

# THE QUENCHING OF FLAME BY PERFORATED SHEETING AND BLOCK FLAME ARRESTERS

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## 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 apertures. No significant differences were found in the flame quenching abilities of brass and polyvinylchloride sheeting, under the conditions of test. 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.

## Introduction

Most flame arresters or flame traps consist of a solid matrix containing a group of small narrow passages or apertures through which gases or vapours can flow, but which are intended to be too small for a flame to pass through. Thus as the flame enters the arrester it is subdivided into flamelets, and it is clear that all of these should be quenched if the flame is not to propagate to the other side of the arrester. The various types of flame arrester differ mainly according to how this subdivision is obtained and the number and size of the apertures produced. The more common types of arrester include wire gauzes, perforated sheeting, crimped metal ribbon, sintered metal, and towers packed with pebbles or Raschig rings. The arresters differ considerably in their resistance to gas flow. This resistance is an important consideration because in many industrial applications a flow of gas is required through the arrester, and where the gas is propelled by a fan the maximum pressure drop that can be tolerated across the arrester may be only one or two inches water gauge. Where gas is withdrawn from a cylinder, or is pumped, a much higher pressure drop across the arrester is often permissible.

The types of plant and equipment in which flame arresters are now used cover a wide range, so that a complete classification cannot be attempted. Flame arresters are frequently used in solvent-vapour recovery systems, in the vent pipes of storage tanks for flammable liquids, for preventing flash-back in gases supplied to burners or furnaces, and for preventing ignition from the exhaust of motors working in flammable atmospheres. The performance required of the flame arrester depends on the type of system in which it is installed. It is unusual for the system to be completely enclosed, and to remain enclosed should an explosion occur. It is far more usual for a part of the system to be open to the atmosphere either through a duct opening, or a restricted opening such as a nozzle, or through a vent which opens when the gas pressure changes from the normal working range. If ignition occurs between the opening and the flame arrester then the bulk of

the hot explosion products are expelled to the atmosphere and the arrester is required only to quench the flame front. If ignition is between a closed end and the arrester, with the opening on the far side of the arrester, then some of the combustion products are expelled through the arrester, which is required to absorb heat from these products as well as from the flame front. In addition, if the gas mixture is flowing through the arrester, and continues to flow after ignition, a flame can stabilize on the arrester or upstream of it, so that overheating can soon develop. It may be necessary to install a detector near the arrester which can activate a valve to cut off the flow of gas.

In order to specify economic designs for flame arresters, information is required on the relation between the structure of the arrester and its flame quenching properties. Recent reviews have shown that in many cases the available information was insufficient,<sup>1,2</sup> so recent experimental work has concentrated on providing this information. Experiments with wire-gauze arresters<sup>3</sup> showed that the velocity of the flame as it approached the arrester determined whether the flame passed through; the velocity of the flame that was just quenched by the arrester was related to the size of the mesh of the gauze. Cabbage<sup>4</sup> has studied the behaviour of crimped-ribbon arresters against town gas/air flames propagating at high velocities, up to detonation. The present paper describes tests in which arresters consisting of sheeting and blocks perforated with circular holes were subjected to propane/air explosions. Perforated metal sheeting was used because it is sometimes installed as an alternative to wire-gauze arresters; some tests were also carried out with perforated polyvinylchloride sheeting to compare the performance of arresters of different thermal properties, although these arresters would not be of practical use due to the ease with which they distort and melt. The perforated-metal block arresters were used to determine the effect of substantially increasing the thickness of the arrester, and also to provide a link in design between the thin perforated sheeting and crimped-ribbon arresters which are much thicker but which have non-circular apertures. The velocities of the flames that perforated sheeting and block arresters can quench have been related to the size of the perforations and the thickness of the arresters.

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### Experimental

#### Material and apparatus

The perforated sheeting was a commercial product and consisted of brass or polyvinylchloride perforated with regularly-spaced circular holes. The holes had square 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 used; details of the dimensions and spacing of the holes are given in Table I. The diameters of the holes were accurate to  $\pm 0.25\%$  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  $\pm 0.5\%$ , but with the larger holes the tolerance rose to  $\pm 1.0\%$ . 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.

