p}{k} = \frac{d u}{\alpha}$$

$Pe(H)$ represents the ratio of bulk heat transfer to conductive heat transfer. For mass transfer $Pe(M) = Re.Sc$ where Sc is the Schmidt number (ratio of kinematic viscosity to molecular diffusivity)

$$Pe(M) = \frac{\rho d u}{\mu} \cdot \frac{\mu}{\rho D} = \frac{d u}{D}$$

$Pe(M)$ represents the ratio of bulk mass transfer to diffusive mass transfer.

Potter did not mention the simplified theoretical model of Holm⁽⁴²⁾ who considered an hemispherical flame extinguished by heat loss from the flame surface to unburnt gas ahead of the flame

Holm's model was expressed

$$D_o = \frac{4\bar{k}(T_i - T_o)}{v(Q - \bar{c}_p(T_f - T_o))} \quad 2.5$$

D_o is the limiting diameter

$\bar{k}$ is the mean thermal conductivity between T_o and T_i

Q is the heat released per cm^3 of gas mixture

$\bar{c}_p$ is the mean specific heat, expressed per cm^3 of gas mixture
k between T_o and T_f

T_o is ambient temperature

T_i is the temperature of the flame 'surface'

T_f is the average temperature of the burnt gas

and v is a limiting value for the flame propagation velocity

Rewriting in terms of heat release per unit mass (Q') and specific heat per unit mass ($\bar{c}_p'$) and rearranging;

$$\frac{D_o v \rho \bar{c}_p'}{k} = \frac{4(T_i - T_o)}{[Q'/\bar{c}_p' - \bar{c}_p'(T_f - T_o)]} = Pe(H) \quad 2.6$$

Friedman (35) considered a rectangular geometry and heat losses to the walls of a rectangular gap, ignoring end effects. Again by equating heat generation to heat loss at the quenching condition he could write

$$x = \frac{D_{11}}{2} = \frac{k}{sC} \left[\frac{1}{f} \left(\frac{T_f - T_i}{T_i - T_o} \right) \right]^{1/2} \quad 2.7$$

D_{11} is the quenching distance

k is the thermal conductivity

s is the burning velocity

C is the heat capacity of cold gas at T_o (per unit volume)

f is a dimensionless geometric factor

T_o is the ambient temperature

T_i is a notional 'ignition' temperature and T_f the flame temperature, both defined by the Mallard-le Chatelier equation for burning velocity

$$s = \frac{k}{C} \left(\frac{T_f - T_i}{T_i - T_o} \right) \frac{1}{d} \quad 2.8$$

Rewriting,
$$\frac{D S G_P \rho}{k} = \left[\frac{4}{f} \left(\frac{T_f - T_i}{T_i - T_0} \right) \right]^{0.5} = Pe(H) \quad 2.9$$

Simon Belles and Spakowski⁽³⁶⁾ considered a general geometry in which diffusion of free atoms/radicals ahead of the flame front was considered the dominant mechanism. A balance was struck between the number of collisions encountered by the diffusing active species before their destruction at a wall and the minimum number of such collisions necessary for continued flame propagation. They wrote:

$$D = \left(\frac{G.A.P.}{N_f \sum_j \frac{p_i k_i}{D_j}} \right)^{0.5} \quad 2.10$$

Where D is quenching diameter when G = 32

D is quenching distance when G = 12

A is the fraction of molecules in the gas phase which must react for continued flame propagation

P is total pressure

N_f is number of fuel molecules per cm^3

p_i partial pressure of active species

k_i is a specific rate constant

D_j is the diffusion coefficient for the active species

The model can be written, for a single active species

$$D = \left(\frac{G.A.P. D_i^2}{N_f p_i k_i D_j} \right)^{0.5} \quad 2.11$$

Writing Tanford's general equation for burning velocity in the following manner

$$S_u^2 \propto N_f p_i k_i D_j / \beta \quad 2.12$$

Where β is a constant related to the stoichiometry

$$D = \left(\frac{G.A.P. D_i^2}{S_u^2 \beta} \right)^{0.5} \quad 2.13$$

$$\frac{D S_u}{\alpha} = (G.A.P / \beta)^{0.5} = Pe(M) \quad 2.14$$

Potter and Berlad⁽³⁷⁾ developed a thermal analog to the above in which quenching occurred if the heat lost from a flame element was greater than a critical fraction (~ 0.78) of the heat generated. They followed Simon et al but introduced a global expression for the bimolecular, first order reaction of fuel and oxygen, of the Semenov-Arrhenius type:

$$w = B \cdot a \cdot b \cdot T_f^{1/2} \exp(-E/RT_f) \quad 2.15$$

w is the reaction rate per unit volume
 B is the Arrhenius constant
 a, b are the fuel and oxygen concentrations
 T_f is a flame temperature
 E is activation energy

Overall, their result was summarised by

$$D^2 = \frac{F \cdot G \cdot N \cdot X_f \cdot k}{C_p \cdot w} \quad 2.16$$

D is the quenching dimension appropriate to the geometric constant G
 F is the critical fraction of heat generated
 K is thermal conductivity in the reaction zone
 C_p is the molar heat capacity
 X_f is the mole fraction of fuel in the unburnt gas
 G is a geometric factor
 N is Avogadro's number
 The flame velocity is related to the rate of reaction per unit cross sectional area of flame, therefore Su can be written

$$S_u = f \cdot w \cdot D$$

where fD is a measure of the flame thickness, assuming it to be proportional to the flame linear dimension at quenching.

Potter and Berlad's results can be rewritten

$$\frac{C_p \rho \cdot D S_u}{k} = (f F G N X_f) = Pe(H) \quad 2.17$$

Ferguson and Keck⁽⁴³⁾ considered two cases; flame approaching normally to a solid surface and flame propagating parallel to the walls of a duct (tube). By a heat balance of the type already seen above and accounting for the variation of burning velocity with temperature by the use of the empirical relationship:

$$\frac{S_u}{S_u^0} = \exp \left[\frac{-E}{2R} \left(\frac{1}{T_b} - \frac{1}{T_b^0} \right) \right]$$

they wrote, for the perpendicular case

$$\frac{\rho_u S_u^0 C_p D}{k} = \left(\frac{T_b - T_u}{T_b^0 - T_u} \right) \exp \left[\frac{-E}{2R} \left(\frac{1}{T_b^0} - \frac{1}{T_b} \right) \right] = Pe(H)(\perp) \quad 2.18$$

and for the parallel case

$$Pe(H)(\parallel) = G. \delta / l . Pe(H)(\perp) \quad 2.19$$

where G is a geometric constant (4 for tubes, 2 for parallel plates)

δ is the flame thickness

l is the dead space, between the flame edge and the wall.

With regard to the more comprehensive treatments, most workers have approached the problem by setting up steady state conservation equations (of heat and mass) for the plane laminar adiabatic flame but incorporating a heat loss term. The latter has been, for the most part, considered to be predominantly heat conduction/convection at least when the flame is confined in geometries of quenching dimensions. Heat losses by radiation, when they have been considered, have been found to provide only an insignificant contribution. In geometries an order of magnitude larger, eg in the limit tube apparatus, radiation is significant and often dominates heat losses from flames. Comprehensive treatments involving loss of active species by diffusion to walls have apparently not been made (cf Simon et al⁽³⁶⁾)

The conservation equations will be discussed in chapter 4.

The energy conservation equation is usually couched in the following manner, or variations on it;

Conservation of energy:

$$\frac{d}{dx} \left(k \frac{dT}{dx} \right) - \rho_u S_u C_p \frac{dT}{dx} + w_F Q = \dot{Q} \quad 2.20$$

Conservation of mass, eg fuel species:

$$\frac{d}{dx} \left(D_F \rho \frac{dM_F}{dx} \right) - \rho_u S_u \frac{dM_F}{dx} = w_F \quad 2.21$$

A similar equation can be written for the conservation of oxygen mass.

The differences between the various approaches summarised here lie principally in the expressions developed for the heat loss term (X) and the methods employed for solving the conservation equations, particularly the assumptions made and the boundary conditions defined.

Mayer's⁽⁴⁰⁾ approach is not based on rigorous conservation equations. His treatment of the problem is a significant contribution on account of his treatment of heat loss mechanisms in the context of Arrhenius reaction kinetics. A quenching Peclet number was devised which can be written explicitly as

$$Pe = 2 \exp \left[\frac{E}{2R} \left(\frac{T_f^a - T_f}{T_f^a} \right) \right] \left[\left(\frac{T_f + T_u}{2T_u} \right)^{5/2} \left(\frac{T_f - T_u}{T_f^a - T_f} \right) \right]^{0.5} \quad 2.22$$

Mayer's expresses his result in terms of a temperature defect function

$\psi = (T_f^a - T_f)/T_f^a$, which he proposes takes the value 0.15. His calculated values of the Peclet number vary between 35 and 60 for the range of activation energies (E) 30-50 kcal/mole and adiabatic flame temperature (T_f) 1800-2600K. Spalding's⁽⁴¹⁾ treatment was quite rigorous in terms of the conservation equations employed. He devised an expression for the quenching Peclet number for lean flames propagating in tubes which can be written

$$Pe = \left[\frac{16}{K_c \lambda} \mathcal{K} \right]^{0.5} \quad 2.23$$

where K_c is a critical ratio of heat loss rate to chemical reaction rate

λ is a function of flame speed

$\mathcal{K}$ is, inter alia, a thermal conductivity function

For a typical lean flame, Spalding calculated a Peclet number of 60.5.

Berlad and Yang⁽⁴⁴⁾ coupled conservation equations for energy and mass with Arrhenius kinetics and a gaussian error function representing the flame temperature profile. They calculated that for quenching, radiation

represented only less than one per cent of the total heat loss from the flame. A theoretical expression for a quenching Peclet number was developed of the following form

$$Pe = \frac{A \tau (\sigma/d)}{[H] - \tau}$$

A is a constant
 $\tau = (T_f - T_u)/(T_f^a - T_u)$
 $[H]$ is a heat release term
 σ represents 'flame depth'
 d is quenching dimension

The RHS of this expression is independent of the quenching dimension^{2.24} if the assumption is made that $\sigma = f d$ where $f \ll 1$

Using this expression quenching diameters for stoichiometric propane-air and propane-oxygen flames were calculated which were in good agreement with experimentally determined values.

Yang⁽⁴⁵⁾ solved the equations previously⁽⁴⁴⁾ established by analogue computation, establishing temperature, fuel reactant and heat release profiles for chosen values of the mass burning rate and tube diameter of the order of the quenching dimension. For a diameter somewhat greater than the quenching diameter the results indicated that the inclusion of reactant diffusion in the treatment, ie Lewis-Semenov number (~~Le~~) equal to one rather than zero reduced the mass burning rate of stable flame.

The majority of theoretical models have been developed in terms of or can be expressed in terms of a quenching Peclet number. Similarly, experimental results can be correlated using this dimensionless number. Rozlovskii and Zakaznov⁽⁴⁶⁾ have calculated Peclet numbers from the results of most of the available experimental studies, where this had not already been done by the authors. They conclude that all the evidence points to a mean constant value for Pe of 65 (based on quenching diameters). Significant deviations from this value were argued to be due to the effect of pressure on quenching diameter and flame speed.

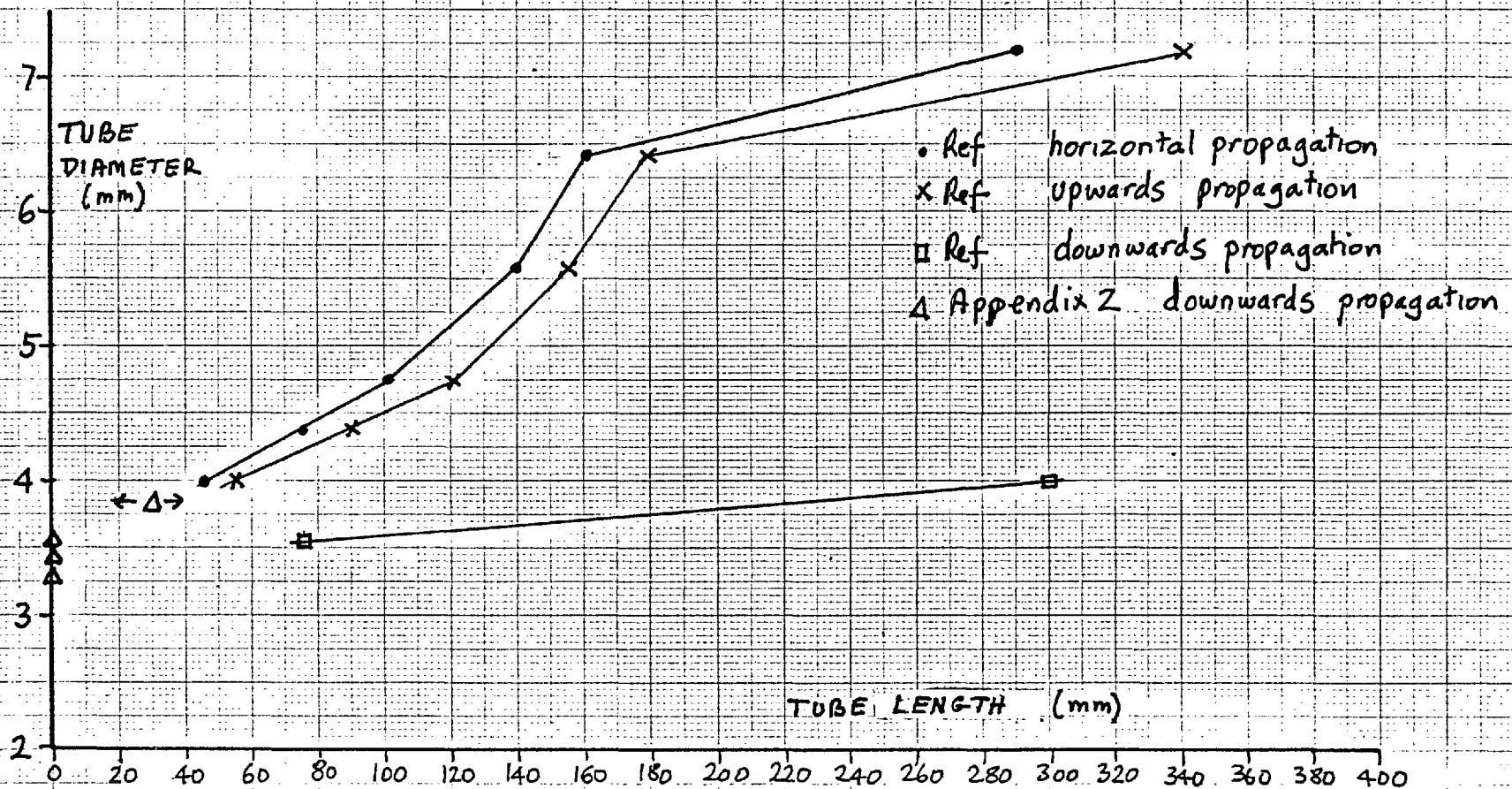


Fig.2.1. The effect of tube length on quenching diameter for methane/air flames ($\phi=1.05$)
 - Summary of experimental data, Refs and Appendix 2.

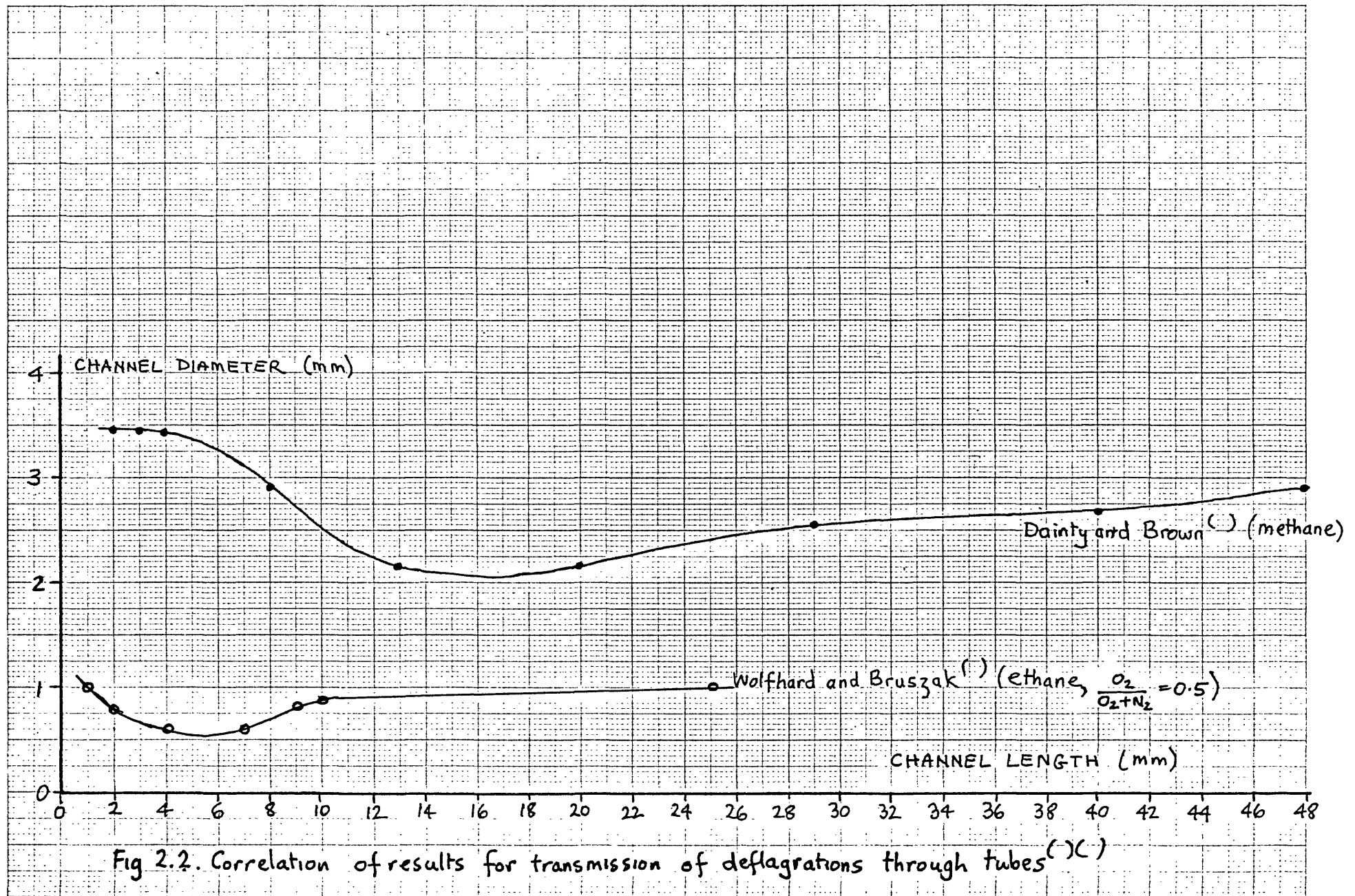


Fig 2.2. Correlation of results for transmission of deflagrations through tubes () ()

CHAPTER 3

SUMMARY OF PRESENT WORK

In the present work quenching distances (D_{11}) for the series of paraffins n-hexane to n-decane plus iso-octane have been measured at 100°C by the 'flashback' burner method as a function of stoichiometric ratio (ϕ). The results are shown in Figs 6.1 to 6.3 and values for D_{11} at $\phi = 1$, the minimum value for D_{11} and the ϕ at which it occurred plus the D_{11} for rich ($\phi = 1.5$) mixtures are summarised in Table 6.2. The effect of molecular weight on D_{11} at various ϕ is illustrated by Fig 7.1. The most important result is that, for $\phi = 1.5$, $D_{11} \propto M^{-0.3}$. This result agrees with similar results for other hydrocarbons.

For downwards propagating n-hexane/air flames the effect of increasing the quenching gap length from 3.2mm to 25.4mm in factors of two has been examined. There is no effect for $\phi \leq 1$ but for $1.0 < \phi < 1.4$ there is a progressive increase in D_{11} with gap length, Figs 6.4 and 6.5. The effect is broadly constant at different values of stoichiometric ratio (ϕ) at about 0.08mm increase in D_{11} for each 1mm increase in gap length beyond 3.2mm up to 25.4mm.

Also for n-hexane/air flames the effect of altering the direction of flame propagation from vertically downwards to vertically upwards is consistently significant for the 25.4mm long gap for $\phi > 1$, but consistently measurable differences were obtained with the 3.2mm deep gap only at $\phi = 1.2$, with which mixture minimum quenching distances are normally measured. With the 25.4mm deep gap horizontal propagation gave the same result as vertically downwards propagation. Flames at orientations between 90° and 180° were stable on the burner, of the instabilities reported by Sturmon⁽¹⁶⁾ (see section 2.1.). The effects of orientation are seen in Figs 6.7 and 6.8 and summarised in Tables 6.6 and 6.7.

In Chapter 4 a model is proposed to account for the experimental observations. The approach follows that taken by other workers in that it presupposes a thermal mechanism for wall quenching. The model is developed further than that put forward by Mayer⁽⁴⁰⁾, in order to

account for the effect of quenching passage length. The fact that many geometrical changes to the flashback burner affect the results only for rich ($\phi > 1$) mixtures suggests that preferential diffusion in the unburnt gas approaching the flame, of oxygen compared with the fuel is an important factor in the quenching mechanism. Modifications to the basic model resulting from a preferential diffusion phenomena are discussed in Chapter 7. The modified model accounts for the difference in behaviour between stoichiometric/lean flames and rich flames.

The effect of superimposed unburnt gas velocity, for rich ($\phi = 1.2$) mixtures of n-hexane/air, on quenching distance has been investigated for 3.2mm and 25.4mm long quenching gaps. The unburnt gas velocity was generated by the expansion of burnt gas behind a flame approaching the gap along a short run-up tube. Flow in both the run-up tube and the quenching gap was laminar. The unburnt gas velocity in the gap was measured from recordings with time of the pressure differential across the gap utilising a specially designed and constructed sensitive pressure gauge. The upstream pressure was of the order of 30mm water gauge or less. Therefore the pressure at the entrance to and the pressure gradient in the gap were both substantially less than those encountered in determinations of the "Maximum Experimental Safe Gap". Yet the quenching distance was reduced to a value considering the 25.4mm long gap, comparable with the "MESG", although a 'safe gap' mechanism for flame propagation of the type described by Phillips⁽²⁰⁾ is not considered to be operating in these experiments. The accumulation of a laminar boundary layer in the quenching gap is considered to be an essential feature in the mechanism of flame transmission through the gap but the experiments reveal little of required detail.

It is considered that detailed structural studies using optical techniques of flames undergoing quenching in both quiescent and flowing gas mixtures, would yield much information of value in elucidating the actual mechanism of flame failure, particularly in rich mixtures.

CHAPTER 4

THEORETICAL CONSIDERATIONS

A general theoretical basis for the non-adiabatic, plane laminar flame front will be outlined as a background against which the results of the present investigation can be considered. Although non-planar flames have been discussed (Lewis and von Elbe⁽⁴⁷⁾) the plane flame is a sufficient representation for these purposes.

4.1. The adiabatic plane laminar flame

It is useful to start with the adiabatic plane laminar flame, based on a 'thermal' theory for flame propagation. Consider the scheme sketched in Fig 4.1(a) for the 'steady state' situation. The plane flame propagates normally to itself through a quiescent flammable gas/air mixture. Conventionally the flame is set at rest relative to a reference system into which unreacted gas/air mixture uniformly flows at a mass rate of $\rho_u S_u$, and temperature T_u .

The flame can be sub-divided into four regions.

- (I) the far upstream region in which there is no reaction and no preheating of the unburnt mixture
- (II) the preheating zone in which there is no significant chemical reaction but reactants are preheated by conduction from the flame zone from T_u to T_i
- (III) the reaction zone in which the reactants at temperature undergo chemical reaction with a resulting increase in temperature to T_f^a (for the adiabatic flame)
- (IV) the post reaction (or burnt gas) zone in which hot products of combustion expand away from the reaction zone but in which the gas temperature falls only slowly

The overall energy conservation equation can be written generally as follows

$$\frac{\partial}{\partial x} \left(\rho_u S_u C_p T - k \frac{\partial T}{\partial x} \right) - \dot{w}_F Q = 0 \quad 4.1$$

and the mass conservation equation thus, for the fuel,

$$\frac{\partial}{\partial x} \left(\rho_F \frac{\partial m_F}{\partial x} - \rho_u S_u m_F \right) - \dot{w}_F = 0 \quad 4.2$$

Similar equations can be written for other reacting species, eg oxygen.

Of the four flame regions outlined above, two are of principal interest. They are:

- 1) the preheat zone, in which there is negligible reaction but the reactant increase in temperature from T_u to T_i , the so-called 'ignition' temperature (not to be confused with the normal spontaneous ignition temperature which is strongly time dependent). In this zone $\partial^2 T / \partial x^2 > 0$

and a mass element is essentially a heat sink gaining heat faster by conduction from hotter elements downstream than it loses to cooler elements upstream.

- 2) the reaction zone in which the rate of reaction increases rapidly with distance, controlled by an exponential Arrhenius law towards a maximum before falling steeply at $x = \delta$ and $T \rightarrow T_f$. In this zone $\partial^2 T / \partial x^2 < 0$ and a mass element is a heat source its temperature continuing to rise because of heat evolved by the chemical reaction. The reaction rate equation can be written ^(4.3)

$$\dot{w} = K [r]^n \exp(-E/RT) \quad 4.3$$

$$\text{where } [r] = [r_u] \left(\frac{T_u}{T} \right) \left(1 - \frac{T - T_u}{T_f^a - T_u} \right) = [r_u] \left(\frac{T_u}{T} \right) \left(\frac{T_f^a - T}{T_f^a - T_u} \right) \quad 4.4$$

The temperature (T^1) at which the maximum reaction rate occurs can be shown to be

$$T^1 = \left(n R/E + 1/T_f^a \right)^{-1} \quad 4.5$$

At the notional interface between the preheat and reaction zones,

$$T = T_i, \quad \partial^2 T / \partial x^2 = 0$$

4.2. The non-adiabatic plane laminar flame

For a similar flame propagating through a channel, heat losses to the wall must be considered. If the channel dimensions approach the quenching dimensions then radiation can be neglected (see eg Berlad and Yang⁽⁴⁴⁾ who showed that in this situation radiation represented less than one per cent of the total heat loss). Principally heat will be lost by conduction/convection from the reaction zone although the proximity of walls will result in a similar type of heat loss from the preheat zone and the post reaction zone.

Representing, for the moment, the rate of heat loss per unit volume of flame by Λ the energy conservation equation can be rewritten

$$\frac{\partial}{\partial x} \left(\rho_u s_u c_p T - k \frac{\partial T}{\partial x} \right) - \omega_F Q = \Lambda \quad 4.6$$

Theoretical treatments of wall quenching such as have been summarised in Chapter 2 have tacitly assumed a steady state phenomenon: flame is either viable or it is not. There has been no attempt to consider transition from viability to non-viability. Such a transition must occur for finite rates of heat loss, especially when the flame **is** propagating in a channel only slightly larger than the quenching dimension (corresponding to a channel length approaching zero). Weinberg⁽⁴⁹⁾ shares this view (see Fig 3.1. of that reference).

The formulation of an unsteady state theory is beyond the scope of the present work and its application, if developed, would depend upon the availability of experimental data on the rate processes involved: such information is not available.

For the non-adiabatic plane laminar flame, the scheme shown in Fig 4.1. requires modification to account for the following

- a) heat loss from the reaction zone
- b) heat loss from the preheat zone (of lower order than (a))
- c) heat loss from hot combustion products (the post reaction zone)

In all three zones heat will be lost to walls by conduction and a term $\frac{\partial}{\partial x} \left(\frac{\partial}{\partial y} k \frac{\partial T}{\partial y} \right)$ should be introduced into the energy

conservation equation to account for it. In addition heat will be lost from the reaction zone and the post reaction zone by convection and from the reaction zone by additional conduction into the now cooler post-reaction zone. The corresponding reduction in flame temperature will have the effect of reducing the burning velocity and increasing the reaction zone thickness according to $\delta \propto \bar{\alpha}/S_u$

The resulting scheme may well be similar to that sketched in Fig 4.1(b).

4.3 The nature of the heat loss parameter $\mathcal{L}$

Terms accounting for conduction can be introduced into the energy conservation equation. The latter can be applied to the post-reaction zone for the non-adiabatic flame and at the boundary of the reaction and post-reaction zones the heat loss is equal to

$$-k_f \left(\frac{\partial T}{\partial x} \right)_{x=\delta}$$

However global expressions for $\mathcal{L}$ can be developed which account for total heat transfer (conductive and convective). Neglecting, for these purposes the heat additional conduction loss from the reaction zone to the post-reaction zone which will not be significant compared with the losses from the reaction zone to the walls because

$$\left(\frac{\partial T}{\partial x} \right)_{x=\delta} \ll \left(\frac{\partial T}{\partial y} \right)_{y=0, x=\delta}$$

, one can consider heat losses in terms of the dimensionless Nusselt number (Nu) which is equal to hD/k where h is the overall heat transfer coefficient in the equation

$$Q = h \cdot A \cdot \Delta T = Nu \frac{k}{D} A \Delta T$$

The area available for heat transfer is taken to be the hydraulic perimeter of the channel (in cross section) multiplied by the flame thickness (δ)

$$\text{for a tube} \quad A = \pi D \delta$$

$$\text{for a slot} \quad A = 2\delta \quad \text{per unit slot width}$$

The volume of flame from which heat is abstracted is given by,

$$\begin{array}{ll} \text{for a tube} & \pi D^2 \delta / 4 \\ \text{for a slot} & D \delta \end{array} \quad \text{per unit slot width}$$

Therefore the volumetric heat loss parameter $\mathcal{L}$ is given by the following expressions

$$\begin{array}{ll} \text{for a tube} & \mathcal{L} = 4 N_u k \Delta T / D^2 \quad 4.7 \\ \text{for a slot} & \mathcal{L} = 2 N_u k \Delta T / D^2 \quad 4.8 \end{array}$$

For only heat conduction $N_u = 2$

For forced convection in turbulent flow

$$Nu = 0.023 Re^{0.8} Pr^{0.3}$$

For gases the Prandtl number (Pr) is approximately constant at 0.74

$$Nu = 0.021 Re^{0.8}$$

For streamline (laminar) flow the length/diameter ratio of the passage is a parameter. Specifically the Nusselt number is a function of the dimensionless group $Re Pr d/l$. It will be remembered from section 2.2. that the group $Re \cdot Pr$ is the Peclet number (Pe) for heat transfer.

