DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH AND FIRE OFFICES' COMMITTEE
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THE QUENCHING OF FLAMES BY CRIMPED RIBBON FLAME ARRESTERS

by

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Summary

The performance of some crimped ribbon flame arresters has been investigated using propane-air mixtures. The arresters were mounted in horizontal tubing systems of various lengths filled with gas 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 crimps, provided that the size was less than the quenching diameter for the gas mixture.

A comparison is made of the performance of crimped ribbon and other types of arrester, which demonstrates the high effectiveness in flame quenching that can be obtained with suitable crimped arresters. The theoretical relation previously found between the performance and the structure of perforated sheeting and block arresters was in reasonable agreement with the results for the crimped arresters.

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Introduction

Crimped ribbon flame arresters are in wide industrial use. They are frequently installed in ducting systems extracting flammable gases and solvent vapours, and they have been recommended for use in pipelines carrying premixed gases to burners in furnaces. These arresters have the advantages of good flame-quenching properties allied to considerable mechanical strength and thermal capacity. They may be obtained in a range of sizes of aperture, but even with apertures of small size the blockage caused by the metal ribbon, and the resistance to gas flow, are not large provided that the gas is clean and deposition of dust etc. or corrosion are prevented. If the apertures through the arrester are unnecessarily small clogging may be a continual nuisance, whereas if the apertures are too large the flame will pass through the arrester. It is necessary, therefore, to have accurate design data and this will depend on the system in which they are installed as well as upon the composition of the flammable gas mixture.

Although crimped ribbon arresters are used in industry their use has been largely based on previous experience with arresters installed in various systems, and until lately there has been relatively little experimental investigation of their properties[1]. The major contribution has been the recent study by Cubbage[2] of the arresting of town gas/air detonations by crimped ribbon arresters. These detonations could be quenched, without mechanical damage to the arrester, if the crimp height was sufficiently small and the arrester was sufficiently thick. In most of the reported tests the crimp height was 0.017 in. and an arrester of this type whose thickness was 3 in. arrested a detonation propagating at 6,000 ft/sec. In this case the arrester was the same diameter as the pipeline into which it was inserted. Cubbage showed that if the arrester was contained in a housing of greater diameter than the pipe, the detonation was checked as it entered the housing and its velocity was reduced. If the length of the housing was not too large, the detonation did not re-establish itself before the flame reached the arrester and hence an arrester of lesser thickness could be used. Cubbage gave details of housings and flame arresters suitable for protecting pipelines up to 4 in. in diameter. The results are likely to be applicable to other fuel/air mixtures, providing these have the same or lower burning velocities than town gas/air mixtures. However, much industrial ducting would be unable to withstand the pressure associated with detonations, and means have to be taken to keep flame velocities down, e.g. by providing vents and by installing flame arresters near the source of ignition. Consequently in many industrial applications the arresters may be required to deal only with slower-moving flames, and crimps of larger size can then be used safely.

Where crimped ribbon arresters are installed in extraction ducting, the maximum permissible drop in pressure across the arrester may be small. As a result, it is desirable to use a crimp size as large as possible, even when the pressure drop is reduced by enlarging the ducting near the arrester. Under these conditions, the use of relief vents to keep flame velocities down is again advisable.

Much of the remaining work carried out on crimped ribbon arresters has been in connection with methane drainage installations in coal mines. Maas and Quaden[3] carried out tests in which an arrester was inserted in tubes of 5 cm diameter, having lengths up to 42 m, filled with town gas/air mixtures or mixtures of air with an industrial gas which was mainly methane with 11.5 per cent hydrogen. Tests were carried out with the gases initially quiescent or flowing, and the igniter was either upstream or downstream of the arrester. Maas and Quaden showed that under their conditions of test the arrester was able to quench violent explosions, but no precise examination of the capabilities of the arresters was reported, e.g. by measuring flame velocities. Further tests on various crimped ribbon arresters, using methane/air mixtures, have been reported[4]; these tests included an investigation of the heating up of an arrester by a flame stabilised on it.

Measurements of the drop in pressure across crimped ribbon arresters, with various gas flows, have recently been reported by Cubbage[2] and by Lindley[5].

The experiments described in the present Note were carried out with crimped ribbon arresters having a range of cell sizes, most of which were larger than those studied by Cubbage, in order to determine how the flame quenching ability depended upon the cross-section and length of the passages through the arresters. Comparison could then also be made with the behaviour of sheet metal and block arresters, perforated with multiple circular holes, which has already been described[6].

