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DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH AND FIRE OFFICES' COMMITTEE
JOINT FIRE RESEARCH ORGANIZATION

# THE FUNDAMENTAL STUDY OF FLAME ARRESTERS.

## 3. WIRE GAUZE ARRESTERS IN LONG NARROW DUCTS.

by

K. N. Palmer and P. S. Tonkin

## Summary

The performance of single layers of wire gauze as flame arresters has been studied using horizontal ducts, of 6.4 cm. internal diameter, and lengths 237 and 392 cm. The flammable mixtures, containing propane as fuel, were ignited by an electric spark either at the open or at the closed end of the ducts. The quenching of the flame by the gauze was dependent upon the velocity of approach of the flame, and considerably faster flames were obtained than in previous experiments with the same flammable mixtures in a shorter duct.

Some theoretical considerations of the quenching are also given.

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## Introduction

In previous papers describing experiments with wire gauze flame arresters for gas explosions (1, 2) it was shown that the velocity of the flame as it approached the arrester was an important factor in the quenching of the flame by the arrester. It appeared that with a given gauze arrangement there was a critical velocity of approach of the flame below which the flame was quenched by the arrester and above which it passed the arrester. All experiments were carried out with a short tube in which the gas mixture was ignited at the open end, with the other end closed. The flame velocity varied with the composition of the combustible mixture and with the direction of propagation and was particularly dependent upon the run-up, i.e. the length of tube between the arrester and the source of ignition. Thus with the short tubes used the flame velocity increased markedly with the run-up. The experiments described in the present note were carried out with a longer tube than that used hitherto, so that the effectiveness of gauze arresters in quenching high velocity propane flames resulting from the longer run-up could be studied. In the tests the igniting spark was either near the open end of the tube, so that the flame propagated towards the closed end of the tube as in the earlier experiments, or at the closed end of the tube so that the flame propagated towards the open end. In all experiments the unburnt gas mixture was stationary at the moment of ignition.

## Experimental

### Materials and apparatus

The arresters consisted of single layers of gauzes of various meshes, some characteristics of the gauzes are listed in Table 1. In each case the values for the wire diameter and the mesh width (the width of a hole in the gauze) are the means of three determinations.

Table 1

Characteristics of the wire gauzes.

| Material of gauze | Nominal mesh | Nominal wire gauze S.W.G. | Mesh width cm. | Wire diameter cm. | Surface area of wire in unit area of gauze $cm^2$ |
|---|---|---|---|---|---|
| Brass | 6 | 20 | 0.329 | 0.0940 | 1.40 |
| " | 10 | 24 | 0.198 | 0.0559 | 1.39 |
| " | 18 | 28 | 0.106 | 0.0356 | 1.58 |
| " | 40 | 34 | 0.0404 | 0.0231 | 2.29 |
| " | 60 | 37 | 0.0248 | 0.0175 | 2.60 |
| " | 80 | 39 | 0.0192 | 0.0130 | 2.54 |
| Phosphor Bronze | 120 | 43 | 0.0125 | 0.0089 | 2.61 |
| " " | 200 | 46 | 0.0065 | 0.0061 | 3.04 |

The propane used in the preparation of the explosive gas mixtures was specified by the manufacturers as being at least 97 per cent pure; particularly fast flames were obtained by enriching the propane/air mixture with oxygen, the oxygen was of normal commercial purity.

The tube used for the explosions was mounted horizontally and was of perspex, the internal diameter being 6.4 cm. and the wall thickness being 0.6 cm. The length of the tube and the position of the arrester were changed for different experimental conditions. In experiments in which the explosion propagated from the open end of the tube the total length of the tube was 392 cm., the arrester was inserted 325 cm. and the igniting electrode was 12.7 cm. from the open end of the tube. In experiments in which the explosion propagated from the closed end the total length of the tube was either 237 cm. or 392 cm. and the arrester was sited 165 cm. or 320 cm. respectively from the closed end. The igniting electrode was 7.6 cm. from the closed end in both cases.

Measurements of flame velocities near the arrester were made using a rotating drum camera; the speed of the drum was calibrated either by means of an argon lamp giving 50 flashes/sec. or by a signal generator in conjunction with a cathode ray oscilloscope. The camera did not photograph the flame directly but via two plane mirrors which reflected the top surface of the tube into the camera. The camera lens was focussed on a point 2.1 cm. below the interior top surface of the tube. The reason for this arrangement was that when viewed from above in a horizontal tube the flame appears more symmetrical than when viewed from the side. Also, the foremost part of the flame propagated about one centimetre above the axis of the tube.