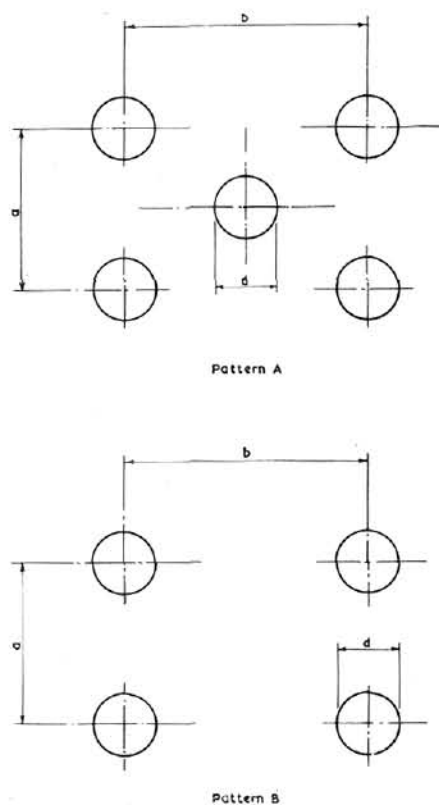


Fig. 1.—The spacing of the holes in the perforated sheeting and blocks

A set of perforated blocks was also made in brass with holes of diameter 0.175 cm arranged in the same pattern as the corresponding perforated brass sheeting (Table I). The 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.

The tube used for the explosions was mounted horizontally and was made from Perspex, the internal diameter being 6.4 cm and the wall thickness 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 and in Table II. The wide range of run-ups (distance I-J, Fig. 2) between the igniter and the arrester was used because the velocity of approach of the flame was varied by altering the run-up rather than by changing the gas mixture composition.

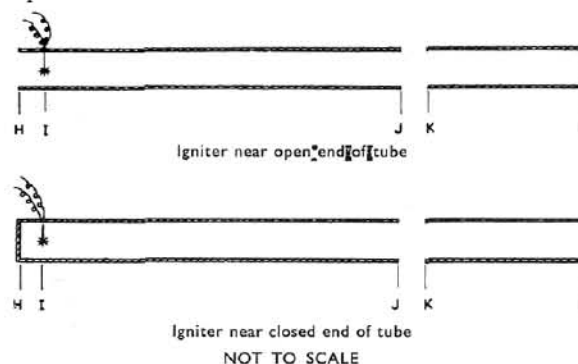


Fig. 2.—Details of explosion tube arrangement

The propane used as fuel was specified by the manufacturers as being at least 97% 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.

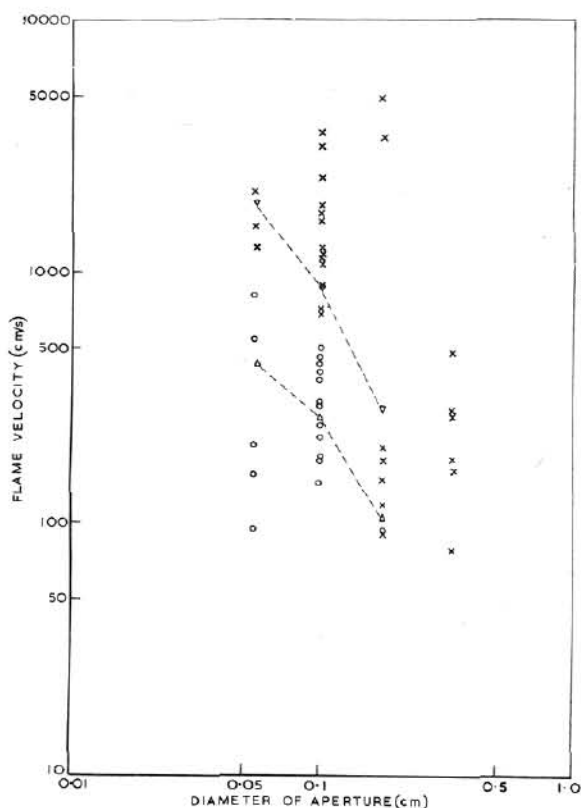
TABLE I.—Characteristics of the Perforated Brass and Polyvinylchloride Sheeting