Coulson and Richardson⁽⁵⁰⁾ give the following expressions

$$\text{for } Pe d/l > 12 \quad Nu = 1.62 (Pe d/l)^{1/3}$$

$$\text{for } Pe d/l < 17 \quad Nu = 4.1$$

The heat loss parameter for the two cases becomes

$$\mathcal{L} = 1.62 A (Pe d/l)^{1/3} k \Delta T / D^2 \quad 4.9$$

$$\mathcal{L} = 4.1 A k \Delta T / D^2 \quad 4.10$$

respectively where $A = 4$ for a tube and 2 for a slot

The parameter $(Pe d/l)^{1/3}$ based on $Re = 2 \times 10^3$ and $Pr = 0.74$ is less than 12 for D/l ratios less than 1.2, ie channel lengths not less than 85 per cent of the quenching dimension. Except for passages formed in quite thin plates this will normally be the case and a value of 4.1 can be taken for Nu for all cases.

The heat loss parameter then simplifies to

$$\begin{array}{ll} \text{for tubes} & \mathcal{L} = 16.4 \, k \, \Delta T / D^2 \quad 4.11 \\ \text{for slots} & \mathcal{L} = 8.2 \, k \, \Delta T / D^2 \quad 4.12 \end{array}$$

Most of the studies summarised in section 2.2 treat the tube geometry and give similar expressions for $\mathcal{L}$, eg Spalding⁽⁴¹⁾, Berlad and Yang⁽⁴⁴⁾ as a solution to the radial heat conduction equation. Palmer⁽²⁷⁾, however followed a treatment given by Coulson and Richardson⁽⁵⁰⁾. They write a cubic relation for the excess temperature (with respect to the wall) profile,

$$\frac{\theta}{\theta_s} = \frac{6}{5} \frac{y}{r} + \frac{3}{5} \left(\frac{y}{r} \right)^2 - \frac{4}{5} \left(\frac{y}{r} \right)^3 \quad 4.13$$

where θ is the difference between the temperature at distance y from the wall and the wall temperature, θ_s is the difference between the axial temperature, distance and from the wall and the wall temperature. Fourier's heat conduction law is

$$\begin{aligned} q &= -k \left(\frac{\partial \theta}{\partial y} \right)_{y=0} \\ &= -6/5 \, k \theta_s / D = -2.4 \, k \theta_s / D \end{aligned}$$

This is the expression given by Palmer. The axial temperature can be shown to be $1.72\theta_B$ where θ_B is the bulk mean temperature. The volumetric heat loss rate can be written, therefore

$$\mathcal{L}_{\text{tube}} = 2.4 \times 1.72 \, \frac{k \theta_B}{D} \cdot \frac{\pi D \delta}{\pi D^2 \delta / 4} = 16.5 \, k \Delta T / D^2 \quad 4.14$$

Therefore it can be seen that all approaches to the tube quenching problem have employed the same basic form of the heat loss parameter, (excluding radiation).

A similar approach can be taken for quenching distance (slot). The corresponding cubic equation for a flat plate is

$$\frac{\theta}{\theta_s} = \frac{3}{2} \left(\frac{y}{\delta_c} \right) - \frac{1}{2} \left(\frac{y}{\delta_c} \right)^3 \quad 4.15$$

Where δ_t is the thickness of the thermal laminar boundary layer and y is the distance from the plate. For a parallel slot, width D ,

$$\frac{\theta}{\theta_s} = 3\left(\frac{y}{D}\right) - 4\left(\frac{y}{D}\right)^3$$

$$\left(\frac{\partial \theta}{\partial y}\right)_{y=0} = 3\theta_s/D$$

and using Fourier's law

$$q = -k \left(\frac{\partial \theta}{\partial y}\right)_{y=0}$$

$$L_{\text{slot}} = -\frac{3k\theta_s}{D} \cdot \frac{2\delta}{D\delta} = -6k\theta_s/\delta^2 \quad 4.16$$

For the parabolic profile

$$\theta_s = 1.72 \theta_\delta$$

$$L_{\text{slot}} = -10.32 k \Delta T / \delta^2 \quad 4.17$$

Dividing

$$\frac{L_{\text{slot}}}{L_{\text{tube}}} = \frac{10.32}{16.5} = 0.625$$

The corresponding ratio of D_{11} to D_0 is equal to $\sqrt{0.625} = 0.79$, compared with the empirical value of 0.65 and the value calculated by Potter and Berlad⁽⁵⁾ from a diffusional theory, of 0.61. The value of 0.5 for $L_{\text{slot}}/L_{\text{tube}}$ discussed previously leads to $D_{11}/D_0 = 0.71$

In addition to the thermal aspects discussed above, the stoichiometry of the flame is no less important, particularly in respect of what has been described as preferential diffusion.

The variation of many flame parameters eg burning velocity, flame temperature, ignition energy and quenching dimension, with stoichiometric ratio is well known. The fact that the maximum (or minimum) value of this parameter occurs on the fuel rich side of stoichiometric ($\phi = 1$)

for fuels of higher molecular weight than the oxidant or at or on the lean side of stoichiometric ($\phi = 1$) for fuels of lower molecular weight than the oxidant is subject to discussion.

The traditional view concerning the occurrence of maxima (minima) at $\phi > 1$ invokes dissociation phenomena, particularly as represented by calculation and measurement of hydrogen atom concentrations which are found to be a maximum when other flame properties such as flame velocity are a maximum (see for example the review by Evans⁽⁵²⁾). However the concept of preferential diffusion (of one reactant with respect to a second) satisfactorily explains such phenomena as cellular flames; Markstein,⁽⁵³⁾ Sivashinsky⁽⁵⁴⁾.

Strehlow⁽⁵⁵⁾ has discussed the occurrence of minimum ignition energies at $\phi > 1$ for many hydrocarbons in terms of preferential diffusion. Potter, in his review,⁽¹⁾ expresses the view that for rich high molecular weight hydrocarbon in air flames quenching may well be controlled by preferential diffusion. Strong support for this view is found in the results of the present work, as discussed later.

Recently Sen and Ludford⁽⁵⁶⁾ have discussed the role of preferential diffusion of reactants in determining the location of maximum burning rate. Their argument admits a major role for product dissociation in influencing the stoichiometry of the maximum adiabatic flame temperature but only a minor one for maximum burning rate. Put simply, preferential diffusion is a phenomena which occurs in a mixture of, say, two components of disparate molecular weight (molecular diffusivity). The lighter component, of higher diffusivity, (oxygen in the case of a mixture of, say, n-hexane and air) will preferentially diffuse towards a region (the flame) which is acting as a sink for both reactants. The mixture entering the flame will therefore be leaner than the bulk mixture composition. The region immediately upstream will consequently be correspondingly richer. As mentioned above, cellular flames are a well known and documented example of a phenomena controlled by preferential diffusion.

Diffusion coefficients are dependent upon absolute temperature to a power n. According to Kanury⁽⁵⁷⁾ n is 1.75 for permanent gases

eg oxygen and 2 for condensible gases, eg hydrocarbon vapours. One can write, therefore

$$\left(\frac{D(O_2)}{D(F)} \right)_{T_2} = \left(\frac{D(O_2)}{D(F)} \right)_{T_1} \left(\frac{T_1}{T_2} \right)^{0.25} \quad 4.18$$

The relative diffusivity of oxygen with respect to fuel increases, if only weakly, with reduction in temperature. Any flame phenomenon, therefore, in which the general levels of flame temperature are reduced, eg quenching, will tend to enhance the effects of preferential diffusion. For example a 20 per cent reduction in temperature increases relative diffusivity by 5 per cent.

A quasi non-steady state model for the quenching of flame in a passage of length L can be developed as follows. Consider, with Mayer⁽⁴⁰⁾ the energy conservation equation and integrate over the flame thickness, δ , ie between the unburnt and burnt boundaries, u and b , remembering that at these boundaries $(\partial T / \partial x)_u, (\partial T / \partial x)_b \rightarrow 0$

One can then write

$$\rho_u S_u C_p T + w_F Q - \rho_u S_u C_p T_b = \Delta \quad 4.19$$

But

$$w_F = \rho_u S_u$$

and

$$Q = C_p (T_f^a - T_u)$$

therefore:

$$\begin{aligned} \Delta &= \rho_u S_u C_p (T_u + T_f^a - T_u - T_b) \\ \Delta &= \rho_u S_u C_p (T_f^a - T_b) \end{aligned} \quad 4.20$$

Substituting an Arrhenius expression, $B \exp(-E/2RT_b)$, for S_u

the heat loss from the flame can be written

$$\Delta = \rho_u C_p B (T_f^a - T_b) \exp(-E/2RT_b) \quad 4.21$$

The heat loss parameter, $\bar{L}$, for a channel or slot is

$$\bar{L} = 2 N_u \frac{\bar{k}}{D^2} (T_b - T_u)$$

Since Δ is expressed as heat loss per unit flame front area it can only be equated to a modified heat loss parameter

$$\mathcal{L}'' = \mathcal{L} \delta$$

Using an expression for δ developed by Penner (58)

$$\delta = \frac{k_u}{\rho_a c_p B} \left(\frac{T_b + T_u}{2T_u} \right)^{1+m} \exp(E/2RT_b) \quad 4.22$$

where $0.5 < m < 1$

$$\mathcal{L}'' \text{ becomes } \frac{2 Nu \bar{h} k_u}{\rho_a c_p B D^2} \left(\frac{T_b + T_u}{2T_u} \right)^{1+m} (T_b - T_u) \exp(E/2RT_b) \quad 4.23$$

The functions $\mathcal{L}''$ and Δ are shown schematically in Fig 4.2 . In the expression for Δ the exponential term will predominate at low values of T_b but will decrease rapidly to zero as $T_b \rightarrow T_f^a$. The expression for $\mathcal{L}''$ is more involved but again the exponential term is dominant, resulting in an increase in $\mathcal{L}''$ as T_b is reduced, explainable by the corresponding increase in flame thickness.

Consider the general proposition that as a flame propagates along a channel somewhat larger than but close to quenching dimensions there will be a progressive reduction in flame temperature from an initial value T_{b0} . In Fig 1 the point P_1 corresponds to the stable propagation at a distance L_1 along a channel of width D . The flame temperature is now T_{b1} . A similar analysis shows the flame propagating to a second stable configuration at P_2 where the flame temperature is further reduced to T_{b2} . A third similar step leads to quenching at point P_3 after the flame has propagated a distance L_3 . The differences between the drawn curves have been exaggerated for illustrative purposes. Similar arguments apply for smaller and larger channel dimensions. A set of curves at different L for smaller dimensions lies above and the set for a larger dimension lies below those drawn.

The model discussed so far is that of a plane laminar adiabatic flame propagating through a quiescent mixture towards the closed end from the open end. The tube and unburnt gas do not move relative to each other.

A boundary layer does not exist in the unburnt gas and only in the burnt gas insofar as the hot combustion products expand downstream towards the open end of the tube. If ignition occurred at the closed or partially closed end then expansion of hot combustion products would cause flow of the unburnt gas and a boundary layer would be expected to develop in that flow. This would occur whatever the reason for the superimposition of a flow of unburnt gas in the same direction as the flame movement.

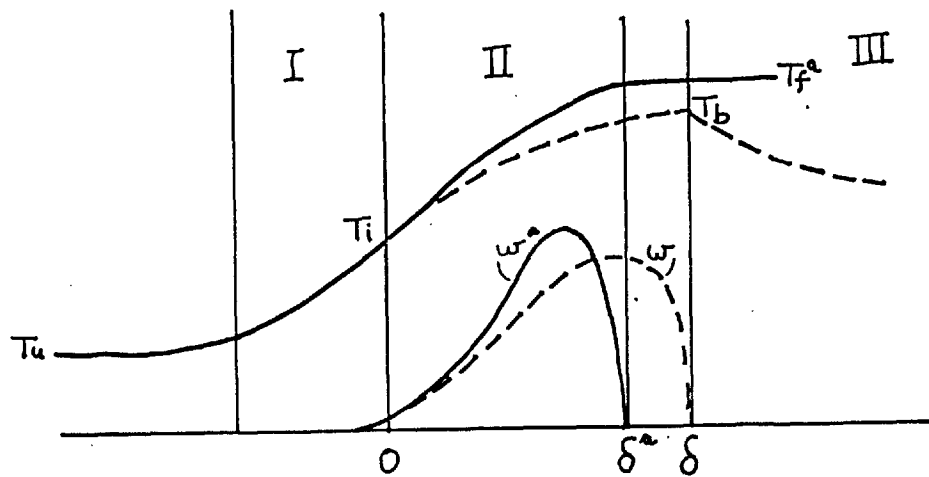
In small passages of quenching dimensions, neglecting buoyancy effects it is reasonable to assume that the shape of a flame propagating through a quiescent mixture will be closely planar except close to the walls⁽⁴⁷⁾⁽³⁴⁾. Holms⁽⁴²⁾ model is practically the only one that assumes a spherical flame shape, a priori.

A superimposed flow of unburnt gas will^{produce}/a developed or partially developed boundary layer: a flame propagating through this mixture will tend to relate its shape to that of the velocity profile.

Thus deviation from a uniform profile will increase the flame surface area and, for a given geometry, decrease the rate of heat loss to the walls per unit flame surface area, L'' .

The superimposed flow will also effectively increase flame speed relative to the channel i.e. increase Δ and increase the rate at which heat must be extracted to effect quenching L'' .

The nett effect of the superimposed flow is to require a decrease in D, the reduction being a function of the reciprocal of the channel length.



I Preheat Zone

II Reaction Zone

III Post-reaction Zone

(a) ————— adiabatic flame

(b) - - - - - non-adiabatic flame

Fig 4.1. Temperature (T) and reaction rate (w) profiles for adiabatic and non-adiabatic flames.

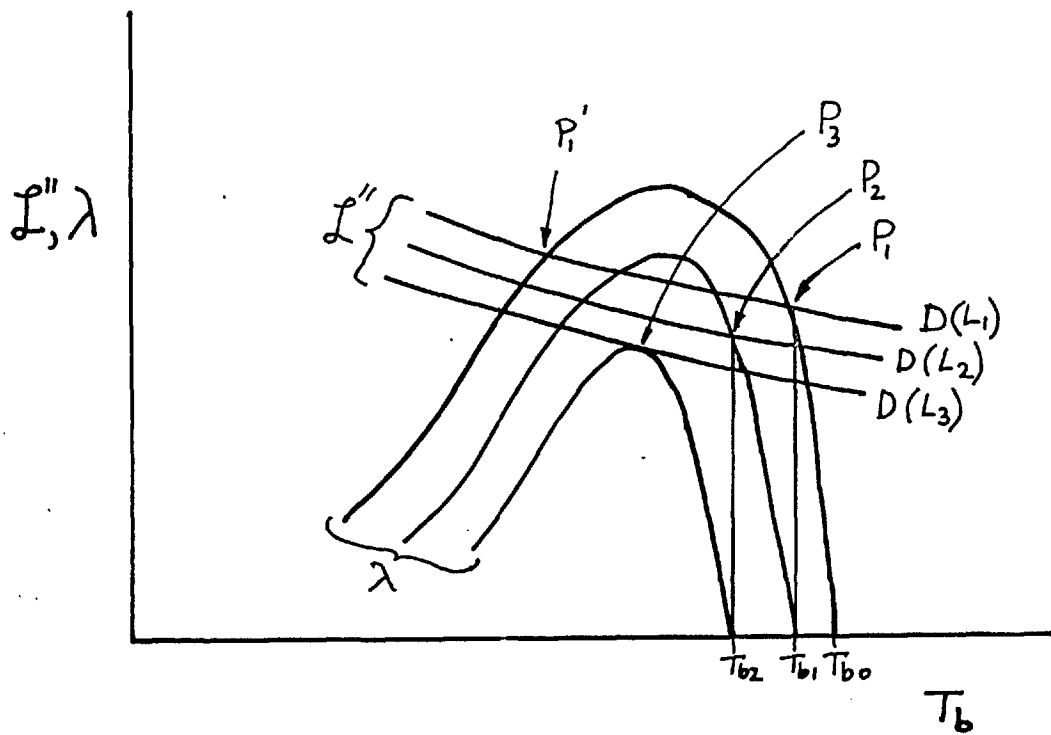


Fig 4.2. Heat loss parameters L'' and λ for flame quenching in channels of different length (L).

CHAPTER 5

EXPERIMENTAL - METHOD, APPARATUS AND PROCEDURES

The methods available for measuring Quenching Distances have been described in section 2.1 . The method chosen as being most convenient for this investigation was the "flashback" method employing a variable width slit burner. The advantages of this particular method are that it is capable of yielding precise results, it is economical in materials, it is simple, easy and quick to use and it is versatile in that several parameters may be investigated using the same basic apparatus eg temperature, fuel, configuration of quenching passage.

5.1. BASIC APPARATUS

The apparatus described in this section was designed and constructed in order to measure quenching distance as a function of stoichiometric ratio for the range of normal paraffin n-hexane to n-decane plus iso-octane. The apparatus was designed to operate at 100°C in order to prevent condensation of fuel vapour and to be versatile in that modifications could be made readily in order to investigate the effect of quenching passage length and orientation and of the flow through the quenching passage of unburnt gas ahead of the flame, as described in subsequent sections.

The basic apparatus is shown schematically in Fig 5.1.

5.2. AIR SUPPLY

Atmospheric air was pumped by a rotary compressor (1) through an oil filter packed with felt pads and cotton wool (2), a damping chamber (3), two drying towers packed with silica-gel (4) and a needle valve (V1) to the flow meters. These were a rotameter (5) and a capillary flow meter (6) containing dibutyl phthalate stained with methyl red. A manometer (7) containing the same liquid measured the air pressure. The flow meters were calibrated against a bubble meter.

Before entering the evaporator (9), the air could if necessary be preheated, by passing through glass tubing heated by electrical windings (8). This was done when the less volatile fuels were being handled especially n-nonane and n-decane. The temperature of the air could be measured by means of a

thermocouple immersed in the air stream. The E.M.F. of the thermocouple was read on a millivoltmeter connected to it via a multichannel selector switch. The readings from all thermocouples were obtained in this way.

5.3. LIQUID FUEL SUPPLY

Liquid fuel was metered into the evaporator from a brass syringe (10), 20mm I.D., 75mm long, the piston of which, was driven into the barrel at a constant predetermined speed. The piston was, by itself, a loose fit in the barrel. Three "Teflon" piston rings 0.8mm thick, separated by brass washers 0.8mm thick, were expanded by screwing the end cap of the piston into the main body of the piston. A liquid-tight seal was thus made between the piston and the barrel. No liquid was ever observed to seep past the seal.

The barrel contained enough fuel for 40 minutes continuous running. After that time the syringe was refilled from a reservoir (11) consisting of a Buchner funnel incorporating a sintered glass disc which filtered the fuel. The procedure for refilling was to first detach the piston from the drive mechanism and then close valve V2, open valve V3 then withdraw the piston slowly sucking in liquid from the reservoir. Valve V3 was closed again, valve V2 opened and the piston reattached to the drive mechanism which had itself been readjusted.

The speed of the D.C. shunt motor (12), energised from a 10V D.C. supply was adjusted to the chosen value by means of a rheostat in the field circuit. The speed was read from a tachometer (13) driven via a flexible drive (14) consisting of a short length of rubber pressure tubing, by one end of the shaft which protruded from each end of the motor. The speed chosen for all experiments was 3750 r.p.m. and this remained constant ± 20 r.p.m, only small adjustments of the rheostat being necessary from time to time to compensate for small changes in frictional resistance between the piston and barrel.

The mixture strength was conveniently varied by adjusting the air flow rate. The flames produced on the burner with this liquid delivery rate and the air flow rates necessary to produce mixtures between the stoichiometric ratios 0.9 to 1.6, were stable.

The other end of the shaft was attached, via a second flexible drive (14), a 65:1 reduction gear train (15), to the worm drive mechanism.

A 40 T.P.1. threaded shaft (16) rotated and advanced a sliding bracket (17) which had a 40 T.P.1. threaded semi-circle cut out of the edge which engaged the threaded shaft. The bracket was held against the shaft by a spring. The bracket advanced and pushed the piston into the barrel. On refilling, the bracket was lifted away from the shaft, slid back to the starting position and re-engaged with the shaft.

5.4. THE EVAPORATOR

The evaporator is shown in Fig 5.2 . It consisted of a glass tube 25mm diameter and 280mm long, held vertically, with a glass capillary tube protruding upwards from the bottom about 100mm into the tube and concentric with it. The liquid fuel from the metering system flowed up the capillary tube and down the outside forming a falling film.

The dry, and when necessary heated, air entered the bottom of the evaporator and flowed up and past the falling film counter-currently. The liquid evaporated into the air stream from the film. The glass wool plug (A) absorbed any liquid not evaporated from the film and this was evaporated from the plug. No liquid was observed to seep past the plug, indicating that evaporation was complete.

A glass wool plug (B) at the top of the evaporator ensured good mixing of the vapour and air. Other plugs situated at suitable points in the line leading to the burner, while assisting in mixing, were intended as flame arresters in the event of a flashback into that line. Steady, uniform flames were stable on the burner for long periods indicating complete mixing.

When handling the less volatile fuels the air was preheated as described above and the evaporator was also warmed by electrical windings to maintain all surfaces at a temperature higher than the dewpoint of the desired mixture. The connection between the evaporator and pre-heater was also warmed in a similar manner.

A three-way tap (V4) was situated just after the evaporator in order to cut off the fuel/air supply to the burner when "flashback" determinations

were made. A valve (V5) in the by-pass line was adjusted to present the same resistance to flow as that offered by the preheater and burner. Although the fuel/air supply was diverted only momentarily during determinations, this precaution ensured that equilibrium in the evaporator was disturbed as little as possible when the flow needed to be diverted for a significant time, as in the experiments to measure the effect of gas flow on quenching distance.

5.5. THE PREHEATER

As quenching distances were measured at 100°C it was necessary to preheat the fuel vapour/air mixture to this temperature. In this phase of the work the gas mixture was preheated by passing it through a narrow bore copper coil immersed in an oil bath (18) held at $100^{\circ}\text{C} \pm 1^{\circ}\text{C}$ by a thermostat.

The short length of copper pipe connecting the coil to the burner (20) assembly was heated to $100^{\circ}\text{C} \pm 1^{\circ}\text{C}$ by electrical windings controlled by a rheostat. The temperature was measured by a thermocouple clamped to the outside of the tube.

5.6. THE VARIABLE WIDTH SLIT BURNER

The burner, constructed entirely of brass, is shown in Fig 5.3. Two brass plates, forming a gap 3.2mm ($\frac{1}{8}$ in) deep, 20mm broad were held in the burner assembly which was formed from two parts held together by four screws. One plate was fixed and the other could be moved to vary the width of the gap.

The width of the gap was measured using a micrometer head graduated to .01mm which could be read to the nearest 0.005mm, ie $\pm 0.0025\text{mm}$. The difference between the micrometer reading with the gap closed and that with the sliding plate adjusted to form a gap was taken to be the gap width. The sliding plate was locked in position by compressing the springs pushing two small ball bearings against the edge of the moveable plate. The precision with which gap width could be measured was therefore $\pm 0.005\text{mm}$.

To facilitate the micrometer readings the micrometer head was electrically insulated from the burner assembly and a circuit arranged so that when

contact was made between the micrometer head and the end of the sliding plate, a bulb lit up. Thus all readings were taken in a reproducible manner.

In order to establish the overall accuracy of the quenching distance measurement it was necessary to gauge any deviation from parallelism of the plates forming the quenching gap. This examination was conveniently carried out using an "image shearing eyepiece" (of magnification X10) in a microscope fitted with a low power (X5) objective lens of short physical length. By means of rotatable prisms incorporated into this device the image of an object examined could be split into twin images, one red, the other green.

The difference between two readings on a scale on the eyepiece, when the image was not sheared and the other when the two sheared images were just abutting was a measure of the image size. The eyepiece was calibrated against a stage micrometer scale graduated to 0.01mm. The resolution of this optical arrangement was better than 0.002mm ($2\mu\text{m}$). Examination of small ($< 0.1\text{mm}$) gaps showed that the 3.2mm ($\frac{1}{8}\text{in}$) plates when assembled in the burner were parallel to within this resolution (0.002mm), over at least 95 per cent of the gap breadth.

The burner assembly was screwed into a flashback chamber 25mm I.D. and 75mm long. This chamber contained a crimped ribbon type flame arrester to prevent flashback into the evaporator. The combustible gas mixture entered the burner at the bottom of the flashback chamber below the flashback arrester.

The burner was heated to a temperature of $100 \pm 1^\circ\text{C}$ by means of electrical windings controlled by rheostats from a 10V A.C. transformer. The current required was of the order of 3 amps.

Temperatures were measured by thermocouples. The slit plate temperature was measured by inserting a fine thermocouple into a hole drilled along the axis of the fixed plate to within 3mm of the end.

Other thermocouples were situated at the points indicated in Fig 5.3 .

5.7. EXPERIMENTAL TECHNIQUE

The procedure for determining quenching distances on the apparatus described was as follows. The pump, motor and heaters were all switched on and left running until a steady state had been attained at the required conditions for a particular determination. The piston was then attached to the sliding threaded bracket on the drive mechanism, the syringe being full of the fuel being investigated as was the pipe line leading to the evaporator. Experience showed that on starting up, equilibrium in the evaporator was attained in a matter of a few minutes.

For the given mixture, with the gap width at a particular setting, a flame was lit by a small pilot flame and allowed to burn momentarily on the burner before the fuel/air supply was quickly diverted by the three-way tap. The flame then either went out or propagated down through the gap and ignited the gas in the flashback chamber resulting in an audible 'pop'.

The gas supply was then restored and the apparatus left a short while for equilibrium to be re-attained. Depending on whether the flame was quenched or not the gap was widened or closed and the experiment repeated until a change in result occurred.

By careful adjustment of the gap width it was then possible to obtain two values within 0.01mm: at the larger value flames always propagated back through the slit, at the smaller value flames were always quenched. The quenching distance was taken to be the mean of these two values.

In some cases it was possible to obtain these two values to within 0.005mm.

Correction of quenching distances to 760mm Hg pressure was made by using the relationship $D_{11} \propto P_a^{-0.9}$

The corrected experimental results for quenching distance are not quoted to a precision greater than 0.005mm in Tables

Fig 5.4 shows a typical flame stabilised on the burner prior to interrupting the fuel/air supply.

5.8. FUELS INVESTIGATED

The liquid fuels listed, together with the manufacturer's specification, below were tested.

<u>Fuel</u>	<u>Specification</u>	<u>$\phi=1$, % v/v</u>
n-pentane	B.P.: 34 to 38°C	2.55
n-hexane	B.P.: 67 to 70°C	2.16
n-heptane	I.P. Specification	1.87
n-octane	B.P.: 125 to 126°C	1.65
iso-octane	95% boiling range: 98 to 99.5°C	1.65
n-nonane	95% m/m pure	1.47
n-decane	B.P.: 172 to 175°C	1.33

5.9. MODIFICATION OF APPARATUS TO INVESTIGATE THE EFFECT OF QUENCHING GAP DEPTH AND ORIENTATION

5.9.1. Variation of depth

The burner assembly holding the two plates could be dismantled and different plates fitted to form quenching passages of 6.4mm ($\frac{1}{4}$ in), 12.7mm ($\frac{1}{2}$ in) and 25.4mm (1 in) in addition to the 3.2mm ($\frac{1}{8}$ in) deep passage already described. These plates are shown in Fig 5.5.

The parallelism of each of the three additional pairs of plates when assembled in the flashback burner was examined as described above for the 3.2mm ($\frac{1}{8}$ in) plates. As before the plates were seen to be substantially parallel within the resolution of the optical examination device (.002mm).

5.9.2. Variation of orientation

The burner assembly was mounted on a circular wood base-board 500mm diameter. This was held vertically and pivoted at its centre so that it could be rotated to, and clamped at, any orientation from vertical between 0° and 180°. The periphery of the board was marked in 15° intervals. The burner assembly was mounted so that the major axis of the gap was perpendicular to the plane of the baseboard. This arrangement is shown in Fig 5.6.

5.9.3. Modification to preheating arrangements

It was no longer possible to use the oil bath when the burner was oriented. For these experiments the fuel vapour/air mixture was preheated to 100°C by passing it through a length of copper pipe (19, Fig 5.1) heated by electrical windings from a 100 volt AC supply regulated by rheostat. The current required was of the order of 1.5 amps. The temperature was measured by a thermocouple immersed in the gas stream at a point just before it entered the flashback chamber.

5.9.4. Modification to experimental technique

The technique for taking measurements was as described in Section with the following differences. All experiments were carried out using n-hexane/air mixtures. Quenching distance stoichiometric ratio curves were obtained for all gap depths at the following orientations: 0° , 90° , 135° , 180° . An orientation of 0° from vertical means downward propagation and one of 180° means upward propagation. No difficulty was experienced in handling flames with the burner inverted. The flames were small and allowed to burn for only a fraction of a second.

The precision with which it was possible to locate the gap widths corresponding to the "Flashback" and "Quenching" conditions in this phase of the work was generally as before, ie to within 0.01mm. Again, as before, the corrected experimental results are reported to the nearest 0.005mm in Tables 6.3 to 6.7.