## Procedure

The gauzes were cut to form circular discs whose diameter equalled that of the outside of the tube and were then washed in carbon tetrachloride to remove oil and grease. The gauze arrester was then inserted in the tube, as described earlier (1), and the junction between arrester and tube sealed with transparent tape. The gas mixture was metered through the tube, allowing about ten changes of gas in the tube, and the supply was then cut off. The quiescent gas mixture in the tube was ignited by an induction spark from a small coil and the movement of the flame near the guaze was recorded by the drum camera. The velocity of the flame was measured at a point 1.5 cm. from the gauze surface on the approach side. The flame velocity was calculated from measurements of the slope of the flame front on the photographic record and the speed of rotation of the camera drum.

## Results

The arresting of flames by single layers of a wide range of wire gauzes was studied using the 392 cm. tube with ignition near the open end, and the results are plotted in Fig.1. The flame velocity is plotted against the mesh width, on logarithmic axes, and distinction is made as to whether or not the flame passed the gauze. A straight line could then be drawn on the graph which, with some exceptions, separated the results of experiments in which the gauze quenched the flame from those results for which the flame passed through the gauze. The line was arranged so that equal numbers of the exceptional results fell on each side of it. At this stage no account was taken of variation in the composition of the explosive mixture, although in order to obtain the slow flames required with coarse gauzes it was necessary to use near-limit mixtures; further discussion of this point is given later.

The results shown in Fig. 2 and 3, for experiments with ignition at the closed end of the tube, are again plotted on logarithmic axes. In all the experiments in Fig. 1 - 3, the velocity of the flame was measured relative to the tube, and not relative to the unburnt gas.

## Discussion

### Correction of results for variation in the composition of the gas mixture.

In previous experiments with wire gauze arresters it was possible to obtain empirical relations between the mesh width and the critical velocity of approach at which the flame was just quenched, without taking into account the variation made in the composition of the gas mixture (1, 2). The composition of the gas varied in order to change the velocity of the flame without alteration of the tube arrangement. As the tubes were relatively short, slowly-moving flame could be obtained with fuel-air mixtures whose compositions were not near to the flammability limits. In the present experiments, with a much longer run-up distance between the igniting source and the arrester, it was necessary to use near-limit gas mixtures to obtain flames sufficiently slow to be quenched by the coarse gauzes; an allowance must therefore be made for the greater ease with which near-limit flames may be quenched, as compared with near-stoichoimetric flames moving with the same velocity. An estimate of the required allowance may be obtained from Botha and Spalding (3) who measured the variation in the burning velocity of propane-air mixtures with the amount of heat absorbed from the flame by a water-cooled surface, using a flat-flame burner. They showed that in order to reduce the burning velocity of a stoichiometric propane-air flame to that of a lower limit flame a quantity of heat 5.0 cal./ml. propane must be extracted from the flame. It was assumed earlier (1) that if this amount of heat were removed from the stoichiometric flame then the flame would be quenched. However, with near-limit flames the amount of heat to be removed would be less; thus with a 2.5 per cent propane-air flame only 1.8 cal./ml. propane need be removed. In addition, when the composition of the flammable mixture is varied the temperature of the flame alters and so properties of the flame gases, such as the thermal conductivity, also change.

Now the relation derived previously (1) between the gauze mesh width and the approach velocity of the flame that was just quenched by the gauze, assuming that as ignition was at the open end of the tube the unburnt gas was stationary, was given by

$$V = \frac{1.75k\ (T_h - T_g)}{m^{0.9} \quad Q/x_o} \quad - - - - - - - - - - - - \quad (i)$$

The symbols are defined on page 5. The terms k, $(T_h - T_g)$, $Q/x_o$ depend upon the composition of the flame. Values of the correction factor for flames of different compositions were derived from Botha and Spalding (3) and other sources (4, 5) and are given in Appendix 1 (final column); the factor is unity for stoichiometric propane-air flames. In some cases the method involved extrapolation from published data. The results given in Fig, 1 - 3 have been corrected for variation in mixture composition by multiplying the flame velocity by the correction factor. The corrected velocities, which are the velocities of equivalent stoichiometric propane-air flames, are re-plotted in Fig. 4 - 6.

### The quenching of a flame by gauze

The theoretical line for stoichiometric propane-air flames ignited at the open end of the tube, represented by Eq.(i), is included in Fig.4 and it may be seen that the theoretical value of V is too small by a factor of about 3. A similar underestimation was obtained previously for the experiments with shorter run-up lengths.(1). In the derivation of Eq(i) the data of McAdams (6) were used for the transfer of heat between a gas and a single wire and a value of 0.32 was taken for the Nusselt number; it was assumed that the gas was quiescent and the Reynolds number was negligible. However in practice the boundary layers in the gas around the wires of the gauze interact and the gas may have been in motion through the gauze. Motion of the gas could arise from the movement of expanded exhaust gases out of the tube and to acoustic vibrations excited by the flame. Both boundary layer interaction and motion of the gas would improve the performance of the gauze.

