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THE FUNDAMENTAL STUDY OF FLAME ARRESTERS: PERFORATED SHEETING AND BLOCK ARRESTERS

by

K.N. Palmer and P.S. Tonkin

SUMMARY

The performance of flame arresters consisting of metal or polyvinylchloride sheeting or blocks, perforated with circular holes, has been investigated. The arresters were mounted in horizontal tubing systems of various lengths filled with flammable propane/air mixtures which could be ignited either at the open end or at the closed end of the tube. The velocity of the flame that was just quenched by an arrester was directly proportional to the thickness of the arrester and varied inversely with the size of the holes in the arrester. No significant differences were found in the flame quenching abilities of brass and polyvinylchloride sheeting, under the conditions of test. The behaviour of arresters consisting of brass sheeting perforated by a single circular hole was erratic, when compared with that of similar arresters perforated by multiple holes.

A comparison is made between the behaviour of perforated metal and wire gauze arresters. Some theoretical consideration is given to the behaviour of the perforated arresters.

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Fire Research Station,
Boreham Wood,
Herts.

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Introduction

This note describes investigations of the behaviour of blocks and sheets of metal and polyvinylchloride perforated with circular holes as arresters for flames propagating along straight smooth-walled tubes. In previous reports[1,2,3] the behaviour of wire gauze arresters in similar systems was described and the present work was carried out in order to extend the range of arresters investigated. Both perforated metal sheeting and wire gauze arresters are used in industrial plant, for instance they are frequently installed in the vent pipes and valves of storage tanks for flammable liquids. The tests with polyvinylchloride sheeting were made to compare the performance of arresters of different thermal properties, although the polyvinylchloride arresters are unlikely to be of much practical use due to the ease with which they distort and melt. The perforated metal block arresters were tested in order to study the effect of substantially increasing the thickness of the arrester, and also because they approached in design crimped ribbon arresters but were more convenient to use experimentally. The tests with metal block arresters gave information that was later used in discussing the behaviour of crimped ribbon arresters, which are of considerable industrial importance. This work with crimped arresters is being reported separately. Finally a short investigation was made of the flame quenching properties of thin metal plates perforated with a single hole, for comparison with the behaviour of the perforated metal plates, which contained multiple holes of the same diameters.

The experimental technique was the same as that with wire gauze arresters; the velocity of the flame as it approached the arrester was measured by means of a drum camera. The camera record also showed whether or not the flame passed through the arrester. Tests were carried out under two conditions of combustion: in one the flame approached the arrester from the open end of the tube towards the closed end, and in the other the flame propagated from the closed end towards the open end and was thus propagating through a fast-moving gas stream when the flame reached the arrester.

Experimental

Materials and apparatus

The perforated sheeting was a commercial product and consisted of brass or polyvinylchloride perforated with regularly-spaced circular holes. The holes had 90° edges and were perpendicular to the surface of the sheet. In all cases except one the pattern of spacing of the holes was Pattern A, see Fig.1, but in one case Pattern B was supplied; details of the dimensions and spacing of the holes are tabulated below, (Table 1). The diameters of the holes were accurate to ± 0.25% but the accuracy of the spacing distances (a and b) depended upon the diameter of the hole. With diameters not greater than 0.175 cm the values of a and b were constant to within ± 0.5%, but with the larger holes the tolerance rose to ± 1.0%. The tabulated values of a and b are means of at least three determinations. These lengths are respectively the least and the greatest distance between the centres of neighbouring holes, measured at right angles to each other.

Table 1

Characteristics of the perforated brass and polyvinylchloride sheeting

Material	Diameter of hole (d) cm	Thickness of sheeting (y) cm	Pattern	a (Fig.1) cm	b (Fig.1) cm	Area of hole in unit area of sheeting
Brass	0.559	0.124	A	0.843	1.42	0.41
"	0.340	0.118	A	0.442	0.764	0.54
"	0.175	0.073	A	0.283	0.466	0.37
"	0.100	0.072	A	0.176	0.291	0.31
"	0.055	0.046	A	0.112	0.180	0.24
P.V.C.	0.339	0.129	A	0.454	0.793	0.48
"	0.174	0.087	A	0.259	0.450	0.41
"	0.065	0.059	B	0.149	0.159	0.14

The two sets of perforated blocks were also made in brass with holes of diameters 0.340 and 0.175 cm arranged in the same pattern as the corresponding perforated brass sheeting (Table 1). Each set of blocks consisted of five units, each 1.00 cm thick and 7.6 cm in diameter, that could be placed in contact so that the holes were accurately aligned. By means of this arrangement arresters from 1 to 5 cm in thickness were available in two sizes of perforation.

The brass plates perforated with a single circular hole were also 7.6 cm in diameter; the other dimensions are given in Table 2. The accuracy of measurement was the same as with the plates perforated with multiple holes. In each plate the centre of the hole was 1.1 cm from the centre of the plate.

Table 2

Details of the brass plates perforated by a single hole

Diameter of hole (d) cm	0.559	0.340	0.175	0.100	0.075	0.055
Thickness of plate (y) cm	0.144	0.157	0.151	0.156	0.154	0.160

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; details of these arrangements are given in Fig.2. The wide range of run-ups (IJ, Fig.2) between the igniter and the arrester was required because the velocity of approach of the flame was not varied by changing the mixture composition, as was done in previous experiments. Instead the mixture composition was maintained constant during a group of tests and the flame velocity was varied by altering the run-up. In the tests with the brass plates perforated by a single hole, carried out with the igniter at the open end of the tube only, the end of the tube at L (Fig.2) was closed by a rubber bung instead of the usual metal fitting. By this means the pressure developing in the tube KL when the flame passed through the arrester was vented safely as the bung became dislodged. The other types of arrester were sufficiently porous to make this precaution unnecessary.

As sufficiently high flame velocities were not obtained with the usual open tube arrangement to rigorously test the 4 and 5 cm thick brass block arresters with 0.175 cm holes, a few experiments were carried out in which the flame velocity was boosted artificially. The booster consisted of the brass plate with the single 0.559 cm hole (Table 2) since this produced the maximum effect. This plate was installed 116 cm from the open end of the tube and the arrester under test was placed 30.5 cm further along the tube towards the closed end; the distance between the test arrester and the closed end was 61 cm. Between the test arrester and the booster a $2\frac{1}{2}$ in. B.S. pipe tee was installed so that when the flame had passed through the booster the exhaust gases could vent to atmosphere along the stem of the tee which was only a few centimetres in length, and the axis of which was at right angles to the explosion tube.

The propane used as fuel was specified by the manufacturers as being at least 97 per cent pure; it was mixed with atmospheric air in the preparation of the explosive gas mixtures.

Measurements of flame velocities near the arrester were made using a rotating drum camera; the speed of the drum was calibrated electronically by means of a time period counter. 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 at a point 2.1 cm below the interior top surface of the tube (1.1 cm above the axis 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 slow flames propagated about a centimetre above the axis of the tube.

Procedure

The arresters were in the form of circular discs or blocks whose diameter equalled that of the outside of the tube. Before use the arresters were washed in carbon tetrachloride to remove oil and grease, and after drying they were inserted in the tube; the junction between the arrester and the tube was then 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 arrester was recorded by the drum camera. The velocity of the flame was measured at apoint 1.5 cm from the arrester on the approach side, although the velocity of approach was usually constant over several centimetres near the arrester. 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. The value obtained was of course the velocity relative to the tube, and not necessarily relative to the gas.

Results

Two series of tests were carried out with arresters made from perforated brass sheeting and with the igniter near the open end of the tube; the results for the first series using 4 per cent propane/air mixtures (stoichiometric) are given in Fig.3. The results for the second series, using 2.75 per cent propane/air mixtures (0.69 x stoichiometric), are given in Fig.4. In both Figures the flame velocity is plotted against the diameter of the aperture on logarithmic scales, and distinction is made as to whether or not the flame passed through the arrester. Details are also given of the various tube lengths used in each series of tests, in general the flame velocity increased as the run-up length (LJ, Fig.2) was increased, although there was a good deal of overlapping of the flame velocities obtained with neighbouring run-up lengths. The results of tests carried out under the same conditions with perforated polyvinylchloride arresters are given in Fig.5 and 6. When the polyvinylchloride arresters quenched a flame they appeared to be quite undamaged, as were the perforated brass arresters. However if the polyvinylchloride arresters failed to quench the flame considerable charring and melting could occur, whereas the brass arresters remained unaffected.

The results of tests with brass block arresters of various thicknesses are shown in Fig.7 and 8; in both cases the igniter was situated near the open end of the tube. In order to save space only the greatest velocity at which a flame was quenched and the least velocity at which it passed through the arrester are represented in Fig.8, each pair of points is joined by a vertical line. If only one of the points was obtained it is shown in isolation. Two propane/air mixtures were again used and both sets of blocks, perforated with holes 0.175 and 0.340 cm in diameter, were investigated although the number of tests with the 2.75 per cent propane/air mixture in conjunction with the arrester having the smaller holes was restricted because of the difficulty in photographing fast dim flames. All 4 per cent propane/air flames easily passed through the arrester with 0.340 cm diameter holes and the results are not shown graphically. Some of the high velocity flames in Fig.7 were obtained using artificial boosting, as described earlier. As the conditions of test were not the same as in the majority of experiments the results are marked separately on the graph. Also included in Fig.7 and 8 are the results obtained with perforated brass plate arresters with the same sized holes (Fig.3 and 4).