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1. Rotary air compressor
 2. Oil Filter
 3. Damping Chamber
 4. Drying towers
 5. Rotameter
 6. Capillary Flow Meter
 7. Manometer
 8. Heated section of glass tube
 9. Evaporator - see Fig .
 10. Syringe assembly - for piston detail see Fig .
 11. Liquid fuel reservoir
 12. DC Shunt motor
 13. Tachometer
 14. Flexible drives
 15. Gear train
 16. Screwed drive rod
 17. Drive bracket
 18. Heating coil in oil bath
 19. Electrically heated copper pipe
 20. Flashback burner - see Figs and .
- V1 to V5. Valves as described in the text

Key to Fig 5.1. opposite

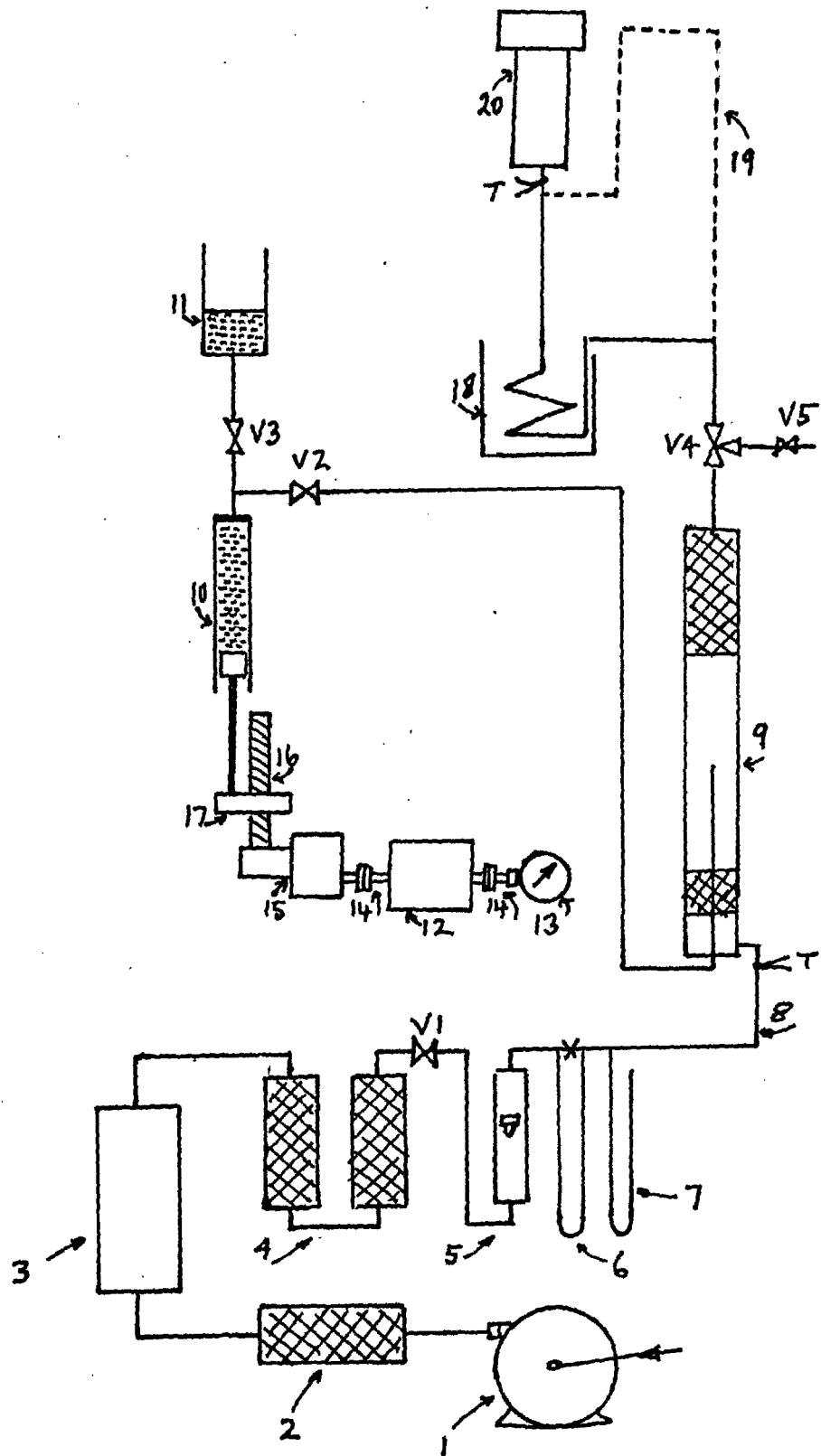


Fig 5.1. General arrangement of basic apparatus (Not to Scale)

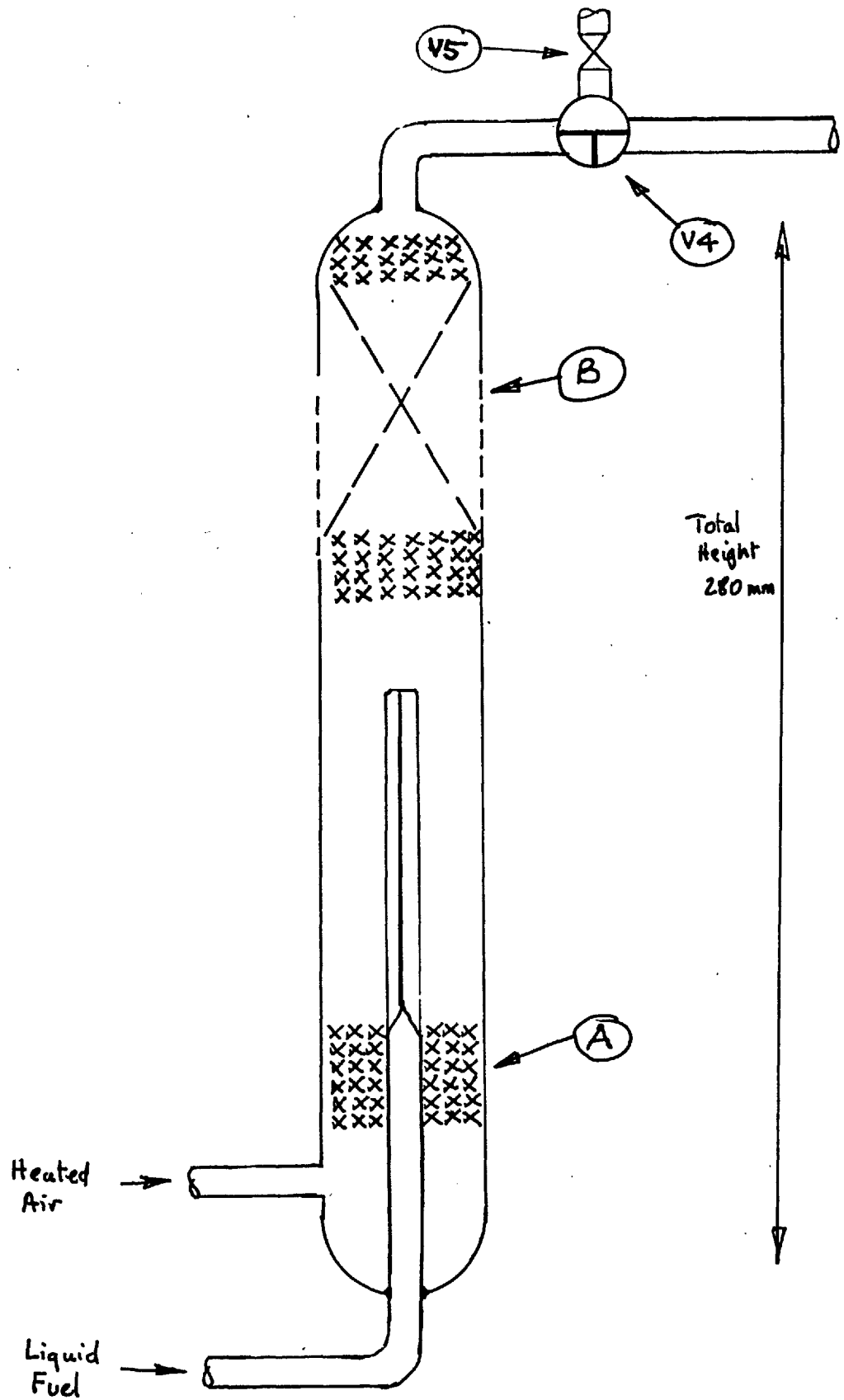


Fig 5.2. Fuel Evaporator. Scale: approx. full size

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1. Plate holder
- 2A. Fixed plate
- 2B. Moveable plate
3. Micrometer head
4. Flashback chamber
5. Flame arrester
6. Gas mixture inlet

T: Thermocouples, as described in text

Key to Fig 5.3. Basic burner assembly

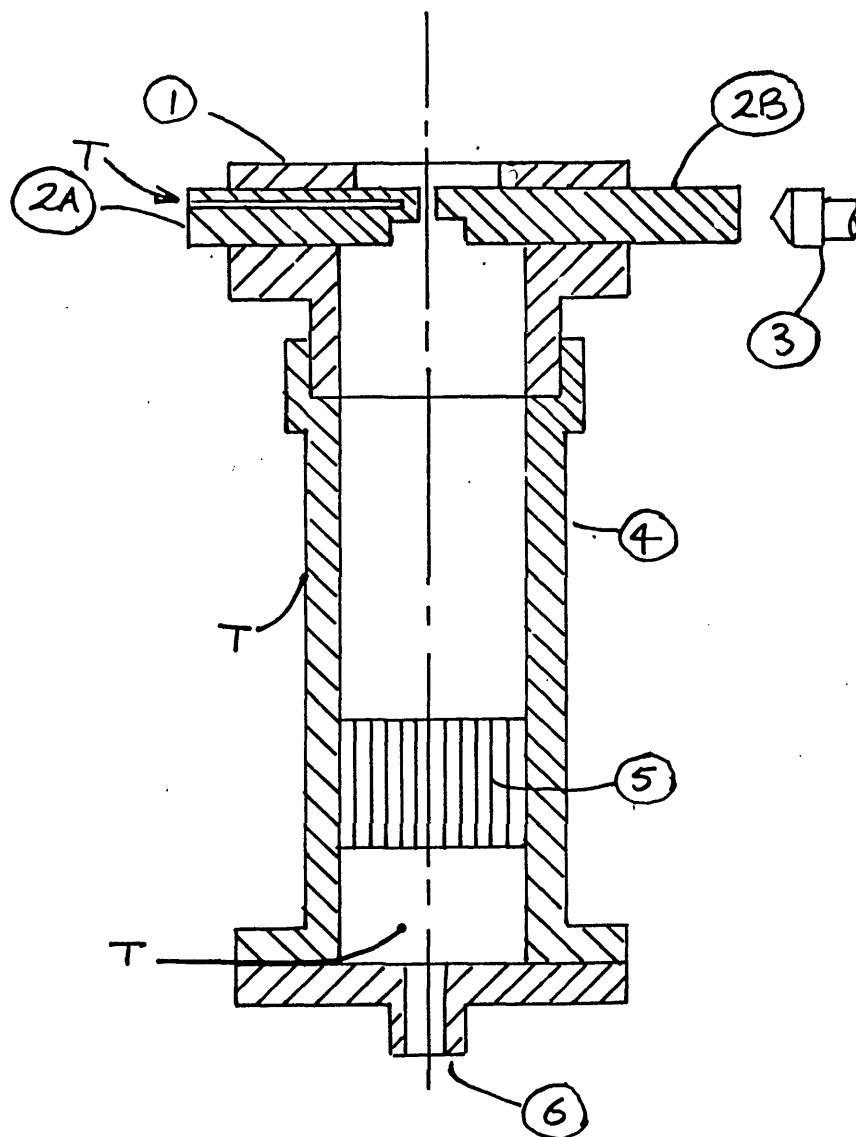


Fig 5.3. Basic burner assembly

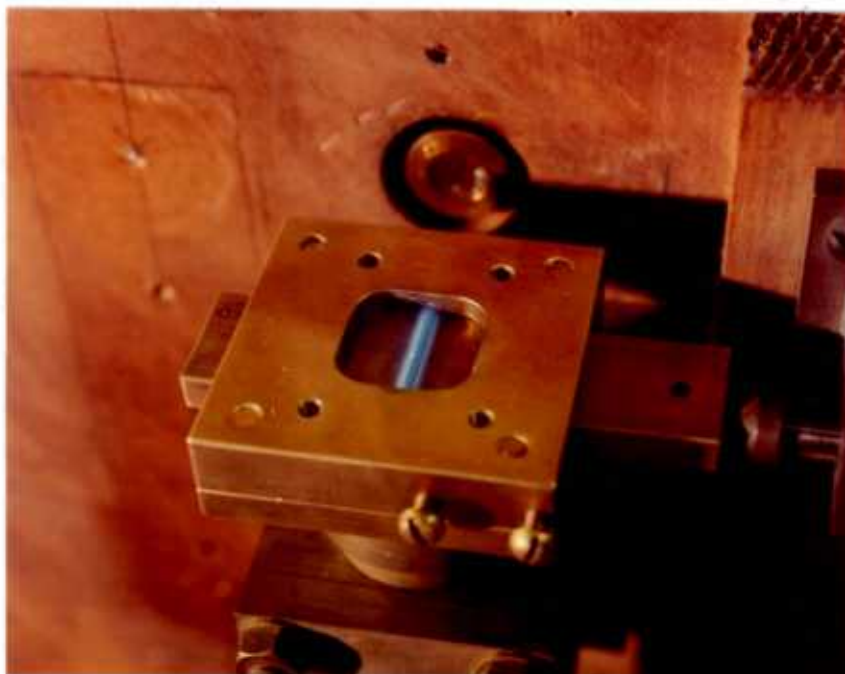


Fig. 5.4. Typical flame stabilised on burner

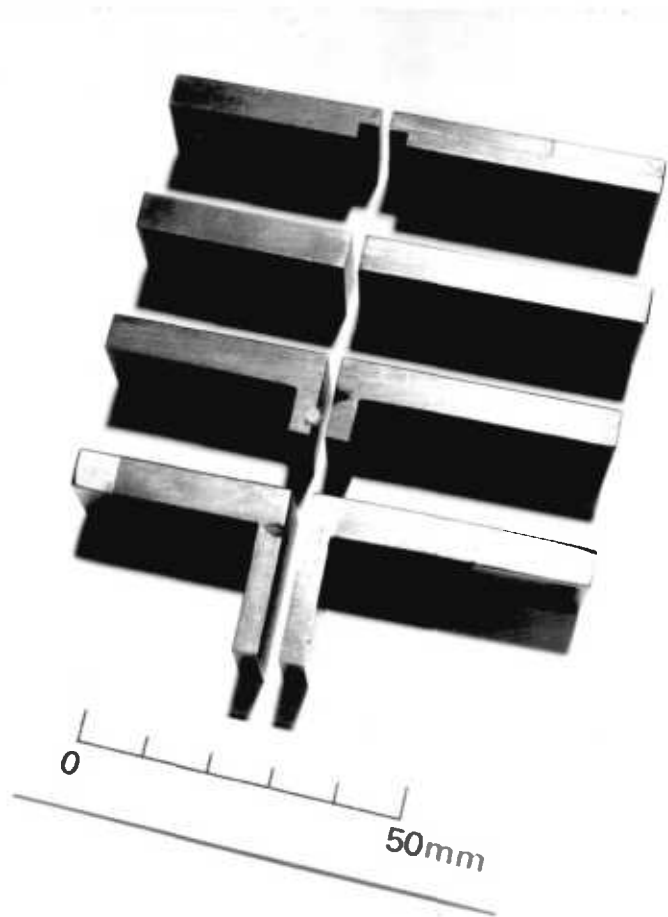


Fig. 5.5. The Slit Plates



Fig. 5.6. Flashback burner mounted on baseboard

5.10. MODIFICATION OF APPARATUS AND EXPERIMENTAL PROCEDURE TO INVESTIGATE THE EFFECT OF GAS FLOW IN THE QUENCHING GAP

5.10.1. General approach

Flow of the unburned gas through the gap was produced by the following method.

A flame was allowed to propagate up to the gap, along a run-up tube attached to the face of the burner, the flashback chamber being empty and open to atmosphere, and the amount of venting for the hot products of combustion at the ignition end of the run-up tube being adjustable. Thus the rate at which the hot products exhausted to atmosphere at the ignition end of the run-up tube and consequently the rate at which these hot gases expanded towards the gap, could be varied. This expansion caused the unburned gas ahead of the flame to flow through the gap, at a velocity dependent upon ^{the} amount of venting at the ignition end of the run-up tube.

The method of measuring the gas velocity in the gap should

- 1) not disturb the flow
- 2) not be damaged by flame
- 3) be of quick response
- 4) be sensitive

A method which fulfilled these criteria utilised the resistance to flow offered to the gases by the gap. This resistance resulted in a small pressure differential across the gap. By measuring and recording this pressure differential and using experimentally determined calibration charts, the mean velocity in the gap at any instant during flame travel could be deduced.

5.10.2. Modification to basic apparatus

The modified apparatus is shown in Fig 5.4. The brass run-up tube (2) 305mm (12 inches) long and 25.4mm (1 inch) ID was attached to the face of the basic burner (1) by four screws. To the other end of this tube was bolted the ignition and venting attachment (3). This was also of brass, the main dimensions being, length 76mm (3 inches), ID 25.4mm (1 inch). The flashback chamber was extended (4) by attaching to it a short brass tube of the same diameter 64mm ($2\frac{1}{2}$ inches) long,

the flame arrester being removed.

The fuel/vapour air mixture was introduced at the side of this extension, the inlet pipe (5) being packed with glass wool for about 25mm to act as a flame arrester. The end of the extended flashback chamber was covered by a swivelling brass plate (6) which could readily be swung open.

5.10.3. Ignition

Ignition was achieved by means of an inductive spark formed between two copper electrodes (7). These were made of 22.S.W.G. copper wire mounted in "Tufnol" inserts which were screwed into opposite sides of the ignition attachment. With these bare wires, arcing occasionally occurred between one wire and the brass tube. This was prevented by insulating the wires with porcelain beads fixed in position with epoxy resin, leaving only the tips of the electrode wires exposed, see Fig 5.8. A low voltage pulse from a 6 volt accumulator was fed into an induction coil by means of a camera shutter synchronised for flash. This produced a spark of approximately 40ms duration. This low voltage pulse was also used to trigger the oscilloscope used to display the signals from the pressure gauge (see Appendix 2). Fig 5.9. shows the arrangement of the ignition circuit.

5.10.4. Variable venting

The amount of venting at the ignition end of the run-up tube was varied by means of the iris diaphragm (9) of a second camera shutter (8) which was screwed into the end of the ignition and venting attachment. In the early stages of the work, as a precaution, to prevent the thin metal of the diaphragm leaves from being damaged by the hot combustion products, a 40mm length of crimped ribbon type flame arrester element (10) was inserted, in the attachment, between the spark gap and the shutter. The function of this was to act purely as a heat sink to cool the hot products before they reached the diaphragm.

The diaphragm aperture was continuously adjustable between 1.3mm and 15mm diameter giving a range of values for "K" between 3 and 400, where

$$K = \frac{\text{Cross sectional area of empty tube}}{\text{Area of venting aperture}}$$

When velocities smaller than the lowest that this arrangement would

produce were required, then the heat-sink arrester was removed and a shorter length inserted or occasionally the attachment was used with no heat sink thus lowering the resistance to the flow of hot combustion products through the venting attachment. For the limited number of ignitions produced under these conditions, no apparent damage was caused to the diaphragm. A number of experiments were also carried out using only different lengths of heat-sink arrester and no diaphragm.

The apparatus was heated, as before, by electrical windings, temperature measurement being by thermocouples.

Although the apparatus was, again as before, mounted on the circular baseboard, experiments were carried out for horizontal flame propagation only. The general arrangement is shown in Fig 5.9.

5.10.5. Measurement of pressure differential

In order to measure the pressure differential between suitably placed tappings a sensitive diaphragm pressure gauge was designed and constructed. The capacitance of the gauge varied as the diaphragm deflected under pressure and this change was measured electronically, amplified and displayed on a cathode ray oscilloscope screen, the resulting trace being recorded photographically.

Preliminary calculations of likely pressure differentials were made for laminar flow in the 25.4mm (1 inch) and 6.4mm ($\frac{1}{4}$ inch) long gaps at the gap separations of interest, using the formula for streamline flow between parallel plates:-

$$\Delta p = 12 \mu L / D^2 \quad 5.1.$$

These revealed that pressure differentials in the range 0.1mm Hg to 10mm Hg (1.3 to 130mm water) would probably require to be measured. In the event the majority of pressures encountered were below 2mm Hg (25mm. water).

The design and construction and ^{of} the theory underlying the sensitive capacitance type pressure gauge developed specially for this investigation are fully described and discussed in Appendix 2. The gauge is

illustrated in Fig A.2.4.

5.10.6. The pressure tappings

The pressure tappings were placed as closely as possible to the front and back faces of the gap plates. Initially, the tappings consisted of 2mm diameter hypodermic steel tubing let in flush with the inside walls of the run-up tube in front of the slit and the flashback chamber behind the slit. Traces obtained using these tappings showed that secondary pressure vibrations had been picked up by the gauge resulting in jagged traces in which the fundamental pressure variation was obscured by the secondary oscillations.

Not until tubing 0.75mm I.D. was used for the tappings were smooth pressure-time traces obtained. With this narrower tubing it was possible to place the tappings closer to the slit than had been previously possible. By milling a suitable channel, the upstream tapping (P1), see Fig 5.7, could be placed directly against the front face of the slit plate. The second tapping was mounted in a position flush with wall of the flashback chamber and opposite the end of the 25.4mm (1 inch) deep slit when that was being used (P2A). When the 6.4mm ($\frac{1}{4}$ inch) deep slit was being used the tapping was mounted against the back face of the plate as with the first tapping (P2B).

5.10.7. The recording of pressure-time traces

The traces were recorded photographically on FP3 35mm film using a single lens reflex camera fitted with extension tubes and a Primoplan f 1.8 58mm lens used at a working aperture of f 2.8.

A perspex screen covered with a grid with 1cm spacings was fixed against the oscilloscope and the trace was photographed through this screen.

The camera was mounted rigidly in front of the oscilloscope screen and square with it. A light tight hood was fitted between the lens and the screen to cut out extraneous light. The depth of field with this arrangement was deep enough to bring both the screen coating and the grid lines into sharp focus. The shutter was opened immediately before ignition and closed again immediately after the event had terminated.

The film was developed for 3 minutes in Ilford Contrast F.F. developer

diluted 1:4 then fixed and washed in the usual way.

5.10.8. Gas flow calibrations

Calibration curves correlating pressure differential (ΔP) across the slit, average velocity ($\bar{u}$) through the gap and gap width (D) were determined for each gap depth. Compressed air was metered through a rotameter and heated to 100°C by passing through a glass tube heated by electrical windings, the temperature being measured by a thermocouple immersed in the air stream. With the venting shutter removed and the flashback chamber open to atmosphere the hot air was passed through the apparatus from the ignition end. For a range of values of D, readings of ΔP and rotameter setting were noted.

ΔP was measured by means of a sensitive direct reading diaphragm gauge (brand name "Magna-helic") reading up to 25mm water gauge which could be read to the nearest 0.25mm water.

From the rotameter reading, the mean velocity in the slit was calculated. These velocities were plotted against ΔP for each of the values of D used. From this plot a set of calibration curves was compiled in which ΔP was plotted against D for a range of values of $\bar{u}$, 0.1 to 1.5 ms^{-1} , at 0.1 ms^{-1} intervals. The calibration for the 6.4mm ($\frac{1}{4}$ inch) deep gap is shown in Fig 5.10 .

For a given setting of D, values of ΔP were obtained from the pressure-time traces and the corresponding values of $\bar{u}$ were read from the calibration chart interpolating where necessary.

The capacitance pressure gauge was calibrated by plotting output voltage against pressure differential across the gauge. The output voltage was taken as the half trace height (cm) x oscilloscope gain (volts/cm). The "magna-helic" gauge and the diaphragm gauge were connected in parallel to one limb of a mercury filled manometer, the other limb of which was of adjustable height. The low pressure connections of both gauges were open to atmosphere.

Readings were noted for a sensitivity setting (S) of 25. The calibration curve is shown in Fig 5.11 .

5.10.9. Experimental technique

Fuel vapour/air mixtures were produced in the same way as previously described.

The procedure was as follows:-

The gap width was set to a predetermined value.

The apparatus was flushed out by and filled with vapour/air mixture at a stoichiometric ratio of 1.2. With the venting diaphragm fully open the closed shutter presented only a small resistance to this gas flow. The purging and filling of the apparatus was equivalent to twenty volume changes. The working temperature was 100°C . The vapour/air mixture was diverted and the swivel plate end of the extended flashback chamber opened. The venting camera diaphragm was set at the required value for that ^{experiment} / and the camera shutter opened. The mixture was immediately ignited by firing the synchronised camera shutter in the ignition circuit, this also triggering the oscilloscope trace. After the event the camera shutter was closed, the film wound on, the swivel end closed, the venting diaphragm opened and the gas mixture fed back into the apparatus.

The ejection of flame from the end of the flashback chamber was the adopted criterion for flame propagation having occurred. The non-appearance of flame was taken to indicate that the flame had been extinguished in the gap and no reignition had occurred.

Between runs the balance of the gauge was checked and when necessary, very slight adjustments made to the fine balance control. With the thermostatted water bath this was only rarely necessary. The experiment was repeated with different vent settings until a change in result occurred. Repeat runs were carried out at settings straddling the critical one in order to define as closely as possible what it in fact was.

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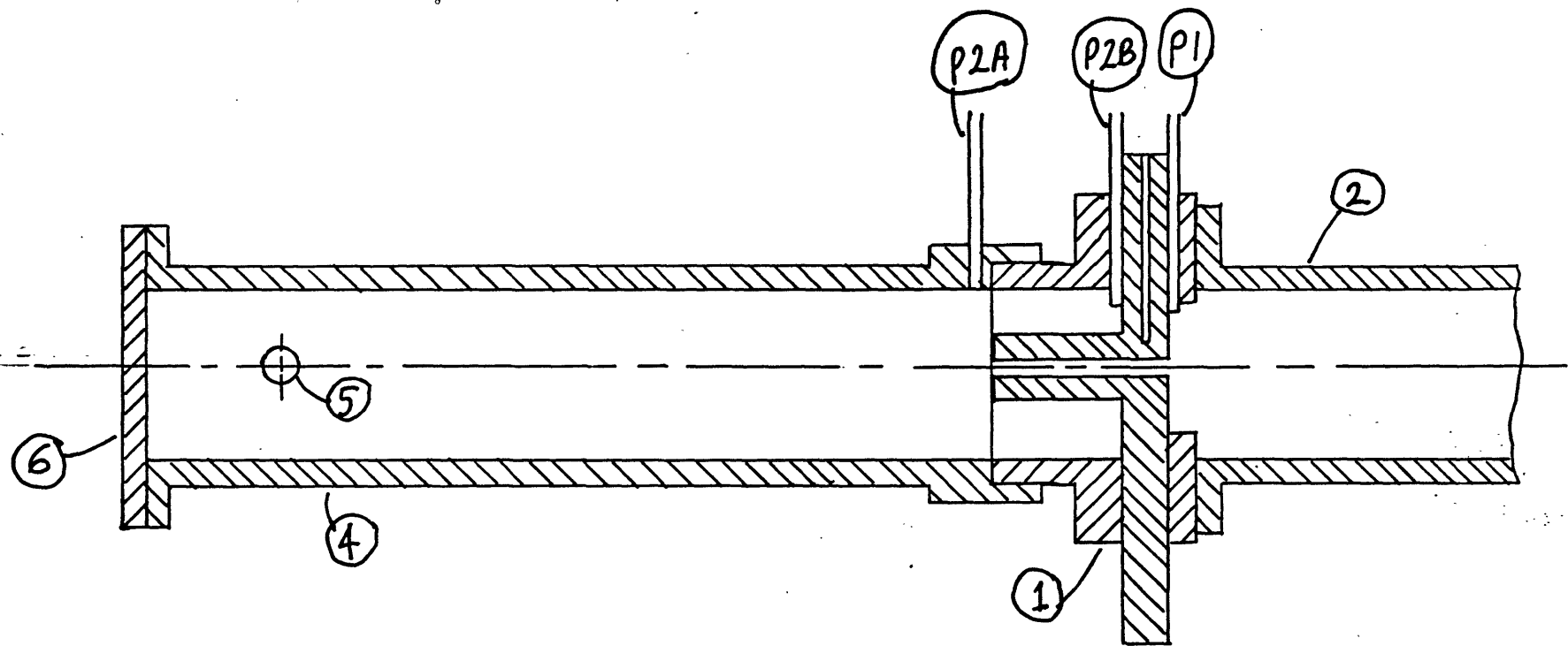


Fig 5.7(a) Modified apparatus for investigating gas flow: Flashback chamber and pressure tapings

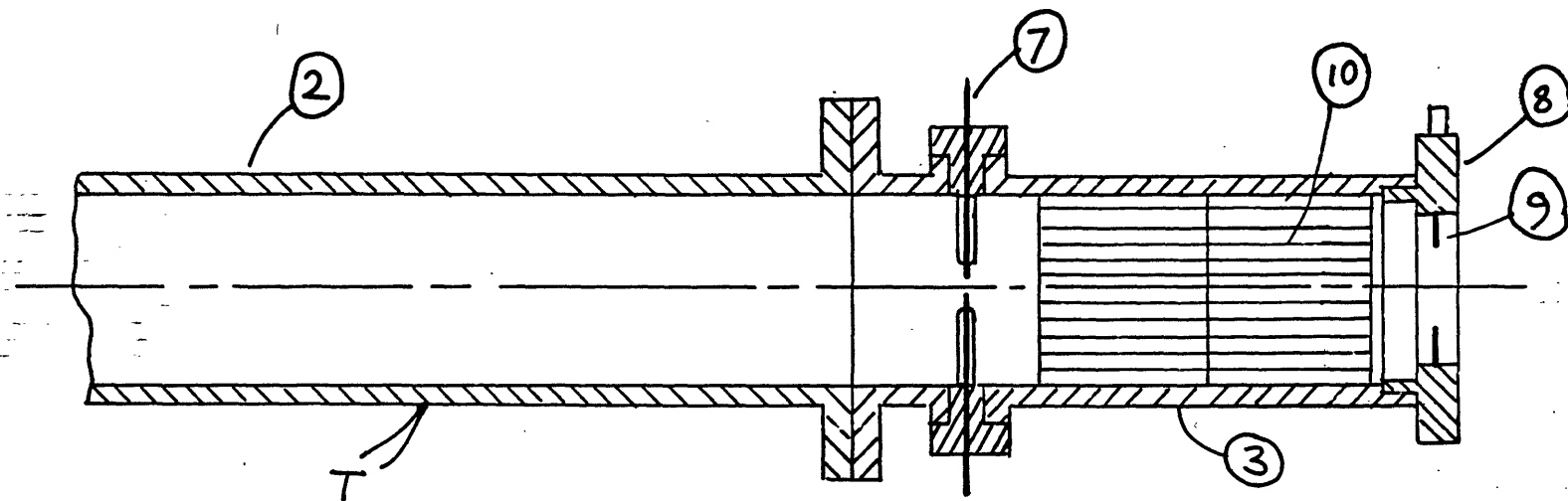


Fig 5.7(b) Modified apparatus for investigating gas flow: Ignition and venting attachment.