An alternative theoretical approach may be made by considering the gauze to be an array of short tubes, rather than an assembly of wires, and that the length of the tubes is two wire diameters. It is also assumed that there is a flow of gas, of velocity v, sufficient to establish a boundary layer in the tubes. Then the velocity of the flame relative to the tube, which is the quantity measured in the experiments, is given by

$$V + v = \frac{4.8\pi\ kd}{(m + d)^2}\ \frac{(T_h - T_g)}{Q/x_o} \quad - - - - - - - - - - - - \quad (ii)^{(7)}$$

A line representing Eq(ii) is shown in Fig. 4 - 6. In Fig. 4, Eq(ii) is in better agreement than is Eq(i) with the results for tests with ignition at the open end of the tube. Eq(ii) also represents the results fairly well for the case where ignition was at the closed end of the tube and the flame was propagating through a fast-moving gas (Fig.5 and 6). Eq(ii) thus represents approximately the behaviour of arresters consisting of sheeting and blocks perforated by circular holes (7) as well as wire gauze arresters irrespective of whether ignition was at the open or the closed end of the tube. The agreement is only expected to be approximate since it is assumed in deriving Eq(ii) that the streamline flow through the apertures is fully established, entrance effects being ignored.

Another estimate of the heat transfer coefficient may be obtained from results given by Grootenhuis (8) for the resistance to airflow of wire gauzes, either in single layers or in packs, and by the use of the simple Reynold's analogy between heat and momentum transfer. A value of 2.9 is obtained for the Nusselt number, and this gives a theoretical value of V too large by a factor of about 3. There is however, some doubt as to whether the simple Reynold's analogy is applicable to the flow of gases through packed beds of solids.

## Conclusions

1. The quenching of propane flames by wire gauze arresters mounted in a long narrow tube was dependent upon the velocity with which the flame approached the gauze, whether the explosion was initiated at the open end of the tube or at the closed end.

2. Considerably faster flames were obtained with a given flammable mixture in the present apparatus, with a run-up distance of 312 cm. between the igniting point and the arrester, than in the previous apparatus having a run-up of 59 cm.

3. The simple theory derived previously relating the velocity of the flame that was just quenched by the arrester to the mesh size of the gauze was again shown to hold approximately. A method was given of making allowance for the variation in ease of quenching resulting from the use of flammable mixtures of different compositions.

## Acknowledgment

Miss J. S. Hall assisted in the experimental work.

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## Notation

| Symbol | Definition |
|---|---|
| d | Wire diameter. |
| F | Fraction of gas mixture consumed as fuel. |
| k | Thermal conductivity of flame gases at mean film temperature. |
| m | Width of mesh in the gauze. |
| Q | Total amount of heat lost by unit area of flame. |
| $T_g$ | Temperature of the gauze. |
| $T_h$ | Mean bulk temperature of flame gases through the gauze. |
| V | Velocity of the flame relative to the unburnt gas. |
| v | Velocity of the unburnt gas relative to the tube. |
| $x_o$ | Thickness of flame travelling at standard burning velocity. |
| $\theta$ | Adiabatic flame temperature. |

