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THE PERFORMANCE OF FLAME ARRESTERS AGAINST FLAMES PROPAGATING IN
VARIOUS FUEL/AIR MIXTURES

by

B. Langford, K. N. Palmer and P. S. Tonkin

SUMMARY

The quenching of flames propagating in vapour/air mixtures of seven different solvents is compared with that of propane flames, reported previously, and with that of ethylene flames. The arresters were perforated sheets and blocks, and were mounted in a horizontal explosion tube; all the solvents were of types in common industrial use. Measurements of flame velocities showed that the ease of quenching of flames propagating in the solvent/air mixtures was similar to that of propane flames propagating at the same velocity. Thus when a flame arrester is installed in an industrial plant dealing with several vapours, the design of the arrester can be based on the range of flame velocities to be expected and the variations in the thermal properties of the flames can be ignored.

The experiments with ethylene flames showed that if the apertures in the arrester were nearly as large as the quenching diameter, the effectiveness of the arrester was low. This is discussed on a theoretical basis.

The ease of quenching of cool flames propagating in horizontal or vertical tubes was about the same as that of ordinary hot flames propagating at the same velocity. Arresters designed for ordinary flames would be capable of quenching cool flames.

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INTRODUCTION

Previous reports in this series (1,2,3) have described work carried out on flame arresters consisting of wire gauze, perforated plate, perforated block, or crimped ribbon, using propane as fuel. It was shown that the velocity of the flame as it approached the arrester determined whether or not the flame passed through the arrester; if the flame was sufficiently slow it was quenched, whereas faster flames passed through the arrester. Similar behaviour was observed in a short series of experiments with wire gauze arresters, using ethylene as fuel (1). Cabbage (4), who worked mainly with crimped ribbon arresters and town gas, also found that the velocity of the flame determined whether it would pass through a given arrester. In this work flame velocities up to detonation were studied. However, there was no published information on the behaviour of a flame arrester when used with a wide range of fuels, and especially whether an arrester would be equally effective against flames propagating at the same velocity in different fuels.

In the work described in the present note a limited range of arresters, consisting of perforated brass plates and brass blocks, has been studied using a number of different fuels. The object of the first part of the investigation relating to ordinary hot flames, as opposed to cool flames, was to ascertain whether the performance of each arrester in turn was the same against flames originating from different fuels. If this were the case, industrial plants in which the vapours of several solvents were handled in turn could be satisfactorily protected by a single arrester.

The range of fuels used consisted of ethylene and the vapours of seven solvents in common industrial usage and covering a range of classes of organic compounds. In all cases excepting methanol, which would have condensed out at room temperatures, stoichiometric fuel/air mixtures were used. The experiments were carried out with a simple explosion tubing system, and it is possible that in a more complex system faster flames would be produced with some of the fuels than with propane. However, apart from ethylene which has a maximum laminar burning velocity of about 70 cm/s, the maximum burning velocities of the other fuels are close to that of propane (about 40 cm/s) and so in simple straight tubing systems the flame velocities obtained with the solvents should not differ appreciably from those obtained with propane. The behaviour of the flames generated by a stoichiometric propane/air mixture was taken as a convenient reference for comparison with the flames produced by the fuels examined.

Finally, where cool flames could be generated at atmospheric temperature and pressure, these were also investigated to see if arresters were equally effective against cool flames as against hot flames of similar velocities. Cool flames are of relatively low temperature and only partially oxidise the fuel through which they propagate. Fuel/air mixture that are too rich to support hot flames may in some cases support cool flames; the cool flames can lead to explosions if they propagate into mixtures able to support hot flames. Because cool flames

are at a low temperature the rate of transfer of heat to an arrester is less than with flames of higher temperature. Against this, only part of the fuel is oxidised, so that the amount of heat that it is necessary to abstract from a cool flame to quench it will be less than with hot flames. As a result the behaviour of a cool flame in contact with a flame arrester cannot at present be predicted.

EXPERIMENTAL

Materials and apparatus

The arresters used in the experiments were of two kinds: brass plates of different thicknesses perforated with circular holes of various diameters, and brass blocks perforated with circular holes. The perforated brass sheets used for the plate arresters were commercial products. The pattern of the holes is shown in Fig.1; details of the dimensions and spacings of the holes are given below in Table 1. The diameters of the holes were accurate to ± 0.25 per cent but the accuracy of spacing distances a and b was dependent 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 per cent but with larger holes the tolerance rose to ± 1.0 per cent. 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 perforated plates

Diameter of hole d cm	Thickness of plate y cm	a (Fig.1) cm	b (Fig.1) cm	Area of hole in unit area plate (P)
0.559	0.124	0.843	1.42	0.41
0.340	0.118	0.442	0.764	0.54
0.175	0.073	0.283	0.466	0.37
0.100	0.072	0.176	0.291	0.31
0.075	0.052	0.138	0.251	0.26
0.055	0.046	0.112	0.180	0.24

The block arresters were made from 1 cm thick brass drilled with holes 0.175 cm in diameter to the same arrangement as in the corresponding plate arrester. These arresters were constructed so that they could be combined by dowels in packs of two or more, with the holes accurately aligned.

The tube used for the explosions was mounted horizontally for all the hot flame and some of the cool flame experiments, for the remainder of the cool flame experiments, it was mounted vertically. The tube was made of perspex, 6.4 cm internal diameter and wall thickness 0.6 cm. The length of the tube on the ignition side of the arrester (the run-up) could be varied from 11.4 cm up to a maximum of 313 cm. In the hot flame experiments, the flame velocity increased with the length of run-up. Details of the explosion tube and of the arrester positions are given in Fig.2 for the various fuels. In all experiments, ignition was near to the open end of the tube.

The fuels used are listed below.

Table 2

List of fuels and specified purities

Fuel	Quality
Benzene	Analar
n-Hexane	Standard
Acetone	Analar
Ethyl acetate	Analar
Acetaldehyde	Lab. reagent
Diethyl ether	Analar
Methanol	Commercial
Ethylene	98.2 per cent

Where possible in the hot flame experiments stoichiometric fuel/air mixtures were used, the compositions of these mixtures are shown in Table 3. In the case of the liquid fuels the mixture was prepared by vaporizing the fuel, in an airstream, in the apparatus sketched in Fig. 3. This was essentially a glass vessel containing steel ball bearings of several sizes, to give a large heat exchange surface. The vaporizing vessel was heated externally by a thermostatically controlled heating tape. Fuel was delivered into the vaporizer by a micropump, which could be set by a micrometer control to deliver the liquid at the required rate. Air was passed through the vaporizer, the flow being measured by a rotameter. With acetaldehyde and ether it was necessary to cool the reservoir of liquid fuel with ice to prevent the formation in the pump of vapour locks resulting from the high vapour pressures of these fuels at room temperatures.