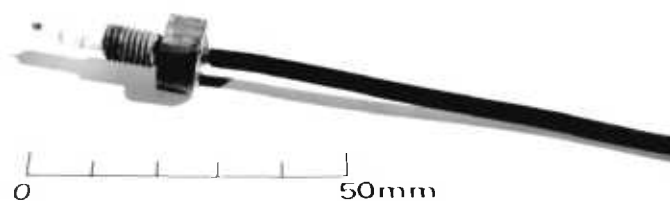


Fig 5.8(a) Ignition Electrode

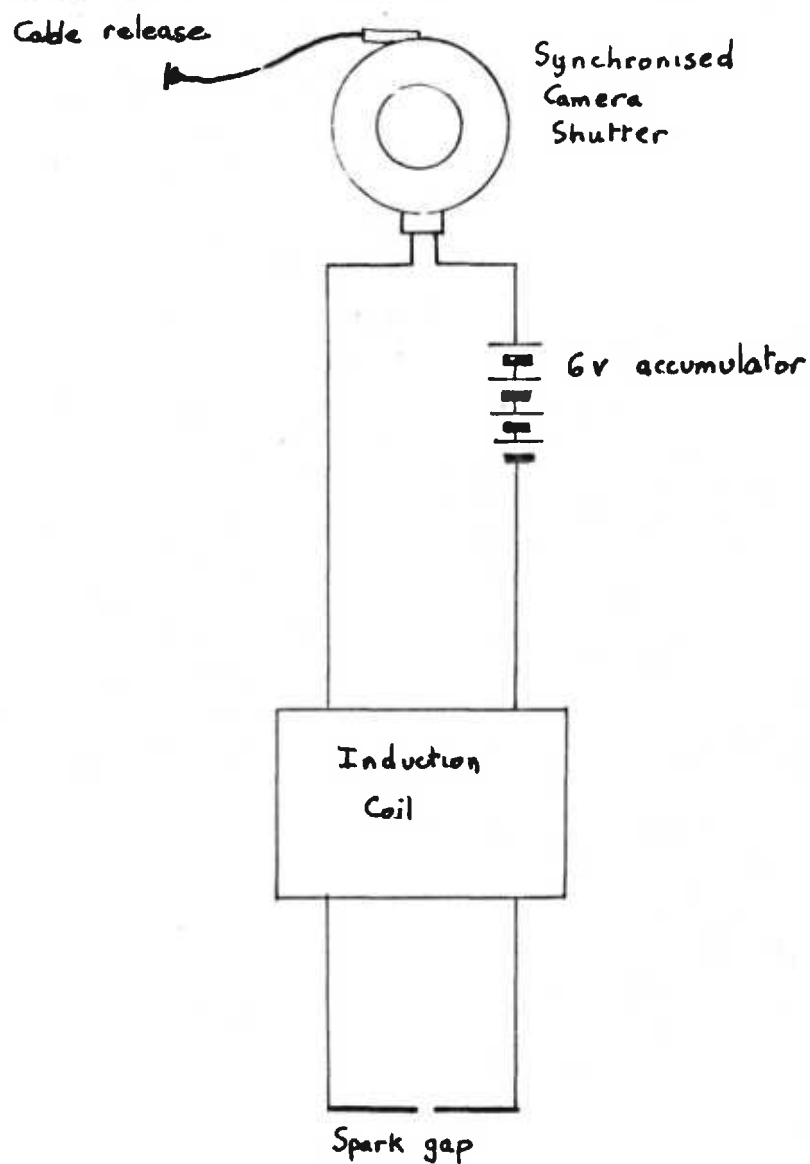


Fig 5.8(b) Ignition Circuit

Fig 5.8 , Ignition Circuit and Electrode

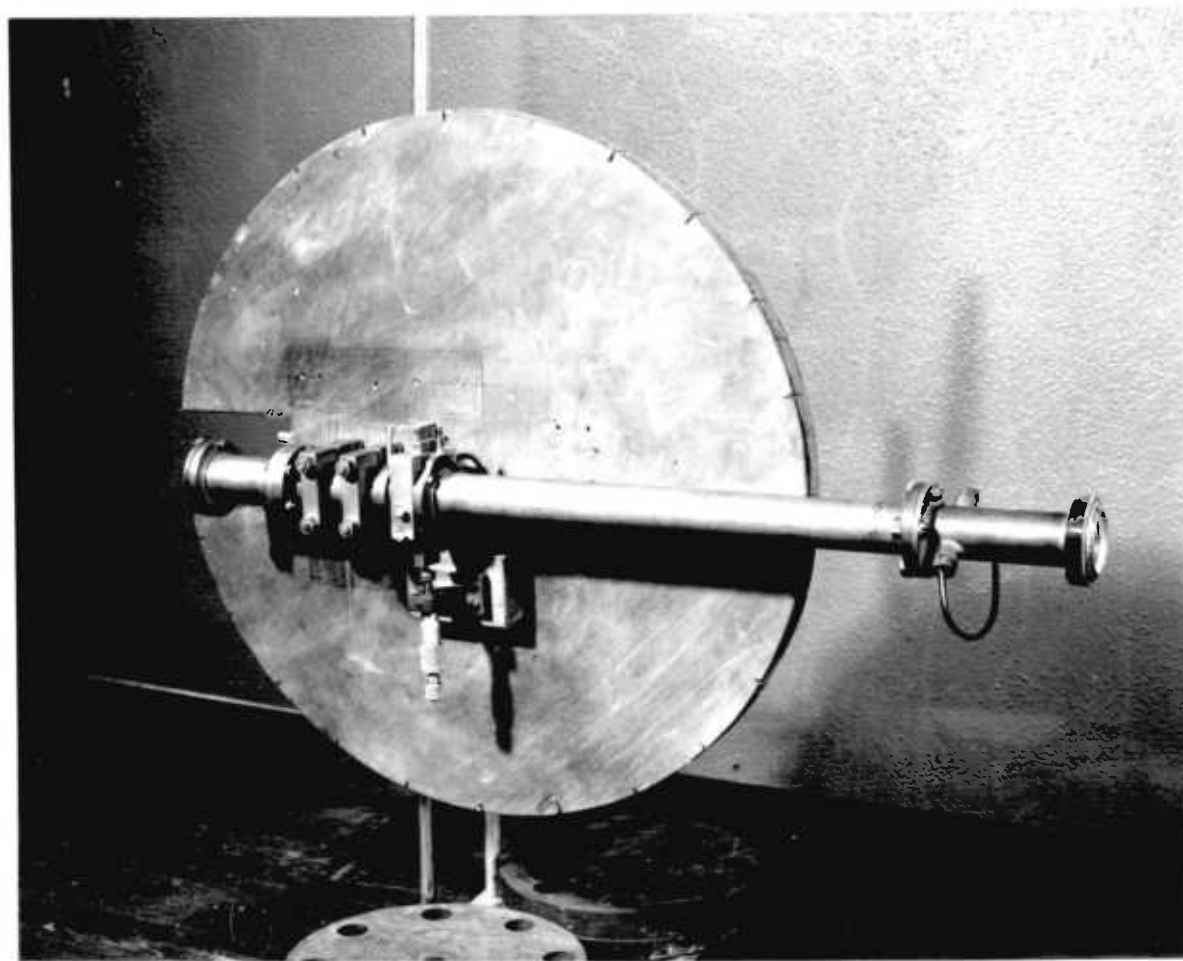


Fig. 5.9. Modified Apparatus for investigating gasflow: general view, mounted on baseboard

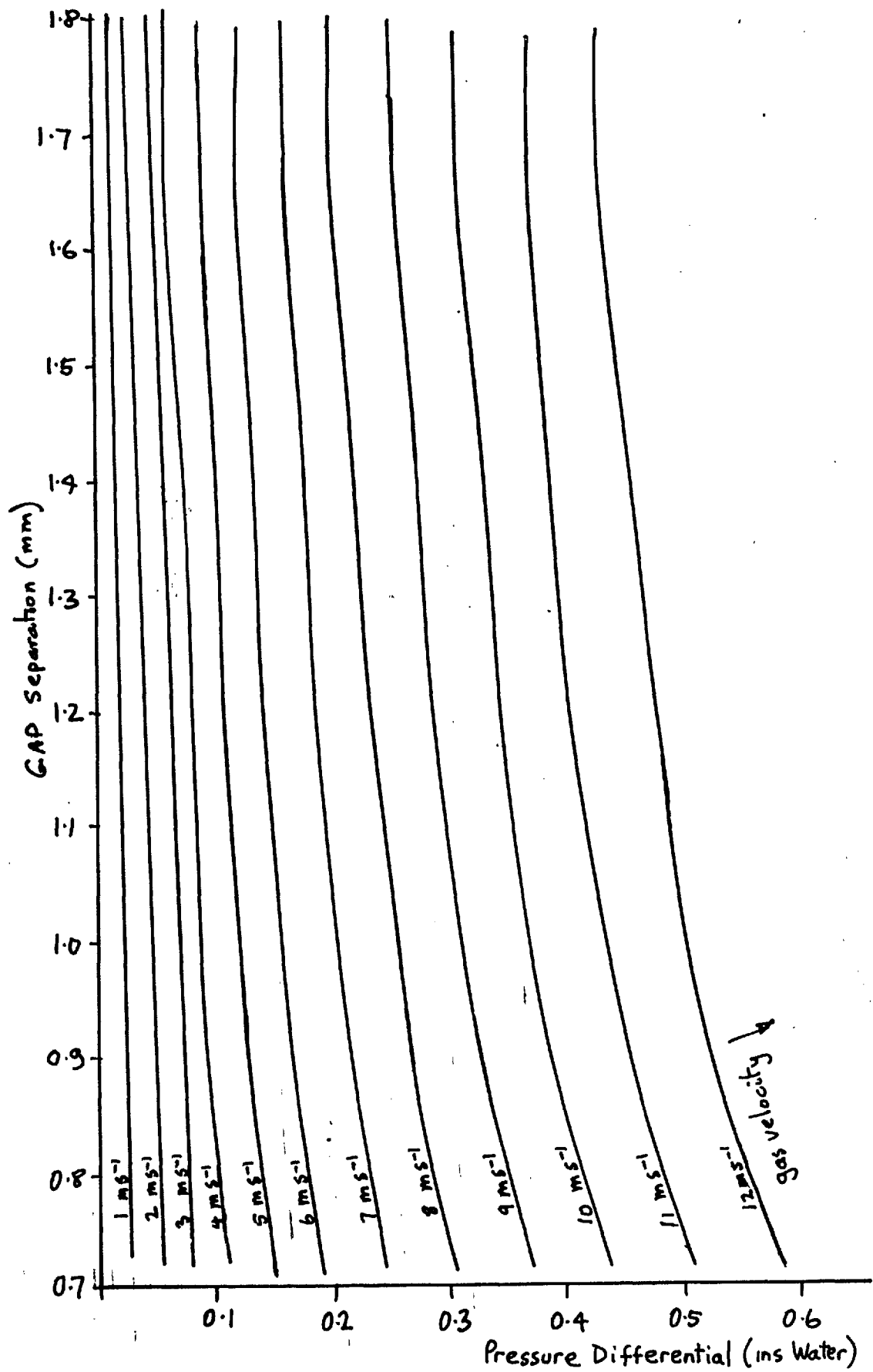


Fig. 5.10 Gas flow calibration chart for 6.4mm (1/4in) gap

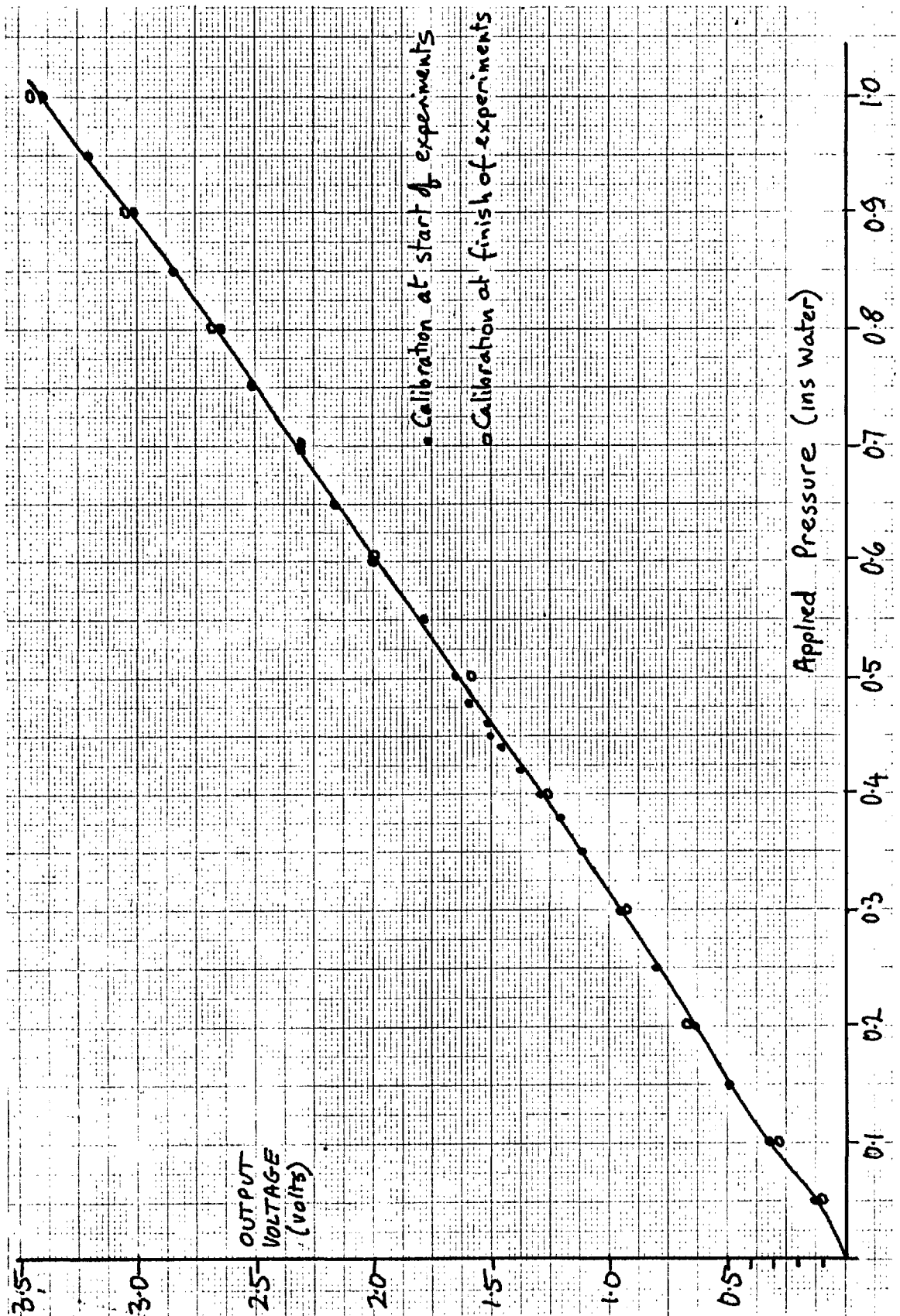


FIG 5.11. CALIBRATION OF PRESSURE GAUGE. OUTPUT FROM CAPACITANCE METER VERSUS APPLIED PRESSURE. GAUGE TEMP. 30 C. SENSITIVITY(S)=25.

CHAPTER 6

EXPERIMENTAL RESULTS

6.1. Flame quenching in stationary gas mixtures.

6.1.1. Effect of fuel structure.

The results of the determinations of quenching distance at 100°C for a slit depth of 3.2mm ($\frac{1}{8}$ in) for the homologous series n-pentane to n-decane inclusive plus iso-octane are given in Table 6.1 .

The results are plotted as quenching distance (D_{fl}) versus stoichiometric ratio (ϕ) in Fig 6.1 for n-pentane - n-hexane and n-heptane, Fig 6.2 for n-octane and iso-octane and in Fig 6.3 for n-nonane and n-decane. From these graphs have been taken the values of quenching distance for stoichiometric mixtures ($\phi = 1$), the minimum quenching distance and the stoichiometric ratio at which the minimum quenching distance occurred. These are set out in Table 6.2. These values of quenching distance have been corrected to 25°C using the relation -

$$D_{fl} \propto T^{-0.5} \quad \text{Where } T \text{ is in degrees absolute (K)}$$

and have been included in the compilation of experimentally determined quenching distances in Appendix 1 .

6.1.2. The effect of quenching passage depth

The determinations of quenching distance made using n-hexane at quenching slit depths of 3.2mm ($\frac{1}{8}$ in) 6.4mm ($\frac{1}{4}$ in) 12.7mm ($\frac{1}{2}$ in) and 25.4mm (1 in) at 100°C are given in Table 6.3. The results are plotted as quenching distance (D_{fl}) versus stoichiometric ratio (ϕ) in Fig 6.4. From the curves in Fig 6.4 have been taken values of quenching distance for stoichiometric mixtures, ($\phi = 1$), the minimum quenching distance for each slit depth and the stoichiometric ratio at which these minima occurred. These are set out in Table 6.6, & 6.7. Also taken from the curves in Fig 6.4 are the quenching distances at stoichiometric ratios (ϕ) of 1.1, 1.2, and 1.3 for each slit depth and these together with quenching distance for stoichiometric mixtures ($\phi = 1$) are given in Table 6.7, and plotted as a function of slit depth in Fig 6.5.

6.1.3. The effect of quenching passage orientation

The determination of quenching distance made with the 3.2mm ($\frac{1}{8}$ in) and 25.4mm (1 in) deep slits are given in Tables 6.4 and 6.5. The results are plotted in Figs 6.6, 6.7 as quenching distance (D_{11}) versus stoichiometric ratio (ϕ) for the orientations (θ) of 0° , 90° , 135° and 180° from the vertically downward direction. Curves based on the results for the 3.2mm ($\frac{1}{8}$ in) deep slit have not been drawn since there are no apparently consistent trends. Curves showing significantly consistent trends of variation of quenching distance with slit orientation (θ) have been constructed for the results obtained with the 25.4mm (1 in) deep slit (Fig 6.8). From these curves quenching distances for stoichiometric mixtures ($\phi = 1$), minimum quenching distances and the stoichiometric ratios at which these minima occurred have been taken and are set out in Tables 6.6, 6.7. In Table 6.7 are given the quenching distances for each orientation at the stoichiometric ratios 1.0, 1.1, 1.3 and 1.5.

6.2. FLAME QUENCHING IN FLOWING GAS MIXTURES

6.2.1. Interpretation of Pressure-Time Traces

A typical simplified pressure-time record is shown in Fig 6.9 . Examples of typical actual traces are reproduced in Fig 6.9 . The records can be separated into three distinct basic episodes.

1. The portion A-B is a peak of short duration. It is caused by the spherical propagation of flame away from the spark gap. It has been ascertained that the spark itself produces no detectable shock wave. The pressure reaches its maximum (P) and starts to decay as soon as the flame front reaches the walls of the run-up tube. The rate of decay is highest with large vents. The immediately subsequent event involves two flame fronts propagating in opposite directions away from the spark gap. That propagating towards the vent is short-lived particularly when the flame arrester matrix is in position.

2. The middle section, B-C, traces the propagation of the flame front up the run-up tube towards the quenching gap assembly. The pressure in this region has been depicted as constant although in many cases it increases slightly. Occasionally when the venting is quite limited and the initial peak has decayed only relatively very slowly, a continual decline in pressure is seen throughout this section. The value of the pressure at the point C was taken to define the velocity of unburnt gas flowing through the quenching gap ahead of the flame when the latter interacts with the quenching gap.

3. The form of the trace in this section C-D, represents events subsequent to the interaction of the flame front with the quenching gap. In most records the pressure trace can be seen to fall towards a zero value then reverse its sense and produce a positive pressure in the flashback chamber. Two quite different forms of the second reversed peak C-D can be distinguished:-

- a) When 'propagation' occurs leading to a deflagration in the flashback chamber the second peak is always smooth and regular
- b) When 'propagation' does not occur then the second peak assumes a jagged and irregular shape

The smooth shape of the second peak when propagation occurs is caused

by the regular propagation of a flame front away from a lenticular kernel of flame, or sufficiently reactive gas, emerging from the gap.

When flame is quenched in the slit, hot combustion products flow from the slit into the flashback chamber which has a confining effect.

It is not considered that these conditions are conducive to the type of ignition associated with Phillips' theory of safe gaps.⁽²⁰⁾

Nonetheless there is enough mixing of hot combustion products with combustible vapour/air mixture for some unsteady state consumption of reactants and associated heat release to be initiated leading to the development of pressure in the manner shown.

From the pressure-time records the mean flame speed in the run-up tube can be estimated. The time of flame travel between ignition and interaction with the quenching gap is taken to be the period P-C in Fig 6.9 .

6.2.2. Presentation of results

The results obtained from the experiments on the effect of gas flow in the quenching gap are, therefore

- a) the velocity of the unburnt gas in the quenching gap ahead of the flame at the moment the flame interacts with the quenching gap (V_{ug}) can be obtained from the pressure differential across the gap (of known width) and the calibration charts for the slit.
- b) by a simple adjustment by the ratio of the gap area to the cross sectional area of the run-up tube the velocity in the run-up tube of the unburnt gas ahead of the flame as the flame approaches the quenching gap (V_{ut}) can be calculated
- c) the mean flame velocity for the duration of flame travel in the run-up tube (V_{ft}) can be calculated from the time P-C on the pressure time record, knowing the distance between the spark gap and the quenching gap

These three velocities are tabulated for each gap length investigated

(6.4 and 25.4mm) together with the value of the gap width at which they were obtained and the result of the experiment, ie whether flame propagated through the slit or was quenched, in Tables 6.8 and 6.9..

The results have been plotted as V_{ug} versus D_{11} for each gap length in Figs 6.10 and 6.11 .

Also shown on the graphs is a line denoting the transition from laminar to turbulent flow ($Re = 2000$) calculated for air at $100^{\circ}C$ and at $1000^{\circ}C$, the latter figure being chosen to represent burnt gas conditions allowing for an arbitrary amount of wall cooling.

TABLE 6.1. QUENCHING DISTANCES MEASURED AT DIFFERENT STOICHIOMETRIC RATIOS FOR THE HOMOLOGOUS SERIES N-PENTANE TO N-DECANE PLUS ISO-OCTANE

Temp. 100°C

Press. 1 atm.

Slit depth. 3.2mm ($\frac{1}{8}$ in)

Downward propagation.

Fuel	Stoichiometric Ratio (ϕ)	Quenching Distance (D_{11}) (mm)
n-pentane	1.05	1.850
	1.12	1.795
	1.165	1.755
	1.20	1.735
	1.255	1.775
	1.38	1.905
n-hexane	0.94	2.180
	0.965	2.075
	1.010	1.905
	1.085	1.780, 1.790
	1.150	1.730, 1.735
	1.20	1.735
	1.24	1.740
	1.295	1.775, 1.785
	1.420	1.900, 1.920
	1.490	2.030
	1.575	2.205
n-heptane	0.969	1.860
	0.995	1.810
	1.045	1.745
	1.120	1.690
	1.190	1.670, 1.690
	1.240	1.670
	1.270	1.680
	1.340	1.700
	1.470	1.730, 1.740
	1.540	1.740, 1.760
	1.630	1.770, 1.850

Table 6.1 (continued)

Fuel	Stoichiometric Ratio (ϕ)	Quenching Distance (D_H) (mm)
n-octane	1.010	1.965
	1.065	1.770
	1.14	1.710
	1.212	1.690
	1.268	1.670
	1.32	1.665
	1.363	1.665
	1.42	1.665
	1.575	1.675
	1.652	1.710
	1.745	1.765
n-nonane	1.01	1.860
	1.09	1.755
	1.17	1.705
	1.30	1.665
	1.40	1.655
	1.53	1.680
	1.71	1.780
n-decane	1.110	1.800
	1.190	1.730
	1.32	1.710
	1.42	1.690
	1.565	1.695
	1.73	1.710

TABLE 6.1 (continued)

Fuel	Stoichiometric Ratio (ϕ)	Quenching Distance (D_{fl}) (mm)
iso-octane	1.00	2.350
	1.05	2.070
	1.12	1.970
	1.25	1.865
	1.285	1.865
	1.345	1.875
	1.48	1.975
	1.55	2.075
	1.64	2.155
	1.715	2.360
	1.82	2.575

TABLE 6.2 STOICHIOMETRIC AND MINIMUM QUENCHING DISTANCES MEASURED FOR THE HOMOLOGOUS SERIES N-PENTANE TO N-DECANE PLUS ISO-OCTANE

Temperature: 100°C.

Pressure: 1 Atm.

Depth of quenching passage: 3.2mm ($\frac{1}{8}$ in)

Fuel	Stoich. D_{fl} (mm)	Min. D_{fl} (mm)	ϕ at min. D_{fl} .
n-pentane	1.92	1.735	1.20
n-hexane	1.96	1.73	1.20
n-heptane	1.81	1.67	1.20
n-octane	2.00 ⁺	1.665	1.35
iso-octane	2.35	1.865	1.30
n-nonane	1.87	1.655	1.40
n-decane	1.95 ⁺	1.69	1.45

+ extrapolated values

TABLE 6.3 QUENCHING DISTANCES MEASURED AT DIFFERENT STOICHIOMETRIC RATIOS FOR SLIT DEPTHS IN THE RANGE 3.2mm ($\frac{1}{8}$ in) TO 25.4mm (1 in)

Fuel: n-hexane

Temp: 100°C

Press: 1 atm.

Downward propagation

Stoichiometric Ratio (ϕ)	Quenching Distances (D_{fl}) for slit depths (mm)			
	3.2 ($\frac{1}{8}$ in)	6.4 ($\frac{1}{4}$ in)	12.7 ($\frac{1}{2}$ in)	25.4 (1 in)
0.94	2.180	—	—	{ 2.155 2.180
0.965	2.075	—	2.125	2.100
1.01	1.905	—	1.925	1.950
1.04	—	1.840	1.890	—
1.085	{ 1.780 1.790	1.790	1.840	1.895
1.125	—	1.765	1.820	—
1.15	{ 1.735 1.730	1.755	1.800	1.885
1.19	—	1.755	—	—
1.20	1.735	1.755	1.800	1.885
1.235	—	1.760	1.805	—
1.24	1.740	1.770	1.810	—
1.295	{ 1.775 1.785	—	1.840	1.930
1.31	—	1.830	—	—
1.37	—	1.865	1.940	—
1.42	{ 1.90 1.920	—	—	2.040
1.445	—	—	2.040	—
1.49	2.025	—	—	2.230
1.575	2.205	—	—	2.440

TABLE 6.4 QUENCHING DISTANCES MEASURED AT DIFFERENT
STOICHIOMETRIC RATIOS FOR SLIT ORIENTATIONS
0° TO 180° AT SLIT DEPTH OF 3.2mm ($\frac{1}{8}$ in)

Fuel: n-hexane

Temp: 100°C

Press: 1 atm.

Stoichiometric Ratio (ϕ)	Quenching Distances (D_{fl})(mm) for orientations(θ)			
	0°	90°	135°	180°
Slit depth <u>3.2mm</u>				
0.94	2.180	—	—	—
0.965	(2.075 2.076)	2.030	—	2.040
1.01	1.905	1.840	—	1.885
1.085	(1.780 1.790)	1.750	—	1.750
1.15	(1.730 1.735)	1.730	—	1.720
1.20	1.735	1.725	—	1.720
1.24	1.740	—	—	—
1.295	(1.775 1.785)	1.810	—	1.785
1.42	1.900	1.920	—	1.940
1.49	2.025	2.150	—	—
1.575	2.205	—	—	—

TABLE 6.5 QUENCHING DISTANCES MEASURED AT DIFFERENT
STOICHIOMETRIC RATIOS FOR SLIT ORIENTATIONS
0° TO 180° AT SLIT DEPTH OF 25.4mm (1 in)

Fuel: n-hexane

Temp: 100°C

Press: 1 atm.