## Appendix 1

### Quenching of propane flames; correction for changes in mixture composition

$T_g = 290^\circ K$

| Mixture composition per cent propane in air | $\frac{Q}{x_o}$. | Flame temperature θ °K | $T_h$ °K | k at film temp. $\frac{(T_h + T_g)}{2}$ | Fraction of original mixture burnt for fuel (F) | $= \frac{Q}{x_o} \times \frac{1720 \times 2.898}{(T_h - T_g) k} \times \frac{2260}{\theta} \times \frac{F}{0.04}$ |
|---|---|---|---|---|---|---|
| 2.5 | 0.36 | 1750 | 1750 | 2.704 | 0.025 | 0.36 |
| 2.75 | 0.46 | 1840 | 1800 | 2.750 | 0.028 | 0.47 |
| 3.0 | 0.56 | 1920 | 1840 | 2.780 | 0.030 | 0.57 |
| 3.25 | 0.70 | 1990 | 1870 | 2.796 | 0.033 | 0.74 |
| 3.5 | 0.80 | 2080 | 1920 | 2.842 | 0.035 | 0.82 |
| 3.75 | 0.92 | 2180 | 1970 | 2.870 | 0.038 | 0.94 |
| 4.0 | 1.00 | 2260 | 2010 | 2.898 | 0.040 | 1.00 |
| 4.5 | 0.97 | 2240 | 2000 | 2.898 | 0.040 | 0.99 |
| 5.0 | 0.80 | 2160 | 1960 | 2.870 | 0.040 | 0.87 |
| 5.5 | 0.60 | 2060 | 1910 | 2.828 | 0.040 | 0.71 |
| 6.0 | 0.48 | 1950 | 1850 | 2.780 | 0.040 | 0.64 |
| 6.5 | 0.40 | 1850* | 1800 | 2.750 | 0.040 | 0.59 |
| 7.0 | 0.36 | 1800* | 1780 | 2.734 | 0.040 | 0.55 |
| 7.25 | 0.34* | 1780* | 1770 | 2.720 | 0.040 | 0.53 |
| 7.5 | 0.33* | 1760* | 1760 | 2.720 | 0.040 | 0.53 |
| 8.0 | 0.32* | 1750* | 1750 | 2.704 | 0.040 | 0.52 |
| Mixture composition, parts by volume. Propane: oxygen : nitrogen. | | | | | | |
| 1:5:17.1 | 1.10* | 2320 | 2040 | 2.926 | 0.043 | 1.12 |
| 1:5:16.0 | 1.17* | 2350 | 2050 | 2.926 | 0.045 | 1.22 |
| 1:5:15.1 | 1.24* | 2380 | 2070 | 2.940 | 0.047 | 1.32 |
| 1:5:13.3 | 1.32* | 2450 | 2100 | 2.968 | 0.052 | 1.46 |
| 1:5:11.3 | 1.44* | 2530 | 2140 | 2.996* | 0.058 | 1.68 |
| 1:5: 9.5 | 1.54* | 2600 | 2180 | 3.024* | 0.065 | 1.89 |
| 1:5: 8.5 | 1.60* | 2640 | 2200 | 3.036* | 0.069 | 2.04 |
| 1:5: 7.6 | 1.64* | 2680 | 2220 | 3.050* | 0.074 | 2.17 |

* extrapolated value.