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 ( $P$ )
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

TABLE II.—Dimensions of Tube Systems used in Centimetres. This Table refers to Fig. 2

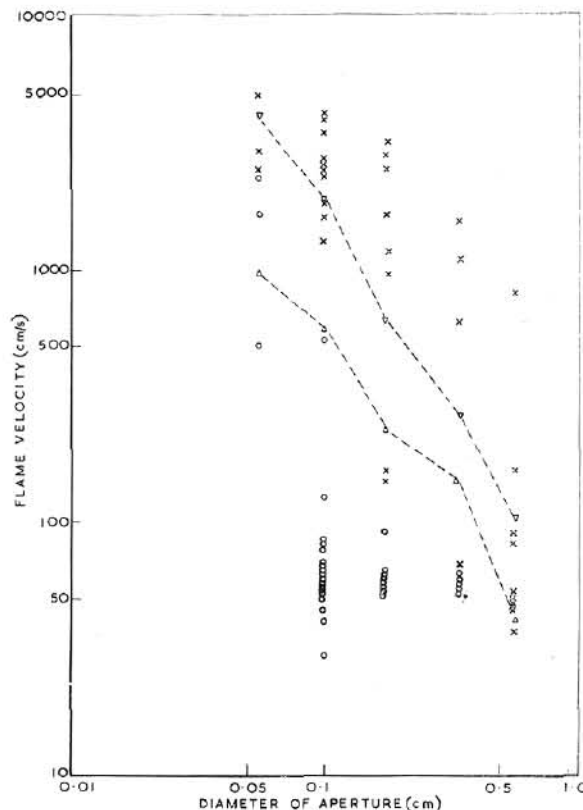
		Arrangement	HI	IJ	KL
Igniter near open end of tube	i		7.6	16.5	63.5
	ii		12.7	34.5	63.5
	iii		12.7	46.0	63.5
	iv		12.7	79.0	63.5
	v		12.7	122	63.5
	vi		12.7	153	63.5
	vii		12.7	305	63.5
	viii		30.5	452	63.5
	ix		30.5	790	231
	x		30.5	1140	262
Igniter near closed end of tube	xi		8.9	11.4	68.5
	xii		7.6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

Before use the arresters were washed in carbon tetrachloride to remove oil and grease, and after drying 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: 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 recorded by the drum camera. The velocity of the flame was measured at a point 1.5 cm from the arrester on the approach side,



4% propane/air mixtures  
Ignition near open end of tube  
Tube arrangements (Table II): i-iv, vi  
O = Arrester quenched flame  
X = Arrester did not quench flame  
Δ ∇ = Theoretical points from equations (1) and (2) respectively

Fig. 3.—The quenching of flames by perforated brass sheeting arresters



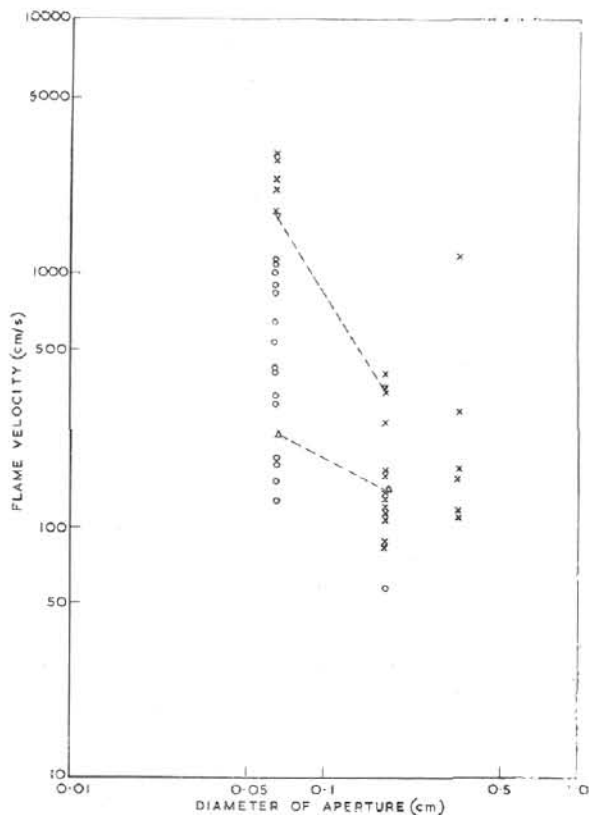
2.75% propane/air mixtures  
Ignition near open end of tube  
Tube arrangements (Table II): ii-vii  
O = Arrester quenched flame  
X = Arrester did not quench flame  
Δ ∇ = Theoretical points from equations (1) and (2) respectively