Stoichiometric Ratio (ϕ)	Quenching Distances (D_{fl})(mm) for orientations θ			
	0°	90°	135°	180°
Slit depth <u>25.4mm</u>				
0.94	(2.155 2.180	—	2.175	2.235
0.965	2.10	2.145	2.035	(2.070 2.075
1.01	1.950	1.955	1.940	1.910
1.085	1.895	1.885	1.875	1.860
1.15	1.885	1.875	(1.870 1.860	1.850
1.2	1.885	1.890	1.870	1.850
1.24	—	1.895	—	—
1.295	1.930	—	1.910	1.890
1.3	—	1.950	—	—
1.42	2.040	2.055	2.015	1.980
1.49	2.230	2.255	2.135	2.055
1.575	2.440	—	—	—

TABLE 6.6 MINIMUM QUENCHING DISTANCES (D_{μ} (MIN)) AND THE
STOICHIOMETRIC RATIO (ϕ (MIN)) AT WHICH THEY
OCCURRED FOR DIFFERENT QUENCHING PASSAGE LENGTHS (L)
AND ORIENTATIONS (θ)

Temperature: 100°C

Pressure: 1 atm.

Fuel: n-hexane

L (mm: in)	θ ($^{\circ}$)	D_{μ} (min) (mm)	ϕ (min)
3.2: $\frac{1}{8}$	0	1.73	1.18
6.4: $\frac{1}{4}$	0	1.75	1.18
12.7: $\frac{1}{2}$	0	1.80	1.18
25.4: 1	0	1.885	1.18
"	90	1.885	1.18
"	135	1.865	1.15
"	180	1.85	1.17

TABLE 6.7 EFFECT OF QUENCHING PASSAGE DEPTH (L) AND ORIENTATION (θ) ON QUENCHING DISTANCE (D_{11}) AT SELECTED VALUES OF STOICHIOMETRIC RATIO (ϕ)

Temperature: 100°C

Pressure: 1 atm.

Fuel: n-hexane

L (mm): (in)	θ (°)	D (mm) at					
		$\phi = 1.0$	$\phi = 1.1$	$\phi = 1.2$	$\phi = 1.3$	$\phi = 1.4$	$\phi = 1.5$
3.2: $\frac{1}{8}$	0	1.95	1.76	1.73	1.78	1.89	2.04
6.4: $\frac{1}{4}$	0	1.95	1.78	1.755	1.81	1.92	-
12.7: $\frac{1}{2}$	0	1.95	1.83	1.80	1.85	1.98	-
25.4: 1	0	1.96	1.89	1.885	1.93	2.02	2.26
"	90	1.96	1.89	1.885	1.93	2.02	2.26
"	135	1.95	1.87	1.87	1.91	2.00	2.16
"	180	1.93	1.855	1.85	1.89	1.96	2.07

Table 6.8

Results of Gas flow experiments for 6.4mm ($\frac{1}{4}$ ") long gap

Expt Number	D ₁₁ (mm)	Unburnt gas velocity on arrival of flame at gap		Mean Flame Speed in run-up tube (ms ⁻¹)	Prop or Quench	
		gap velocity V _{ug} (ms ⁻¹)	tube velocity V _{ut} (ms ⁻¹)			
C	3	1.01	2.0	0.08	1.1	Q
	4	1.01	4.6	0.18	1.27	Q
	5	1.01	8.4	0.33	1.77	P
	8	0.815	8.8	0.28	1.30	Q
	9	0.815	9.0	0.29	1.36	Q
	10	0.815	10.8	0.35	1.49	Q
	11	0.815	11.2	0.36	1.62	P
	12	0.615	11.3	0.28	1.46	Q
	17	1.18	6.8	0.32	0.93	P
	18	"	4.2	0.2	1.36	P
	19	"	<1.0	<0.05	1.06	Q
	20	"	<1.0	<0.05	1.06	Q
	21	1.4	2.0	0.11	1.06	Q
	22	"	4.0	0.22	1.21	P
	23	"	<1.0	<0.06	1.1	P
	24	"	5.0	0.28	1.06	Q
	25	1.62	4.2	0.27	1.04	Q
	26	"	<1.0	<0.06	1.08	P
	27	"	5.0	0.32	0.97	P
	28	"	5.7	0.37	0.90	P
	29	"	<1.0	<0.06	1.17	P
	30	"	2.0	0.12	1.24	P
	33	0.9	10.6	0.38	1.36	P
	34		9.3	0.33	1.39	P
	35		9.8	0.35	1.36	P
	36		9.5	0.34	1.39	P
	37		9.5	0.34	1.29	P
	38		8.0	0.28	1.06	P
	39		5.2	0.19	0.91	Q
	40		7.5	0.27	0.83	P
	41		6.0	0.21	0.81	Q
	44		6.0	0.21	0.89	Q
	45	1.09	1.5	0.06	1.1	Q
	46		2.0	0.08	1.2	Q
	47		3.0	0.11	1.3	Q
	48		3.0	0.11	1.24	Q
	49		4.5	0.18	1.6	Q
	50		4.3	0.17	1.45	P
	51		3.5	0.14	1.42	Q
	52		4.6	0.18	1.94	P

Table 6.8 (continued)

Expt Number	D ₁₁ (mm)	Unburnt gas velocity on arrival of flame at gap		Mean Flame Speed in run-up tube (ms ⁻¹)	Prop or Quench
		gap velocity V _{ug} (ms ⁻¹)	tube velocity V _{ut} (ms ⁻¹)		
53	1.30	1.0	0.05	1.06	Q
55	"	2.0	0.10	0.95	P
56	"	2.0	0.10	1.04	P
57	"	4.1	0.21	0.97	Q
58	"	2.0	0.10	1.06	Q
59	"	1.5	0.08	1.12	Q
60	"	1.0	0.05	1.02	P
61	1.5	1.7	0.10	1.1	P
62	"	2.0	0.12	1.19	Q
63	"	4.0	0.24	1.21	Q
64	"	2.1	0.12	1.17	P
65	"	2.8	0.17	1.24	P
66	"	2.8	0.17	1.21	P
67	"	2.8	0.17	1.14	P
68	1.215	1.0	0.05	1.17	Q
69	"	2.0	0.10	1.21	P
70	"	1.75	0.08	1.19	Q
71	"	1.9	0.09	1.02	Q
72	"	2.0	0.10	1.45	Q
73	"	2.2	0.11	1.24	Q
74	"	2.5	0.12	1.36	Q
75	"	2.2	0.11	1.29	Q
76	"	3.7	0.18	1.36	P
77	"	3.1	0.15	1.45	P
78	1.35	1.05	0.06	1.17	Q
79	"	1.8	0.10	1.29	P
81	1.325	1.7	0.09	1.19	Q
82	"	1.4	0.07	1.1	Q
84	"	2.0	0.11	1.21	P
85	"	1.25	0.07	1.1	Q
86	"	1.4	0.075	1.21	Q
87	"	1.45	0.08	1.17	Q
88	"	1.75	0.09	1.22	P
89	"	1.45	0.08	1.21	Q
90	1.42	1.5	0.08	1.24	Q
91	"	1.8	0.10	1.30	P
92	"	1.8	0.10	1.30	P
93	"	1.7	0.10	1.30	Q
94	"	1.3	0.07	1.30	Q
95	"	2.0	0.11	1.30	P
97	1.565	1.5	0.09	1.17	P
100	"	1.0	0.06	1.17	Q
101	"	1.3	0.08	1.24	P
102	"	1.1	0.07	1.21	Q
103	1.68	1.8	0.11	1.21	P
106	"	1.6	0.10	1.21	P

Table 6.9. Results of gas flow experiments for 25.4mm long gap

Expt Number	D ₁₁ (mm)	Unburnt gas velocity on arrival of flame at gap		Mean Flame Speed in run-up tube (ms ⁻¹)	Prop or Quench
		gap velocity V _{ug} (ms ⁻¹)	tube velocity V _{ut} (ms ⁻¹)		
C 107	1.515	11.9	0.70	1.35	P
108	"	11.1	0.66	1.44	P
109	"	6.1	0.37	0.91	Q
110	"	11.3	0.67	1.46	P
111	"	8.4	0.50	1.46	Q
112	"	11.3	0.67	1.53	P
113	"	5.9	0.35	0.88	Q
114	"	12.2	0.73	2.01	P
115	1.4	11.2	0.62	1.19	P
118	"	5.2	0.29	0.80	Q
121	"	10.5	0.58	1.12	Q
122	"	10.2	0.56	1.33	P
123	"	10.2	0.56	1.34	P
124	"	10.8	0.60	1.30	P
127	1.51	9.3	0.52	1.42	P
129	"	4.5	0.25	0.88	Q
130	"	6.25	0.35	0.85	Q
131	"	7.7	0.43	1.19	P
132	"	6.7	0.37	1.30	Q
133	"	5.1	0.28	1.90	Q
134	"	7.3	0.40	1.24	Q
135	"	8.0	0.44	1.33	P
136	1.00	6.8	0.27	1.14	Q
137	"	7.5	0.30	1.10	Q
138	"	8.6	0.34	1.36	Q
139	"	11.0	0.43	1.71	Q
140	"	20.0	0.80	2.08	P
141	"	12.3	0.49	1.77	Q
142	"	20.0	0.80	2.33	P
143	"	23.0	0.90	2.65	P
144	1.09	9.6	0.40	1.46	Q
146	"	10.9	0.47	1.36	P
147	"	10.2	0.44	1.30	Q
153	1.255	7.0	0.34	0.91	Q
154	"	6.2	0.30	0.94	Q
155	"	7.0	0.34	0.99	Q
156	"	7.8	0.39	1.08	Q
157	"	8.3	0.41	1.21	Q
158	"	8.6	0.43	1.24	P
159	"	8.3	0.41	1.21	Q
163	"	7.8	0.39	1.17	Q
164	"	9.8	0.49	1.62	P
165	"	9.0	0.45	1.49	P
166	"	7.8	0.39	1.36	Q
167	"	7.2	0.36	1.36	Q

Table 6.9 (continued)

Run	D_{11} mm	Unburnt gas Velocity on arrival of flame at gap		Mean flame speed in tube ms^{-1}	P or Q
		gap velocity $V_{ug} \text{ ms}^{-1}$	tube velocity $V_{ut} \text{ ms}^{-1}$		
168	1.345	6.25	0.33	1.24	P
169	"	6.25	0.33	1.30	Q
170	"	7.0	0.37	1.36	P
171	"	6.25	0.33	1.19	P
173	"	8.2	0.44	1.36	P
174	"	6.8	0.36		Q
175	"	7.0	0.37	1.49	Q
176	"	9.25	0.49	1.24	Q
177	"	8.5	0.45	1.30	P
179	"	8.8	0.47	1.30	P
180	"	8.8	0.47	1.06	Q
181	1.16	7.0	0.32	1.3	Q
182	"	7.75	0.36	1.46	Q
183	"	9.5	0.44	1.46	P
185	"	8.8	0.40	1.71	P
186	"	8.8	0.40	1.36	P
187	"	8.3	0.38	1.1	P
188	"	8.1	0.37	1.08	Q
189	1.05	10.2	0.42	1.46	Q
190	"	12.4	0.50	1.77	Q
192	"	15.8	0.65	1.85	P
193	"	14.0	0.58	1.85	P
194	"	13.9	0.58	1.69	P
195	"	13.9	0.58	1.62	P
196	"	10.8	0.45	1.17	Q
197	"	10.8	0.45	1.29	Q
198	"	12.4	0.51	1.53	Q
199	"	13.2	0.55	1.71	P
200	1.19	8.4	0.39	1.08	Q
201	"	9.2	0.43	1.21	P
202	"	9.9	0.47	1.39	P
203	"	9.0	0.42	1.1	P
205	"	9.2	0.43	1.06	P
206	"	9.0	0.42	1.00	P
207	"	6.8	0.32	0.88	Q
208	0.9	> 2.0	0.70	1.94	Q
209	"	"	0.70	2.65	Q
210	"	"	0.70	-	Q
211	"	"	0.70	-	Q

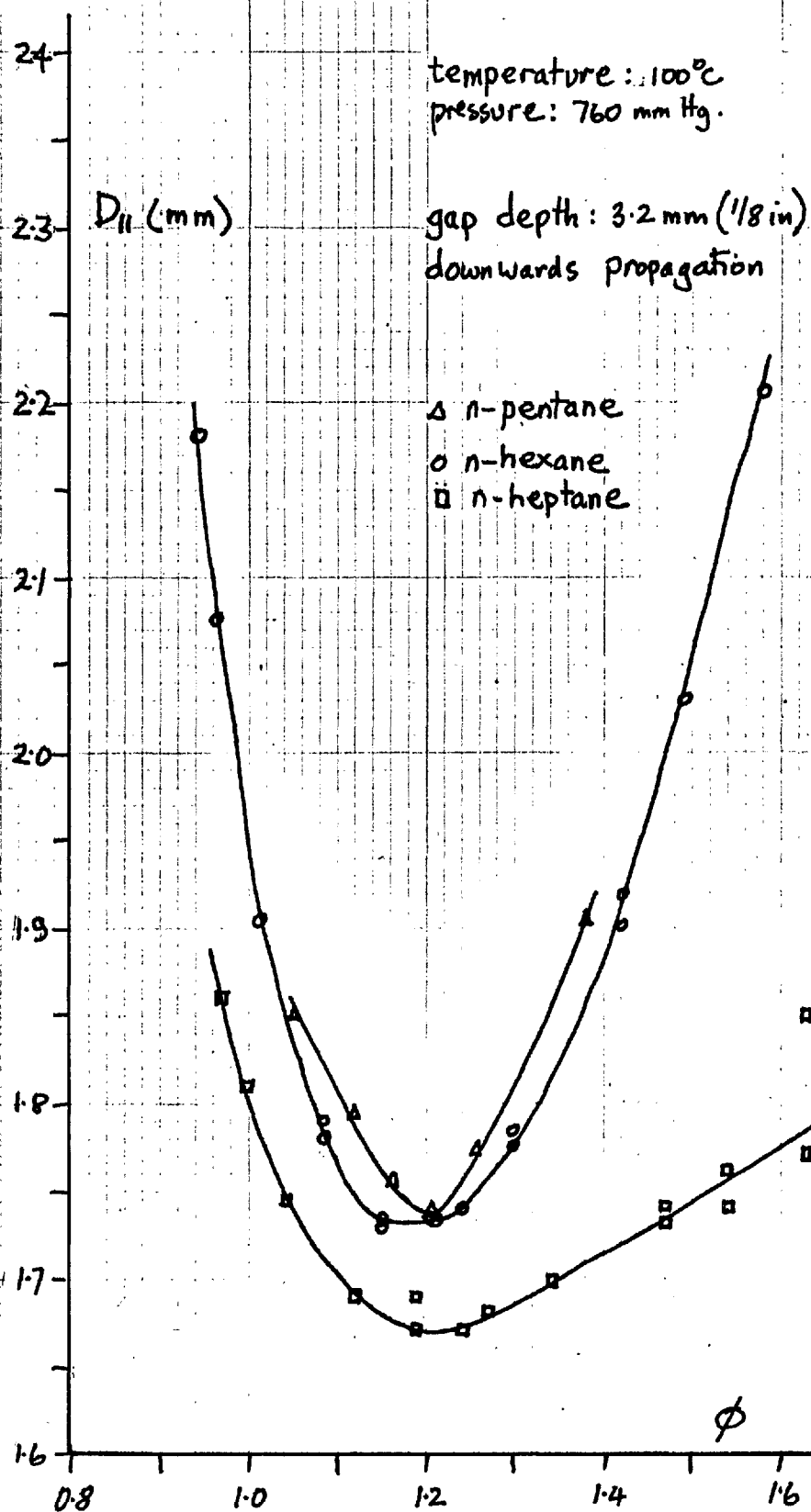


Fig 6.1.

Variation of quenching distance (D_{II}) with stoichiometric ratio (ϕ) for n-pentane, n-hexane and n-heptane.

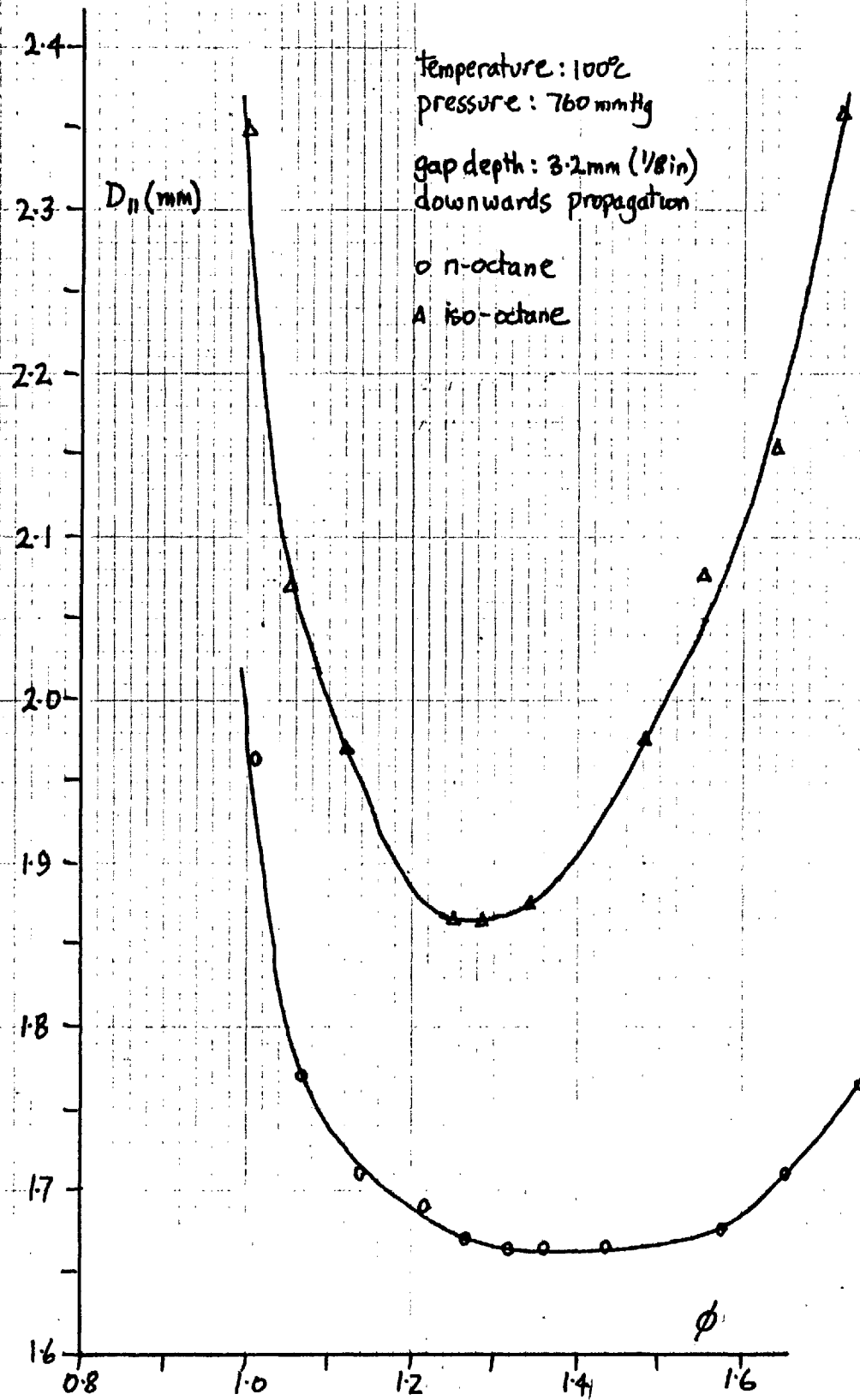


Fig 6.2.
 Variation of quenching distance (D_{II}) with stoichiometric ratio (ϕ)
 for n-octane and iso-octane.

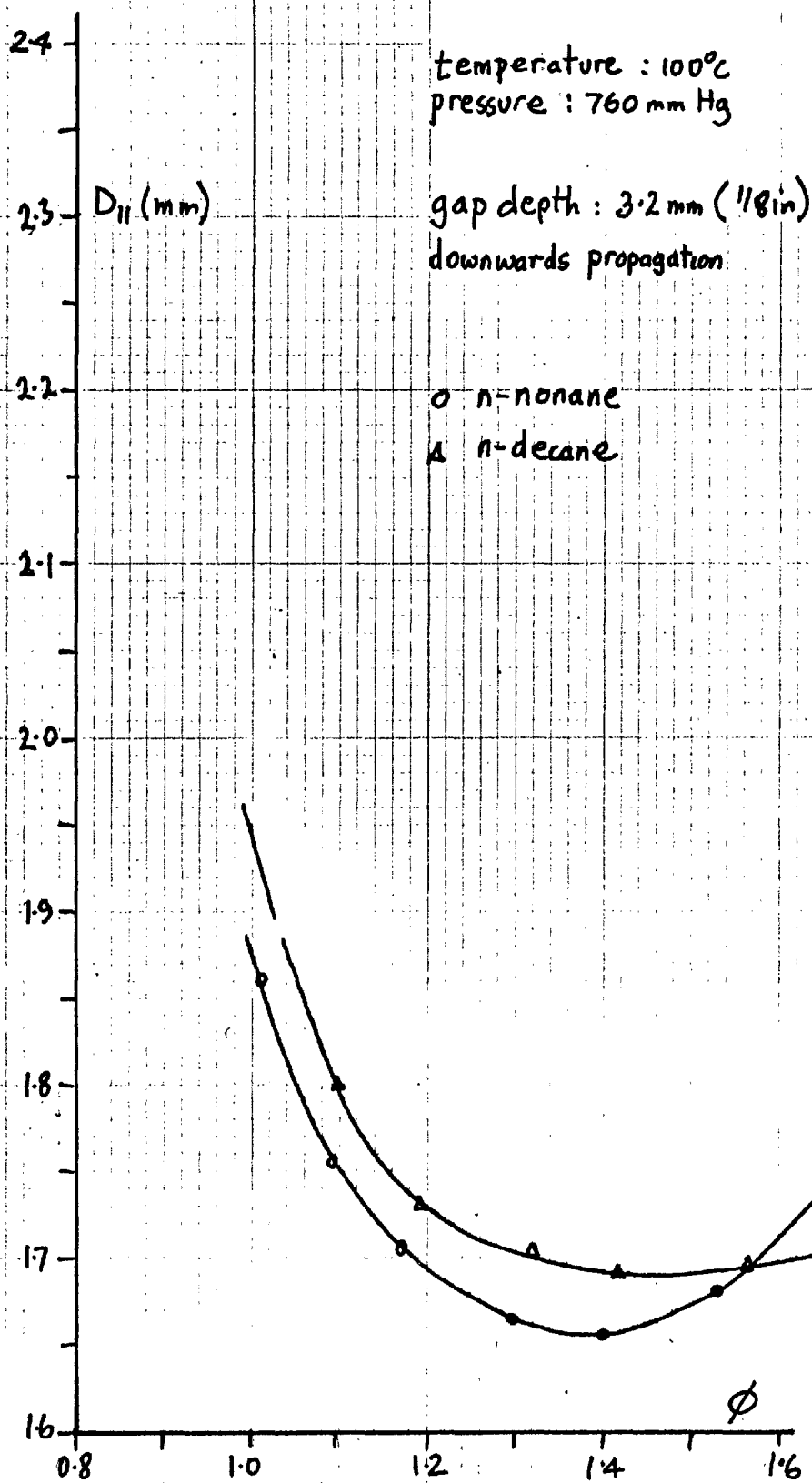


Fig 6.3.
Variation of quenching distance (D_{II}) with stoichiometric ratio (ϕ)
for n-nonane and n-decane

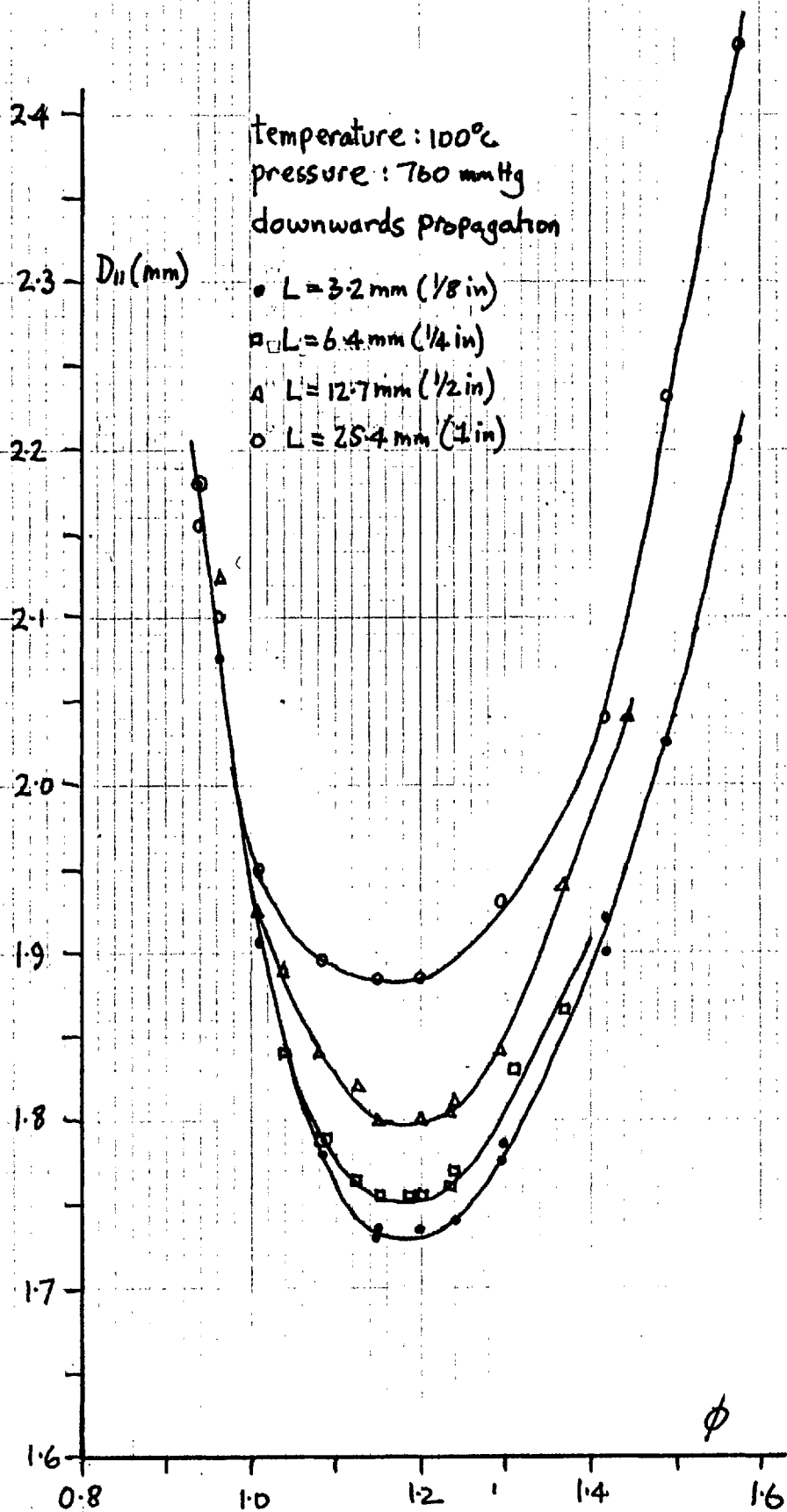


Fig 6.4
 Variation of quenching distance (D_{II}) with stoichiometric ratio (ϕ)
 for n-hexane at different quenching gap depths (L)

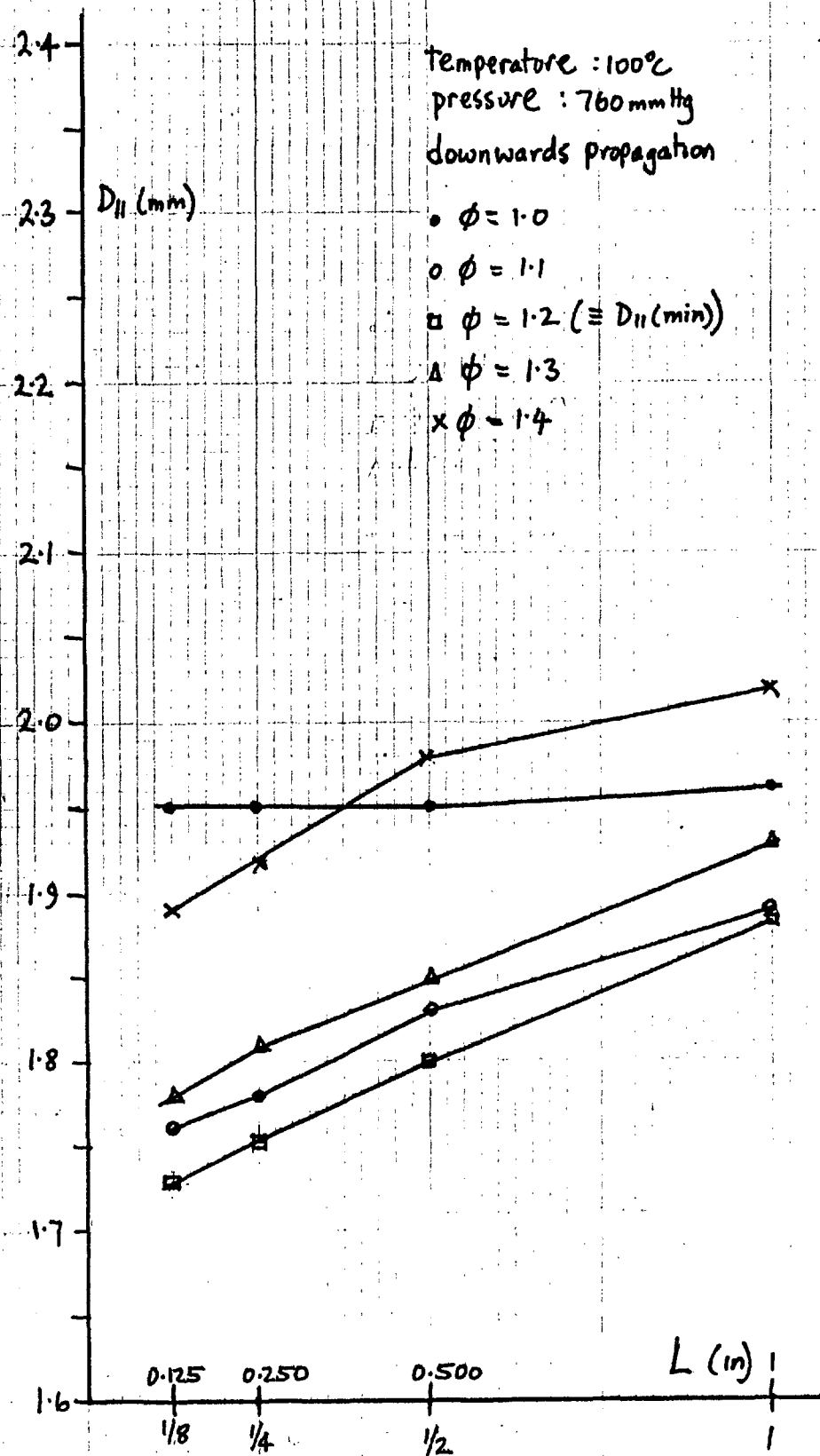


Fig 6.5
 Variation of quenching distance (D_{II}) with quenching gap length (L)
 for n-hexane at different stoichiometric ratios (ϕ)