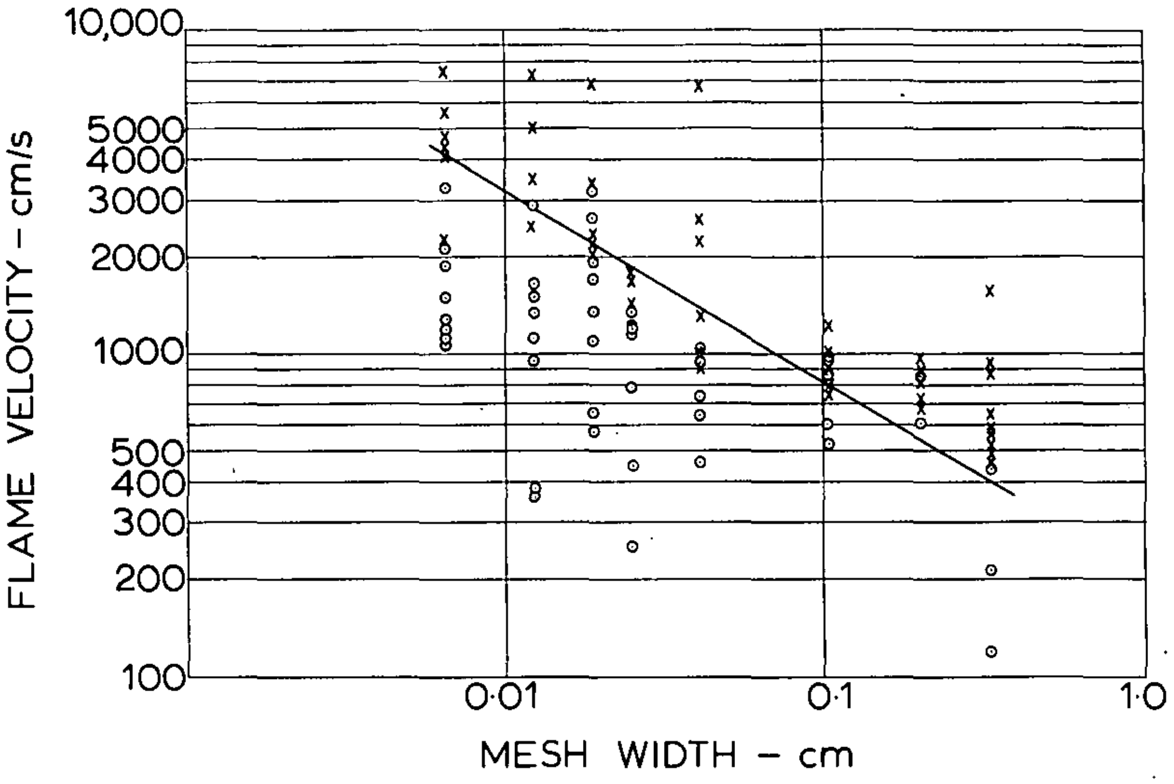

Fig. 1 GAS MIXTURE IGNITED AT OPEN END OF 392cm TUBE

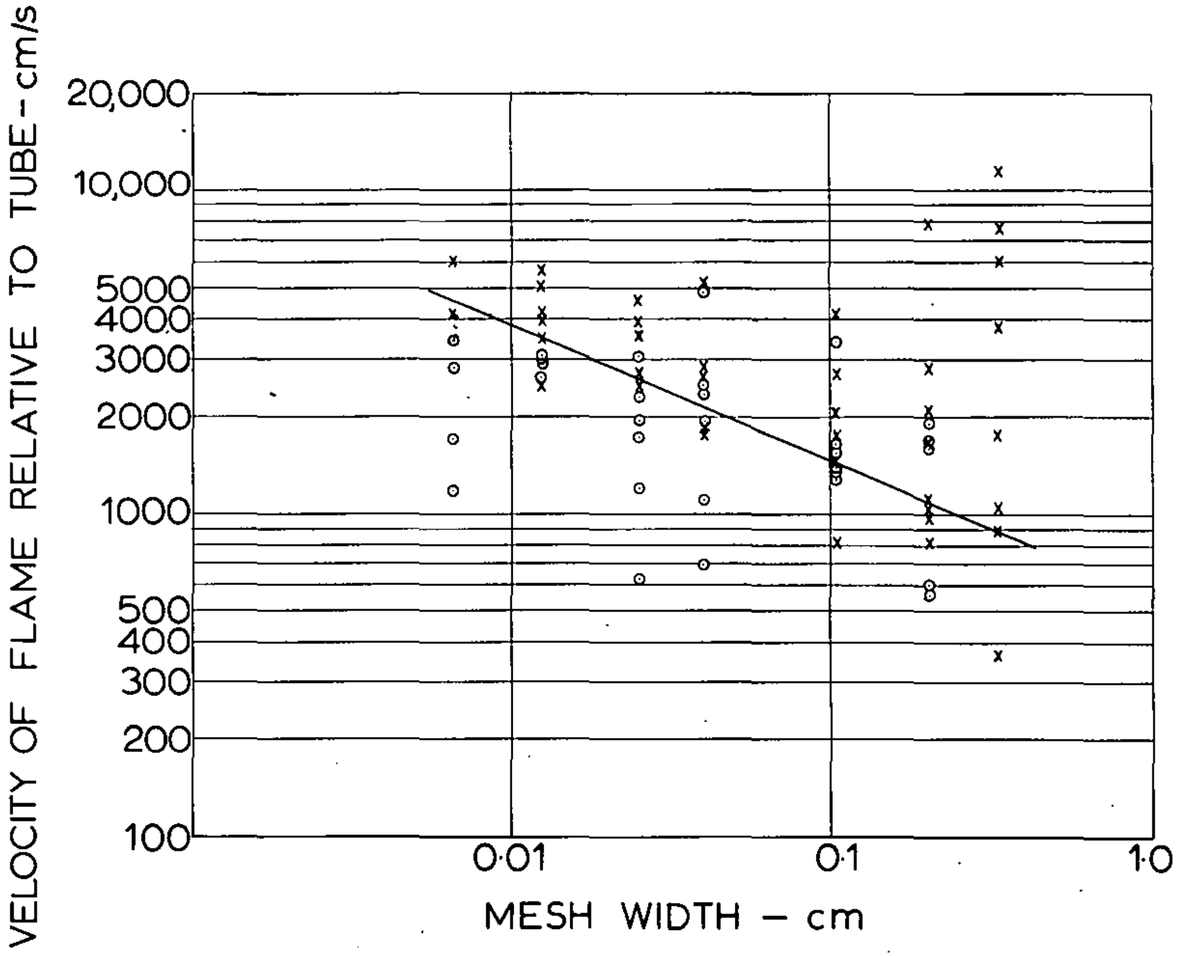

Fig. 2 GAS MIXTURE IGNITED AT CLOSED END OF 237cm TUBE