In all the tests so far with brass block arresters each block was in contact with its neighbours so that the walls of the perforations were continuous through the arrester. The effect of introducing a gap between neighbouring parts of the arrester was also studied. The arrester was built up from two brass blocks, each 1.0 cm thick and with 0.175 cm diameter holes, and they were separated by a perspex ring 2.55 cm in depth. This combination was inserted in the explosion tube and tested in the usual manner, using 4 per cent propane/air flames. The velocity of the flame that was just able to pass through the first block, but which was quenched by the second block, was about 1000 cm/s; the flame that was just able to pass through both blocks travelled at about 1800 cm/s. These velocities are close to those obtained for blocks in contact (Fig.7) and are in fact slightly lower. It follows that for practical purposes the efficiency of the arrester was not increased by the introduction of the gap.

The results obtained with brass block arresters in contact and with the igniter situated near the closed end of the tube are given in Fig.9, where the velocity of the flame relative to the tube is plotted on logarithmic axes against the thickness of the arrester. The gas mixture was 4 per cent propane/air and the diameter of the holes in the arrester was 0.175 cm. In these tests the gas mixture was streaming through the arrester when the flame arrived, due to the expansion of the gas behind the flame caused by the combustion. When the flame reached the arrester its velocity relative to the gas was considerably less than its velocity relative to the tube. This point is discussed later.

Two main series of tests were carried out with brass plate arresters perforated by a single hole, and the results are shown in Fig.10 and 11. In each series the igniter was at the open end of the tube. It may be seen that the flame velocities obtained were lower than in corresponding tests with brass sheeting arresters perforated by multiple holes, and that with some sizes of aperture the quenching of the flame appeared to be much less dependent on the velocity of approach of the flame than was the case with the other arresters. With the smaller diameter apertures the flame tended to be quenched even when propagating at a relatively high velocity. Additional tests to those represented in Fig.10 and 11 were carried out in which a thin wire was stretched diametrically across the aperture in the plate; it was thought that the wire could act as a flame-holder and enable the flame to stabilise itself in the neighbourhood of the aperture and that more consistent results might be obtained. In fact, however, no significant change in the results was observed. The tests were carried out with the disc with the 0.175 cm hole (Table 2), using a stoichiometric gas mixture, and with a 38 S.W.G. wire in contact with the disc on the approach or the departure side or with the wire fixed 3 mm away from the disc on the departure side. The plate with the 0.559 cm diameter hole was tested with 2.75 per cent propane/air mixtures, with the wire in contact with the plate either on the approach or on the departure side.

It was also noted that on some occasions when the flame passed through the arrester the velocity of the departing flame was considerably higher than the approach velocity, and that frequently a loud report was also obtained. This increase in flame velocity was used to produce fast-moving flames in tests with brass block arresters, described above. The high velocity flames were not sustained indefinitely if produced in a long tube, after propagating for a metre or so the velocity diminished to more usual values.

Discussion

Perforated sheeting arresters

The results for the arresters made from perforated brass and polyvinylchloride sheeting, represented in Fig.3-6, show a clearly-defined dependence of the flame quenching ability of the arrester upon the velocity of approach of the flame. For each size of aperture there was a critical velocity of approach of the flame below which it was quenched by the arrester and above which it passed through. The critical velocity increased as the aperture size diminished. Similar behaviour was found previously with wire gauze arresters[1,2,3] although with gauzes the critical velocity was not quite so clearly defined.

The relation between the velocity of approach of the flame that is just quenched, the diameter of the aperture, and the thickness of the plate is discussed in Appendix A. The argument is similar in principle to that already published for wire gauze arresters under similar conditions[1]. It is assumed that the quenching of the flame was an effect caused by transfer of heat from the flame to the arrester, so that if more than a certain critical amount of heat were removed the flame would be quenched. The amount of heat removed from the flame by the arrester was calculated in terms of the velocity, temperature and the thickness of the flame, and the dimensions of the arrester, from the convective heat transfer data given in standard textbooks. The amount of heat to be removed from the flame for quenching was taken from published results for propane flames on a flat flame burner. The previous equation[1] was based on the assumption that the wire gauze arresters were an assembly of single wires, whereas the present equations assume that the arresters were assemblies of apertures. This leads to different values for the heat transfer coefficient, since in the former case interactions between wires were neglected and this approximation is not required in the latter case. Apart from this difference the basic argument is the same in both cases. In the present theory two conditions were considered: firstly where all the flame front was reckoned to be quenched by the walls in the apertures through the arrester, and none by the blank face of the arrester, and secondly where only that portion of the flame front directly opposed to the aperture was quenched by the walls, the remainder being extinguished at the blank face. In practice the behaviour of the arresters should lie between these two limiting cases; further discussion is given in Appendix A. The resulting Equations (A1 and A2, Appendix A) are represented by broken lines in Fig.3-6.

It may be seen from Fig.3-6 that there is fair agreement between the experimental results and the predicted critical values of flame velocities at which the arresters just fail. In each case Equation A1 underestimates the critical velocities for arresters with small holes (diameters not more than 0.1 cm), whereas Equation A2 tends to overestimate the critical velocities. Equation A1 is in better agreement with experiment when arresters with large apertures are considered, but often the theory overestimates the performance of arresters with large apertures. It is not possible to discern in the experimental results any systematic variation with the material of the arrester, and according to Appendix A none would be expected. As both the thermal conductivities and the thermal diffusivities of brass and polyvinylchloride differ by factors of about 500 any dependence of the flame quenching properties on the composition of the arresters ought to be noticeable. The reasons for the discrepancies between the experimental results and the predictions of Equations A1 and A2 are probably connected with the approximations involved in the derivation of the Equations. In particular there was a large temperature difference between the flame and the arrester wall and it was assumed that the viscosity of the gas was a constant mean value across the diameter of the aperture of the arrester. In addition the diameter was always greater than the thickness of the arrester (Table 1) so that entrance effects are therefore probably appreciable.

In attempts to obtain better agreement with experiment several heat transfer mechanisms based on the transient state were considered. It was thought that the quenching of the flame might be due to transient heat loss either through the surface of a hemispherical flamelet into the unburnt gas, or by conduction through the gas to the walls of the apertures of the arrester (assuming no gas movement), or due to heating up the gas boundary layer in the apertures of the arrester (assuming the gas to be in motion). In no case was the agreement with experiment as good as that obtained with Equations A1 and A2.

Perforated block arresters

The results for perforated brass block arresters again show that the velocity of the flame as it approached the arrester from the open end of the tube is an important factor in determining whether or not it was quenched (Fig.7 and 8). There was a marked increase in the flame quenching ability of the arrester as its thickness was increased. The behaviour of the arresters, predicted by Equation A1, is represented in Fig.7 and 8 by broken lines. The line in Fig.7, for arresters with holes of diameter 0.175 cm and for stoichiometric mixtures, is in good agreement with experiment over a very wide range of arrester thicknesses. The line for the same arrester in Fig.8, for 2.75 per cent mixtures, is in reasonable agreement with experiment, although fewer and less reliable results were obtained, as described above. With the arrester with 0.34 cm diameter holes, however, the predicted line considerably overestimates the behaviour of the arrester at all thicknesses. The reason for this is not clear.

When the igniter was at the closed end of the tube the unburnt gas ahead of the flame attained high velocities, owing to the expansion caused by the combustion. As a result entrance effects in the apertures through the arrester might be expected to become more important, since the inlet length required to set up the boundary layer is proportional to the Reynolds number. These effects were not considered in the derivation of Equations A1 and A2. However, the line calculated from Equation A1 is in fair agreement with the results (Fig.9), although overestimating the efficacy of the arresters, but it predicts that the velocity of the flame that is just quenched should increase linearly with the thickness of the arrester, and this is borne out by the results. In deriving Equation A1 it was assumed that the gas flow through the arrester was streamline, although it is of course turbulent in the explosion tube, and this assumption seems to be justified by experiment. If the flow through the arrester were taken to be turbulent the velocity of the flame that was just quenched would be expected to increase with the fifth power of the thickness of the arrester, and this would seriously overestimate the efficacy of thick arresters. If turbulent flow through the arrester could be produced it would presumably lead to a marked increase in the arresting power.

Brass plates perforated by a single hole

In the results obtained with these arresters (Fig.10 and 11), with ignition near the open end of the tube, it was sometimes impossible to stipulate a velocity of approach of the flame above which the flame was not quenched, as was possible with plates and blocks having multiple holes. Thus frequently with the arresters having a single hole flames were quenched when propagating at velocities which would be sufficient to enable them to pass through the other types of arrester. There was even a case where a stoichiometric flame failed to pass through an aperture 0.56 cm in diameter (Fig.10), whereas the quenching diameter[11] is only 0.28 cm. In no case did flames pass more easily through the arresters with a single hole than through corresponding arresters with multiple holes. It was also noticeable that the flame velocities at the arrester where substantially lower than in tests with multiple holed arresters in the same tube and with the same flammable mixture.