Measurements of flame velocities near the arresters in the horizontal tube were made using a drum camera. In most experiments the camera photographed the flame indirectly via two plane mirrors which reflected a view of the top of tube into the camera; by this means the velocity of the flame relative to the tube was measured. In some cases with ethylene as fuel the flame was photographed directly by a camera stationed some distance from the tube in a darkened laboratory; from the photograph the velocity of the flame relative to the tube and to the unburnt gas could be determined. Whether or not the flame passed the arrester was also recorded on the film, as part of the tube on the departure side of the arrester was photographed.

Procedure

The plate arresters were cut in the form of circular discs with a diameter the same as that of the outside diameter of the perspex tube. The arrester was held between the two plane ends of the perspex tube and sealed into position using transparent adhesive tape. The fuel/air mixture was metered through the tube, about ten changes of gas being allowed, and then the supply was cut off. In the experiments with hot flames the quiescent gas mixture was ignited by a high voltage spark near the open end of the tube.

Table 3

Maximum velocities of flames quenched and minimum velocities of flames passed for various fuels and perforated plate arresters

Fuel	Stoichiometric mixture (per cent fuel)	Diameter of apertures in arrester cm									
		0.055		0.100		0.175		0.340		0.559	
		Max. velocity quenched cm/s	Min. velocity passed cm/s	Max. velocity quenched cm/s	Min. velocity passed cm/s	Max. velocity quenched cm/s	Min. velocity passed cm/s	Max. velocity quenched cm/s	Min. velocity passed cm/s	Max. velocity quenched cm/s	Min. velocity passed cm/s
Propane	4.0	800 (iv)	1250 (x)	500 (iv)	650 (iv)	90 (ii)	95 (ii)	-	-	-	-
Hexane	2.2	850 (v)	1200 (vii)	550 (v)	600 (vi)	120 (i)	140 (ii)	-	-	-	-
Methanol	9.4*	-	-	-	-	80 (v)	100 (ix)	85 (vi)	90 (vi)	30 (v)	50 (v)
Acetone	5.0	1000 (vi)	1000 (xi)	600 (iv)	900 (vi)	100 (ii)	120 (ii)	-	-	-	-
Acetaldehyde	7.75	650 (vi)	1000 (xi)	600 (vi)	700 (vi)	-	-	-	-	-	-
Ethyl acetate	4.0	650 (v)	800 (xi)	450 (v)	500 (xi)	100 (ii)	100 (iii)	-	-	-	-
Benzene	2.7	1000 (v)	1100 (vii)	550 (v)	850 (vi)	110 (i)	120 (ii)	-	-	-	-
Diethyl ether	3.4	1050 (v)	1050 (viii)	450 (v)	700 (v)	-	-	-	-	-	-

*The mixture for methanol was not stoichiometric because the fuel would have condensed out at room temperature.

(Roman numerals under flame velocities refer to run-up lengths (see Table 9)).

In experiments with cool flames, the flames were always initiated in the quiescent mixture by a gas flame, again at the open end of the tube. The cool flames were generated in rich acetaldehyde and diethyl ether mixtures and were too faint to provide adequate illumination for a photographic record that could be used for flame velocity determinations. However, the flames were slow and the run-up was sufficiently long for reasonably accurate measurements to be made by timing the flame over a fixed distance, using a stop-watch.

Results

With each combination of arrester and fuel a range of velocities of hot flames was obtained by varying the length of run-up. For most arresters, sufficient flame velocities were measured to obtain a value of the maximum velocity at which the flame was quenched by the arrester. In Table 3 are given the maximum velocity of the flame quenched by each plate arrester, and the minimum velocity of the flame which passed through the arrester, for different fuels. The results previously obtained with propane (2) are included for comparison in Table 3. The results for ethylene flames, with plate arresters, are given in Fig.4. Further tests with ethylene, using the plate arrester of aperture diameter 0.100 cm, showed that flames propagating at velocities up to 200 cm/s relative to the unburnt gas ahead of the flame were quenched. These tests involved direct photography of the explosion tube in a darkened room.

The performances of the 1 cm thick block arrester against flames of several liquid fuels are given in Table 4, and the results for propane are quoted as before for comparison. The results for ethylene flames are given graphically, in Fig.5, because several thicknesses of block arrester were used and there was an ill-defined region near to the critical velocity which prevented values from being obtained for the minimum velocities of flames passing the arresters and maximum velocities for quenching. To obtain more information about this region, further

Table 4

Maximum velocities of flames quenched and minimum velocities of flames passed, for block arresters 1 cm thick

Fuel	Propane	Benzene	Hexane	Acetone	Ethyl acetate
Max. velocity quenched by arrester cm/s	1150	1200	1050	1250	900
Min. velocity passed arrester cm/s	1500	1200	1300	1350	1170

determinations were made of velocities of ethylene flames relative to the unburnt gas ahead of the flame, as well as relative to the tube, by photographing the flame with a camera stationed some distance from the tube. The results are summarised in Fig.6. With a block arrester of 1 cm thickness, ethylene flames propagating at 75-210 cm/s sometimes were not quenched on arrival at the arrester and continued to burn. After a delay of 20-40 m sec the flame propagated through the arrester. These results are marked "D" on Fig.5, and are not strictly comparable with the remaining results because the velocity of propagation on entering the arrester would not be the same as that along the tube. Flames that approached the arrester at higher velocities, and passed through, were delayed at entry for less than 5 m sec.

In experiments with cool flames, using either acetaldehyde or diethyl ether as fuel, the flame velocities were similar in value irrespective of the mixture, the direction of propagation of flame, or the run-up length. Table 5 gives a summary of the results.

Table 5

The quenching of cool flames
(Aperture diameter in arrester 0.559 cm)

Fuel	Per cent by volume in air	Direction of propagation	Range of flame velocities cm/s	Results
Acetaldehyde	35	Horizontal and vertical	28-33	All flames quenched
Diethyl ether	28	Horizontal	29-36	All flames quenched
	18	Horizontal	27-31	All flames quenched
	12	Horizontal and vertical	26 28	All flames quenched Flame passed arrester
	8	Horizontal and vertical	22-35	Flame quenched at 22 cm/s only

Discussion

Flames from different fuels

Results have now been obtained for the quenching of flames of six stoichiometric mixtures of solvent vapours with air (Table 3), and of stoichiometric mixtures of propane (2) and ethylene (Fig.4) with air, by a range of perforated plate arresters. Further results, with a more restricted range of fuels, are available for perforated block arresters (Table 4, Fig.5 and 6 and reference 2). It is convenient to consider all these results together, with the exception of those for ethylene flames acting against arresters with apertures of 0.1 cm and greater, which are dealt with in the next section below.