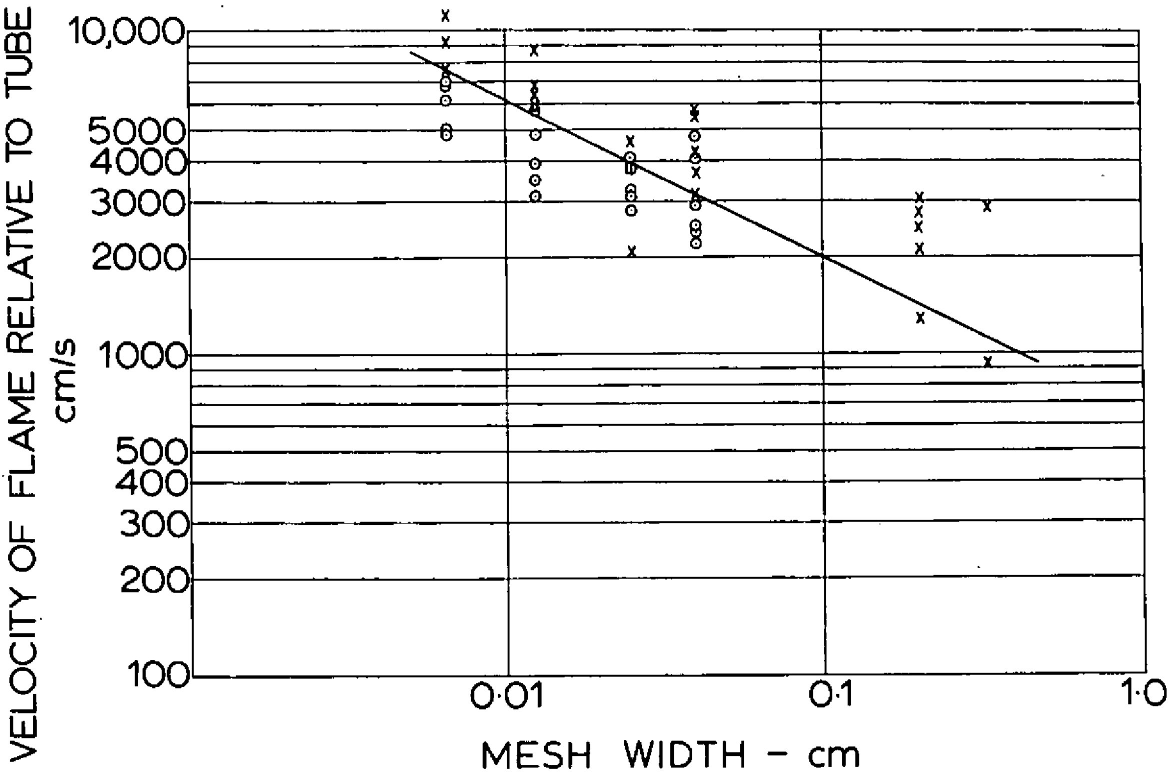

Fig. 3 GAS MIXTURE IGNITED AT CLOSED END OF 392 cm TUBE

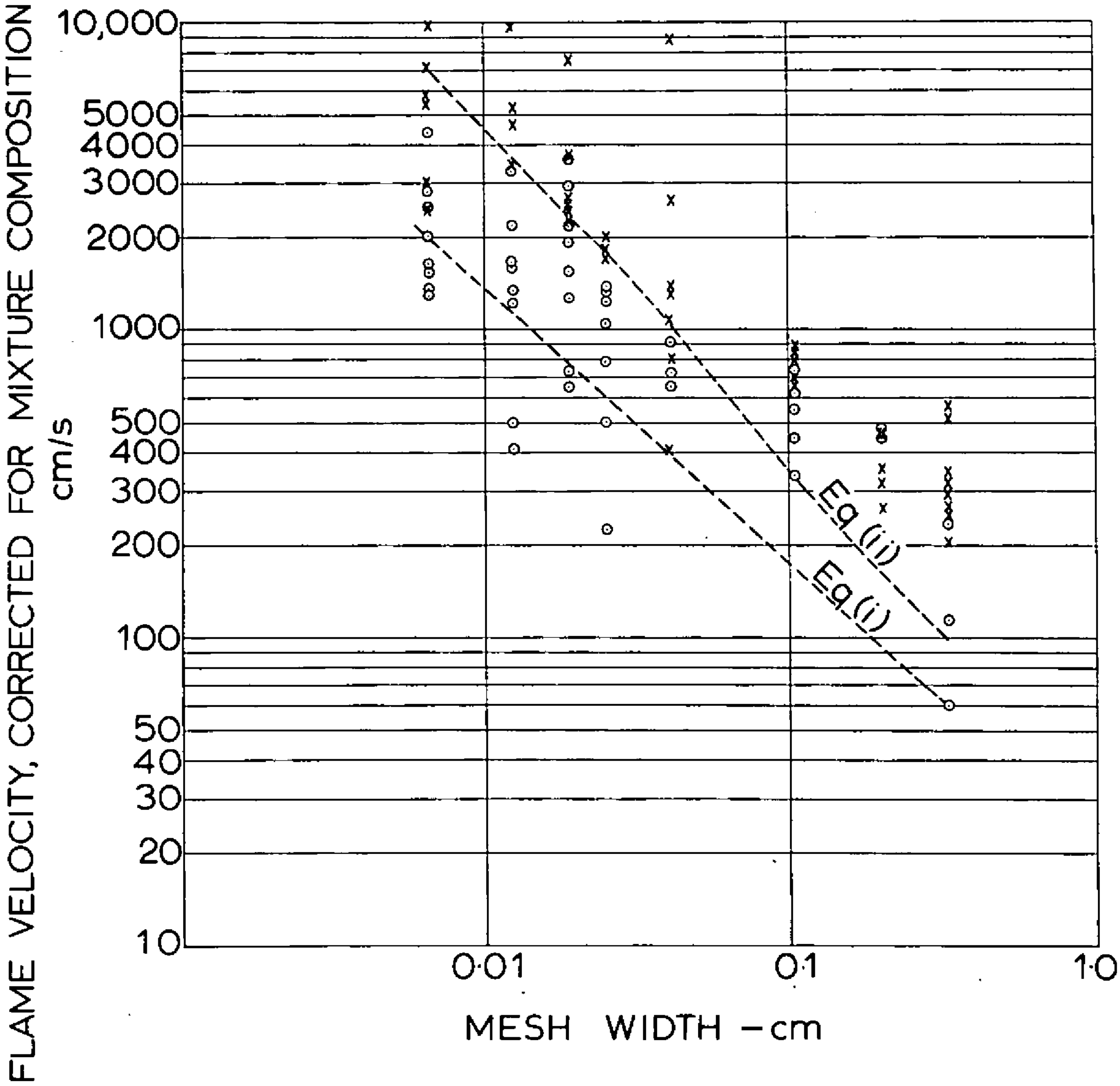

Fig. 4 RESULTS IN FIG. 1 CORRECTED