As the arresters contained only one hole, small in diameter, relative to that of the tube, they would tend to encourage the formation of a node in the acoustic vibrations excited in the tube by the moving flame. At the node there is no movement of the gas and the flame propagates relatively slowly and uniformly. Before arriving at the arrester the flame had been moving more rapidly. Consequently any slight compression ahead of the flame due to the acceleration of the combustion products would tend to be released as the flame neared the arrester, and as the area of aperture was small compared with that of the tube the gas velocities through the aperture could be much higher than when plates with multiple holes were used. The relative movement of flame and gas through the arrester could therefore be quite different to that with the other arresters; further work involving the measurement of both gas and flame velocities is needed.

Comparison with wire gauze arresters

Sufficient information is now available to allow a brief comparison of the merits of wire gauze and perforated sheeting or block arresters. With both types of arrester it is the velocity of approach of the flame that is a major factor in determining whether the flame will pass through a given arrester. As the velocity of the flame depends upon the geometry of the tube along which it propagates, this geometry must clearly be taken into account when considering the installation of these arresters. The position of possible explosion relief vents relative to likely sources of ignition is also important. The experiments described in this Note and elsewhere[1,2,3] show that wire gauze and perforated metal sheeting, of types easily available commercially, have comparable effectiveness in acting as flame arresters. With holes less than 0.1 cm across, the perforated sheeting is slightly more effective than gauze, but with coarser grades the position may be reversed. From the practical point of view there are other factors to be considered in the choice of material for flame arresters; for instance the mechanical strength, the thermal capacity, and the cheapness of proposed arresters must also be taken into account.

The behaviour of the two types of arrester is not always similar. When coarse gauzes are built into regular packs, with the meshes aligned, the effectiveness of the compound arrester is greater than that of a single gauze, but does not continue indefinitely to increase with the thickness of the pack[1]. With metal blocks perforated with holes of about the same size there is a regular increase in efficacy. The relation between the thickness of the metal block arresters and the velocities of the flames they are just able to quench can be applied to crimped ribbon arresters, which are widely used in industry. This is the subject of a further Note.

Conclusions

1. Tests on flame arresters consisting of sheets or blocks perforated with multiple circular holes have been carried out with the arresters mounted in straight horizontal tubing systems. For each arrester there was a critical value of the velocity of approach of the flame below which the flame was quenched and above which it passed through the arrester.

2. Provided that the diameter of the holes in the arrester was less than the quenching diameter for the flammable mixture, the velocity of the flame that was just quenched was proportional to the thickness of the arrester. This relation held whether the gas was ignited at the open or the closed end of the tube.

3. As the diameter of the apertures in the arresters was reduced, faster flames could be quenched. The velocity of the flame that was just quenched was inversely proportional to the 1.5-2 power of the diameter.

4. No significant differences were found in the flame quenching ability of arresters made in brass or polyvinylchloride sheeting. Under the conditions of test, therefore, the flame quenching ability of the arrester did not depend upon its thermal properties.

5. Brass plate arresters perforated by a single hole did not show a clear-cut relation between the flame quenching and the velocity of approach of the flame. Reasons for this behaviour were discussed.

6. Simple theoretical treatments of the quenching of flames by perforated sheeting and block arresters were in reasonable agreement with experiment.

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Notation

a, b	Spacing of the apertures in the arresters (Fig.1).
d	Diameter of aperture.
K	Thermal conductivity.
n	Number of apertures in unit area of arrester face.
q	Heat absorbed by unit area of arrester.
Q	Heat lost by unit area of flame.
S	Standard burning velocity.
T_h	Mean temperature of flame gases in arrester.
T_o	Temperature of the arrester.
v	Gas velocity along the explosion tube.
V	Flame velocity, relative to the unburnt gas.
x	Mean thickness of flame propagating at velocity V.
x_o	Thickness of flame propagating at burning velocity S.
y	Thickness of arrester.
N_u	Nusselt number.
P_r	Prandtl number.
Re	Reynolds number.

Appendix A

The case is considered of a flame propagating along the explosion tube towards an arrester of thickness y perforated with holes of diameter d. The velocity of the flame as it propagates along the tube is the sum of V, the velocity of the flame relative to the gas, and v, the velocity of the gas relative to the tube. In the experiments measurements were made of (V + v). When ignition was at the open end of the tube the assumption was made that owing to the movement of expanded exhaust gases out of the tube, and to the acoustic vibrations excited by the flame, the unburnt gas was slightly compressed ahead of the flame and the motion of the gas was sufficient to establish a boundary layer in the passages through the arrester. When ignition was at the closed end of the tube the gas was streaming rapidly through the arrester when the flame arrived. It may be shown that the flow of the flame gases of 4 per cent propane/air mixtures will be streamline ($Re < 2000$) through apertures 0.175 cm in diameter so long as the velocity of the flame relative to the tube (V + v) is less than 5500 cm/s. Thus about half the results shown in Fig.9 come in this region and most of the remainder are in the region of transition to turbulent flow. It has been assumed that the flow was streamline, whether the flame originated at the open or at the closed end of the tube and that the boundary layer was fully developed, i.e. that entrance effects could be neglected. This latter approximation is discussed below.

Then the rate of heat transfer per unit area of aperture wall is[4,5]

$$\frac{2.4K\,(T_h - T_o)}{d}$$ The symbols are defined on page 9.

Now assuming the apertures are sufficiently close together for the distribution of wall area to be considered uniform, the rate of heat transfer per unit frontal area of arrester is $2.4K\,(T_h - T_o)\pi ny$.

If the flame is of thickness x ($x > y$) and travels at velocity (V + v) it is in contact with the arrester for a time $\frac{x}{V + v}$, so the total heat transferred to unit area of arrester $= q = 2.4K\pi\,ny\,(T_h - T_o)\,\frac{x}{(V + v)}$

The velocity of propagation of the flame is proportional to its surface area, and a flat flame propagates at the adiabatic burning velocity S. As the velocity of the flame relative to the gas is V, each square centimetre of arrester is opposed on the average by V/S cm^2 of flame, i.e. $Q = q\,S/V$. The thickness of the flame, x, is governed by the velocity of the chemical reactions in the flame. If the flame is propagating at velocity V, greater than S, the thickness of the flame is increased by a factor V/S, i.e.

$$\frac{x}{V} = \frac{x_o}{S}$$

So that $$(V + v) = \frac{2.4\pi Kny\,(T_h - T_o)}{Q/x_o} \qquad \text{A1}$$

Although Equation A1 appears to be independent of d, the aperture diameter, it is not so because n is a function of d.

Equation A1 represents a limiting case in which all the flame front is reckoned to be quenched by the walls in the apertures through the arrester, and none by the blank face of the arrester. In the other limiting case only that portion of the flame front directly opposed to the aperture is quenched by the walls, the remainder being extinguished at the blank face. In practice the conditions for the latter case, in which the apertures are sufficiently widely spaced not to interact, are probably modified since some of the flame front near to the aperture, but not directly opposed, may enter the aperture. The area of flame front to be quenched in the aperture is then larger than the area of cross-section of the aperture. These conditions are intermediate between those for the two limiting cases.

Considering then the limiting case when only an area $\frac{\pi d^2}{4}$ of flame is quenched in each aperture

$$q \frac{\pi d^2}{4} = 2.4\pi Ky(T_h - T_o) \frac{x}{V + v}$$

and $$(V + v) = \frac{9.6 Ky (T_h - T_o)}{d^2 Q/x_o} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{A2}$$

In the derivations of Equations A1 and A2 any entrance effects in the apertures of the arrester were neglected. This approximation would be inaccurate with perforated plate arresters, where the diameter of the aperture always exceeded the thickness of the arrester; in tests with these arresters the igniter was always near to the open end of the tube. When the igniter was at the closed end of the tube, metal block arresters were used, and entrance effects would again be expected. Coulson and Richardson[4] give the following empirical equation to deal with entrance effects:

$$Nu = 1.62 \left(Re.Pr. \frac{d}{y}\right)^{1/3}$$

but as the numerical value of $(V + v)$ obtained after employing this equation was close to that given by Equation A1 for metal block arresters the detailed argument is not given in this Note.

Calculation

Information is available from various sources[1,6,7,8,9] on adiabatic flame temperatures and other thermal properties. The following values were taken for 4 per cent propane/air flames: $T_h = 2000°K$, $K = 2.9 \times 5.8 \times 10^{-5}$ cal/cm/s/°K, $Q/x_o = 2.32 \times 10^{-2}$ cal/cm³. Corresponding values for 2.75 per cent propane/air flames are: $T_h = 1800°K$, $K = 2.75 \times 5.8 \times 10^{-5}$ cal/cm/s/°K, $Q/x_o = 8.92 \times 10^{-3}$ cal/cm³.

In both cases $T_o = 290°K$, and values of n were calculated from Table 1.