The earlier work (2), using propane as fuel, showed that with perforated plate and block arresters the velocity of approach of the fastest flame that the arrester could quench varied with the diameter and depth of the apertures in the arrester, provided that the diameter was less than the quenching diameter for the gas mixture. Two limiting cases were considered; in the first, the whole of the flame front was reckoned to be quenched by the walls of the apertures in the arrester, and none by the blank face of the arrester. This is the case when the apertures are close together. In the second limiting case, only that portion of the flame front directly opposed to the aperture

was reckoned to be quenched by the walls, the remainder being extinguished at the blank face of the arrester. This is the case when the apertures are sufficiently widely spaced not to interact. However, this case may never be completely attained since some of the flame front near to an aperture, but not directly opposed, may enter; this condition is intermediate between the two limiting cases. By equating the amount of heat abstracted from the flame by the arrester to the amount of heat that must be taken from a flame in order to quench it, the following equation was derived (2) for the first limiting condition.

$$(V + v) = \frac{9.6 K P_y (T_h - T_o)}{d^2 Q / x_o} \dots\dots\dots (i)$$

The symbols are listed on page 13. This equation was in reasonable agreement with the results for stoichiometric propane/air flames and perforated plate and block arresters of aperture diameter 0.175 cm. No tests were made with arresters of aperture diameter between 0.175 and 0.28 cm, the quenching diameter for the stoichiometric propane/air mixture.

In the other limiting case, the following equation was derived

$$(V + v) = \frac{9.6 K_y (T_h - T_o)}{d^2 Q / x_o} \dots\dots\dots (ii)$$

The results for perforated plate arresters, of aperture diameter 0.1 cm and below, were intermediate between the values predicted by equations (i) and (ii), but tended towards equation (ii) at small diameters, where the apertures are relatively far apart.

In the present work, flames from the various fuels were each tested against the same series of arresters, and so a direct comparison can be made with propane if the differences in the properties of the flame gases are allowed for. In equations (i) and (ii) the properties of the flame that influence $(V + v)$ are represented in the quantity $\frac{K (T_h - T_o)}{Q / x_o}$.

Hence, if the experimental results given in Tables 3 and 4 are multiplied by the value of $\frac{K (T_h - T_o)}{Q / x_o}$ for propane and divided by the value for

the fuel, they become strictly comparable. The reduced results, treated in this way, are included in Tables 6 and 7. The derivation of the values of $\frac{K (T_h - T_o)}{Q / x_o}$ for the various fuels is given in Appendix 1. The

procedure could not be followed for methanol flames, since the mixture was not stoichiometric, but where comparable the results for these flames were similar to those for the other solvents (Table 3).

Table 6
Results in Table 3 reduced for comparison with those for propane

Fuel	Diameter of apertures in arrester cm					
	0.055		0.100		0.175	
	Max. velocity quenched cm/s	Min. velocity passed cm/s	Max. velocity quenched cm/s	Min. velocity passed cm/s	Max. velocity quenched cm/s	Min. velocity passed cm/s
Propane	800	1250	500	650	90	95
Hexane	885	1250	575	625	125	145
Acetone	1090	1090	655	980	110	130
Acetaldehyde	675	1035	620	725	-	-
Ethyl acetate	690	845	475	530	105	105
Benzene	975	1070	535	825	105	115
Diethyl ether	1080	1080	465	720	-	-
Ethylene	700	970	-	-	-	-

The flame velocity at which the 0.175 cm arrester should just fail, calculated from equation (i), is 116 cm/s (except for ethylene).

Table 7

Results in Table 4 reduced for comparison with those for propane

Fuel	Propane	Benzene	Hexane	Acetone	Ethyl acetate
Max. velocity quenched by arrester cm/s	1150	1170	1090	1360	950
Min. velocity passed arrester cm/s	1500	1170	1350	1470	1240

(The flame velocity at which the arrester should just fail, calculated from equation (i), is 1590 cm/s).

Examination of Table 6 shows that with the arrester of aperture diameter 0.055 cm the velocity range for propane is wide, and the values for all the other fuels overlap the range. With the arrester of aperture size 0.1 cm the velocity range for propane was narrower, but only the results for acetone fell outside the range. With the third arrester, of aperture size 0.175 cm, the velocity ranges were much closer and were near to the value of 116 cm/s calculated from equation (i). Table 6 shows that the velocity at which the flames just passed an arrester is not the same for all the fuels, although it should be so when variations in $\frac{K(T_h - T_o)}{Q/x_o}$ have been allowed for. However, the values in Table

6 fall, on the average, within ± 12 per cent of common values for each arrester, and about half of this scatter may be attributed to experimental error in the measurement of flame velocities. Likewise, in Table 7, the velocity at which the flame just passes the perforated block arrester is not the same for all the fuels. The scatter of the values is about equal to that with the perforated plate arresters, all the values are lower than the velocity predicted by equation (i), and experimental error would again account for only about half the scatter.

The origin of the remaining scatter in Tables 6 and 7 is not obvious, but may be connected with the assumption that a constant fraction of the heat released in the flames of all the fuels must be abstracted for quenching (Appendix 1). This assumption may only be approximately true; Potter and Berlad (5) used it for a range of hydrocarbons and for hydrogen and obtained correlations of experimental data to within ± 20 per cent, but the actual error due to the assumption cannot be estimated because other variables were involved. As change in the fraction of heat to be abstracted effects $(T_h - T_o)$ and Q/x_o in opposite senses, it would have a marked effect on the quantity $\frac{K(T_h - T_o)}{Q/x_o}$.

From the practical point of view the relatively slight differences in the effectiveness of the arresters against flames propagating at the same velocity in different fuels would not be important, because the variations in the flame velocities in a given system would be much greater. These variations would arise from two sources: the first being the fact that the flame velocities developed by a given fuel/air mixture in a tube system are not reproducible, and secondly different fuels have different burning velocities which will also yield a range of flame velocities.