Fig. 4.—The quenching of flames by perforated brass sheeting arresters

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.

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% propane/air mixtures (stoichiometric) are given in Fig. 3. The results for the second series, using 2.75% propane/air mixtures (0.69x 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 (I-J, Fig. 2) was increased, although there was a good deal of overlapping of the flame velocities obtained with neighbouring run-up lengths. The overlapping resulted from the variation in the flame velocity obtained from various tests in a tube of given length. The results of tests carried out under similar conditions with perforated polyvinylchloride arresters are given in Fig. 5. When the polyvinylchloride arresters quenched a flame they appeared to be undamaged,



4% propane/air mixtures  
 Ignition near open end of tube  
 Tube arrangements (Table II) : i, iii, iv, vi, vii  
 O = Arrester quenched flame  
 X = Arrester did not quench flame  
 $\Delta$   $\nabla$  = Theoretical points from equations (1) and (2) respectively

Fig. 5.—The quenching of flames by perforated polyvinylchloride sheeting arresters

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. 6, the igniter being situated near the open end of the tube. In all these tests 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 separated by a Perspex ring 2.55 cm deep; this combination was tested in the usual manner, using 4% propane/air flames. The minimum velocity of the flame that could pass through the first block only was about 1000 cm/s. The minimum velocity of the flame required for it to propagate through both blocks was about 1800 cm/s. These velocities are close to the respective values for a single block and for two blocks in contact (Fig. 6) and are in fact slightly lower. It follows that for practical purposes the efficiency of the arrester was not greatly diminished 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. 7. In these tests the gas mixture was streaming through the arrester when the flame arrived, due to expansion caused by the combustion. When the flame reached

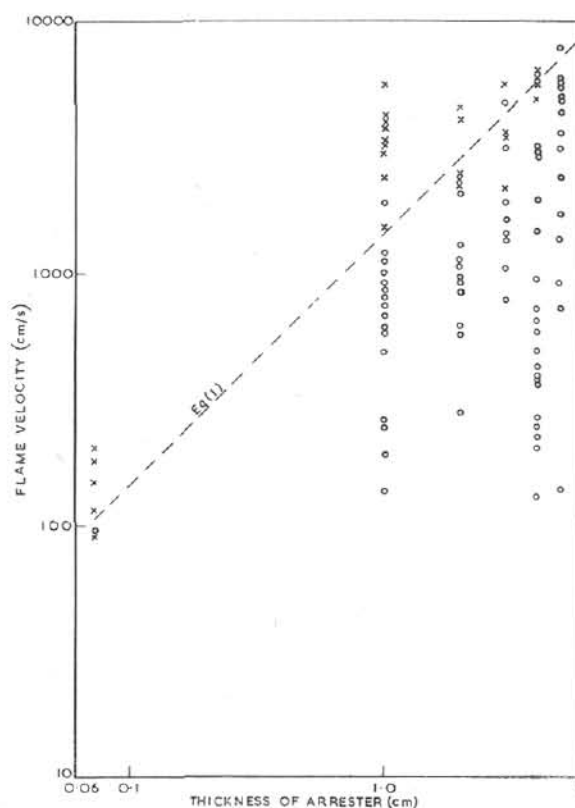
the arrester its velocity relative to the gas was considerably less than its velocity relative to the tube.