The calculated values of $(V + v)$, the velocity of the flame relative to the tube, are included as broken lines in Fig.3-11.

Estimation of quenching diameter

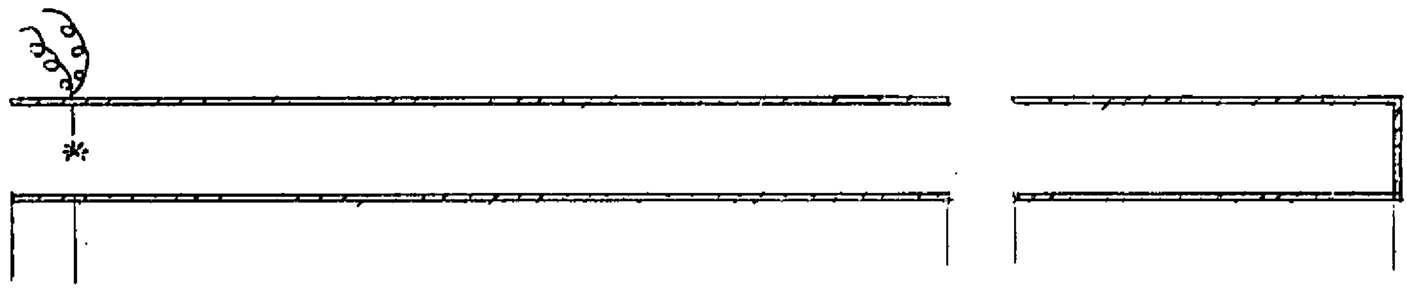
In the derivation of Equations A1 and A2 it was assumed that the zone of the flame that needed to be cooled for quenching to occur was thicker than the arrester (i.e. $x > y$). If the flame were thinner than the arrester ($x < y$) then only a length x of the aperture wall would be employed at any given instant in cooling the flame; the effective thickness of the arrester would be reduced to x. As the flame advanced, further heat would be released as fresh gas entered the combustion zone. Now the quenching diameter for a gas mixture may be regarded as the minimum diameter of the tube along which a flame travelling at the standard burning velocity S is just able to propagate indefinitely[10].

i.e. $V = S$, $y = x_o$, and since the flame is laminar and is propagating from the open end of the tube v has been neglected in comparison with S.

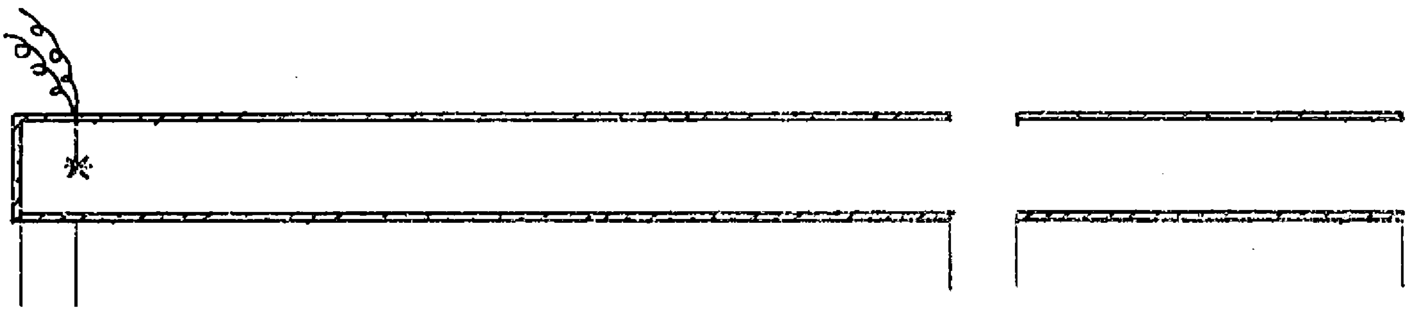
Then from Equation A2 $$d^2 = \frac{9.6 Kx_o (T_h - T_o)}{S \; Q/x_o}$$

For 4 per cent propane/air mixtures[19] $S = 41$ cm/s and x_o is approximately[2] 0.04 cm, giving $d = 0.34$ cm. The experimental determination[11] is 0.28 cm. If d is greater than the quenching diameter then the heat lost by unit volume of flame (Q/x_o) is reduced and becomes insufficient to quench the flame. The flame can therefore continue to propagate indefinitely.

NOT TO SCALE



Igniter near open end of tube



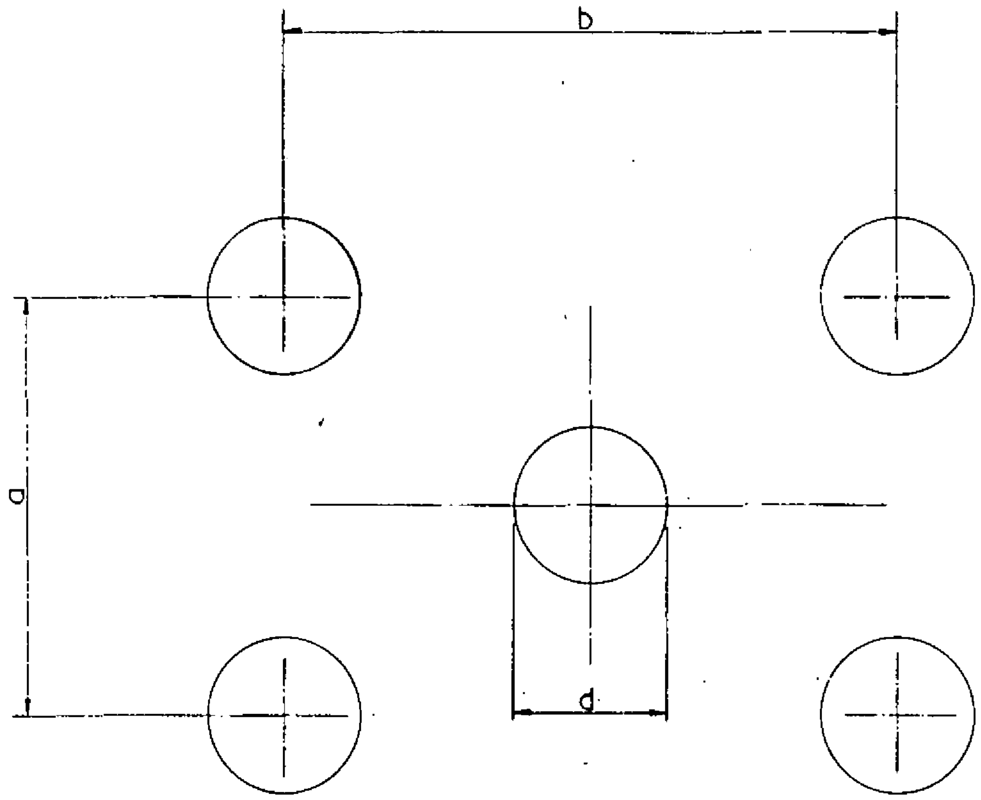
Igniter near closed end of tube

Table 4

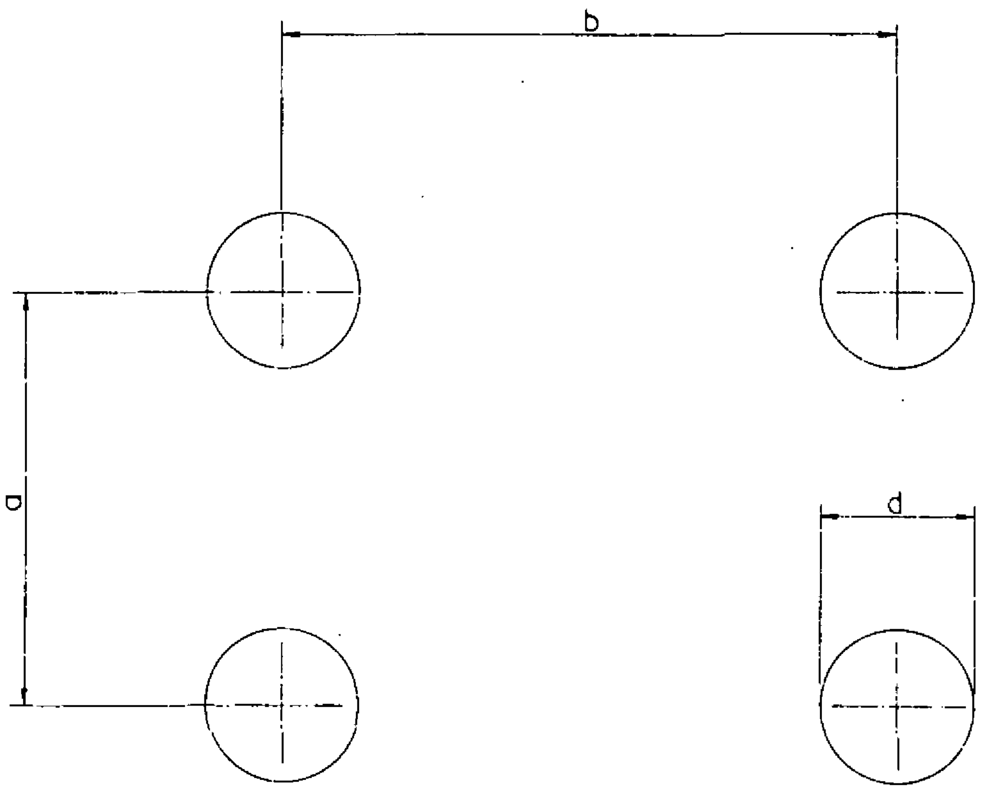
Dimensions in cm of tube systems

	Arrangement	HI	IJ	KL
Igniter near open end of tube	i	7.6	16.5	63.5
	ii	12.7	34.5	63.5
	iii	12.7	46.0	63.5
	iv	12.7	79.0	63.5
	v	12.7	122	63.5
	vi	12.7	153	63.5
	vii	12.7	305	63.5
	viii	30.5	452	63.5
	ix	30.5	790	231
	x	30.5	1140	262
Igniter near closed end of tube	xi	8.9	11.4	68.5
	xii	7.6	16.5	71.0
	xiii	8.9	34.5	63.5