As these variations would be allowed for in the specification of an arrester, the differences due to change in the ease of quenching of different fuels would be negligible - except when the apertures in the arrester were near to the quenching diameter, as in some of the present tests with ethylene, discussed below. It therefore follows that when a flame arrester is installed in a system through which flow different mixtures with air of the fuels studied in the present experiments, the design can be based on consideration of flame velocity in the system and is not directly influenced by thermal properties of the flame (e.g. heat of combustion, or flame temperature). The fuels used in the experiments were chosen so as to cover a wide range of classes of organic compounds, and the conclusions reached as a result of the experiments should be applicable to other compounds of comparable structure in these classes.

Arresters with apertures near to the quenching diameter

The results obtained with ethylene as fuel (Fig.4-6) showed that arresters of aperture diameter 0.100 and 0.175 cm failed at considerably lower flame velocities than with propane, and the critical velocities were ill-defined. For example, with block arresters (Fig.5 and 6) the values predicted by equation (i) are too high by a factor of about 8, whereas with flames of propane and other fuels the predictions were much closer (Table 7) and the experimental values of critical velocities were well-defined. In addition, ethylene flames that were too slow to propagate immediately through a 1 cm thick arrester could sometimes pass through after a delay at the arrester. These discrepancies may be connected with the fact that ethylene is a considerably faster-burning gas than the other fuels and hence its quenching diameter is correspondingly lower. For example, the quenching diameter of the stoichiometric propane/air mixture is 0.28 cm, whereas that for the stoichiometric ethylene mixture is 0.195 cm⁽⁶⁾; and the diameter of the apertures in the block arresters was 0.175 cm.

A flame is able to continue propagating indefinitely in a tube of diameter slightly larger than the quenching diameter, irrespective of the length of the tube. The process of quenching can be regarded as the removal of sufficient heat from the flame before it has time to completely regenerate itself by propagating into fresh unburnt mixture. With a flame of thickness x_0 , propagating at the burning velocity S , the time required for regeneration is $\frac{x_0}{nS}$, where n is the expansion ratio, because a thickness x_0 of flame is produced from a thickness $\frac{x_0}{n}$ of unburnt gas.

The regeneration time is independent of the length of the tube. When the apertures in the arrester are smaller than the quenching diameter, the flame must propagate faster than the burning velocity in order to pass through the arrester. However, if the time of residence of the flame in the arrester is greater than the time for the flame to regenerate, $\left(\frac{x_0}{nV}\right)$,

then only part of the surface area of the passages in the arrester is used before regeneration occurs. The arrester would thus be less effective than would be expected from calculations based on the whole surface area, as in equations (i) and (ii). An estimate of the velocity of the flame that is just quenched when the apertures in the arrester are near to the quenching diameter is given in equation (iii), which only applies under conditions where flame regeneration is a limiting factor. The derivation of equation (iii) is given in Appendix 2.

$$V = S \left(\frac{d_0}{d} \right)^2 \dots\dots\dots (iii)$$

For a stoichiometric ethylene/air mixture, $S = 70 \text{ cm/s}^{(5)}$, $d_0 = 0.195 \text{ cm}^{(6)}$ and when $d = 0.175 \text{ cm}$

$$V = 87 \text{ cm/s}$$

Direct comparison of this value with the experimental results in Fig.4 and 5 is not possible, since the velocity of the flame relative to the gas (V) was not usually measured in these tests. Comparison with the results in Fig.6 shows that the value of 87 cm/s is of the correct order, but is too low, although considerably better agreement is obtained than when using equation (i). Comparison at low flame velocities could not be made because flame propagation was delayed at the surface of arresters 1 cm in thickness. With the perforated plate arresters with $d = 0.100$ cm, $V = 265$ cm/s and is in reasonable agreement with the experimental value of about 200 cm/s. At these velocities the flames were usually laminar, so that there was little gas movement ahead of the flame. The experimental values are for flame velocities at entry to the arrester, but whilst the flame is propagating through an arrester its velocity may decrease from the initial value. Thus, a thicker arrester may require a higher velocity of propagation than a thinner arrester, if a flame is to pass through. As higher values of V generally require increased values of v (unburnt gas velocity), an apparent relationship between $(V + v)$ and y may result. But V does not always increase with v , so an ill-defined critical flame velocity for quenching can be accounted for.

As explained in Appendix 2, equation (iii) can only apply to arresters in which there is ample time for the flame to regenerate. When the residence time is less than the regeneration time the value of the flame velocity predicted by equation (i) is less than that predicted by equation (iii), and equation (i) should apply instead of equation (iii). With the arresters specified in Table 1, equation (i) would be expected to apply to ethylene flames when the diameter of the aperture in the arrester was less than 0.1 cm.

The practical importance of the behaviour of arresters with apertures slightly less than the quenching diameter may not be clear at first sight, since with propane, ethylene and the other fuels tested, arresters with apertures considerably smaller than the quenching diameter can be installed; these arresters are relatively thin. However, with faster-burning fuels, such as hydrogen, or with oxygenated mixtures, the quenching diameter is small. Arresters with apertures considerably smaller than the quenching diameter would be difficult to manufacture accurately and would be very prone to blockage by dust, condensation, etc. Hence, for faster-burning mixtures it would be preferable to use a relatively thick arrester with apertures as near as possible to the quenching diameter. But just how closely the diameter of the apertures in the arrester can safely approach the quenching diameter cannot at present be forecast accurately.

Quenching of cool flames

The results in Table 5 show that cool flames of both acetaldehyde and of diethyl ether propagate slowly and may be quenched by a flame arrester. There is evidence that with ether flames, at least, the critical velocity of propagation for quenching increased as the fuel/air mixture became richer and further from the upper flammability limit for hot flames. Comparison of the results with those of methanol hot flames, using the same arrester (Table 3), indicates that the ease of quenching of cool flames is about the same as that of hot flames propagating at the same slow velocity. The reason for this is not clear.

In practice, a flame arrester would be designed to cope with much faster-moving hot flames, and would therefore be able to quench any cool flames that may be generated.

Conclusions

1. The ease of quenching of flames propagating in a range of combustible vapour/air mixtures was similar, but not identical, to that of propane flames propagating at the same velocity. Part of the difference can be related to variation in the thermal properties of the flames of the different substances.
2. When a flame arrester is installed in an industrial plant dealing with several vapours of the types studied, the design of the arrester should be based on the range of flame velocities to be expected. Only minor consideration need be given to variation in the ease of quenching of flames of the various vapours.
3. If the apertures in the flame arrester are near, but smaller than, the quenching diameter of the fuel/air mixture the arrester can be of very limited effectiveness. This may be due to only part of the cooling area in the arrester being used before the flame completely regenerates itself by propagating into unburnt mixture.
4. The ease of quenching of cool flames was about the same as that of ordinary flames propagating at the same slow velocity. Arresters designed to deal with much faster-moving ordinary flames likely to occur in practice would therefore be able to quench cool flames.