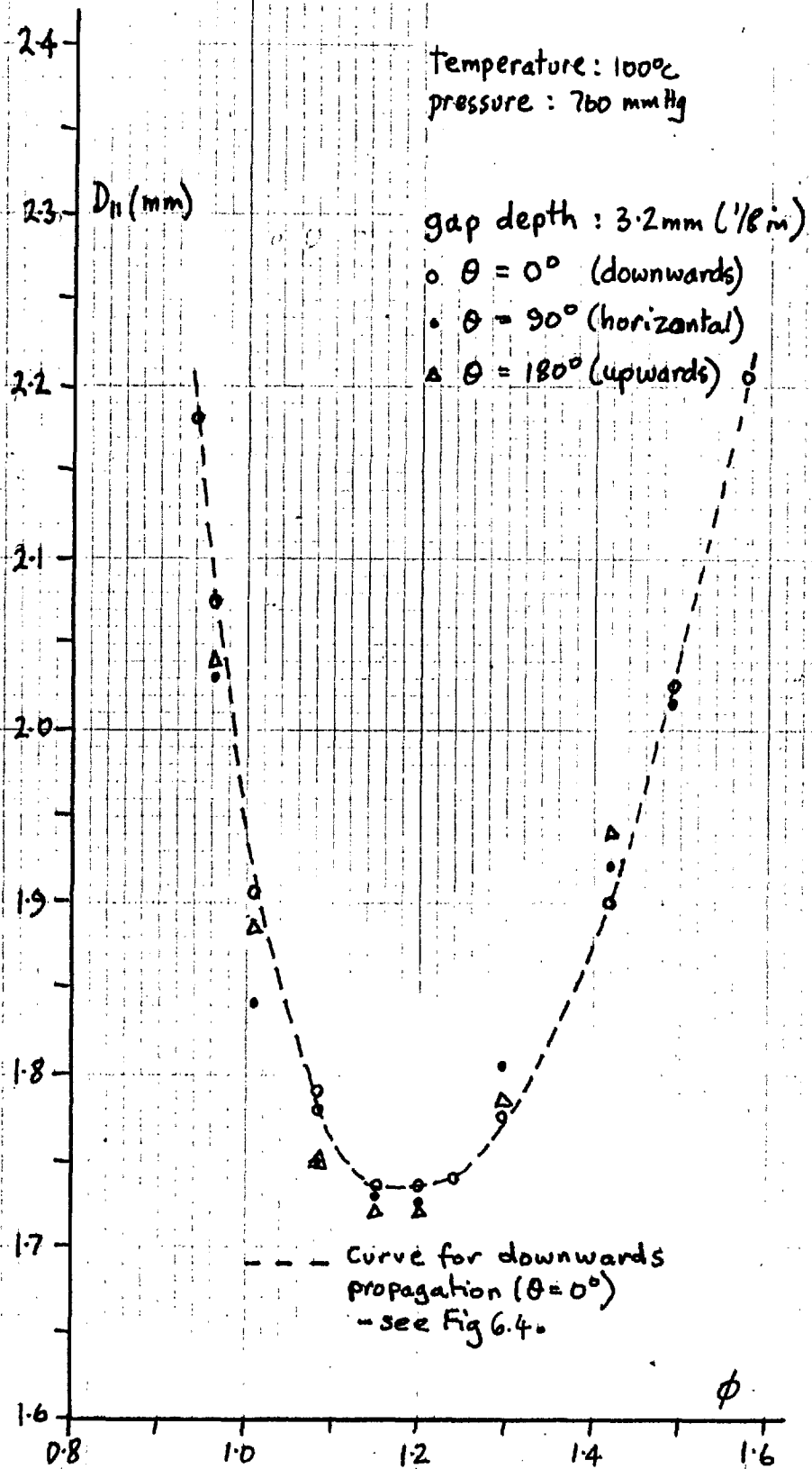


Fig 6.6.
Variation of quenching distance (D_n) with stoichiometric ratio (ϕ)
for n-hexane at different burner orientations (θ)

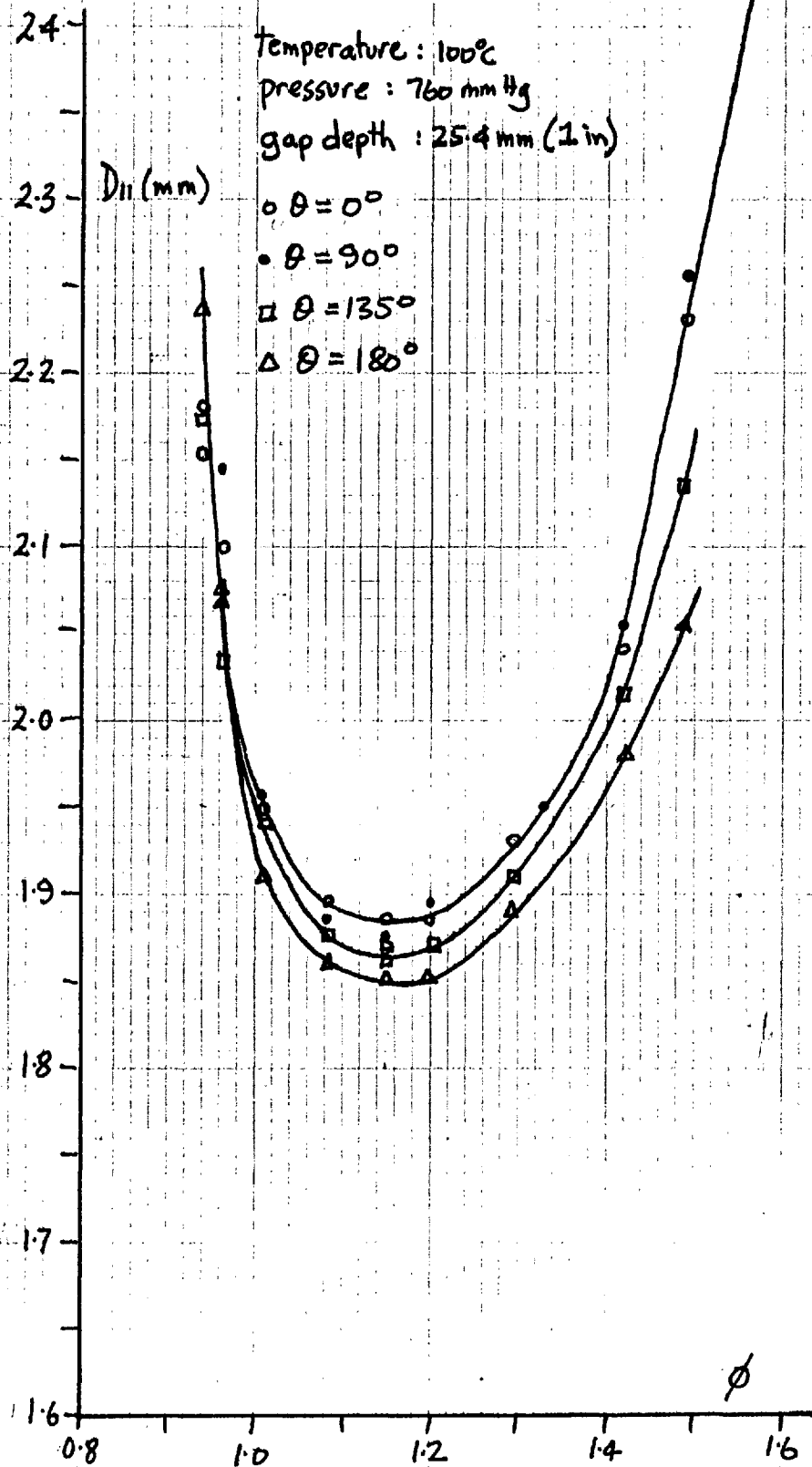


Fig 6.7.
 Variation of quenching distance (D_n) with stoichiometric ratio (ϕ)
 for n-hexane at different burner orientations (θ)

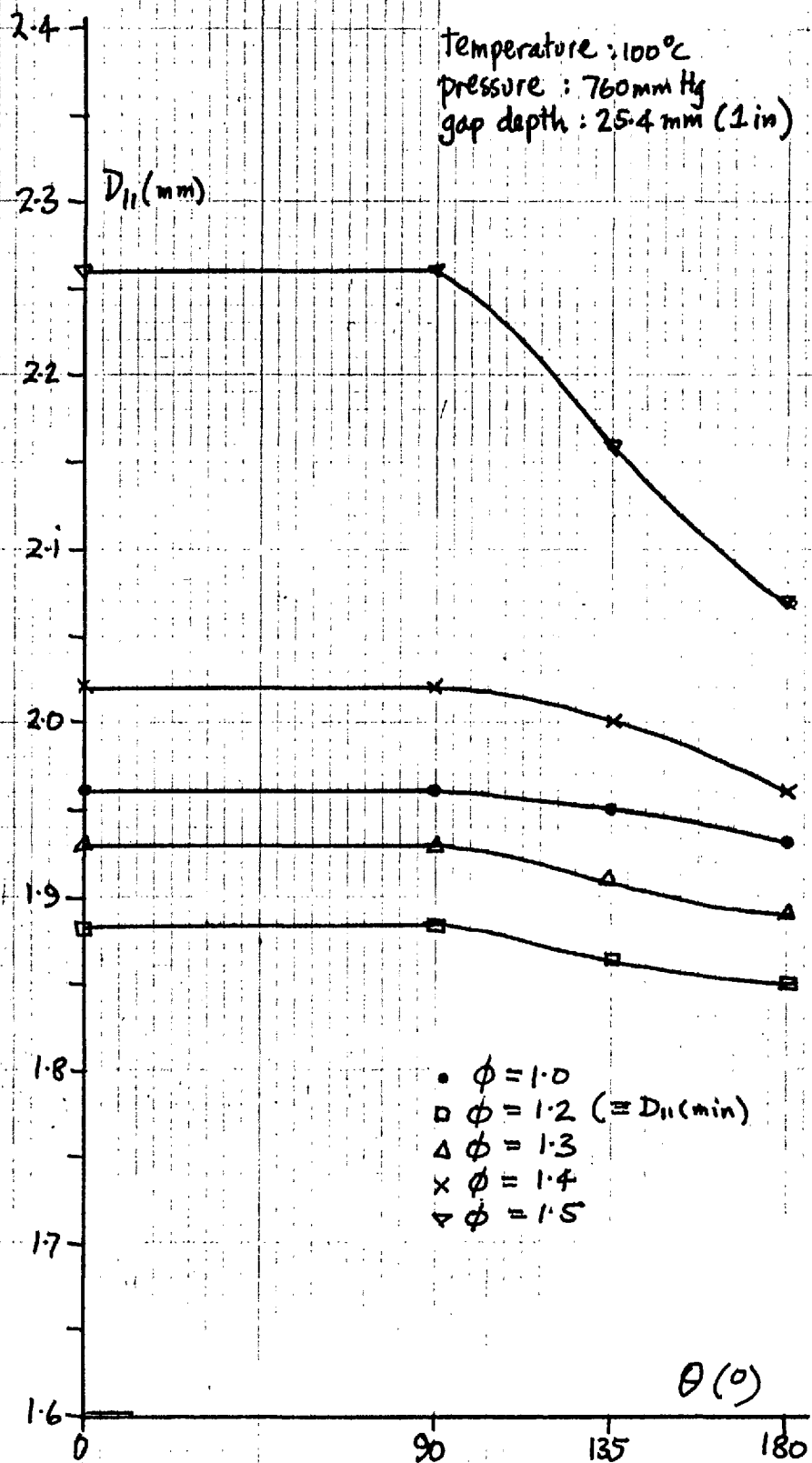
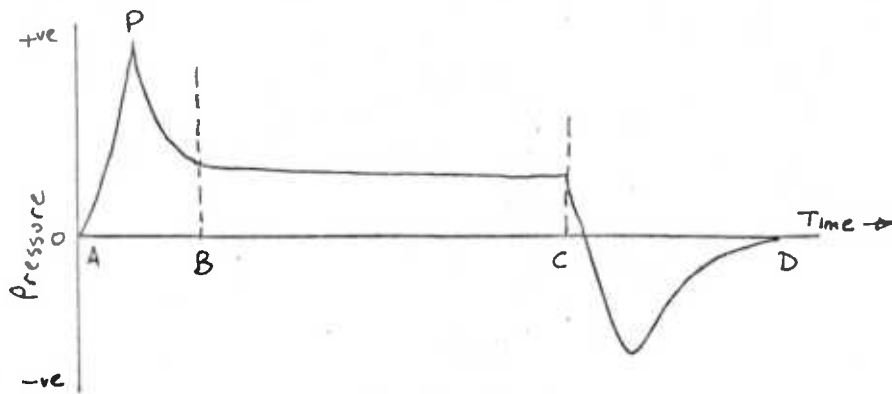
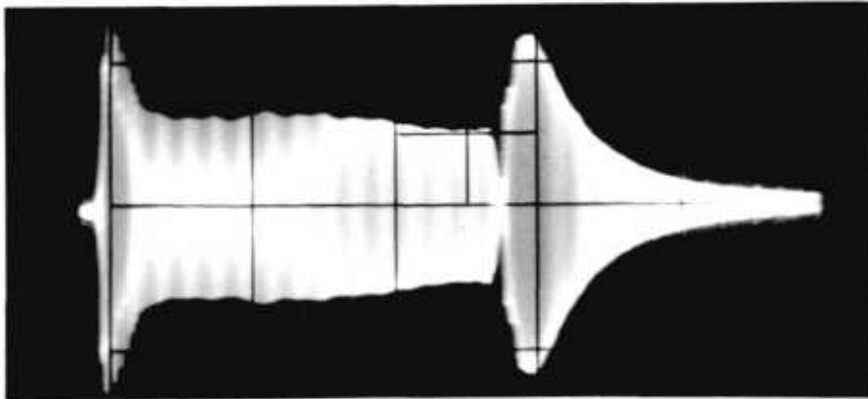


Fig 6.8.

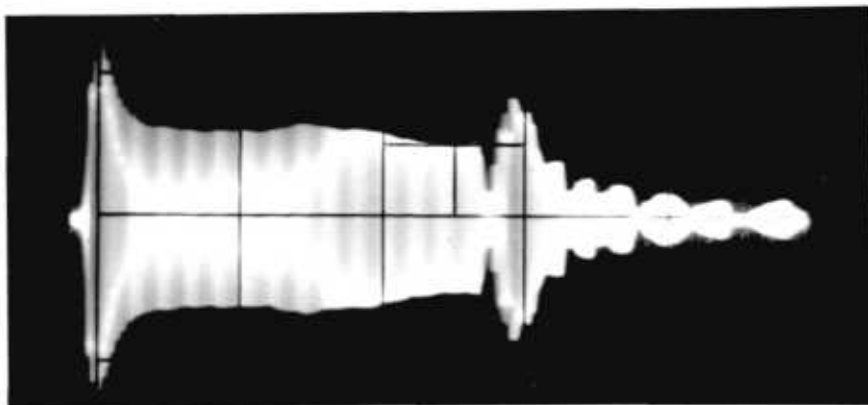
Variation of quenching distance (D_{II}) with burner orientation (θ) for n-hexane at different stoichiometric ratios (ϕ)



- a) Essential features of typical pressure-time record
- for description see text, section 6.2.1.



- b) Typical pressure-time record - flame propagated
Experiment C158, see Table 6.9.



- c) Typical pressure-time record - flame was quenched
Experiment C159, see Table 6.9.

Fig. 6.9. Pressure v. time records from gas flow experiments

Fig 6.10. Results of gas velocity experiments: 6.4 mm ($\frac{1}{4}$ in) gap

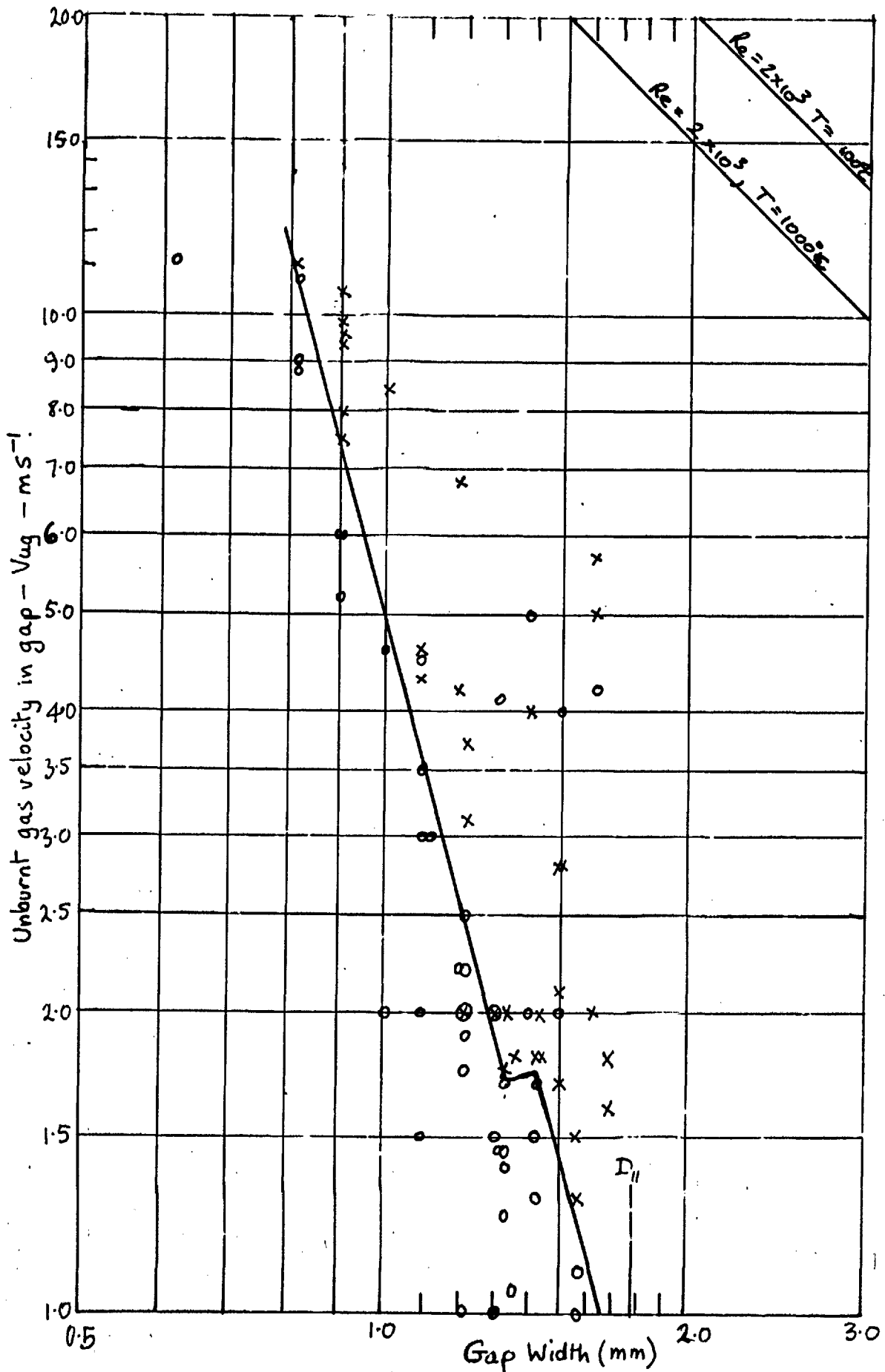
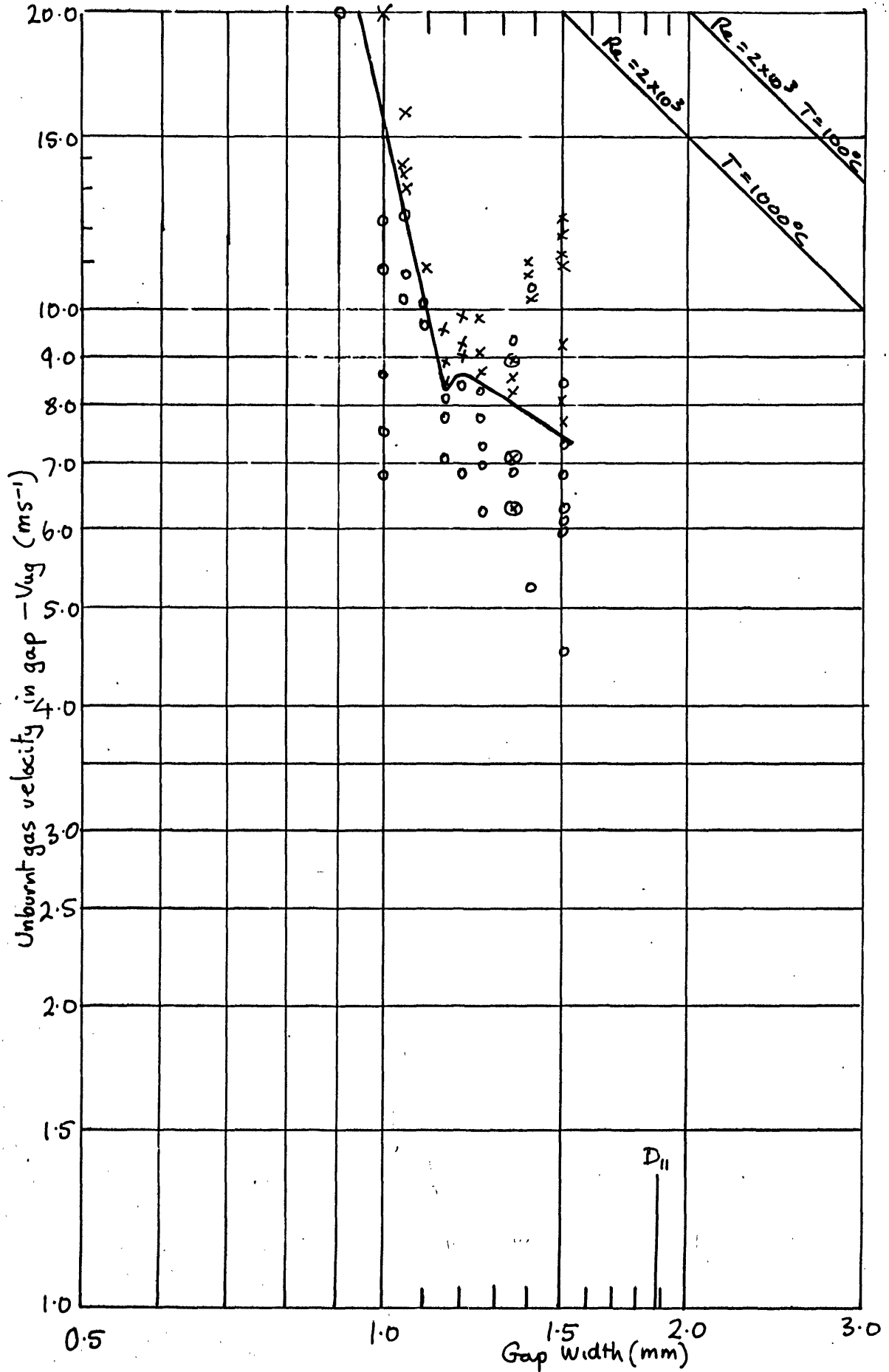


Fig 6.11. Results of gas velocity measurements : 25.4 mm (1in) gap



CHAPTER 7

DISCUSSION

7.1. The effect on quenching dimensions of fuel composition

In Table 6.2. values are given for D_{11} measured with the 3.2mm deep slit at stoichiometric ratios (ϕ) equal to 1 and 1.5, $D_{11}(\text{min})$ and the stoichiometric ratios at which $D_{11}(\text{min})$ occurred. These have been plotted in Fig 7.1. against molecular weight (number of carbon atoms) for the homologous series of alkanes C_5 to C_{10} .

A feature of interest is the decrease in quenching distance for rich mixtures ($\phi = 1.5$). The variation agrees with Potter and Berlads's⁽⁵²⁾ correlation, for a different set of hydrocarbons, of $D_{11} \propto (M)^{-0.3}$. Markstein's⁽⁶⁰⁾ correlation for the size individual cells in cellular flames is also to the -0.3 power of molecular weight, for $\phi = 1.4$. This type of correlation for wide flame quenching distance, the fundamental reason for which is not understood, is evidence that preferential diffusion - accepted as the mechanism for the formation of cellular flames - probably plays an important role in rich flame quenching. As ϕ decreases quenching distance becomes less dependent upon molecular weight; there is the interesting suggestion, in the results, however, that for stoichiometric mixtures there is a regular fluctuation of D_{11} with molecular weight about a fairly constant mean value.

The overall tendency for the stoichiometric ratio at which $D_{11}(\text{min})$ occurs to increase with molecular weight is also in line with the view that preferential diffusion is important for rich mixtures: the relative diffusivity of oxygen with respect to the fuel will increase with molecular weight leading to a correspondingly significant role for preferential diffusion.

7.2. The effect of channel (gap) length

The effect of quenching channel length on quenching distance for flame propagating through initially quiescent gas mixtures is quite marked as illustrated by the results of this investigation; Figs 6.4 and 6.5. The effect, which is absent for $\phi \leq 1$, is to increase the quenching distance, on average, by about 0.08mm per mm increase in channel length. Although Fig 6.5 does show a small amount of variation, the

effect is quite consistent for $1 < \phi < 1.4$.

The main result is for flames propagating downwards. Examination of Figs 6.6 and 6.7 shows that the effect of increasing channel (gap) length is somewhat less (about 0.06mm/mm) when the 25.4mm gap length results are compared with the 3.0mm gap length results at $\phi = 1.2$. This is a reflection of the greater effect of orientation at the larger gap length.

A model based on a heat loss mechanism describing the effect of gap length on quenching distance has been discussed in Chapter 4. It adequately describes a global progressive quenching process proceeding in a stepwise fashion (infinitesimally small steps can be taken). It is therefore only implicit in gap length L in the sense that the model illustrated in Fig 4.2 can be followed until the condition

$$\frac{d\Lambda}{dT_b} = \frac{d\mathcal{L}''}{dT_b} \quad \text{is met.} \quad \text{Formally, one can write}$$

$$\frac{d\Lambda}{dT_b} = f_1(T_b), \quad \frac{d\mathcal{L}''}{dT_b} = [f_2(T_b)]^{\frac{1}{D^2}}$$

Therefore

$$D = \left[f_2(T_b) / f_1(T_b) \right]^{0.5} \quad 7.1$$

Neither $f_1(T_b)$ nor $f_2(T_b)$ are explicit in L and there is little profit in formalising $f_1(T_b)$ and $f_2(T_b)$ and attempting their evaluation.

Considering again Fig 4.2, a number of pairs of curves of Λ and $\mathcal{L}''$ such as are sketched in Fig 7.2 can be visualised. In each pair the curve for $\mathcal{L}''$ is tangential to the Λ curve (the quenching condition), the point of tangency being P , cf P_3 in Fig 4.2. From the discussion of the model in Chapter 4 each curve $\mathcal{L}''$ can correspond to a combination of gap width D and length L .

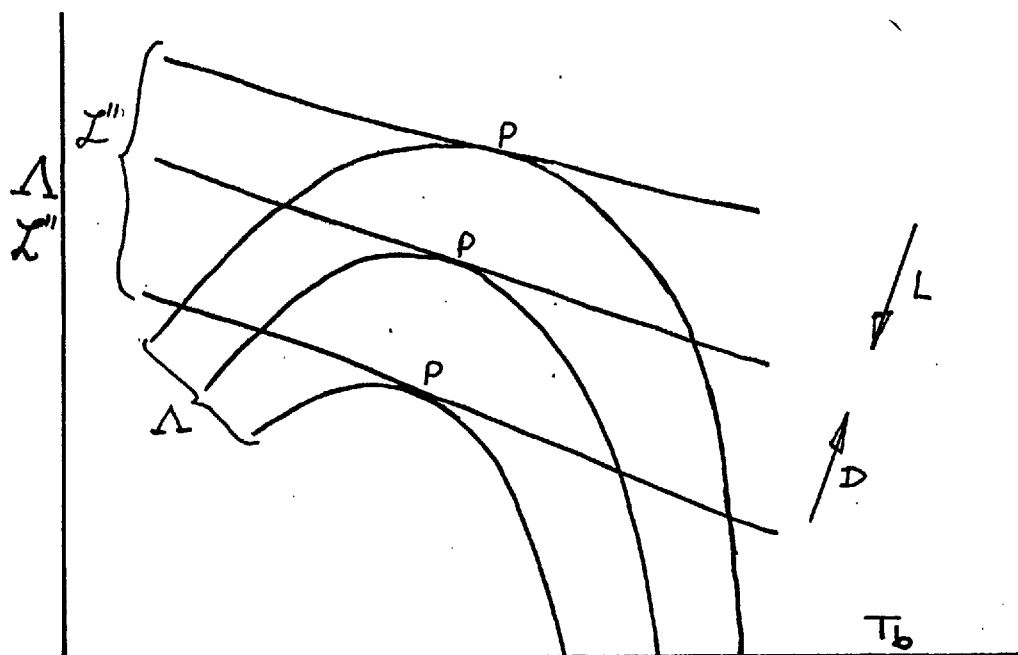


Fig 7.2. Heat loss parameters L'' , Δ , at quenching for different channel length (L) and gap size (D).