EXPERIMENTAL

Materials and apparatus

The arresters consisted of a flat and a crimped metal ribbon wound spirally around a central bob. Each arrester was made rigid by a metal rod inserted in a hole drilled along a diameter of the arrester and held in position by an outer casing of brass. Each cell of the crimp was approximately triangular, and with the smaller crimps the triangles were approximately right-angled (Plate 1). With larger crimps the triangles were more obtuse (Plate 2). The arresters were mounted inside short lengths of perspex tubing, of the same external diameter as the explosion tubing, in order to facilitate the insertion of the arrester in the test system. Some characteristics of the arresters are given in Table 1; the external diameter of each arrester was approximately 6.7 cm. and the thickness of the metal ribbon was 0.0069 cm. The equivalent hydraulic diameter of the triangular cell, listed in Table 1, was taken as $\frac{4a}{p}$ where a is the area of cross-section of the cell and p is the perimeter. The perimeter was measured directly from an enlarged photograph and the area of the cell was either calculated, if the sides of the cell were straight (Plate 1), or measured with a planimeter if the cell were appreciably curved (Plate 2). In each case a mean of at least eight determinations was taken; the variation in perimeters and areas ranged from $\pm$ 12 per cent for the small crimps to $\pm$ 16 per cent for the largest.

TABLE I

Characteristics of the crimped ribbon arresters

Nominal crimp height in.	Thickness of arrester cm. (y)	Total crimped area cm^2	Fraction of crimped area open to gas flow	Area of one cell cm^2	Equivalent hydraulic diameter of cell cm. (d)
0.017	0.80	27.1	0.89	2.2×10^{-3}	0.035
0.024	0.80	27.0	0.90	4.7×10^{-3}	0.057
"	1.10	"	"	"	"
"	1.90	"	"	"	"
"	2.55	"	"	"	"
0.048	1.25	25.4	0.85	1.5×10^{-2}	0.11
"	1.90	25.5	"	1.5×10^{-2}	0.10
"	3.20	24.4	"	2.0×10^{-2}	0.16
0.075	1.30	25.5	0.92	6.5×10^{-2}	0.18
"	2.55	24.5	0.91	6.1×10^{-2}	0.20
"	3.80	24.5	"	8.2×10^{-2}	0.24
"	5.10	24.6	"	8.3×10^{-2}	0.25
0.100	1.25	25.5	0.93	8.3×10^{-2}	0.22
"	2.55	24.6	"	8.3×10^{-2}	0.23
"	3.80	24.4	"	9.8×10^{-2}	0.27
"	5.45	25.3	"	9.6×10^{-2}	0.27

The explosion tube system was mounted horizontally and was of 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. 1. The wide range of run-ups (IJ, Fig. 1) between the igniter and the arrester was required in order to obtain as wide a range of flame velocities as possible, since the velocity of the flame as it reached the arrester depended upon the run-up length. The tube was straight, smooth, and free of obstructions.

The propane used in the preparation of the explosive gas mixtures was specified by the manufacturers as being at least 97 per cent pure, and it was mixed with atmospheric air in the explosive mixtures. In all tests with the explosion tube system a 4 per cent by volume propane/air mixture was used, and it was stationary in the tube at the moment of firing.

Measurements of flame velocities near the arrester were made using a rotating drum camera; the speed of the drum was calibrated with either an oscilloscope, an argon lamp flashing 50 times per second, or an electronic timer. The camera photographed the flame via two plane mirrors which reflected the top surface of the tube into the camera; the 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 appeared more symmetrical than when viewed from the side. Also, the foremost part of the flame propagated about one centimetre above the axis of the tube.

Procedure

Before use the arresters were washed in carbon tetrachloride to remove oil and grease, they were then dried and inserted in the explosion tube and the junction between arrester and tube was sealed with transparent adhesive tape. The gas mixture was metered through the tube, allowing about ten changes to purge the tube, and the supply was then cut off. The quiescent gas mixture 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 a point 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 relative to the gas.

Results

Ignition at open end of tube

Arresters made with the two smallest sizes of crimp, nominally 0.017 and 0.024 in. (Table 1), did not allow the 4 per cent propane/air flames to pass through them with any of the tube lengths tested. The maximum flame velocities attained in tests with these arresters, firing from the open end of the tube, are listed in Table 2, together with the appropriate tube lengths.

The arresters with the larger crimps did permit some of the flames (4 per cent propane/air) to pass. The results obtained with these arresters are shown in Figures 2 - 4, where the flame velocity is plotted against the thickness of the arrester on logarithmic axes, and distinction is made as to whether or not the flame passed through the arrester.