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Symbols

a	}	spacing of the apertures in the arresters (Fig.1)
b		
d		diameter of aperture
d_o		quenching diameter
K		thermal conductivity
n		expansion ratio (volume of products per volume of reactants)
P		area of hole in unit area of arrester face
Q		heat lost by unit area of flame
S		burning velocity
T_h		mean axial temperature of flame gases in arrester
T_o		temperature of the arrester
u		gas velocity in arrester apertures
v		gas velocity in explosion tube
V		flame velocity relative to unburnt gas
x		mean thickness of flame propagating at velocity V
x_o		" " " " " " S
y		thickness of arrester

Appendix 1

Calculation of the value of $\frac{K(T_h - T_o)}{Q/x_o}$ in

equations (i) and (ii), for various fuels

$$\underline{(T_h - T_o)}$$

T_h is the mean axial temperature of the flame gases in the arrester; it was taken as the mean of the adiabatic flame temperature and the temperature of the flame after sufficient heat to just quench it has been removed from it. Adiabatic flame temperatures for stoichiometric fuel/air mixtures were calculated by the method of Gaydon and Wolfhard⁽⁷⁾, allowing for dissociation of the combustion products. Values of thermodynamic properties were taken from reference 8. The adiabatic flame temperatures for stoichiometric mixtures are listed in Table 8 (column 1).

The temperature of the flame after sufficient heat has been removed from it to just quench it was estimated as follows. With propane, the abstraction of 5.0 cal/cm^3 of propane was shown by Botha and Spalding⁽⁹⁾ to reduce the burning velocity of a stoichiometric flame to about $\frac{1}{4}$ cm/s, below which it is unable to survive. Thermodynamic calculations⁽⁸⁾ show that 5.0 cal/cm^3 is equal to $0.229 \times$ the total amount of heat released in the flame. It has therefore been assumed that the removal of this amount of heat from the propane flame is sufficient to quench it. Potter and Berlad⁽⁵⁾ have shown that the fraction of the total heat produced in a flame that the flame must retain in order to exist is approximately constant for a range of hydrocarbons, and for hydrogen, in air. They recommended a value of 0.78 for the fraction, which agrees with the value of 0.771 (= $1 - 0.229$) taken here. The temperatures of flames in which only 0.771 of the heat released is available for heating the gas have been calculated for stoichiometric mixtures of the fuels (neglecting dissociation of the products) and are given in Table 8 (column 2). Values of the temperatures of lower flammable limit flames were also calculated (neglecting dissociation), and are included for comparison (column 3), using the lower limits recommended by Coward and Jones⁽¹⁰⁾.

T_h was then taken as the mean of the values in columns 1 and 2 (Table 8). $T_o = 290^\circ\text{K}$.

K

The mean film temperature of the gas in the arrester apertures was taken as $\frac{T_h + T_o}{2}$, and K was taken from Hilsenrath⁽¹¹⁾ using values for nitrogen (the major constituent of the flames).

Q/x_o

This quantity is the amount of heat to be removed from unit volume of flame in order to quench it. For a 4.0 per cent (stoichiometric) propane/air mixture the value is $0.229 \times \frac{488.6}{22.4} \times 0.040 \times \frac{273}{2260} \times \frac{24.8}{26.3}$ because 1 mole propane releases 488.6 K cal on combustion, the adiabatic flame temperature is 2260°K , and 24.8 mole reactants yield 26.3 mole products after allowing for dissociation. Values of the ratio of reactants to products (in moles) for the fuels are given in Table 8 (column 4).

$$\frac{K(T_h - T_o)}{Q/x_o}$$

Values for the various fuels are given in Table 8 (column 5)

Table 8

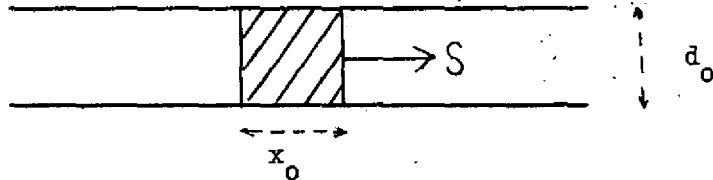
Calculated values of flame properties

Fuel \ Column	1	2	3	4	5
	Adiabatic flame temperature	Flame temperature for quenching	Lower limit flame temperature	$\frac{\text{Mole reactants}}{\text{Mole products}}$	$\frac{K(T_h - T_o)}{Q/x_o}$
	$^{\circ}\text{K}$	$^{\circ}\text{K}$	$^{\circ}\text{K}$		
Propane	2260	1960	1580	24.8/26.3	13.70
Hexane	2250	1970	1680	46.2/49.4	13.15
Acetone	2230	1930	1700	20.5/21.4	12.56
Acetaldehyde	2270	1990	1580	12.9/13.6	13.23
Ethyl acetate	2220	1920	1710	24.8/26.9	12.94
Benzene	2330	2060	1580	36.7/37.8	14.08
Diethyl ether	2260	1970	1640	29.6/31.9	13.32
Ethylene	2350	2090	1510	15.3/15.5	14.14

Appendix 2

Flame propagation in an aperture at or near the quenching diameter.

The relation between the flame velocity and the arrester aperture diameter at quenching can be obtained by a slightly modified form of the method already published (2), and which leads to equations (i) and (ii).



Consider an aperture of diameter d_0 , the quenching diameter, and a flame propagating at the burning velocity S , which is just able to travel through the aperture. Let the flame thickness be x_0 .

Then the rate of heat transfer to unit area of aperture wall = $\frac{2.4K(T_h - T_o)}{d_0}$

Rate of heat transfer per aperture = $\frac{2.4K(T_h - T_o)}{d_0} \pi d_0 \cdot x_0$

Rate of heat transfer per unit area flame front = $2.4K(T_h - T_o) \pi x_0 \frac{4}{\pi d_0^2}$

Time available, before flame regenerates = $\frac{x_0}{nS}$, because a thickness x_0 of flame is produced from a thickness $\frac{x_0}{n}$ of unburnt gas.

Heat abstracted from unit area of flame = $Q = \frac{9.6K(T_h - T_o)x_0^2}{d_0^2 n S}$

Hence $S = \frac{9.6K(T_h - T_o)x_0}{n d_0^2 Q/x_0}$

When the aperture diameter, d , is less than the quenching diameter the flame velocity must increase to V if it is to propagate through the aperture. Then, as above, rate of heat transfer per aperture = $\frac{2.4K(T_h - T_o) \pi d x}{d}$

Area of flame front in each aperture is now $\frac{\pi d^2}{4} \cdot \frac{V}{S}$ and the time available for heat transfer is $\frac{x_0}{nV}$.