## Discussion

### Perforated sheeting arresters

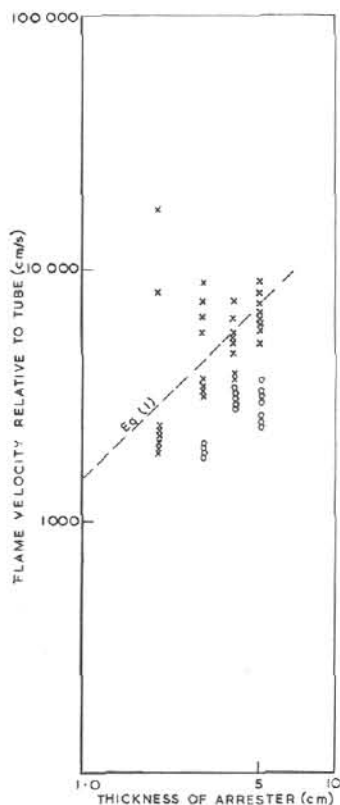
The results for the arresters made from perforated brass and polyvinylchloride sheeting, represented in Figs 3–5, show a clearly-defined dependence of the flame quenching ability of the arrester upon the velocity of approach of the flame. For each size of aperture there was a critical velocity of approach 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<sup>3</sup> 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 the Appendix. The argument is similar in principle to that already published for wire-gauze arresters under similar conditions.<sup>3</sup> 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, tem-



Hole diameter : 0.175 cm  
 4% propane/air mixtures  
 Ignition near open end of tube  
 Tube arrangements (Table II) : iv, vi-x  
 O = Arrester quenched flame  
 X = Arrester did not quench flame

Fig. 6.—The quenching of flames by perforated brass block arresters



Hole diameter : 0.175 cm  
 4% propane/air mixtures  
 Ignition near closed end of tube  
 Tube arrangements (Table II) : xi-xiii  
 O = Arrestor quenched flame  
 X = Arrestor did not quench flame

Fig. 7.—The quenching of flames by perforated brass block arresters

perature and the thickness of the flame, and the dimensions of the arrester. 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. 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 the Appendix. The resulting equations are represented by broken lines in Figs 3–5. The broken lines are not always straight because when the diameter of the apertures in the arrester was changed the thickness of the plate also varied (Table I), and the variation was not uniform.

It may be seen from Figs 3–5 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 (1) underestimates the critical velocities for arresters with small holes (diameters not more than 0.1 cm), whereas equation (2) tends to overestimate the critical velocities. Equation (1) 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 the Appendix 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 thermal properties of the arresters ought to have been detected. Thus, under the experimental conditions, the flame quenching ability of the arrester was probably not governed by the heat transfer properties of the materials of construction of the arrester, but by the rate of transfer of heat to it.

#### Perforated block arresters

The results for block arresters again show that the velocity of the flame as it approached the arrester is an important factor in determining whether or not it was quenched (Figs 6 and 7). 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 (1) is represented in Figs 6 and 7 by broken lines. The line in Fig. 6, for flames propagating from the open end of the tube, is in good agreement with experiment over a very wide range of arrester thicknesses.

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 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 (1) and (2). However, the line calculated from equation (1) is in fair agreement with the results (Fig. 7), although overestimating the efficiency 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 (1) it was assumed that the gas flow through the arrester was streamline, although it is of course turbulent in the explosion tube. If the flow through the arrester were taken to be turbulent the velocity of the flame that was just quenched would increase with the fifth power of the thickness of the arrester, whereas the results in Figs 6 and 7 show the velocity to be directly proportional to the thickness of the arrester.

#### Comparison with wire-gauze arresters

The merits of perforated sheeting and block arresters can be compared with those of wire gauze<sup>3</sup>. With each type of arrester it is the velocity of approach of the flame that is a major factor in determining whether the flame will pass through. As the velocity of the flame depends on the geometry of the duct along which it propagates, this geometry must be taken into account when considering the installation of these arresters. The position of explosion relief vents relative to likely sources of ignition is also important. Both wire gauze and perforated metal sheeting, of the same size of mesh or perforation, have similar effectiveness in acting as flame arresters. These types of arrester are effective only against relatively slowly-moving flames, such as may be generated in short lengths of ducting. Perforated blocks are considerably more effective than sheeting and can be more effective than very fine gauze, which is often ruled out for practical purposes by its high resistance to gas flow and its ease of blockage. For high velocity flames, however, suitable perforated blocks are likely to be impracticable and other

types of arrester, such as crimped-ribbon arresters, should be considered. From the practical point of view there are other factors involved in the choice of arrester; for instance the mechanical strength, the thermal capacity, and the cheapness of proposed arresters must also be taken into account.