FIG. 2. DETAILS OF THE EXPLOSION TUBE ARRANGEMENTS



Pattern A



Pattern B

FIG. 1

THE SPACING OF THE HOLES IN THE PERFORATED SHEETING AND BLOCKS

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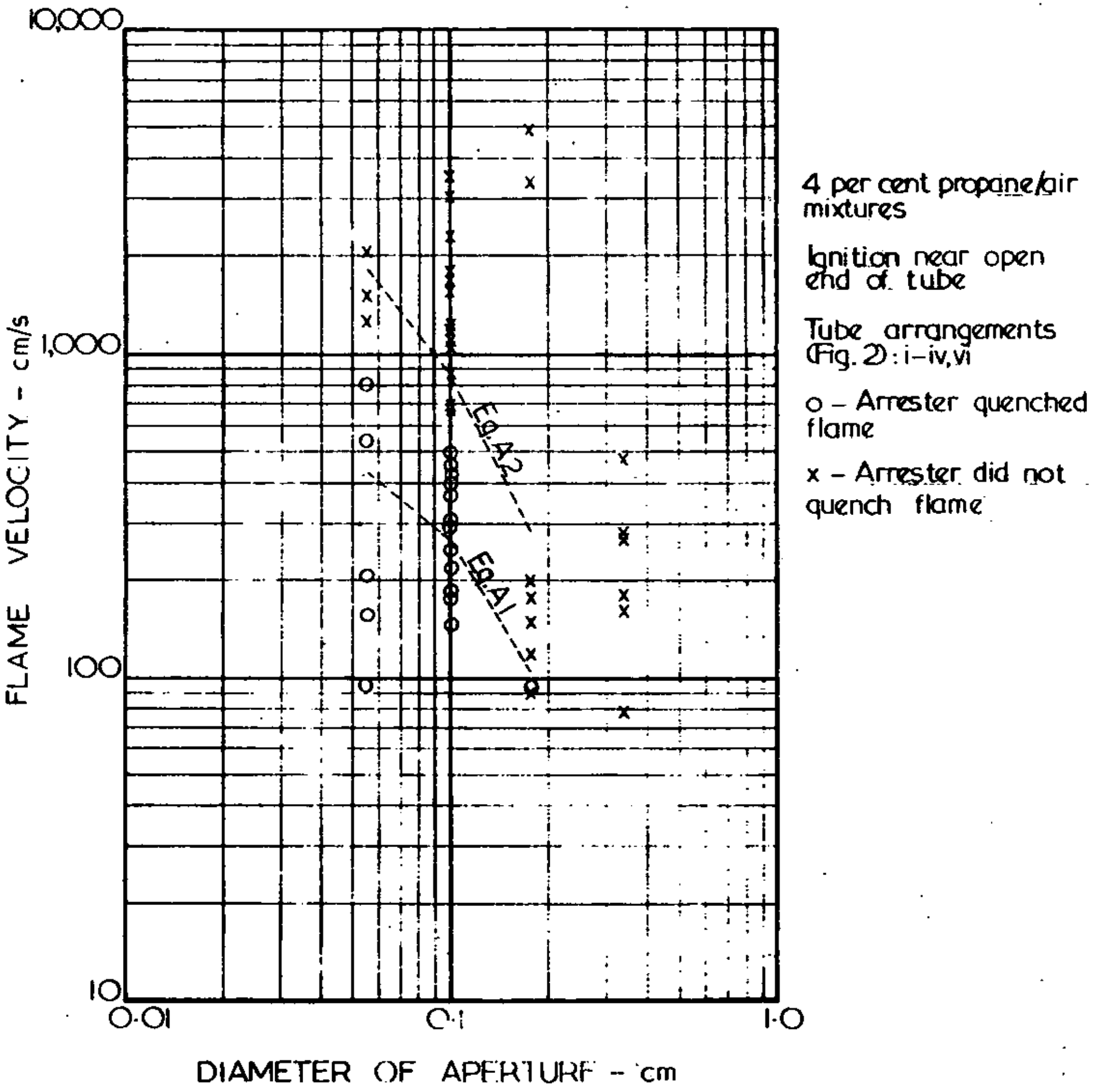