Hence $Q = 2.4K(T_h - T_o) \pi x \frac{4S}{\pi d^2 V} \cdot \frac{x_0}{nV}$

But as $V/S = x/x_0$

$$V = \frac{9.6K(T_h - T_o) x_0}{n d^2 Q/x_0} = S \left(\frac{d_0}{d} \right)^2 \dots \dots \dots (iii)$$

In many cases the gas through which the flame is propagating will be in motion. If the gas velocity, relative to the arrester aperture, is u and the flame velocity is V , relative to the gas, then in time $\frac{x_0}{nV}$ the flame will travel a distance $\frac{x_0}{nV} \cdot (V + u)$ cm. Equation (iii) will thus only apply if $\frac{x_0}{nV} (V + u) < y$, the length of the aperture

(the thickness of the arrester). Initially, when the flame enters the arrester, and before it reaches a steady state, the volume of flame in the arrester may be greater than $\frac{\pi d^2}{4} x$, since the apertures form

only part of the area of the face of the arrester. Equation (iii) only applies to steady-state conditions and y may therefore need to be considerably greater than $\frac{x_0}{nV} (V + u)$ if a steady state is to be

attained during the whole of the time $\frac{x_0}{nV}$.

$$\text{Now } \frac{x_0}{nV} (V + u) < y$$

$$\text{if } \frac{d^2 Q/x_0}{9.6K(T_h - T_o)} (V + u) < y$$

$$\text{or } (V + u) < \frac{9.6K(T_h - T_o)y}{d^2 Q/x_0}$$

If $u > V$ then $(V + u) = \frac{(V + v)}{\rho}$ approximately

i.e. the velocity of the flame relative to the explosion tube $(V + v) < \frac{9.6K\rho(T_h - T_o)y}{d^2 Q/x_0}$. When v is such that $(V + v) = \frac{9.6K\rho(T_h - T_o)y}{d^2 Q/x_0}$

then equation (i) obviously applies.