In the light of the experimental results the model considered in Chapter 4 can only apply to rich mixtures, $\phi > 1$. The weight of evidence overall is that preferential diffusion probably plays a key role in the quenching mechanism for rich mixtures which is therefore likely to be more complex than that proposed.

For mixtures of $\phi \leq 1$ there is no length effect: flame must be quenched immediately upon entering the quenching channel ($L'' \geq \Delta$) or else propagate without significant change. An explanation of the non-applicability of the model to mixtures of $\phi \leq 1$ and its applicability for $\phi > 1$ can be argued along the following lines. For quenching of mixtures of $\phi \leq 1$ a simplified model is applicable. The curve is immediately tangential to the Δ curve. Now consider a mixture, $\phi > 1$, for which a similar situation should apply but does not: the flame propagates. Because of preferential diffusion the mixture strength at the reaction zone is not that supposed from a consideration of the bulk mixture; it is weaker. The kinetics are therefore similarly not as expected but are in fact somewhat faster, the pre-exponential factor B in the Arrhenius equation will have an effective value higher than expected. This will in turn, considering equations 4.21 and 4.23, increase Δ and decrease L'' other things being equal,

leading to the model described in Chapter 4.

7.3. Effect of gap orientation

No consistently significant effect of orientation can be seen for the 3.2mm ($\frac{1}{8}$ in) gap depth, in Fig 6.6, except at minimum quenching distances where a reduction of some 0.15mm is seen for upwards propagation compared with downwards propagation.

The corresponding reduction in D_{11} for the 25.4mm (1 in) deep gap is some 0.35mm, see Fig 6.7. In the latter case there is a consistently significant pattern. Quenching distances for downwards and horizontal propagation are essentially identical and decrease for increasing orientation beyond horizontal. The effect is absent for lean mixtures and increases with ϕ beyond stoichiometric - see Fig 6.8.

The effect of orientation (direction of flame propagation) on conventional flammability limits, in tubes of sufficient (~ 50 mm) diameter for quenching by heat conduction not to be significant, is well known⁽²⁹⁾. Levy⁽³⁰⁾ has described the 'bubble' mechanism which tends to stabilise upwardly propagating lean limit flames. The convective effects he describes are related to a mechanism of progressive flame failure which does not involve heat loss from the flame to the tube walls. It is tempting to consider the 'bubble' mechanism to be relevant to the quenching of upwardly propagating flames. However it must be considered that convective effects, which are undoubtedly present, act to increase the flame surface area by making it convex to the reactants; whether or not the flame is associated with a rising bubble of hot burnt gas, is not the primary feature. If a bubble of hot gas were, in fact associated with the flame it would itself suffer loss of heat (integrity) to the channel walls thus complicating, considerably, the mechanisms involved. A detailed examination of flame failure within channels of quenching dimensions using optical techniques would be valuable, in this, and other, contexts.

Again it is clear that preferential diffusion probably plays an important role in quenching particularly as the effect of increasing orientation is the most for the richest mixtures. Preferential diffusion tends to be most marked at curved flame surfaces⁽⁵³⁾.

7.4. The effect of superimposed gas flow

Inspection of Figs 6.10 and 6.11 shows two features of interest. The first is a discontinuity in each of the curves drawn to divide the 'propagation' region from the "quenching" region. The second is a suggestion that there might be a minimum velocity of unburnt gas ahead of the flame required before quenching distance is reduced below that for quiescent mixtures.

As a general feature of both correlations the slopes of both lines share a common slope of about -3.6 at least for $D_{11} < 0.115$ in the case of the 25.4mm long gap. In this regard the current results are at variance with the work of Palmer⁽¹⁵⁾, discussed in section 2.1., whose results supported a slope of -2.

The reasons for the two features noted above are not readily apparent but the manner in which a laminar boundary layer is developed in the gap can be examined as being a possible factor, in particular the length of gap over which entry effects persist, of the work of Dainty and Brown⁽²¹⁾ discussed in section 2.1.

Coulson and Richardson⁽⁵⁰⁾ give an empirical relationship for the length (l_e) required for a fully developed velocity profile to be established

$$l_e = 0.0288 D Re$$

l_e is the length of tube required for fully developed laminar flow to be established in a tube diameter D at a Reynolds number Re .

A corresponding relationship for a parallel slot can be calculated as follows. The thickness of a boundary layer for laminar flow over a flat plate is given by

$$\frac{\delta}{x} = 4.64 Re_x^{-0.5} \quad 7.2.$$

Where $Re_x = x \rho u_s / \mu$

δ is the thickness of the boundary layer

x is the distance from the leading edge of the flat plate

u_s is the stream velocity at the edge of the boundary layer

ρ, μ are the fluid density and viscosity

For a channel formed by two parallel plates the boundary layer is fully developed when $\delta = D/2$, where D is the plate separation. In this case $u = u_{\max}$ the centre line velocity. For the parabolic profile in channel flow $u_{\max} = 1.5 \bar{u}$.

Therefore one can write,

$$L(\phi) = 0.0174 D Re$$

7.3

For air at 100°C , $\rho = 0.946 \times 10^{-3} \text{ g/cm}^3$, $\mu = 0.21 \times 10^{-2} \text{ Poise}$.

It is possible to calculate the minimum air flow rate at 100°C required for a fully developed flow to be established in the 6.4mm and 25.4mm long quenching gaps set at their respective quiescent gas quenching distances of 1.75 and 1.885mm

Rearranging eq'n 7.3 gives

$$\bar{u} = L(\phi) \mu / 0.0174 \rho D^2$$

which turns out to be 2.83 ms^{-1} for the 6.4mm deep gap
and 9.1 ms^{-1} for the 25.4mm deep gap

In the calculation of these velocities entrance effects are ignored. Bearing this in mind the calculated values are not dissimilar to the minimum values anticipated in Figs 6.10 and 6.11.

It is not possible to go further than to propose that boundary layer development is probably an influential factor for quenching of flames propagating through gas mixtures flowing in narrow channels. Visual examination of flame failure under these conditions by, for example, interferometry would undoubtedly help to elucidate this complex phenomenon.

For laminar flow in the run-up tube the unburnt gas velocity in the tube should not exceed a critical value (u_c) corresponding to a Reynolds number of 2×10^3

$$u_c = 2 \times 10^3 \mu / \rho d = 1.74 \text{ ms}^{-1}$$

Examination of column 4 in Tables 6.8 and 6.9 shows that this condition was always met at the instant of flame interaction with the gap.

Examination of column 5 shows that even the mean flame speed only rarely exceeded this value. It is clear that flow in the run-up tube was essentially laminar in all experiments.

Another complicating factor in the consideration of the results of the 'gas flow' experiments is the interface between 'cold' unburnt gas ahead of the flame and the 'hot' burnt gases behind the flame: the flame is situated at the interface. The viscosity of the hot burnt gases is likely to be some three times higher than that of the unburnt gas. For a given pressure differential across the gap the gas velocity will decrease by up to the same factor when the gap is full of burnt gas. But when flame enters the gap the resistance to the flow of burnt gas away from the flame is increased because that gas then has to flow through a very narrow channel; this will tend to increase the pressure at the entrance to the channel, counteracting the viscous effect.

The work described here has not enabled the individual features in a complex situation to be examined: it was not designed so to do. Further, more detailed examination of flame failure in narrow channels is required before a detailed exploration of the mechanisms involved can be evolved.

7.5. The Peclet number

As discussed in section 2.2 the majority of theoretical approaches to a model for wall quenching can be couched in terms of a Peclet number. Mayers'⁽⁴⁰⁾ empirical predictions for the quenching Peclet number applied to slots lying in the range 22 to 40. Spalding's⁽⁴¹⁾ prediction is 39 for slots and Rozlovski's⁽⁴⁶⁾ survey of experimental values of Peclet number gives a mean value of 42 for slots.

Taking the present results for n-hexane, Table 6.2, a burning velocity of 60 cm/sec at 100°C⁽⁵⁹⁾ and a value for thermal diffusivity (α) of 0.3 cm²/sec based on the properties of air, the slot quenching Peclet numbers are 39 for $\phi = 1$ and 35 for minimum D_{11} at $\phi = 1.2$. The Peclet numbers for the other fuels are, of course similar in magnitude and all are in good agreement with predictions and other results.

Peclet numbers for the results of the gas flow experiments have been calculated using the same values for S_u and α and are plotted against superimposed gas velocity in Fig 7.3. These plots show rather more clearly than Figs 6.10 and 6.11 the possible existence of a minimum unburnt gas velocity before any reduction in quenching distance (Peclet

number) is required. Also indicated on Fig 7.2 are the unburnt gas velocities, calculated above, required for full development of a laminar boundary layer at the respective channel (gap) lengths. As the unburnt gas velocity increases the slot quenching Peclet number decreases, tending towards a constant value for high velocities. An analogy can be drawn with MESH in this respect.

The experimental results do not enable any views to be formed on the role of preferential diffusion in the situation where the unburnt gas is flowing, particularly since experiments have only been made at a single value of stoichiometric ratio ($\phi = 1.2$).

7.6. Relationship of quenching distance to MESH

There is much practical interest centred on a knowledge of values of MESHs for different fuels. Because of the difficulties often associated in the past with the measurement of MESH other easier routes to a reasonable estimate for this parameter have often been sought. Studies of the type reported by Grove⁽¹³⁾, discussed in section 2.1, linked MESH to D_{11} empirically. Phillips⁽⁶⁰⁾ discussed correlation with minimum igniting current. Such correlations can be shown to be reasonably successful. For example using the present result for n-hexane at 25°C and using Grove's correlation an MESH for n-hexane of 0.040 inches is obtained compared with the accepted experimental value of 0.038 inches⁽⁶¹⁾.

However it is of interest to consider whether there is any fundamental reason for any such correlations. The mechanism of the 'safe gap' (MESH) is well described by Phillips⁽²⁰⁾. Following quenching of flame in a gap of dimensions considerably less than the quenching distance, hot burnt gases are ejected as a momentum jet from the gap into the bulk of the still unburnt gas mixture. Depending upon details of the aerodynamics of the jet of hot turbulent burnt gas, unburnt gas is entrained into the jet where it is heated but diluted with burnt gas but sufficient heat may be produced by pre-ignition reactions for an element of the jet at its boundary to become sufficiently hot for ignition to take place. These conditions occur following ignition of a flammable gas mixture inside a closed bomb fitted with the flanges so that flame and hot burnt gas flow through the gap often at quite high velocities. In general, depending upon the velocity, as shown by the current work, there must be

a gradual transition with reduction in gap dimension and/or increase in velocity as follows:

- from a) no quenching of flame in a gap,
- to b) quenching in the gap followed by an increasing tendency as velocity increases for the formation of an incendive jet of hot turbulent gas.

The 'safe gap' mechanism as described by Phillips is a severe example of (b). The propagation of flame through gaps slightly smaller than the quenching distance as described in this work is a modest example of (a). There is an important step change in the mechanism 'en route'.

Phillips' parameter ψ is a function of Arrhenius kinetics, burning velocity, flame temperature etc. From section 2.2 and Chapter 4, D_{11} is also considered to be a function of the same processes and parameters. Similarly the theory of ignition of electric sparks utilises these same physico-chemical features ^(47,55).

Any correlations between MESG, D_{11} and spark ignition parameters are probably fortuitous and arise because their respective formal descriptions utilise common kinetics and thermodynamics although the basic physical processes are quite different.

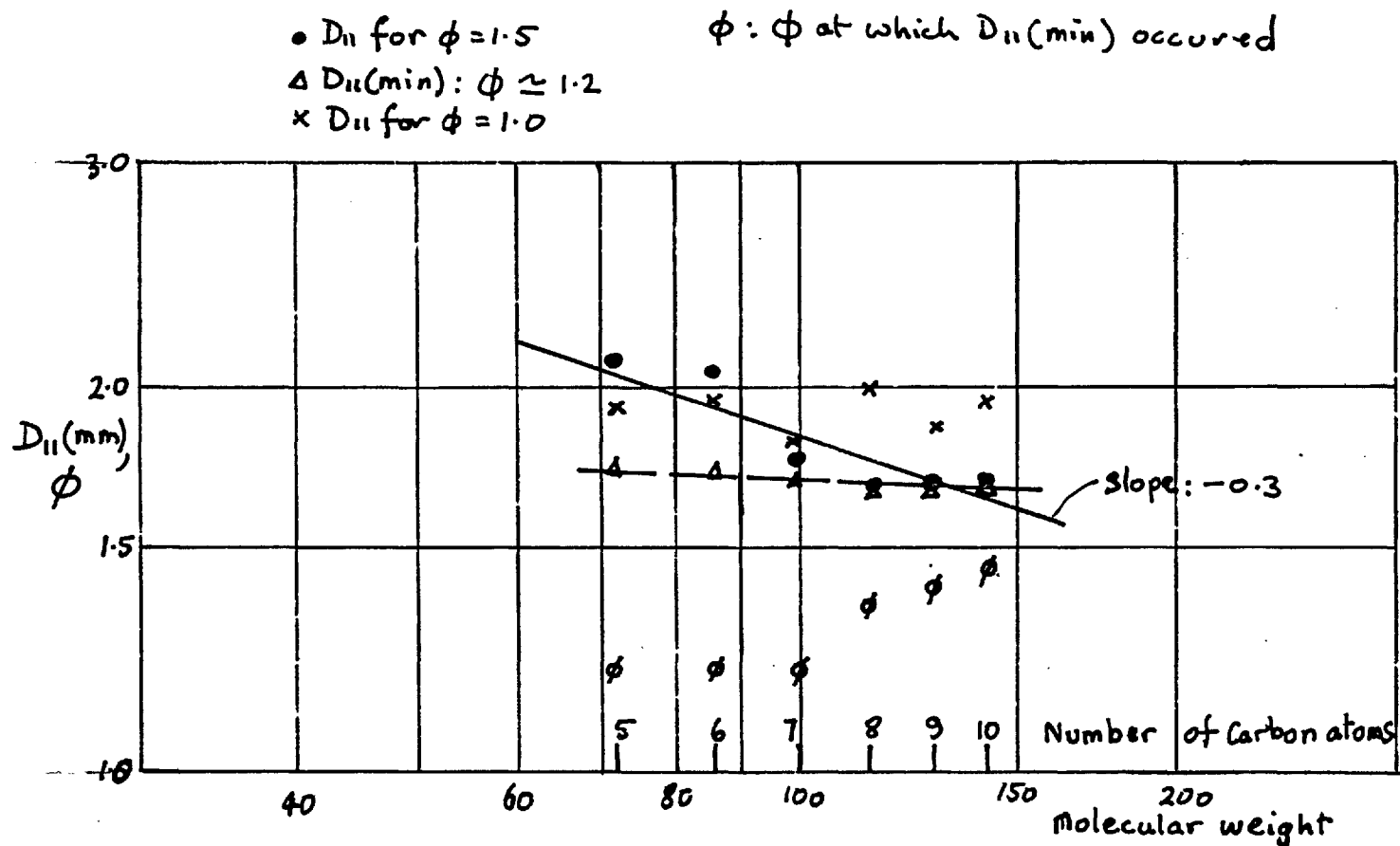


Fig 7.1. Variation of D_{11} with molecular weight for n-alkanes

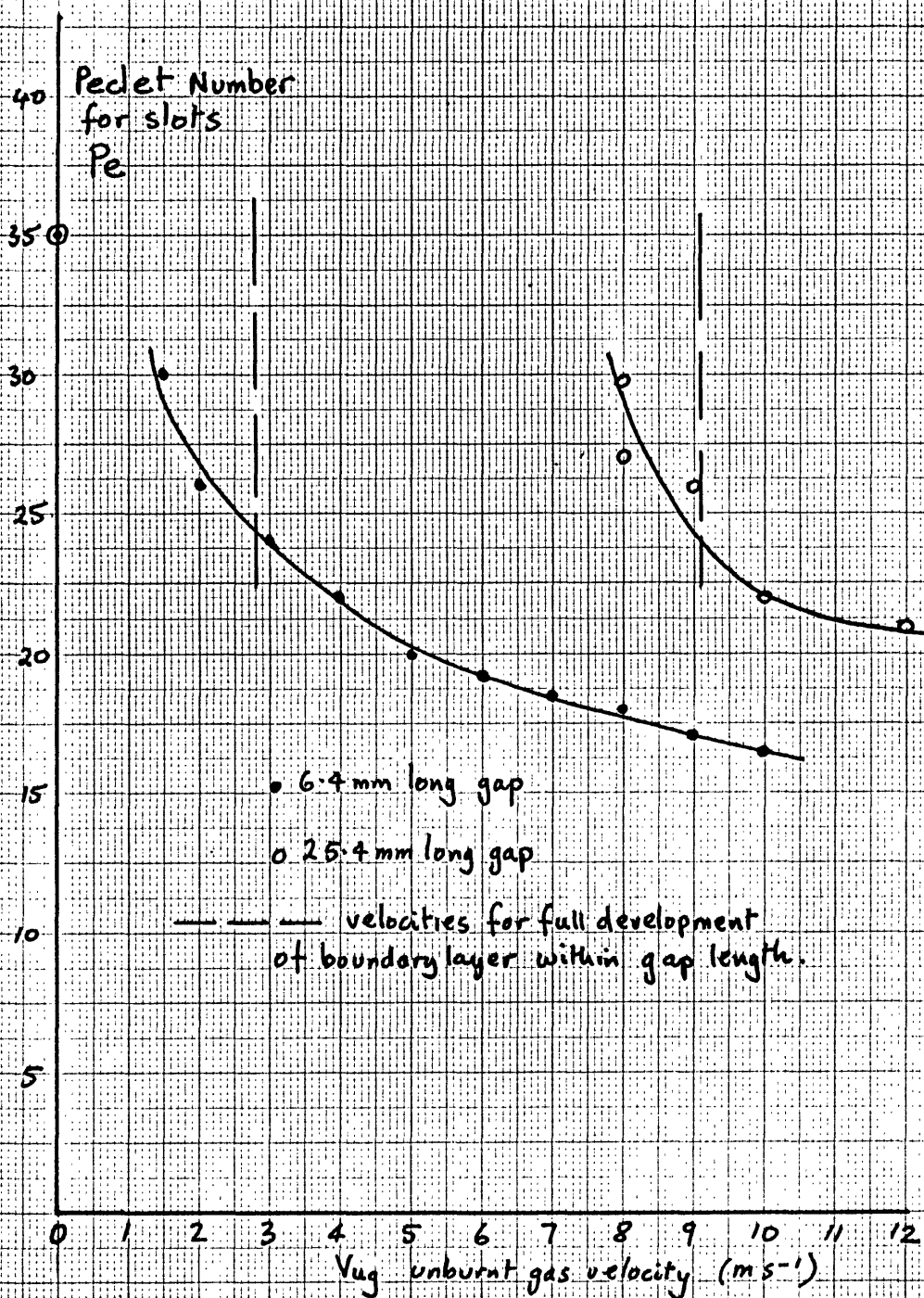


Fig 7.3 Results of gas flow experiments expressed as slot quenching Peclet number as a function of unburnt gas velocity in the slot gap.

CHAPTER 8

CONCLUSIONS

8.1. Quenching distances for rich ($\phi = 1.5$) mixtures of the homologous series of normal alkanes $C_5 - C_{10}$ decreases with molecular weight

This result is in agreement with quenching and cell size data for other hydrocarbon flames.

8.2. Stoichiometric and lean flames of n-hexane in air ($\phi \leq 1$) are not affected in respect of quenching distance by increasing quenching gap length from 3.2mm to 25.4mm.

8.3. Quenching distances of stoichiometric n-hexane/air flames are decreased a small but significant amount by changing the direction of propagation in a 25.4mm long gap from vertically downwards to vertically upwards. Leanflames ($\phi \leq 0.95$) are not affected by changes in orientation nor are stoichiometric and lean flames in gaps 3.2mm long.

8.4. Rich ($\phi > 1$) n-hexane/air flames are affected with regard to their quenching by changes in apparatus geometry, eg length of quenching gap and the direction of flame travel. Flames of stoichiometric ratio ($\phi = 1.2$) are the most affected. The effect of direction of flame propagation is most marked for the largest quenching gap investigated.

8.5. The experimental evidence related to (4) above supports the view that for the quenching of flames of quiescent rich mixtures, preferential diffusion of oxygen, compared with the fuel, plays an important role in the quenching mechanism.

8.6. A model of quenching in narrow passages of different length has been developed which explains, qualitatively, the observed phenomena.

8.7. Detailed structural studies of flames undergoing quenching are required in order to elucidate, more clearly, the physico-chemical mechanisms involved before a more detailed quantitative model of wall quenching can be developed. The phenomenology would probably be most

conveniently examined by optical techniques.

8.8. Simple models based only on heat loss considerations appear appropriate for and can successfully predict only the quenching of stoichiometric and lean flames. The majority of effort to date has concentrated on these flames. The present studies show this approach to be inadequate for flames richer than and more difficult to quench than stoichiometric.

8.9. The effect for rich mixtures ($\phi = 1.2$) of n-hexane in air of superimposed flow of unburnt gas in the same direction as that of flame movement reduces quenching distance by a factor of up to two for the velocities investigated in two gaps of length 6.4mm and 25.4mm. Discontinuities in the results for both gap lengths suggest an important role for the development of a laminar boundary layer, entry effects also being important.

8.10. The results of the experiments with a superimposed flow of unburnt gas do not allow proposition to be made regarding the contribution of preferential diffusion to the phenomenology of quenching in flowing gas mixtures. The manner in which flame is progressively quenched still remains to be examined in detail along the lines suggested in para 8.7.

NOMENCLATURE

The symbols listed below generally have the meanings indicated except where indicated locally in the text. Additional symbols, used occasionally, are defined in the text when used.

- A cross sectional area for heat transfer
- B pre-exponential factor in Arrhenius equation
- C specific heat or a constant
- C_p specific heat at constant pressure
- d linear dimension
- D quenching dimension
- $\mathcal{D}$ molecular diffusivity
- E_i minimum ignition energy
- E activation energy
- h heat transfer coefficient
- $\mathcal{H}$ heat abstracted per unit volume of flame
- k thermal conductivity
- K rate constant
- L length of quenching passage
- $\mathcal{L}$ heat loss parameter
- $\mathcal{L}''$ heat loss parameter, per unit area
- $L(e)$ entry length required for full development of boundary layer
- Le Lewis-Semenov number $(\alpha/\mathcal{D})$
- m mesh width
- M mass fraction of designated species in mixture
- M_w molecular weight
- n number of apertures per unit for area of crimped ribbon flame arrester, or a constant
- Nu Nusselt number (hd/k)
- p partial pressure
- P pressure
- Pe Peclet number, $d \cdot u/\alpha$ for heat transfer
 $d \cdot u/\mathcal{D}$ for mass transfer
- Q heat of reaction
- r concentration of reactant
- R universal gas constant
- Re Reynolds number $(\rho d u/\mu)$
- Re_x Reynolds number based on length (x) $(\rho x u/\mu)$

- S fundamental burning velocity
 T temperature
 u, v velocity
 V_f velocity (flame)
 x distance coordinate
 y thickness of flame arrester, distance from wall, distance coordinate
 α thermal diffusivity ($\rho C_p / k$)
 δ boundary layer thickness or flame thickness
 Λ heat loss parameter
 μ viscosity
 ρ density
 θ temperature difference between fluid and wall
 w rate of consumption of a reactant

Subscripts

- l gap or slit
 o orifice
 b burnt gas
 f flame
 f fuel
 i initial condition
 j species j
 m minimum
 u unburnt gas

Superscript

- a adiabatic

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APPENDIX 1. SUMMARY OF EXPERIMENTALLY DETERMINED QUENCHING DISTANCES

GENERAL NOTES ON THE COMPILATION OF EXPERIMENTAL DATA IN TABLES

1. Only data for which the oxidising atmosphere was normal air or oxygen are included in Table A.1.1. Other atmospheres are given in Table A.1.4.
2. Some data for 'cool' flames are contained in Table A.1.2.
3. Some data for selected decomposition flames are contained in Table A.1.3.
4. Data sources for flames for which the oxidising atmosphere was not normal air or oxygen are referenced in Table .
5. Data has been excluded which would have required very significant extrapolation from 2 measurements obtained at low pressures.
6. The symbol (o) against a value of quenching distance denotes that the original data was a quenching diameter which has been corrected by the factor 0.65 to estimate the quenching distance.
7. The symbol (+) indicates an extrapolated value.
8. The compiled data is for 'room' temperature. Where it is shown that the original experiments were carried out at elevated temperatures, quenching distances have been corrected to 25°C by employing the relationship

$$\text{Quenching Distance} \propto [\text{Temperature (K)}]^{-0.5}$$

NOTES ON THE EXPERIMENTAL TECHNIQUES USED TO OBTAIN THE DATA
IN TABLES

In the tables the experimental techniques designated by letter were, briefly, as follows.

- A. Extrapolation of "flashback/blowoff" stability diagrams, assuming quenching distance $\propto (\text{pressure})^{-1}$.
- B. Flashback technique using a rectangular slit burner. The limiting pressure was determined for quenching and the quenching distance at atmospheric pressure obtained by graphical extrapolation.
- C. Flashback technique using a rectangular slit burner with facility for adjusting the gap width.
- D. Flashback technique using circular holes drilled in brass or copper plates.
- E. Flashback technique using cylindrical burners.
- F. Propagation of flame into a wedge shaped channel.
- G. Spark ignition using flanged electrodes.
- H. Method G but flange diameter specifically 25.4mm (1 in) diameter and energy input "several times" the minimum required for ignition.
- I. Flame propagation in tubes.
- J. Propagation into a closed conical tube, 300mm long.

TABLE A.1.1. Experimental Quenching Distance data (corrected to 25°C and 1 atm.) Oxidant is air unless stated otherwise

FUEL SYSTEM	Stoichiometric Quenching Distance (mm)	Minimum Quenching Distance (mm)	ϕ for Minimum Quenching Distance	Depth of Quenching Passage (mm)	Direction of flame propagation (ϕ) ($^\circ$)	Temperature of original measurement ($^\circ$ C)	Experimental Method	Reference
Acetylene	0.52 $^\circ$						A	3
Acetylene	0.65						H	4
Acetylene		0.55		0.8	0		D	5
Acetylene-oxygen	0.085 $^\circ$						A	3
Ammonia		1.43		0.8	0		D	5
Ammonia-oxygen	0.11	0.09	0.56-0.91		0		C	6
Amyl acetate	2.29 $^+$	2.02	1.2	3.2	0	100	C	2
Amyl acetate		1.9 $^\circ$		0.8	0		D	5

TABLE A.1.1. (continued)

FUEL SYSTEM	Stoichiometric Quenching Distance (mm)	Minimum Quenching Distance (mm)	ϕ for Minimum Quenching Distance	Depth of Quenching Passage (mm)	Direction of flame propagation (ϕ)	Temperature of original measurement ($^{\circ}\text{C}$)	Experimental Method	Reference
Benzene	1.93	1.80	1.15	1	0	105	B	7
Benzene	1.94	1.91	1.10	4.8	0	100	C	8
Benzene	1.95		-				H	4
Benzene	2.0	1.82	1.2				C	2
1.3 Butadiene	1.25						H	4
iso-butane	2.20						H	4
n-butanol	2.08	1.9	1.18	3.2	0	100	C	2
n-butanol		1.75		0.8	0		D	5
iso-butanol		1.88		0.8	0		D	5
n-butanaldehyde		2.20	2.0	3.2	0	100	C	2
di-iso-butylene	3.2						H	4

TABLE A.1.1. (continued)

FUEL SYSTEM	Stoichiometric Quenching Distance (mm)	Minimum Quenching Distance (mm)	ϕ for Minimum Quenching Distance	Depth of Quenching Passage (mm)	Direction of flame propagation (θ)	Temperature of original measurement ($^{\circ}\text{C}$)	Experimental Method	Reference
n-butyl acetate	2.24	2.00	1.2	3.2	0	100	C	2
n-butyl benzene	2.28	1.98	1.3		0	105	B	7
carbon disulphide	0.55						H	4
carbon monoxide	1.7 ^a			2.8			D	9
carbon monoxide		2.31 ^a		0.8	0		D	10
{ carbon monoxide + 10mm water vapour		1.62 ^a		0.8	0		D	10
{ + 20mm water vapour		1.37 ^a		0.8	0		D	10
{ + 40mm water vapour		1.32 ^a		0.8	0		D	10

TABLE A.1.1. (continued)

FUEL SYSTEM	Stoichiometric Quenching Distance (mm)	Minimum Quenching Distance (mm)	ϕ for Minimum Quenching Distance	Depth of Quenching Passage (mm)	Direction of flame propagation (θ)	Temperature of original measurement ($^{\circ}\text{C}$)	Experimental Method	Reference
n-decane	2.08	1.89	1.45	3.2	0	100	C	1
n-decane	2.06	1.86	1.30		0	105	B	7
decene-1	1.97	1.77	1.30		0	105	B	7
ethane	1.30			2.8			D	9
ethane	2.11	1.83	1.23				G	11
ethane- oxygen	0.24	0.2	0.74				G	11
ethanol	2.03	1.84	1.18	3.2	0	100	C	2
ethanol		1.93 ^e		0.8	0		D	5
ethyl acetate	2.29	2.14	1.15	3.2	0	100	C	2
ethyl acetate		2.03 ^e		0.8	0		D	5
ethyl benzene	2.1 ⁺	1.76	1.28	3.2	0	100	C	2

TABLE A.1.1. (continued)

FUEL SYSTEM	Stoichiometric Quenching Distance (mm)	Minimum Quenching Distance (mm)	ϕ for Minimum Quenching Distance	Depth of Quenching Passage (mm)	Direction of flame propagation (θ)	Temperature of original measurement ($^{\circ}\text{C}$)	Experimental Method	Reference
diethyl ether	2.03	2.00	1.05	4.8	0	100	C	8
diethyl ether	1.85						H	4
diethyl ether		1.70 ^a		0.8	0		D	5
ethylene		1.14 ^a		0.8	0		D	5
ethylene oxide	1.18						H	4
ethylene oxide		1.06 ^a					D	5
n-heptane	2.14	1.91	1.25	4.8	0	100	C	8
n-heptane	2.2	-					H	4
n-heptane	2.03	1.89	1.2	3.2	0	100	C	1

TABLE A.1.1. (continued)

FUEL SYSTEM	Stoichiometric Quenching Distance (mm)	Minimum Quenching Distance (mm)	ϕ for Minimum Quenching Distance	Depth of Quenching Passage (mm)	Direction of flame propagation (θ)	Temperature of original measurement ($^{\circ}\text{C}$)	Experimental Method	Reference
n-heptanol	2.09	1.84	1.20	3.2	0	100	C	2
1-heptyne	1.85						H	4
n-hexane	2.05	1.91	1.15		0	105	B	7
n-hexane	2.19	1.935	1.20	3.2	0	100	C	1
cyclo-hexane	3.0						H	4
n-hexanol	2.17	1.86	1.30	3.2	0	100	C	2
hexene-1	1.87	1.75	1.15		0	105	B	7
cyclo-hexene	2.1						H	4
hydrogen	0.506	0.506	1.0		0	40	B	7
hydrogen	0.64	0.64	1.0				G	11
hydrogen	0.60						H	4
hydrogen	0.70 ^e			2.8			D	9
hydrogen		0.58 ^e		2.8	0		D	5
{ hydrogen- oxygen	0.19 ⁺			13	0		C	12.