TABLE 2

Tests with arresters of small cell size; ignition at open end of tube

All flames arrested

Nominal crimp height in.	Thickness of arrester cm	Equivalent hydraulic diameter of cell cm	Tube arrangement (Fig. 1)	Maximum flame velocity attained cm/s
0.017	0.80	0.035	vii	850
0.024	0.80	0.057	vii	800
"	1.10	"	viii	3820
"	2.55	"	ix	2010

Usually an arrester was able to quench flames moving at velocities up to a certain critical value, which depended on the dimensions of the arrester, and failed to arrest flames propagating at higher velocities. Exceptional behaviour was observed with arresters of the largest sized crimp, Fig. 4, which failed to quench slow or fast flames but tended to be successful with flames of intermediate velocity. This point is discussed later.

Ignition at closed end of tube

When the gas was ignited at the closed end of the tube the expansion of the combustion products caused the unburnt gas ahead of the flame to be pushed along the tube towards the open end. As the flame approached the arrester it was propagating through a fast-moving gas stream, and the experimental conditions were therefore different from those in tests where ignition was at the open end of the tube. However, the arresters made with the two smallest sizes of crimp were again successful in quenching all the 4 per cent propane/air flames that could be obtained with the various tube lengths. The maximum flame velocity obtained with each arrester is given in Table 3, together with the appropriate tube lengths.

TABLE 3

Tests with arresters of small cell size; ignition at closed end of tube

All flames arrested

Nominal crimp height in.	Thickness of arrester cm.	Equivalent hydraulic diameter of cell cm	Tube arrangement (Fig.1)	Maximum flame velocity attained cm/s
0.017	0.80	0.035	xii	6960
0.024	1.10	0.057	xiii	13200
0.024	1.90	0.057	xii	8870

The results obtained with arresters of nominal crimp height 0.048 in. are shown in Fig. 5, which is plotted on logarithmic axes. With the arrester of intermediate thickness, 1.90 cm, there was a region of velocities in which the flame was bright and clearly-defined as it approached the arrester but a faint and ill-defined fogging was recorded by the film on the remote side of the arrester. Visual inspection of the explosion showed that when the flame reached the arrester a faint glow developed in the gas on the remote side, a few centimetres away from the arrester, but the luminescence soon died away without continuing to propagate down the tube. The light was not sufficiently intense to be recorded by a cine camera. It was not clear whether or not the flame did actually pass through the arrester, although it was clear that continued propagation did not occur. These results are shown by a special symbol in Fig. 5.

Only one set of tests was carried out with arresters of nominal crimp height 0.075 in., with ignition at the closed end of the tube. With the arrester of thickness 5.10 cm. all flames passed through the arrester using the shortest run-up length (Fig. 1, arrangement x); the slowest flame velocity obtained was 2050 cm/s. No tests with ignition at the closed end of the tube were attempted with the arresters of greatest crimp height (0.1 in., Table 1).

Flashback tests

Each of the arresters was tested to determine whether flashback could occur of a flame burning on the arrester face. Flashback under these conditions would indicate that at least one of the cells had an equivalent hydraulic diameter greater than the quenching diameter. A 4 per cent propane/air mixture was passed upwards through a short vertical tube having an arrester at the upper end. The gas mixture was then ignited, so that the flame burned on the upper face of the arrester, and before appreciable heating of the arrester occurred the gas flow was suddenly cut off. The flame then either extinguished or flashed back through the arrester.

Flashback occurred with arresters of 0.1 in. crimp at all thicknesses and with the thinnest arrester of crimp height 0.075 in. With all the other arresters the flame extinguished.

DISCUSSION

Effectiveness of crimped ribbon arresters

As would be expected, the effectiveness of the crimped ribbon arresters in stopping the propagation of flame increased as the size of the crimp was reduced and as the thickness of the arrester was increased. Similar behaviour was described by Cubbage(2) and was reported previously in tests with arresters made of sheeting or blocks perforated with circular holes(6). In the latter report it was shown that the velocity of approach of the flame that was just able to pass through the arrester (V + v) was related to the thickness of the arrester (y) and the number of holes in unit area of arrester (n) by

$$(V + v) = \frac{2.4\pi K\,(T_h - T_o)}{Q/x_o}\,ny \qquad \text{(i)}$$

Where

K	is	Thermal conductivity of flame gases
n	is	Number of apertures in unit area of arrester face
Q	is	Heat lost by unit area of flame
T_h	is	Mean temperature of flame gases in arrester
T_o	is	Temperature of the arrester
V	is	Flame velocity, relative to the unburnt gas
v	is	Gas velocity along the explosion tube
x_o	is	Thickness of flame propagating at standard burning velocity
y	is	Thickness of arrester

Although equation (i) appears to be independent of d, the aperture diameter, it is not so, because n is a function of d (see below). In the derivation of equation (i) it was assumed that the gas through which the flame propagated was in motion relative to the arrester, and that the gas flow in the apertures of the arrester was fully established streamline flow, i.e. entrance effects were neglected. It was also assumed that the apertures were sufficiently close together for all the flame to be quenched on the walls of the apertures and none on the face of the arrester. Equation (i) can only apply if the diameter of the apertures is less than the quenching diameter of the gas mixture; if it is greater, i.e. if flashback can occur, the arrester would fail no matter what the thickness (y) was.