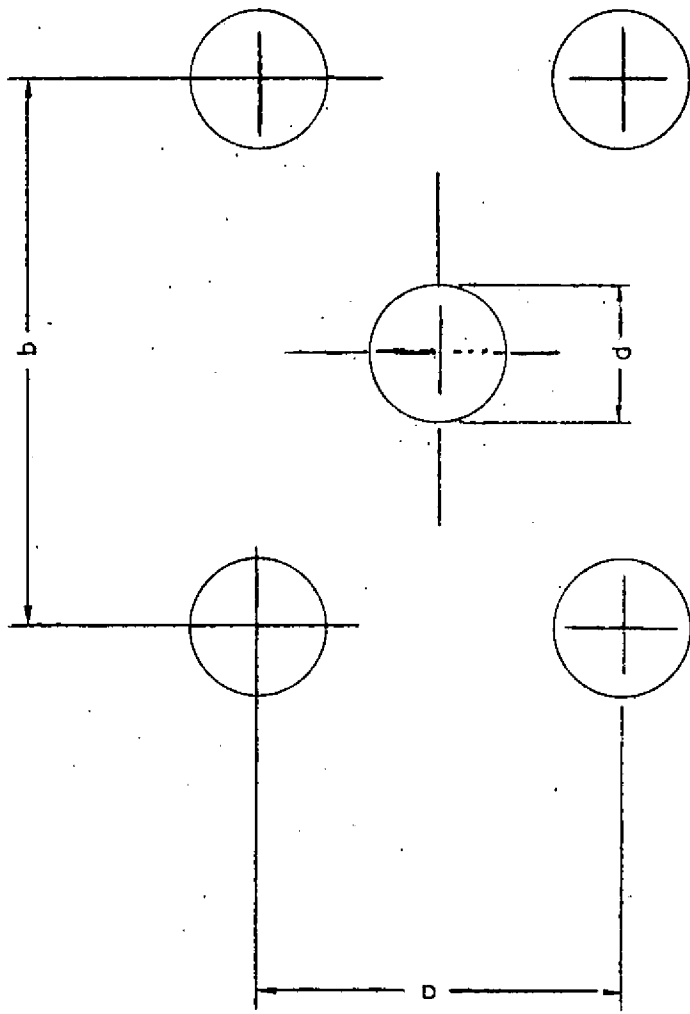


FIG. 1. THE SPACING OF THE HOLES IN THE PERFORATED BRASS PLATES AND BLOCKS

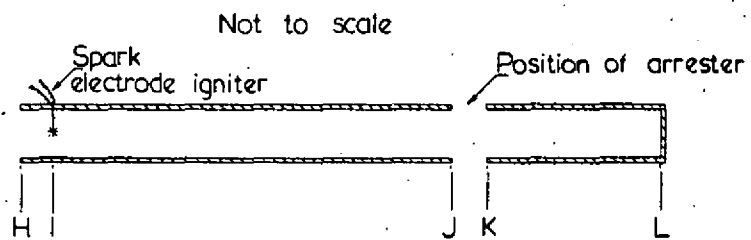


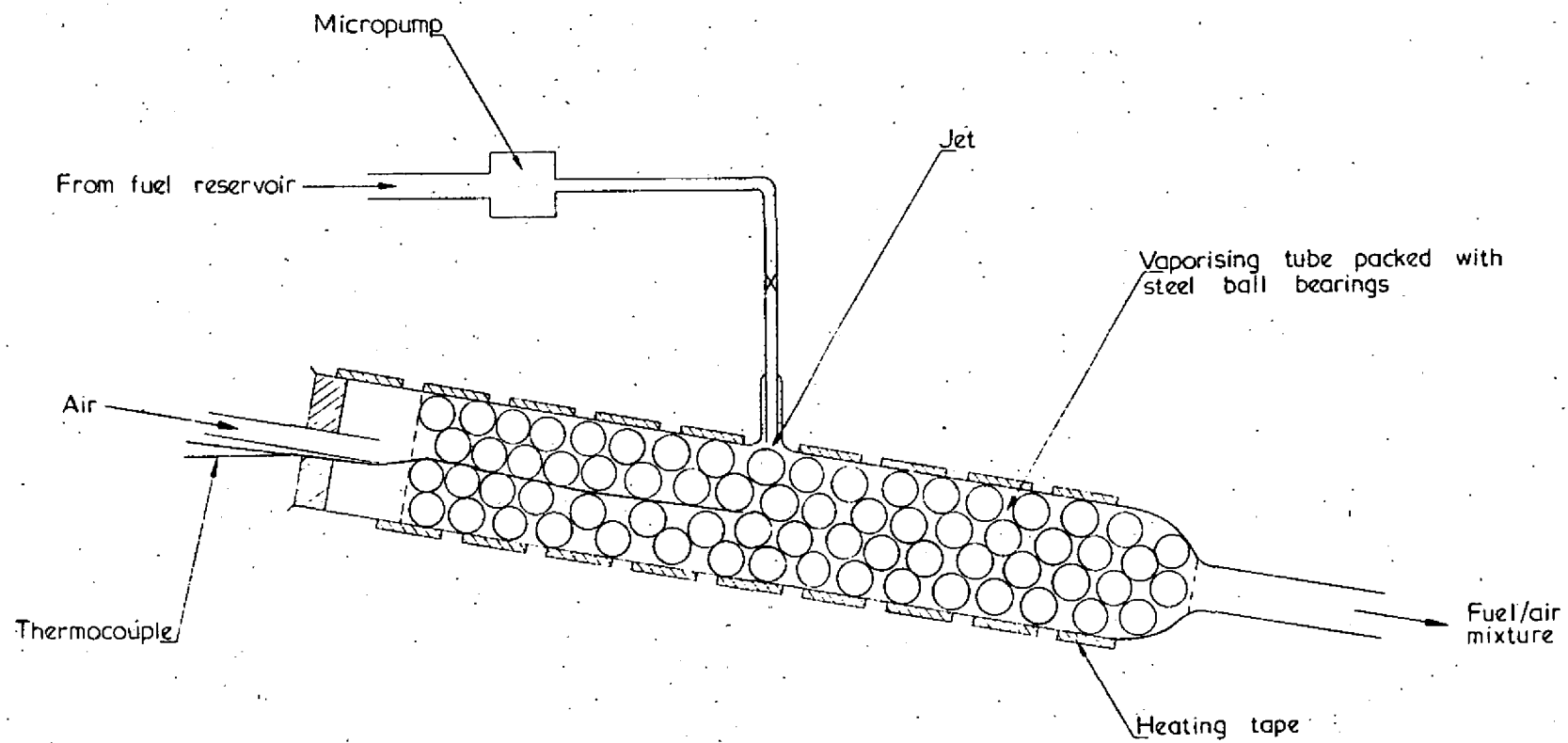
Table 9

Dimensions in cm of tube systems

Arrangement	IJ	KL
(i)	11.4	68.5
(ii)	16.5	68.5
(iii)	21.6	68.5
(iv)	39.4	68.5
(v)	64.7	68.5
(vi)	76.4	68.5
(vii)	92.5	68.5
(viii)	121	68.5
(ix)	140	68.5
(x)	159	68.5
(xi)	313	68.5
(xii)	11.4	25.4
(xiii)	21.6	25.4
(xiv)	39.4	25.4
(xv)	64.7	25.4