TABLE A.1.1. (continued)

FUEL SYSTEM	Stoichiometric Quenching Distance (mm)	Minimum Quenching Distance (mm)	ϕ for Minimum Quenching Distance	Depth of Quenching Passage (mm)	Direction of flame propagation (θ)	Temperature of original measurement ($^{\circ}\text{C}$)	Experimental Method	Reference
hydrogen-oxygen	0.34 [†]						G	10
methane	2.6 ^a						A	3
methane	2.5	2.5	1.0	19 to 38	0		C	13
methane	2.16	2.0	1.12				G	11
methane	2.5 ^b						E	14
methane		2.3		0.8	0		D	5
Methane	2.2	2.2	1.0				H	15
Methane	2.1 ^o	2.1 ^o	1.0	>50	180		J	23
methane-oxygen	0.37	0.36	0.82				G	11
methanol	1.95	1.86	1.12	3.2	0	100	C	4
methanol		1.75 ^a		0.8	0		D	5
methanol		2.05	1.10			71	H	15

TABLE A.1.1. (continued)

FUEL SYSTEM	Stoichiometric Quenching Distance (mm)	Minimum Quenching Distance (mm)	ϕ for Minimum Quenching Distance	Depth of Quenching Passage (mm)	Direction of flame propagation (θ)	Temperature of original measurement ($^{\circ}\text{C}$)	Experimental Method	Reference
{ 20% m/m methanol with iso-octane	1.15	3.04	1.34	3.2	0	100	H	15
methyl acetylene							H	4
{ methyl ethyl ketone		1.74	1.38			100	C	2
methyl formate	1.65						H	4
{ methyl prop- ionate		1.61	1.22	3.2	0	100	C	2
n-nonane	2.09	1.85	1.40	3.2	0	100	C	1
n-octane	2.05	1.86	1.35	3.2	0	100	C	1
iso-octane	2.65	2.09	1.30	3.2	0	100	C	1
iso-octane		1.93 ^a		0.8	0		D	5
iso-octane	3.47						H	4
iso-octane	2.74	2.12	1.30	4.8	0	100	C	8
iso-octane	2.19	2.04	1.15		0	105	B	7
iso-octane		2.69	1.35			100	H	15

TABLE A.1.1. (continued)

FUEL SYSTEM	Stoichiometric Quenching Distance (mm)	Minimum Quenching Distance (mm)	ϕ for Minimum Quenching Distance	Depth of Quenching Passage (mm)	Direction of flame propagation (θ)	Temperature of original measurement ($^{\circ}\text{C}$)	Experimental Method	Reference
n-pentane	2.07						H	4
n-pentane	2.14	1.94	1.2	3.2	0	100	C	1
n-pentanol	2.5	2.01	1.3	3.2	0	100	C	2
n-propane	2.07	1.91	1.15		0	105	B	7
n-propane	2.1	2.0		19-38	0		C	13
n-propane	2.03	1.84	1.16	4.8	0		C	17
n-propane	1.75						H	4
n-propane	2.03	1.92	1.11	-	90		F	16
{ n-propane- oxygen	0.31	0.30		19-38	0		C	13
{ n-propane- oxygen	0.22						G	11
n-propanol	2.10	1.95	1.13	3.2	0	100	C	2

TABLE A.1.1. (continued)

FUEL SYSTEM	Stoichiometric Quenching Distance (mm)	Minimum Quenching Distance (mm)	ϕ for Minimum Quenching Distance	Depth of Quenching Passage (mm)	Direction of flame propagation (θ)	Temperature of original measurement ($^{\circ}\text{C}$)	Experimental Method	Reference
{ propion aldehyde	1.75						H	4
{ n-propyl acetate	2.27	2.24	1.3	3.2	0	100	C	2
{ di-isopropyl ether	3.0						H	4
{ n-propyl formate		1.89	1.30	3.2	0	100	C	2
{ propylene oxide	1.3						H	4
toluene	2.45	2.20	1.20	3.2	0	100	C	2
vinyl acetate	2.35						H	4
xylene		2.02 ^a		0.8	0		D	5
o-xylene	2.62 ⁺	2.29	1.22	3.2	0	100	C	2
m-xylene	2.66	2.46	1.18	3.2	0	100	C	2
p-xylene	2.10 ⁺	2.46	1.18	3.2	0	100	C	2

TABLE A.1.2. Experimental Quenching Distances for some Cool Flames

FUEL SYSTEM	Stoichiometric Quenching Distance (mm)	Minimum Quenching Diameter (mm)	ϕ for Minimum Quenching Distance	Depth of Quenching Passage (mm)	Direction of flame propagation (θ)	Temperature of original measurement ($^{\circ}\text{C}$)	Experimental Method	Reference
Diethyl ether-air n-heptane-air		<6 12.5	<80% stoichio-metric air requirement 41-137% stoichio-metric air requirement	9.4 9.4	0 0	140/230 280/310	D D	18 18

TABLE A.1.3. Experimental Quenching Distances for some Decomposition Flames

FUEL SYSTEM	Stoichiometric Quenching Distance (mm)	Minimum Quenching Distance (mm)	ϕ for Minimum Quenching Distance	Depth of Quenching Passage (mm)	Direction of flame propagation (θ)	Temperature of original measurement ($^{\circ}\text{C}$)	Experimental Method	Reference
Ethylene oxide	10					175		19
Ethylene oxide	32.5 ^a						I	21
Ethylene oxide	45.5 ^a						I	22
Ozone	0.059 ^a			200	90	20		20
<u>Ozone</u> <u>Oxygen</u>								
75 25	0.107 ^a			200	90	20		20
50 50	0.254 ^a			200	90	20		20
25 75	1.07 ^a			200	90	20		20

TABLE A.1.4. References to data obtained for flames in non standard oxidising atmospheres

Fuel	Oxidising atmosphere	Experimental Method	Reference
Hydrogen	Helium/oxygen Argon/oxygen Nitrogen/oxygen Carbon dioxide/oxygen	C	121
Hydrogen	Bromine	I I	24 25
Acetylene	Argon/oxygen	A	26
Acetylene Ethane Ethylene	Oxides of nitrogen Oxides of nitrogen Oxides of nitrogen	A	26

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APPENDIX 2 THEORY, DESIGN AND CONSTRUCTION OF A SENSITIVE DIAPHRAGM PRESSURE GAUGE

Design and construction of the diaphragm gauge

A theoretical treatment of capacitance type diaphragm pressure gauges is given by Lilly, Leglais and Cherry⁽¹⁾ and is outlined below. This shows that the important dimensions to be decided for a given diaphragm material are:

- A the radius of the diaphragm
- B the radius of the fixed electrode
- C the distance separating the diaphragm and the electrode
- T the thickness of the diaphragm

On the basis of a design by Cook and Danbey⁽²⁾ for a capacitance gauge for measuring pressure differentials similar to those predicted for this work, A and B were initially chosen to be 38mm ($1\frac{1}{2}$ inches) and 12.7mm ($\frac{1}{2}$ inch) respectively.

The value of D could be altered by screwing the charged electrode towards or away from the diaphragm. The diaphragm was cut from hardened aluminium foil 0.2mm thick. This thickness could be conveniently handled and with D suitably adjusted the gauge responded satisfactorily to the required range of pressure differentials encountered.

A.2.1.

Fig / shows a cross section through the gauge, the main body (6) of which was circular. The main material of construction was brass with insulating parts made from 'Tufnol'.

The charged electrode (1) had its flat circular face mounted on a threaded shank slotted at the opposite end so that it could be easily screwed towards or away from the diaphragm (2) being at all times parallel with it. The collar (1A) holding the electrode was mounted in the "Tufnol" insulating plate (3) which had four holes bored through it. Also mounted on the insulating plate was the guard ring (4) which was concentric with the electrode and surrounded it.

The guard ring, which was charged independently to the same voltage as

the electrode eliminated the edge effects due to the non-uniformity of the field at the circumference of the electrode and the stray capacitances which would otherwise have been formed between the electrode and other parts of the gauge, and would have interfered with the principal capacitance which was then restricted to that formed by the electrode and the central portion of the diaphragm directly opposite.

The connections to the electrode and to the guard ring were introduced into the body of the gauge through the "Tufnol" insert (5) which was cemented into the wall of the gauge with epoxy resin. The leads were also similarly cemented into the insert thus forming a gas-tight seal. The electrode connection was screwed to the electrode collar (1A) and that to the guard ring passed through one of the holes in the insulating plate (3) and screwed to the back of the ring. The diaphragm was at earth potential being in electrical contact with the gauge body which was itself earthed.

At first, the diaphragm consisted solely of a disc of the aluminium foil. Although the disc was initially flat, when it was clamped to the gauge body by bolting down the cover plate (7A) it tended to buckle at the centre and consequently deflected unevenly. Therefore a diaphragm mounting plate (8) was made. An aluminium foil disc, the same diameter was stuck to the face of the plate, which had a central hole 2 ins diameter, by means of 'Bostik'. The value of 'A' was therefore reduced to 25mm (1in) This assembly could be clamped tightly between the gauge body and the end plate without distortion of the diaphragm. Rubber gasket rings between the body and the diaphragm mounting plate and between the plate and the end cover produced a gas-tight seal. The original intention was to insert a guard diaphragm of much thinner foil between the body and the other cover plate (7B). The purpose of this second diaphragm was to act as a mechanical barrier to prevent fuel vapour entering the gauge via the pressure tapplings and altering the dielectric constant of the medium (air) between the electrode and main diaphragm and hence the capacitance of the gauge. However it was not possible to get a gas-tight seal around this second diaphragm as, even with rubber gasket rings, the diaphragm as, even with rubber gasket rings, the diaphragm was punctured around the periphery when the end plate was

bolted down tight enough to make the seal gas-tight. Subsequently experiments showed that it was in fact not necessary to have this barrier diaphragm. Diffusion of fuel vapour into the gauge body was not detected in terms of change in gauge capacitance.

No attempt was made to design the gauge to be temperature stable and it was therefore temperature sensitive. The gauge's temperature was therefore held constant immersed in a thermostated waterbath held at $30^{\circ}\text{C} \pm 0.1^{\circ}\text{C}$.

The connections to the pressure tapplings consisted of 3mm I.D. pressure tubing 0.5m long terminating above water level. The connections were completed by short lengths of copper tubing connected to the cover plates.

The gauge was connected to the capacitance meter by means of a three-core co-axial cable and suitable plug and socket connectors. The gauge socket was screwed onto a U-shaped brass block (9) soldered to the side of the gauge body so that the leads from the socket to the electrode and guard ring could be passed through the "Tufanol" insert (5). The gauge body was earthed via the socket and plug to the outer screen of the connecting cable.

The electronic measuring and recording equipment

The capacitance measuring and amplifying circuit employed as its principal component a "Proximity Meter type P.M.2" manufactured by Fielden Electronics Limited. The instrument was modified for this particular application.

The signal from the meter was displayed on the screen of a C.R.O. and recorded photographically. The circuit is shown schematically in Fig. A.2.2.

KHz

An oscillator operating at 500 / supplied a small R.F. voltage of about 1 volt R.M.S. to a phase balancing network the output of which consisted of two earth-free, equal and antiphase voltages joined in series at the point P. One side of this circuit was connected to earth via the variable condenser C_1 (balance control) and the other side was fed to

earth via C_2 the capacitance of the pressure gauge.

When C_1 was adjusted to balance C_2 the voltage at the centre point P was zero and the output voltage was therefore also zero. Any asymmetry in the values of C_1 and C_2 (due to deflection of the pressure gauge diaphragm) resulted in an 'out of balance' voltage being fed to the R.F. amplifier which had a variable gain, or sensitivity, control.

In addition to the capacitances shown in the schematic diagram, a further variable condenser was used in conjunction with C_1 as a fine balance control. A resistive balance was also provided to apply power factor connections.

The output signal from the R.F. amplifier consisted of an A.C. voltage which was fed into a cathode ray oscilloscope. This signal caused the spot to oscillate in a vertical direction symmetrically about its original position, the frequency being high enough for the trace to have the appearance of a solid vertical line when stationary.

The screen being initially blank, a single sweep of the trace, the duration of which was chosen to cover the whole of the event, was triggered by the same low voltage pulse produced by the camera shutter in the ignition circuit. Thus ignition and signal display were initiated simultaneously. The time bases used were in the range 50-200 ms/cm. A solid amplitude modulated trace was produced which was symmetrical about the zero baseline.

For determining the pressure from these traces, only the half of the trace above the centre line was measured, ie half trace height.

Summary of theory of capacitance type diaphragm pressure gauge

Following the detailed theory of the response of stiff and flexible diaphragm capacitance type pressure gauges discussed by Lilly et al⁽¹⁾, one can write, for a stiff diaphragm deflected towards the charged electrode

$$\frac{\Delta C}{C_0} = \frac{1}{N} \left[\frac{1}{3} (1-H^3) \omega + \frac{1}{5} (1-H^5) \omega^2 + \dots \right] \quad (1)$$

where C_0 is the total capacitance of the gauge at zero diaphragm deflection

ΔC is the capacitance change resultant upon a deflection of the diaphragm

$$N = \left[\frac{B}{A} \right]^2$$

B is the radius of the charged electrode (cm)

A is the radius of the diaphragm (cm)

$$H = \left[1 - N \right]$$

$$W = y_0 / D$$

D is the distance between the undeflected diaphragm and the charged electrode

The deflection (y_0) of the diaphragm upon application of a pressure differential (p dynes/cm²) is a function of the mechanical properties of the diaphragm. The deflection constant, K (cm²/dyne) is given by

$$K = \left(\frac{y_0}{p} \right) \left(\frac{T^3}{A^4} \right) = \frac{3}{16} \left(\frac{1-t^2}{Y} \right) \quad (2)$$

where T is the thickness of the diaphragm

t is Poisson's ratio for the diaphragm material

and Y is its Young's Modulus

Therefore one can write

$$y_0 = k_1 p \quad (3)$$

where k_1 is a constant involving only the diaphragm dimensions and the properties of the material from which it is made.

Considering the modified capacitance meter (Fielden Proximity Meter), the specified characteristic voltage output signal is substantially linear with change in gauge capacity. This specified performance is not affected by the modifications made. Only at relatively high sensitivity settings, is there significant departure from linearity. At the sensitivity setting used as standard in this work ($S = 25$), specified deviation from linearity is less than $\pm 2\%$

One can therefore write;

$$V = k_2 \Delta C \quad (4)$$

Combining equations (1), (3) and (4) gives

$$V = ap + bp^2 + cp^3 + \dots \quad (5)$$

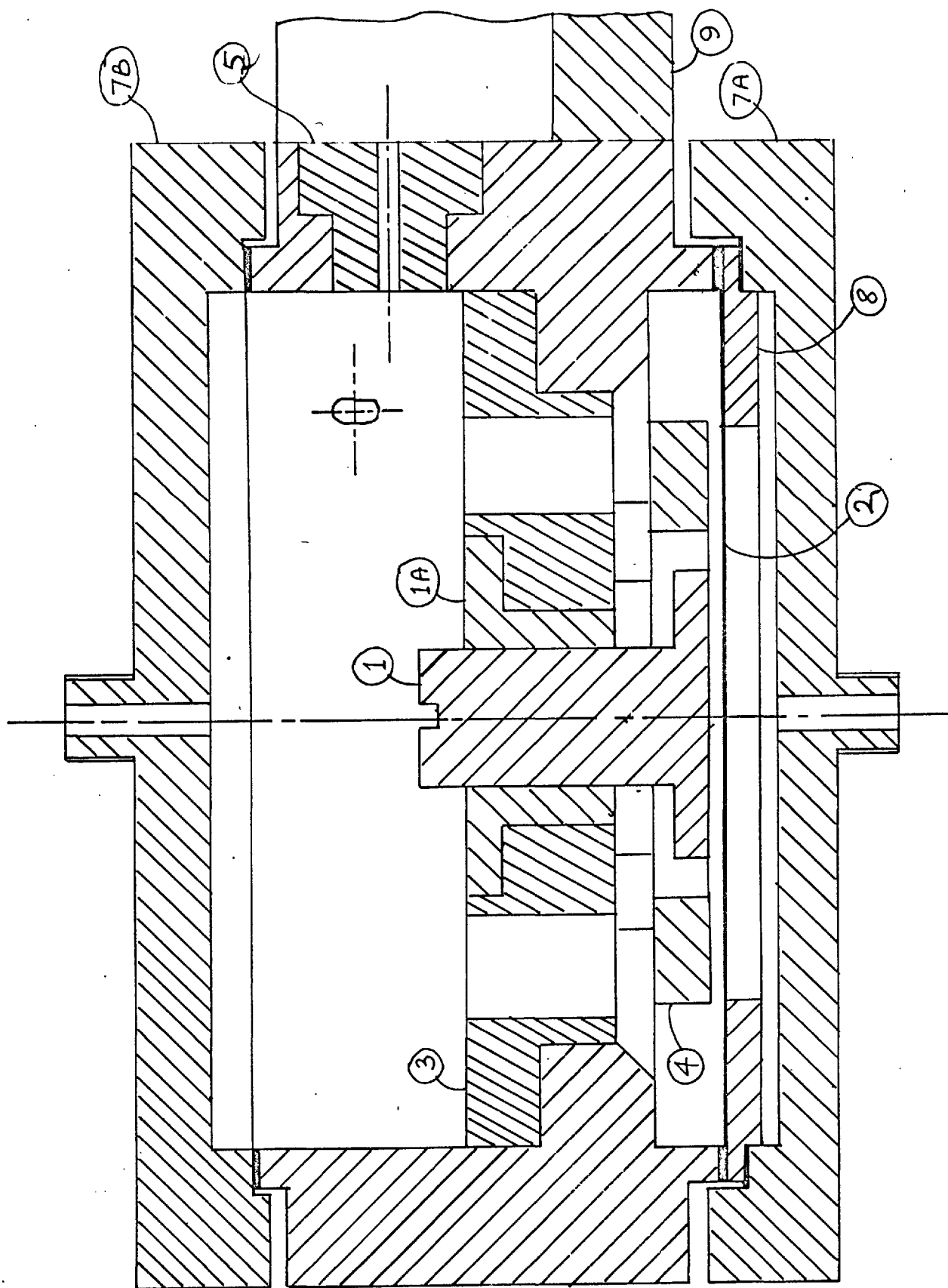
where a, b, c are constants dependent upon the pressure gauge and capacitance meter characteristics.

A.2.3.

The calibration curve shown in Fig / is seen to be of the form of equation (5), with $a = 3.63$ $b = -1.07$, $c = 0.86$ for a coefficient of correlation, 0.999.

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FigA.2.1. Cross section through pressure gauge
showing detailed construction.
Scale: approx twice full size.

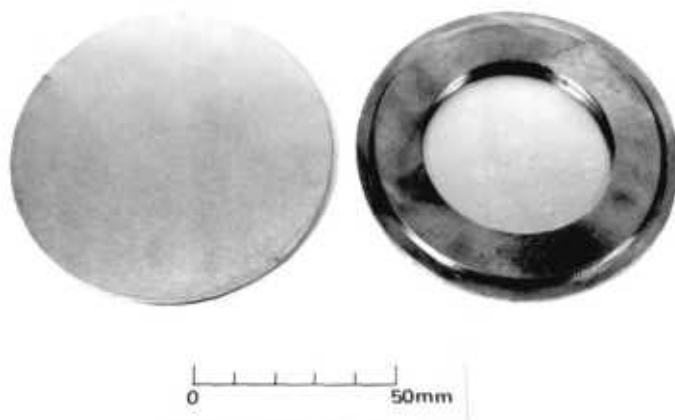


Fig. A.2.2. Front and back view of diaphragm.



Fig. A.2.3. View of gauge showing electrodes

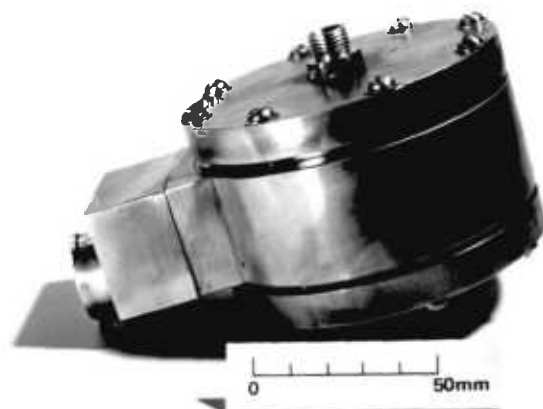


Fig. A.2.4. View of assembled gauge

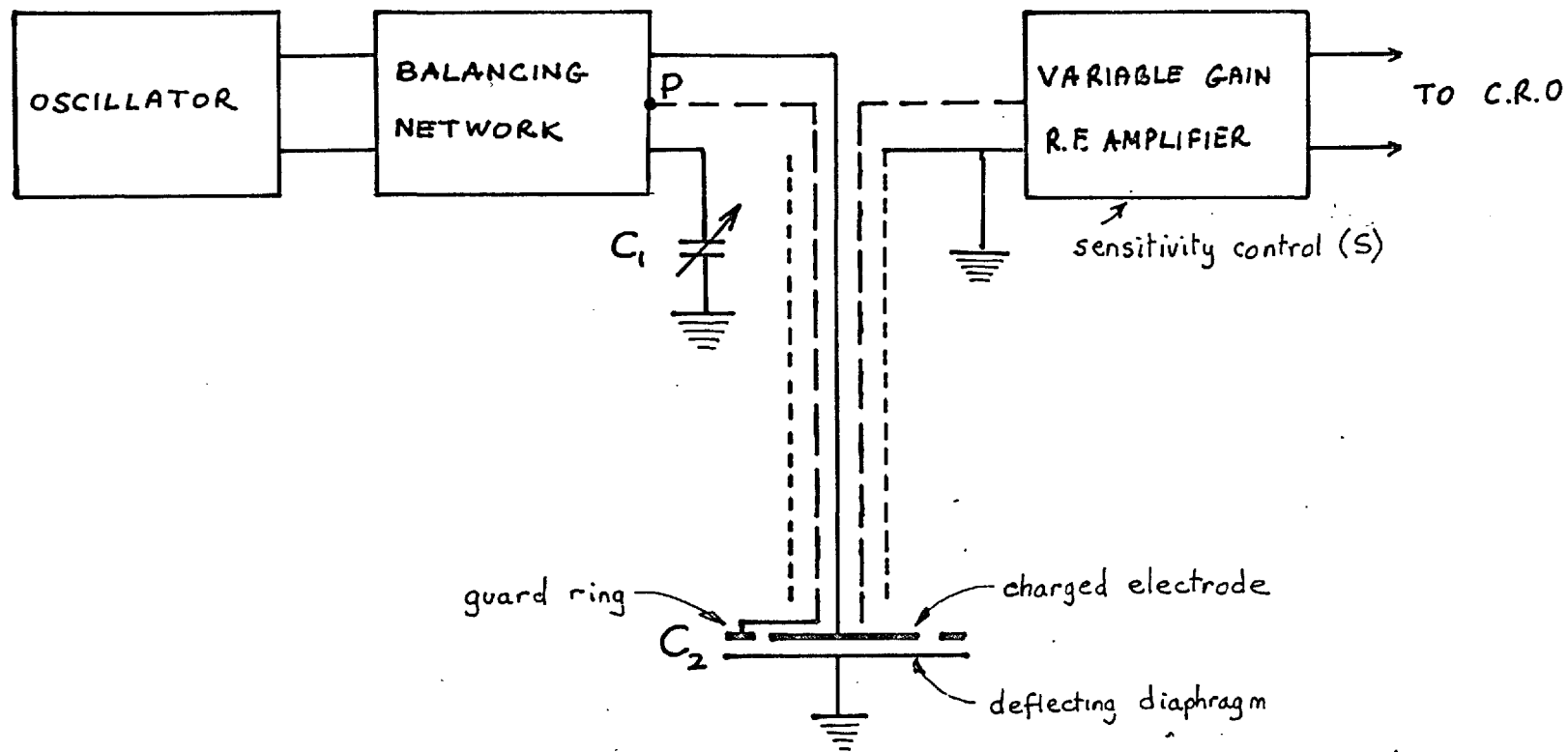


Fig. A.2.5 Electronic Pressure Measuring Circuit

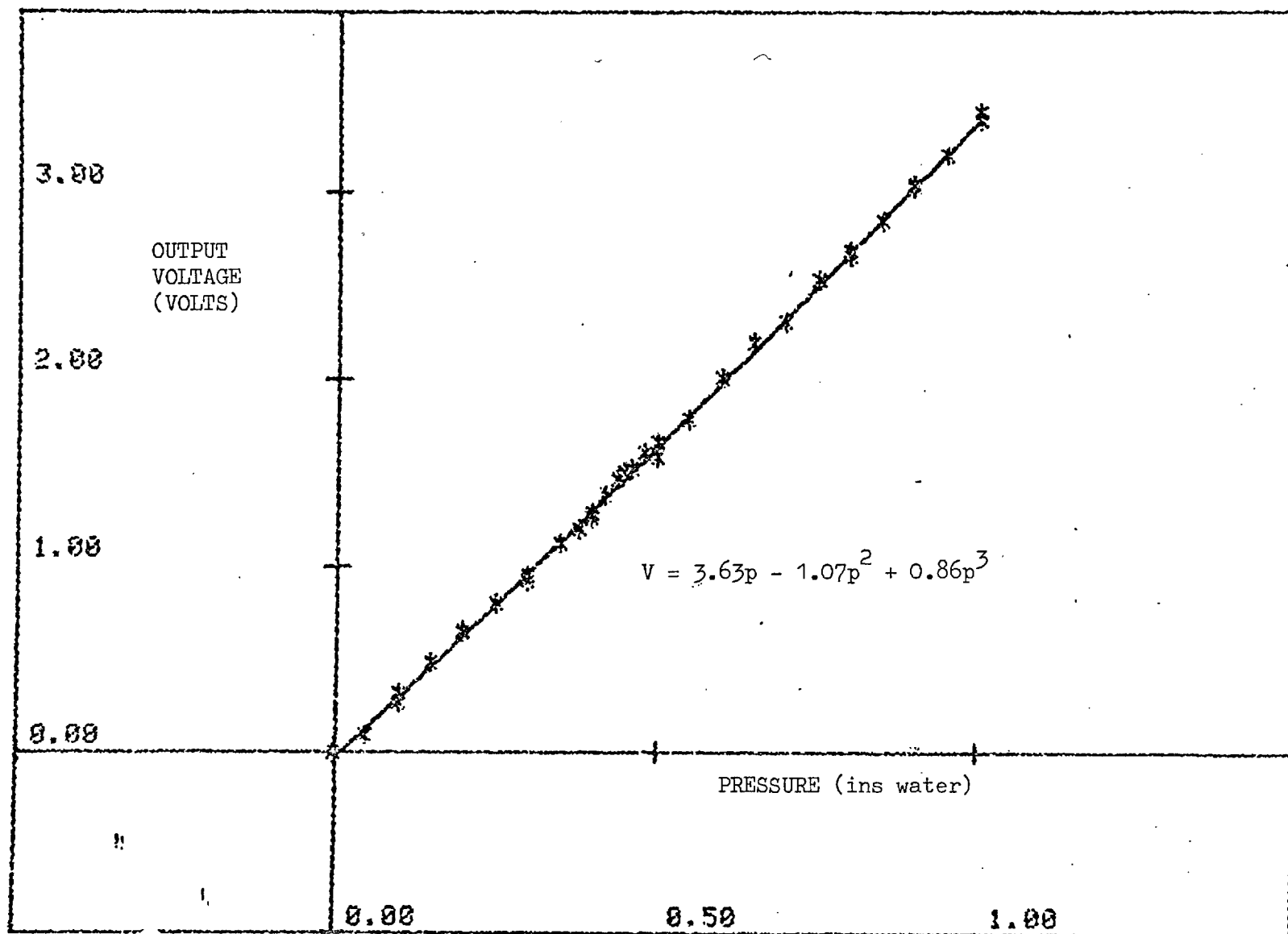


FIG A.26 REGRESSION ANALYSIS OF GAUGE CALIBRATION