FOR MIXTURE COMPOSITION. GAS MIXTURE IGNITED AT OPEN END OF 392 cm TUBE

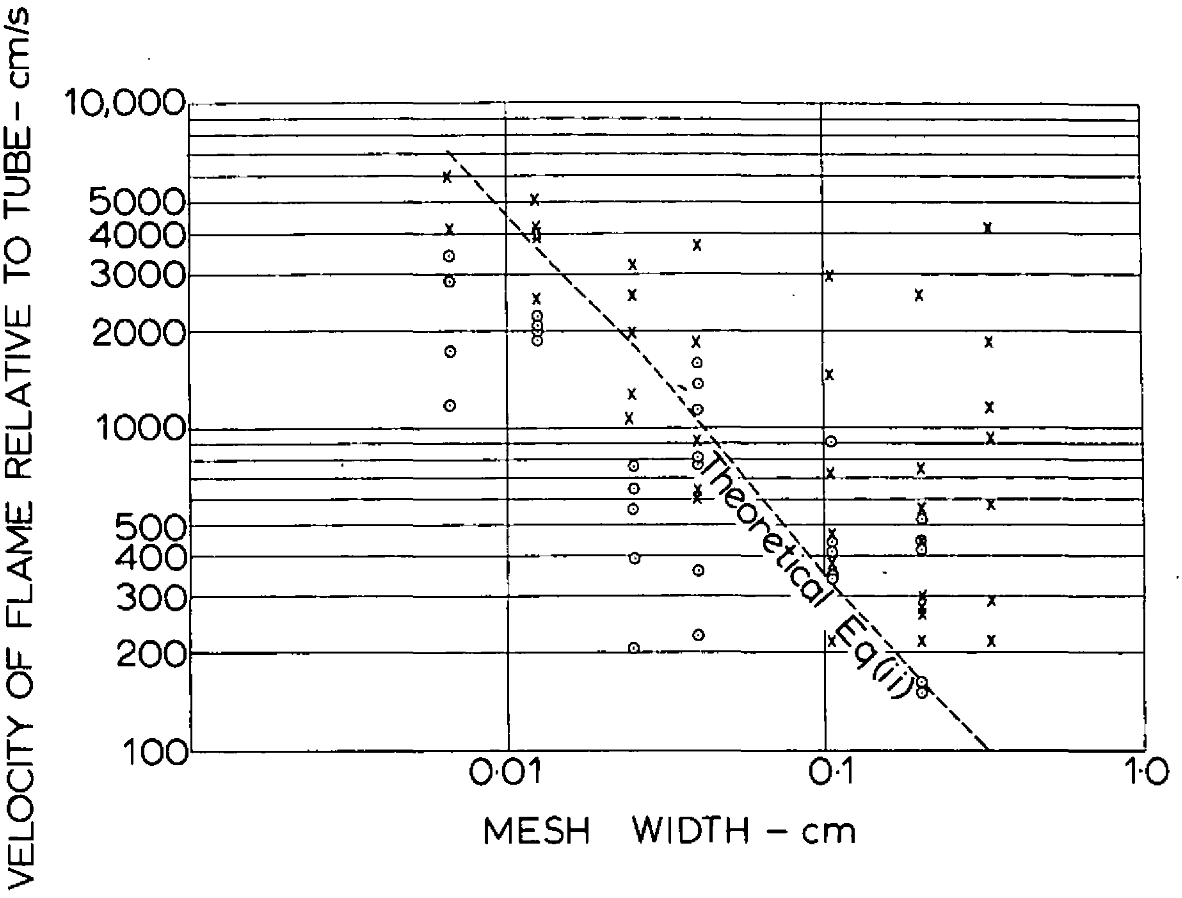

Fig. 5 RESULTS IN FIG. 2 CORRECTED FOR MIXTURE COMPOSITION. GAS MIXTURE