In each case, HI was 12.7 cm and the igniter was near the open end of the tube

FIG. 2. DETAILS OF THE EXPLOSION TUBE ARRANGEMENT



Not to scale

FIG. 3. DIAGRAM OF THE VAPORISER USED TO GENERATE FUEL VAPOUR/AIR MIXTURES

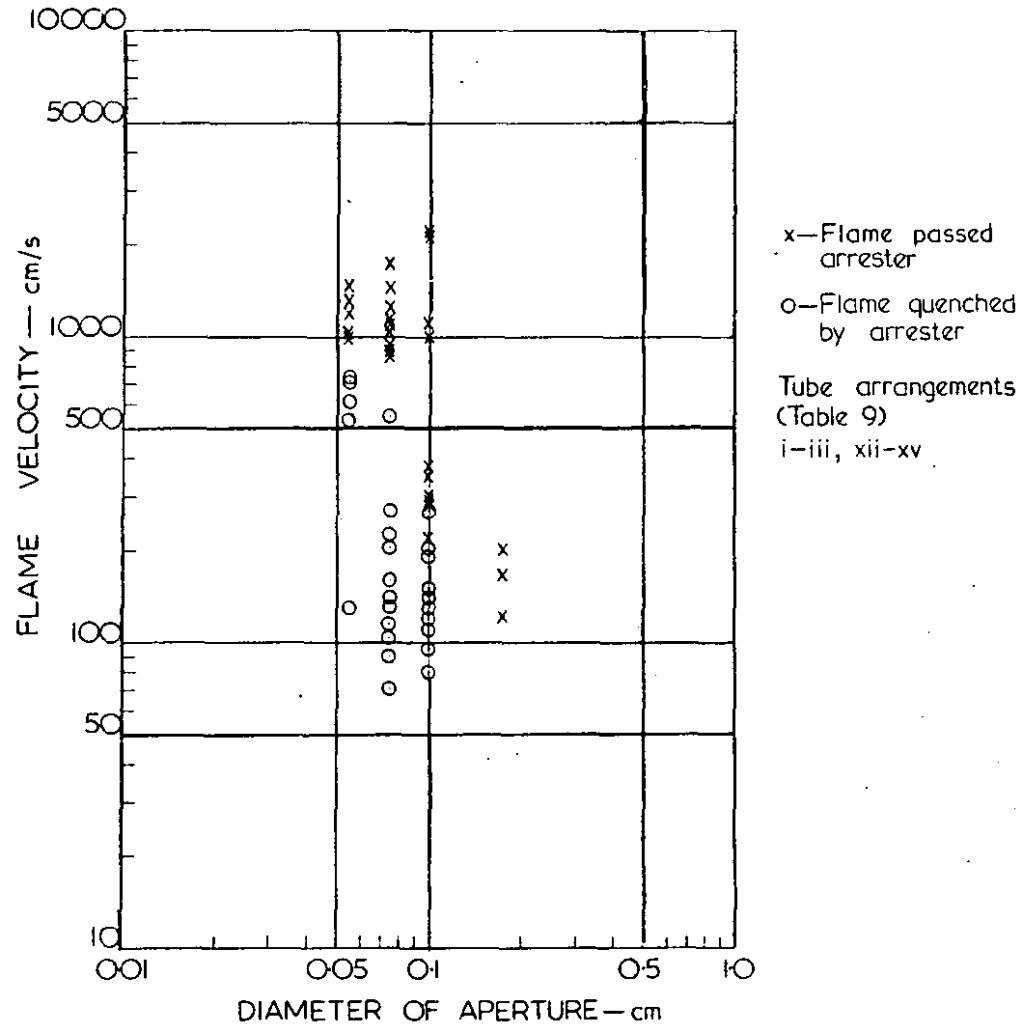


FIG. 4. QUENCHING OF STOICHIOMETRIC ETHYLENE/AIR FLAMES BY PERFORATED PLATE ARRESTERS

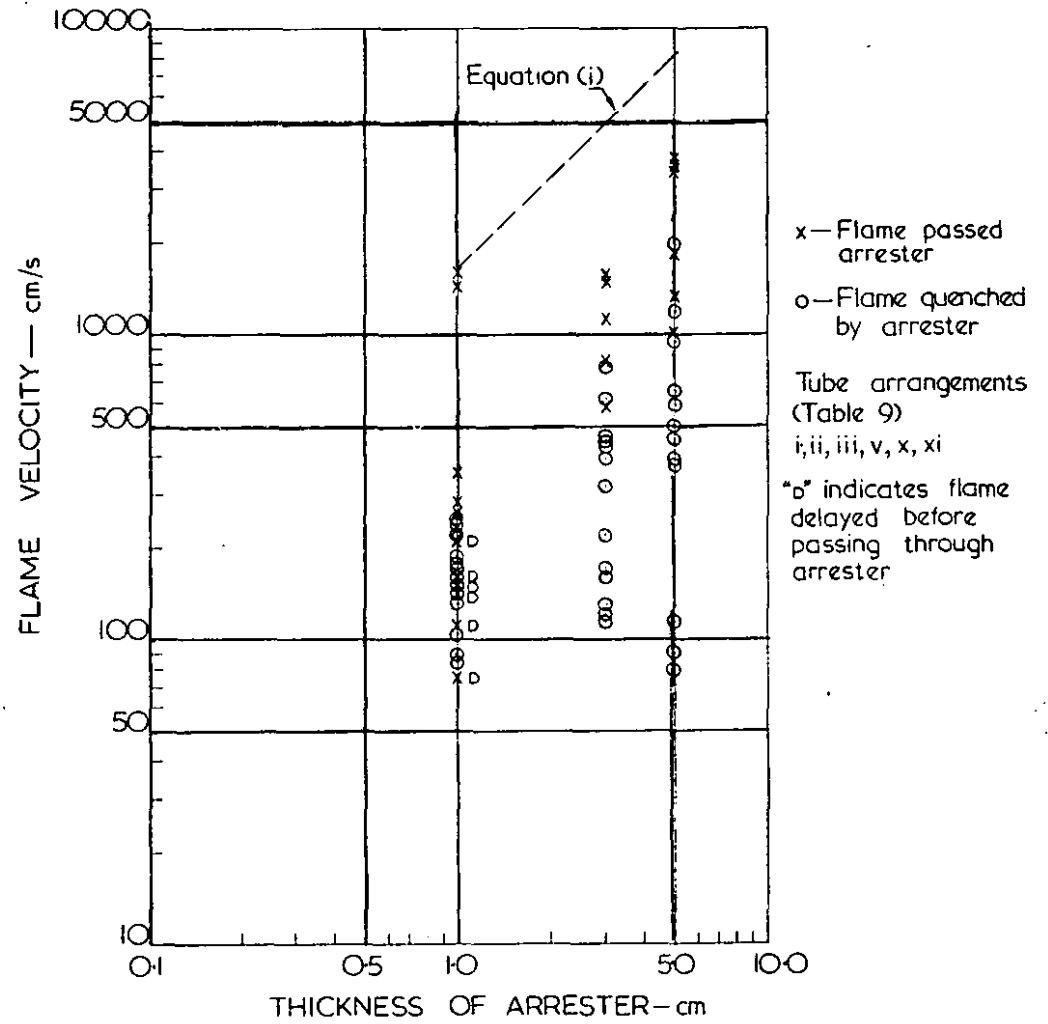
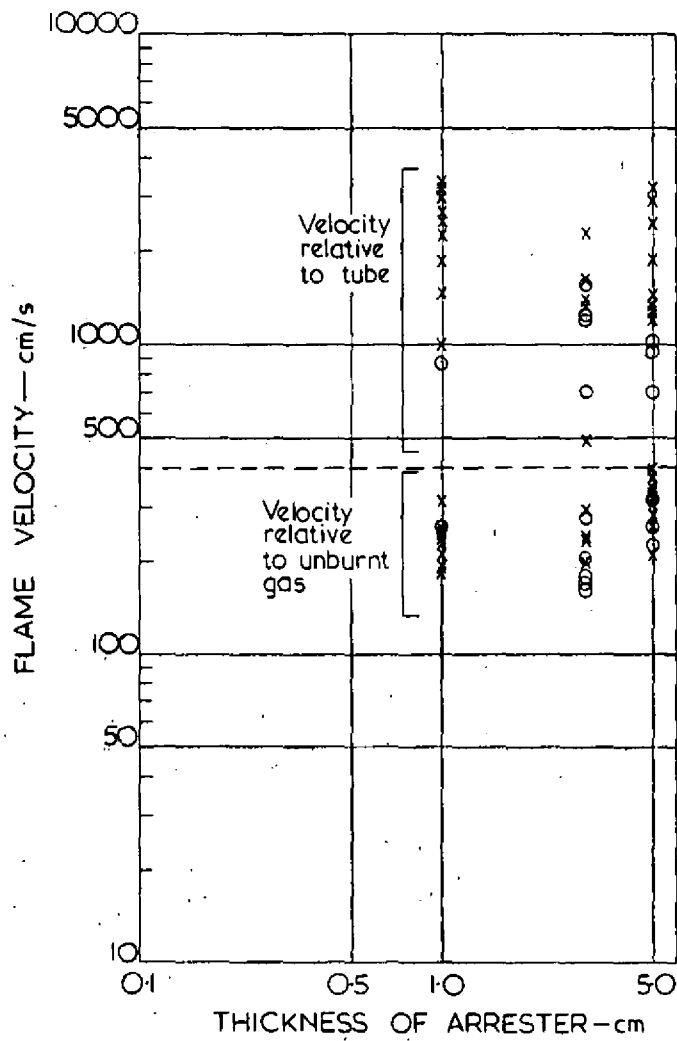


FIG. 5. QUENCHING OF STOICHIOMETRIC ETHYLENE/AIR FLAMES BY BLOCK ARRESTERS



x — Flame passed arrester
 o — Flame quenched by arrester
 Tube arrangements (Table 9)
 x, xi, xiii, xiv, xv

FIG. 6. QUENCHING OF STOICHIOMETRIC ETHYLENE/AIR FLAMES BY BLOCK ARRESTERS, MEASURING BOTH FLAME AND GAS VELOCITIES