FIG. 3

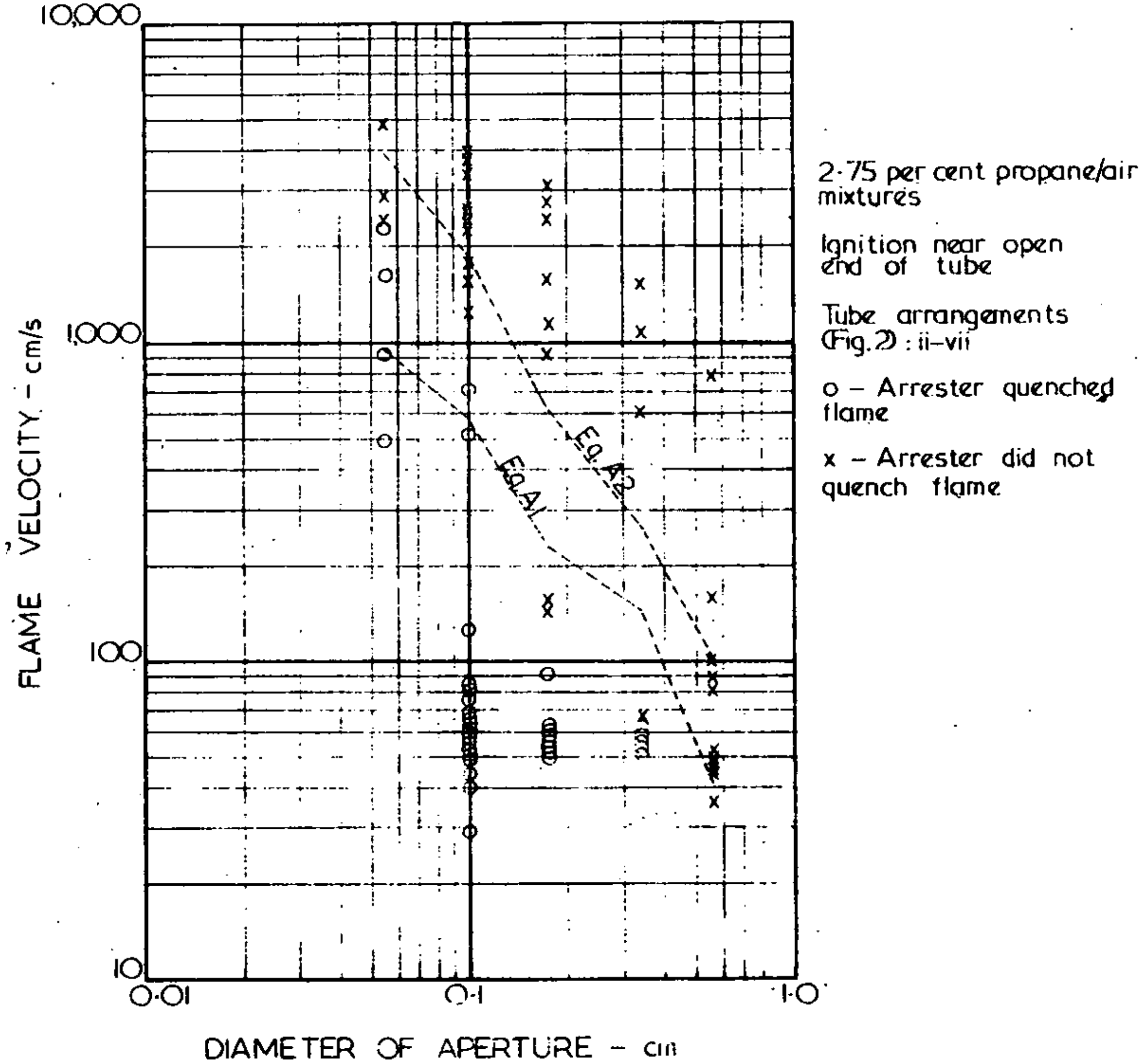


FIG. 4

THE QUENCHING OF FLAMES BY PERFORATED BRASS SHEETING ARRESTERS

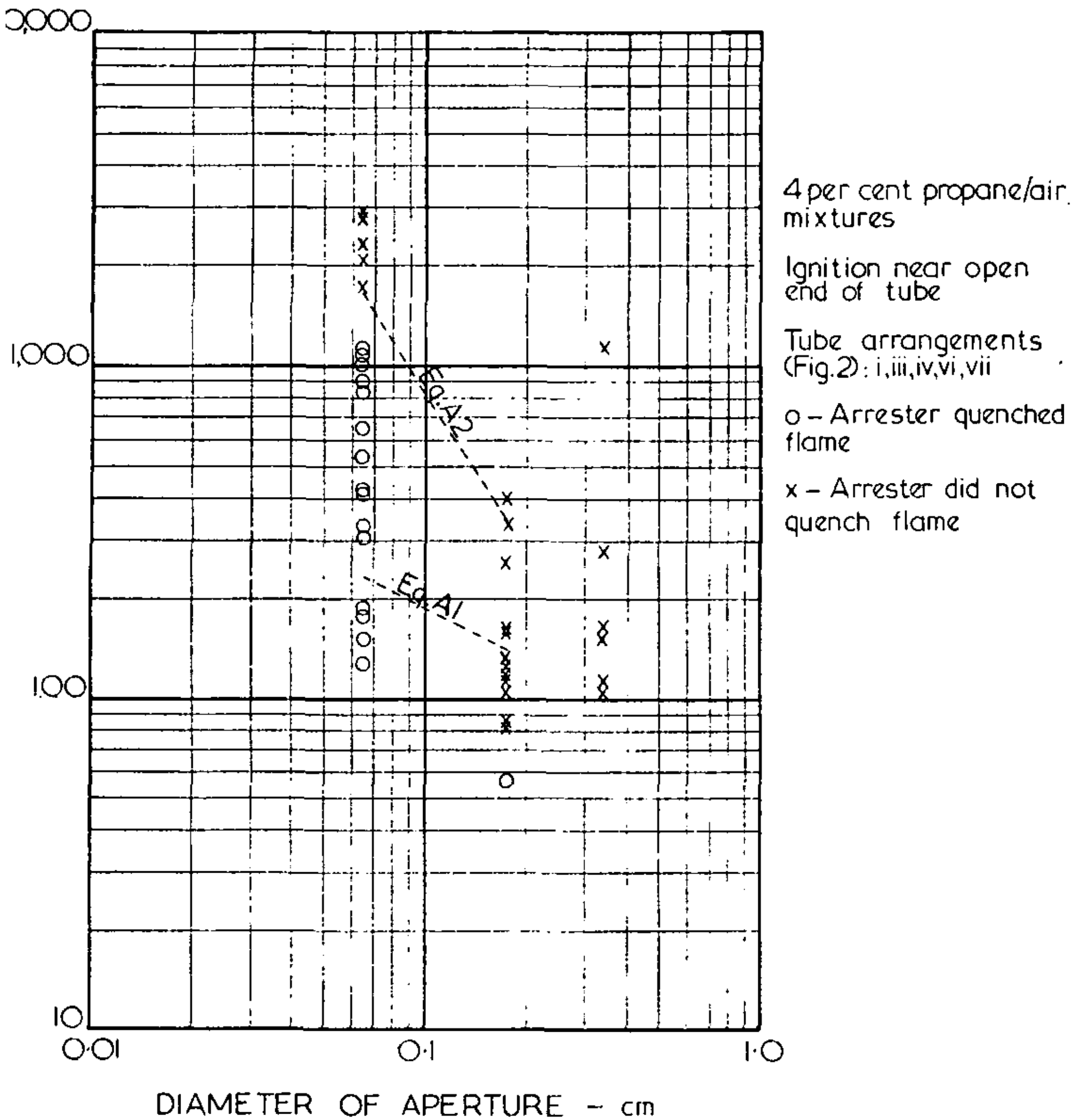


FIG. 5

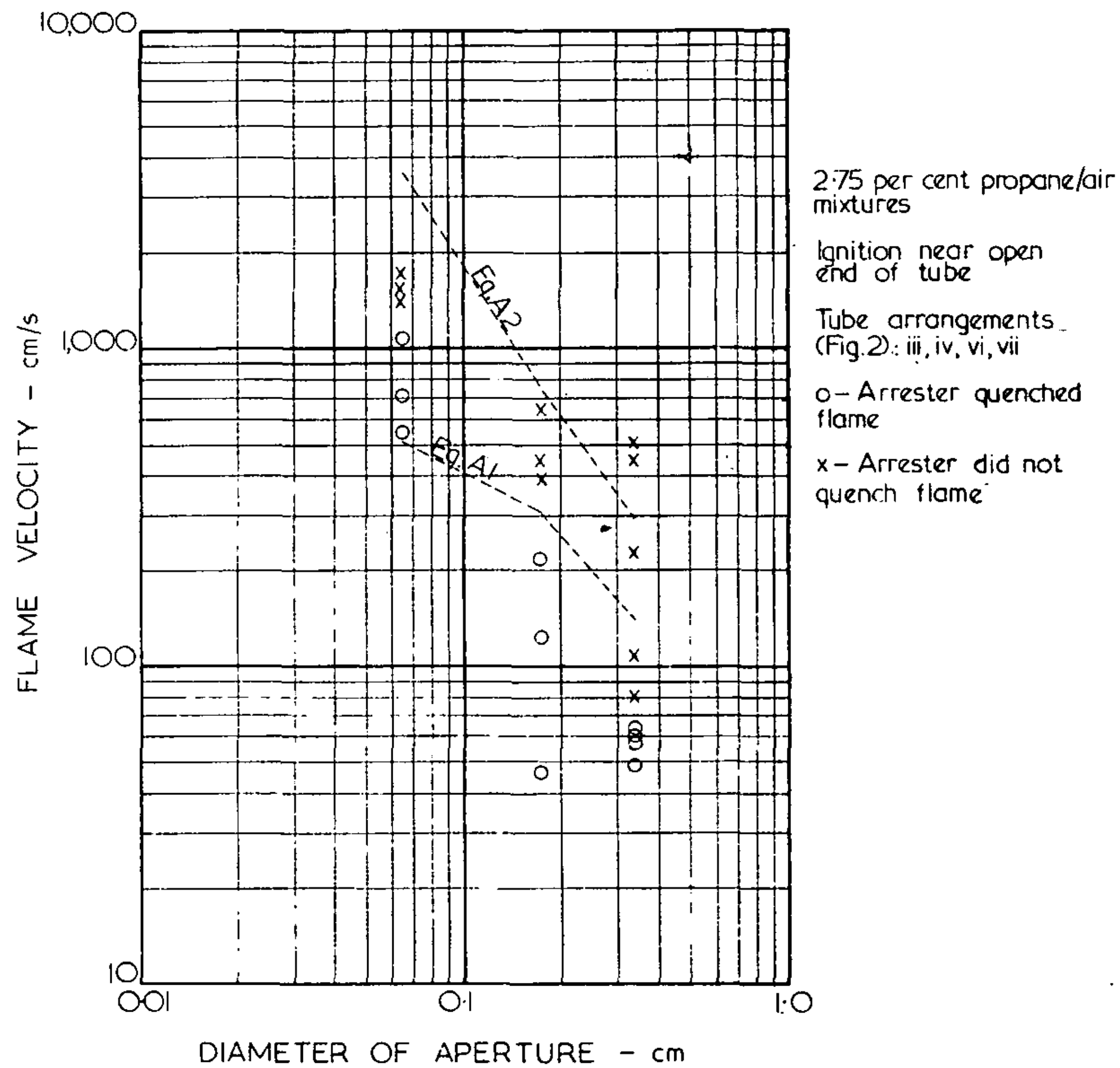
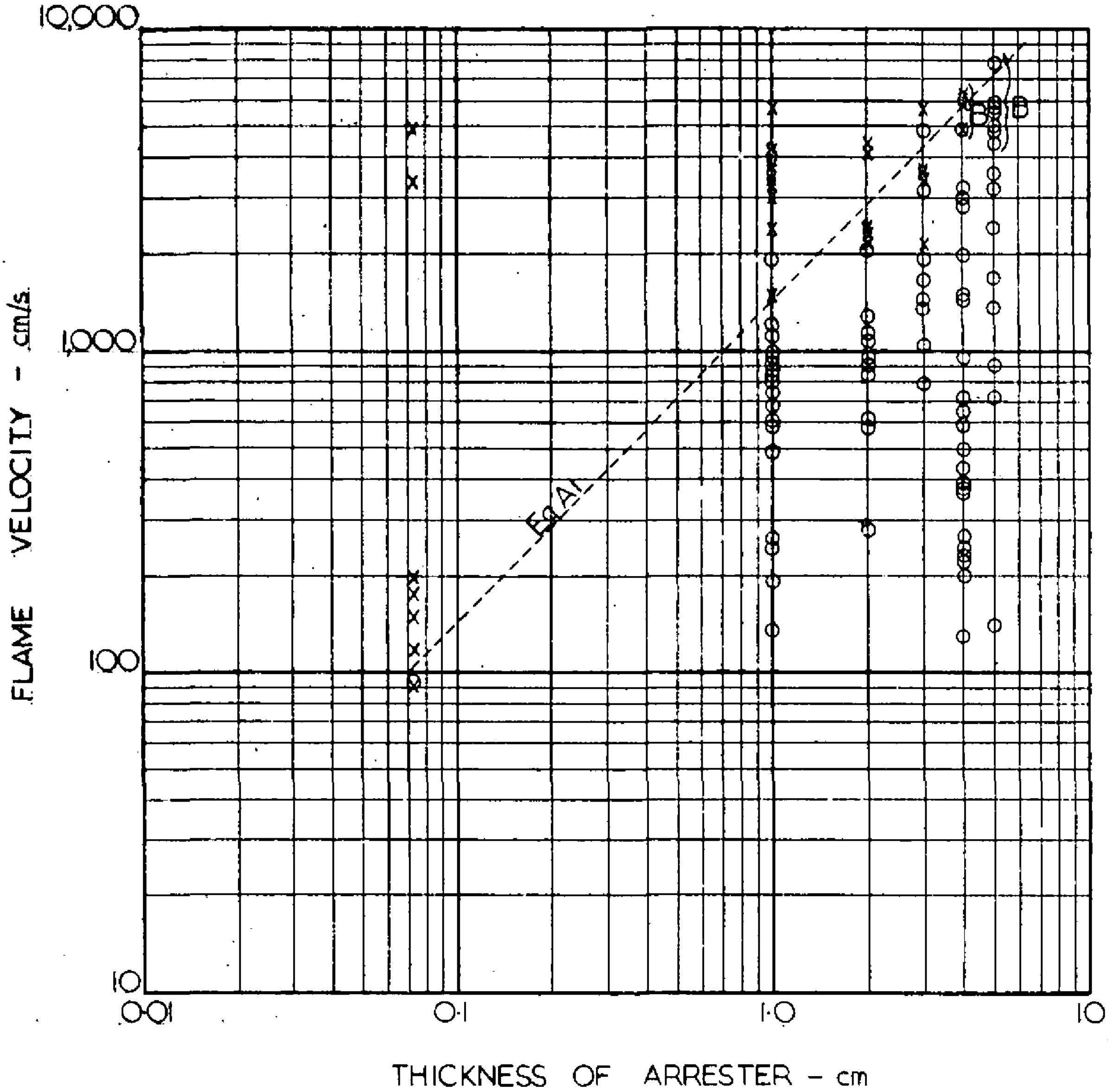