IGNITED AT CLOSED END OF 237cm TUBE

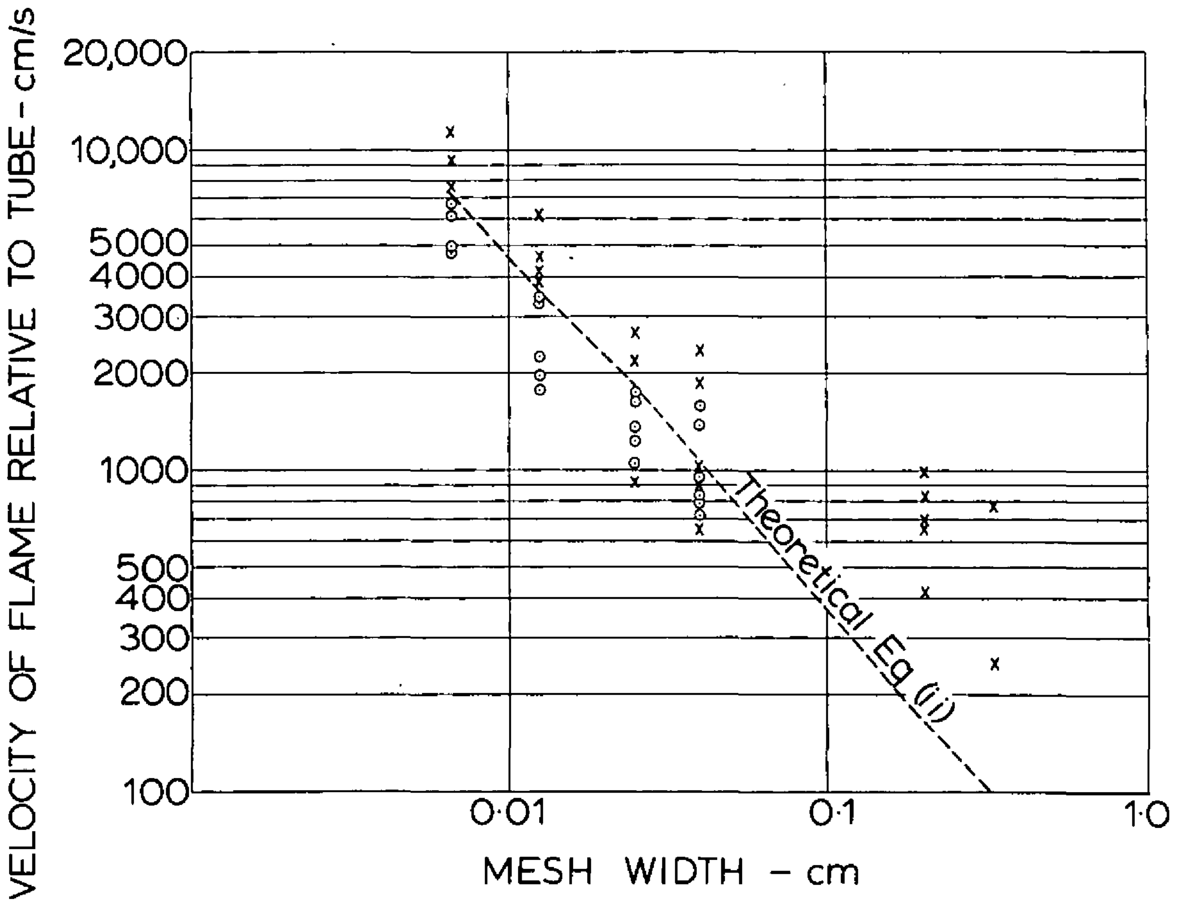

Fig. 6 RESULTS IN FIG. 3 CORRECTED FOR MIXTURE COMPOSITION. GAS MIXTURE IGNITED AT CLOSED END OF 392cm TUBE