#### Acknowledgments

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#### APPENDIX

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% 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. 7 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.

Coulson and Richardson<sup>5</sup> considered theoretically the heat transfer between a tube wall at constant temperature and fluid in streamline flow. By using a cubic relation for the radial distribution of temperature in the fluid, the rate of heat transfer at the tube wall was obtained in terms of the axial temperature of the fluid.

The rate of heat transfer per unit area of tube wall would then be :\*

$$2 \cdot 4K(T_h - T_o)/d.$$

In the present case if the apertures in the arrester are sufficiently close together for all the flame to be quenched by the walls of the aperture, and none by the blank face of the arrester, then unit area of arrester face corresponds to

$$(4P/\pi d^2)(\pi y d) \text{ area of aperture wall} = 4Py/d.$$

The rate of heat transfer per unit frontal area of arrester is

$$9 \cdot 6KP_y(T_h - T_o)/d^2.$$

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  $x/(V+v)$ ,

\* Symbols have the meanings given to them on pp. 56 and 57.

so that the total heat transferred to unit area of arrester

$$= q = 9 \cdot 6KPxy(T_h - T_o)/d^2(V+v).$$

The flame front propagates at right angles to itself at the adiabatic burning velocity  $S$ , and when the flame front is wrinkled the velocity of propagation along a duct is increased in proportion to the greater surface area of the flame. If 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<sup>2</sup> of flame, *i.e.*  $Q = qS/V$ . 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.*  $x/V = x_o/S$ .

$$\text{Thus} \quad (V+v) = \frac{9 \cdot 6KP_y(T_h - T_o)}{d^2 Q/x_o} \quad (1)$$

Equation (1) 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. When only an area  $\pi d^2/4$  of the flame is quenched in each aperture,  $P = 1$ .

$$(V+v) = \frac{9 \cdot 6Ky(T_h - T_o)}{d^2 Q/x_o} \quad (2)$$

Information is available from various sources on adiabatic flame temperatures and other thermal properties.<sup>3,6-8</sup> The following values were taken for 4% propane/air flames:  $T_h = 2000^\circ\text{K}$ ,  $K = 2 \cdot 9 \times 5 \cdot 8 \times 10^{-5} \text{ cal cm}^{-1} \text{ s}^{-1} \text{ K}^{-1}$ ,  $Q/x_o = 2 \cdot 32 \times 10^{-2} \text{ cal/cm}^2$ . Corresponding values for 2.75% propane/air flames are:  $T_h = 1800^\circ\text{K}$ ,  $K = 2 \cdot 75 \times 5 \cdot 8 \times 10^{-5} \text{ cal cm}^{-1} \text{ s}^{-1} \text{ K}^{-1}$ ,  $Q/x_o = 8 \cdot 92 \times 10^{-3} \text{ cal/cm}^2$ .

In both cases  $T_o = 290^\circ\text{K}$ , and values of  $P$  were taken from Table I.

The calculated values of  $(V+v)$ , the velocity of the flame relative to the tube, are included as broken lines in Figs 3-7. In Figs 3-5, where  $(V+v)$  is plotted against  $d$ , the lines are not straight because  $y$  does not vary regularly with  $d$  (Table I).

#### Symbols Used

- $a$  } = spacing of the apertures in the arresters (Fig. 1).
- $b$  }
- $d$  = diameter of aperture.
- $K$  = thermal conductivity.
- $P$  = area of hole 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  $V$ .

$x_0$  = thickness of flame propagating at burning velocity  $S$ .  
 $y$  = thickness of arrester.

The above quantities may be expressed in any set of consistent units in which force and mass are not defined independently.

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