FIG. 6

THE QUENCHING OF FLAMES BY PERFORATED POLYVINYLCHLORIDE SHEETING ARRESTERS



Hole diameter : 0·175 cm

4 per cent propane/air mixtures

Ignition near open end of tube

Tube arrangements (Fig. 2): iv, vi – x

'B' indicates flame velocity boosted

o – Arrester quenched flame

x – Arrester did not quench flame

FIG. 7 THE QUENCHING OF FLAMES BY PERFORATED BRASS BLOCK ARRESTERS

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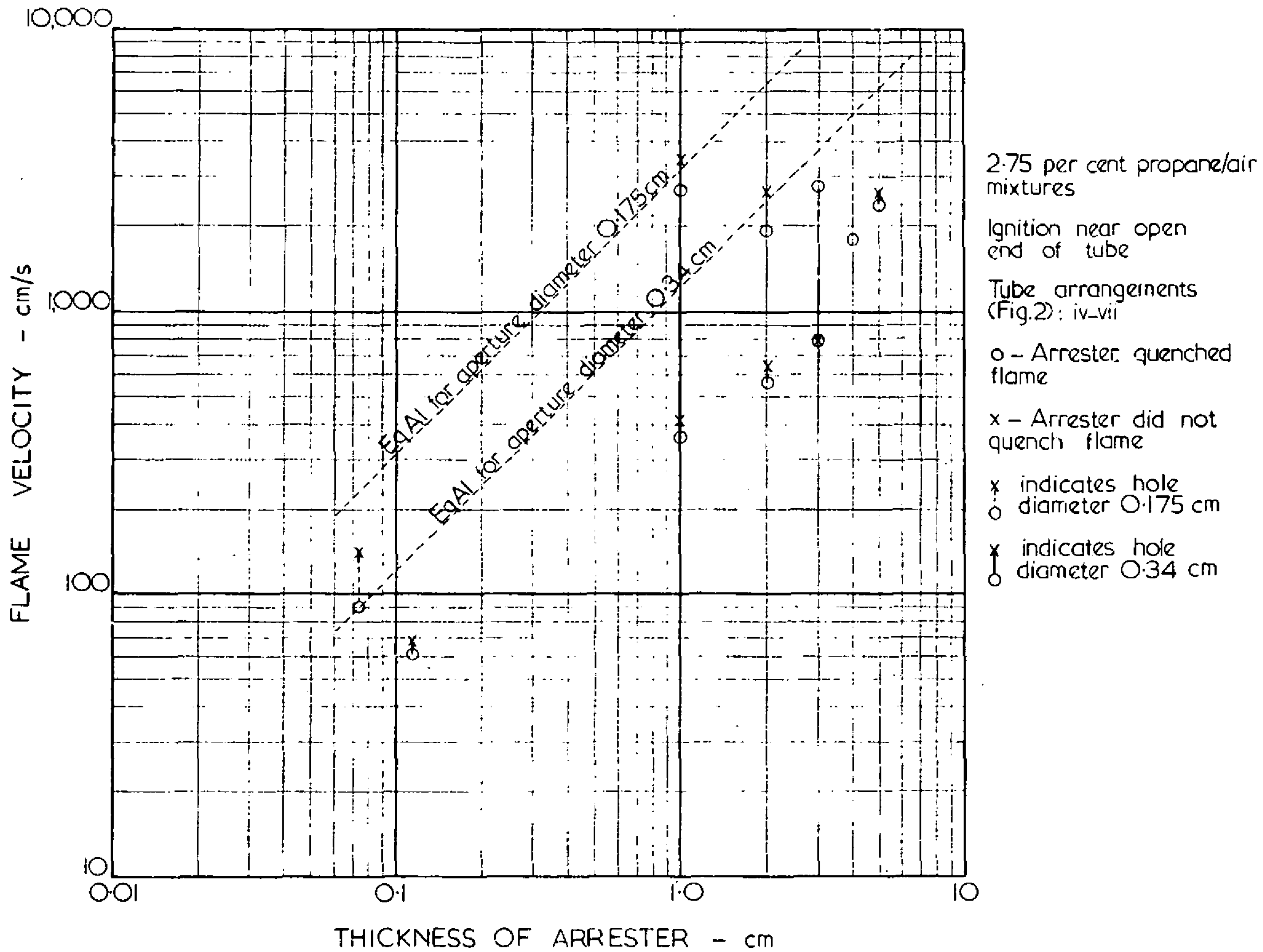

FIG. 8

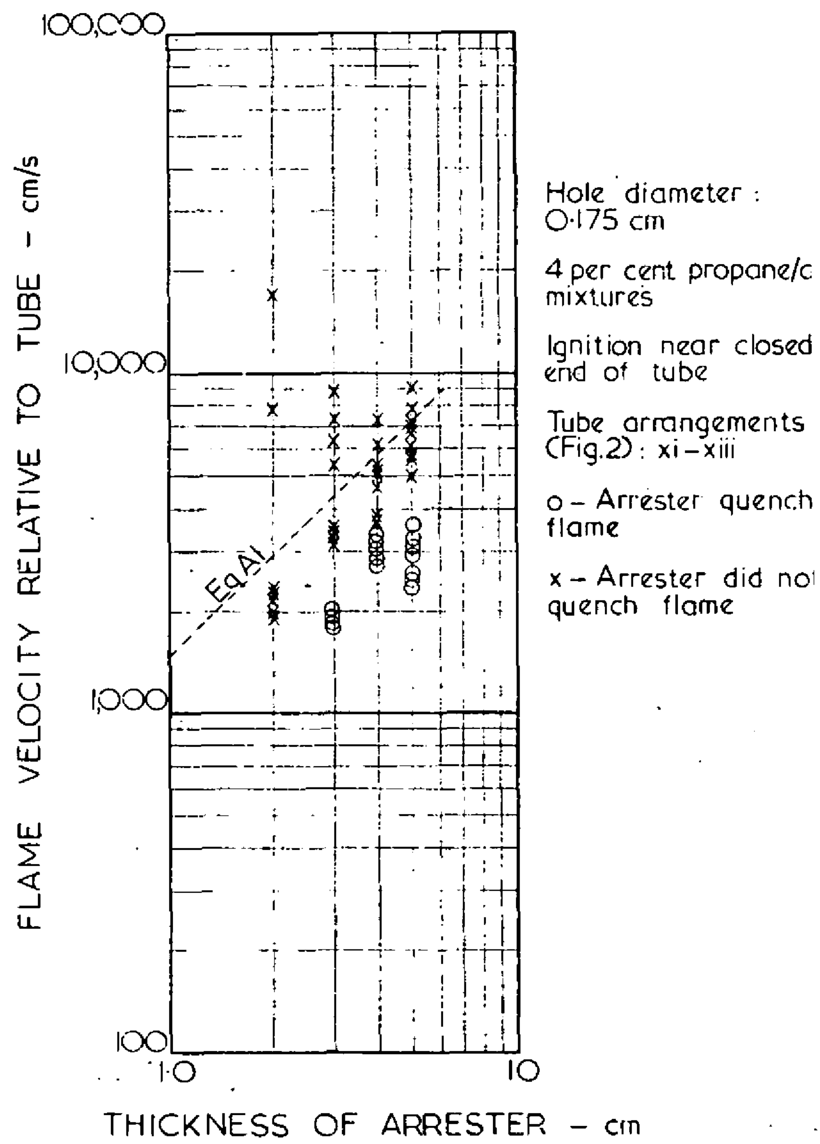

FIG. 9

THE QUENCHING OF FLAMES BY PERFORATED BRASS BLOCK ARRESTERS

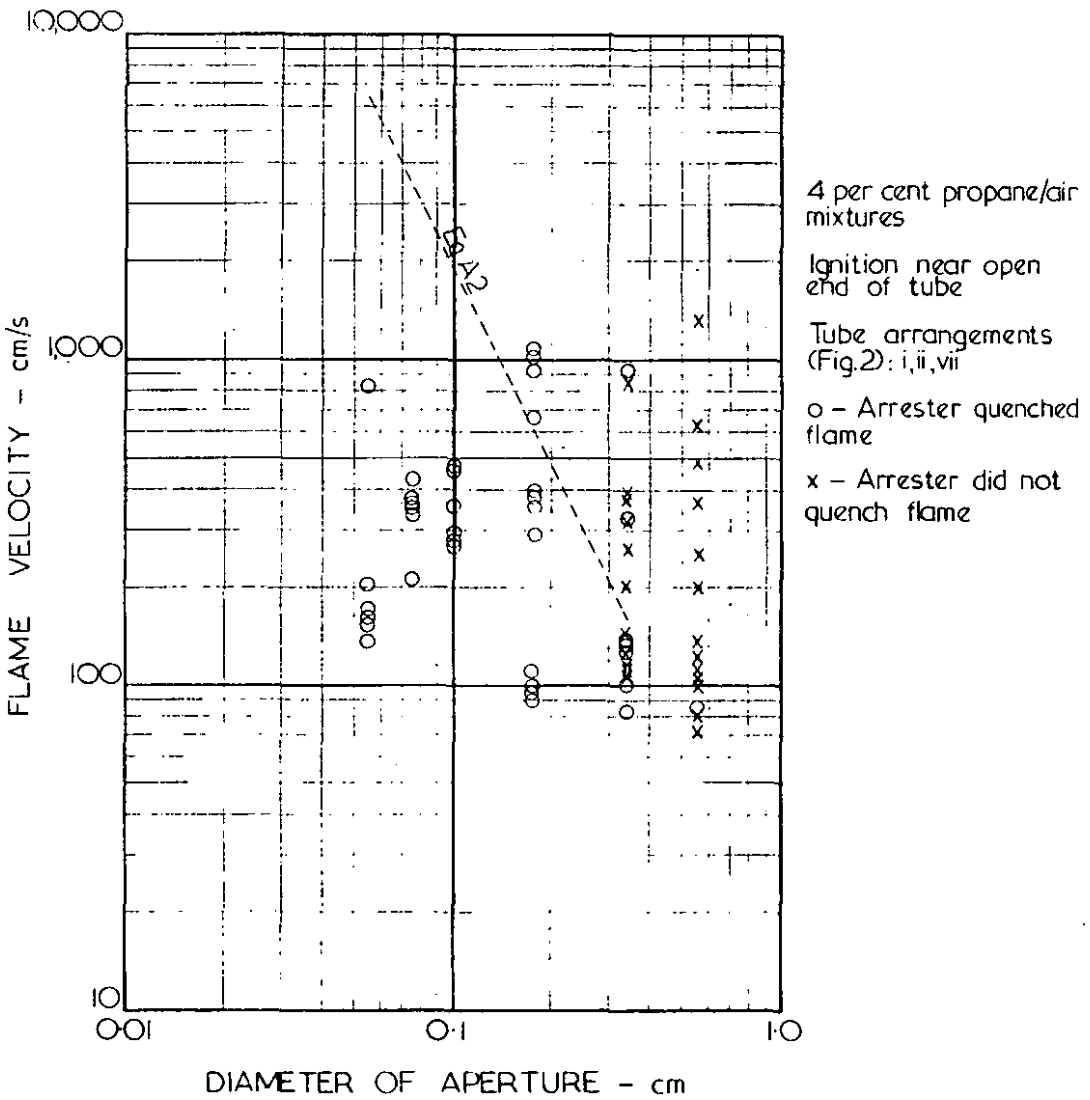

FIG. 10

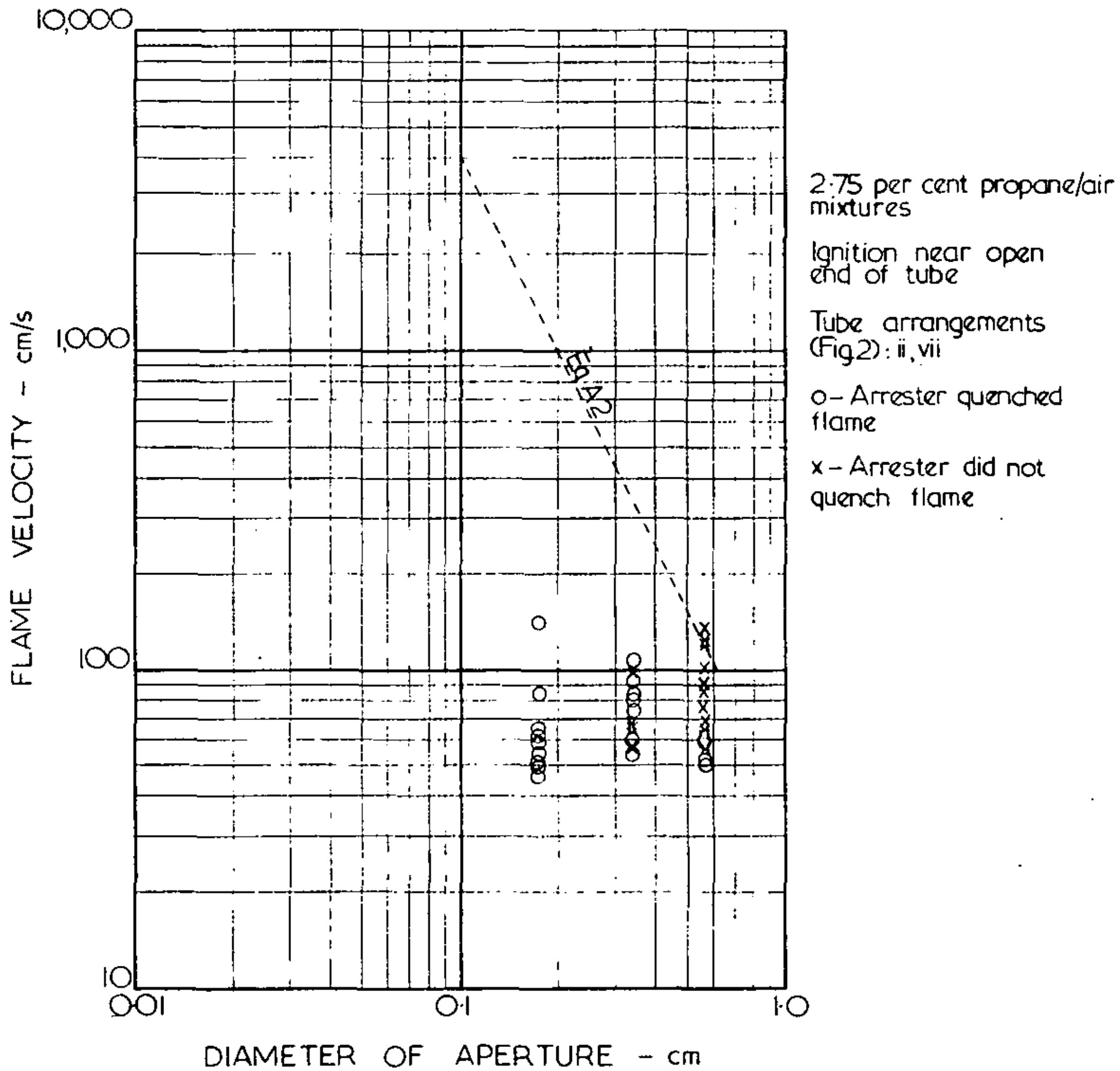

FIG. 11

THE QUENCHING OF FLAMES BY BRASS ARRESTERS PERFORATED BY A SINGLE HOLE