Although it was based on considerable assumptions, equation (i) was in reasonable agreement with the results for arresters of perforated sheeting and blocks(6), irrespective of whether the flame was propagating from the open or the closed end of the tube. Values of the velocity of the flame that is just able to pass through the arresters were calculated from equation (i) for crimped ribbon arresters and are included in Figs. 2, 3 and 5. The following values were taken for the properties of the flames(6):

$$K = 1.7 \times 10^{-4}\ \text{cal cm}^{-1}\text{s}^{-1}\ {}^{o}\text{K}^{-1}$$

$$(T_h - T_o) = 1710^{o}\text{K}$$

$$Q/x_o = 2.32 \times 10^{-2}\ \text{cal/cm}^3.$$

Hence equation (i) became $(V + v) = 93\ ny$.

As the flames obtained in the experiments were not sufficiently fast to pass through the arresters with the two small sized crimps (Tables 2 and 3) no direct comparison can be made between these results and the predictions of equation(i) and in fact the predicted values of the flame velocity at which these arresters would be expected to fail were considerably greater than the maximum values obtained in the experiments. In tests with arresters of nominal crimp height 0.05 in. the line given by equation (i) was in good agreement with the results for tests with ignition near the open end of the tube (Fig. 2). When ignition was at the closed end of the tube the agreement was less good (Fig. 5); equation (i) overestimated the efficacy of the thinnest arrester and underestimated that of the thickest.

With arresters of 0.075 in. crimps (Fig. 3) the predictions of equation (i), where applicable, overestimate the performance of the arresters. However, with these arresters the crimps were not so well formed and regular as in the other arresters and there was a good deal of variation in the areas of individual cells (Plate 2). With arresters of the coarsest crimp, flames approaching with low or high velocities passed through the arrester, whereas flames of intermediate velocities were quenched (Fig.4). The failure of these arresters against flames of low velocity, and the fact that flames burning on the arresters can flash back through them, indicate that in each of these arresters, there was at least one cell whose equivalent hydraulic diameter was greater than the quenching diameter, which is 0.28 cm for a stoichiometric propane/air mixture[6]. Accordingly, equation (i) would not apply to these arresters and no theoretical points are obtainable.

If one or more of the cells were larger than the quenching diameter, the arresters should always fail. On the basis of the existing experimental information, it is not clear why the arresters were able to quench flames moving at intermediate velocities. Subsequent work with ethylene flames and perforated metal arresters, which will be reported later, has shown that when the aperture size was only slightly less than the quenching diameter, similar behaviour occurred. Thus, in the testing of flame arresters whose aperture size is close to the quenching diameter, it is clearly important that the arresters should be subjected to flames propagating at low velocities, even if there is much higher velocity at which flames are apparently just able to pass through the arresters.

<u>Comparison of behaviour of different types of arrester</u>

Information is now available on the performance of perforated sheeting and block flame arresters[6], wire gauzes[7], and crimped ribbon arresters (this Note and Cubbage[2]), based on the velocities of the flames that the arresters can just quench. All these arresters have a low resistance to gas flow. The results reported by Cubbage[2] were obtained with stoichiometric town gas/air mixtures; the remaining results refer to stoichiometric propane/air mixtures.

All the available results are shown in Fig. 6, where log $(V + v)$ is plotted against log (ny). Equation (i) predicts that $(V + v)$, the velocity of the flame just quenched by the arrester, should be directly proportional to (ny), the product of the number of apertures in unit area of arrester and the thickness of the arrester. In Fig. 6 the values of $(V + v)$ were taken as the logarithmic mean of the fastest flame quenched by the arrester and the slowest flame passing through it. The values of n for each type of arrester were calculated as the ratio of the total area of the apertures in unit area of arrester face to the area of one aperture. The values of the thickness of the arrester, y, were either the experimental determinations or, with gauze, twice the diameter of the wires. The variation of $(V + v)$ with (ny), calculated from equation (i), is included as a broken line in Fig. 6.

Fig. 6 shows that the results for different types of arrester may be correlated on a single graph, and that equation (i) gives a fair representation of the flame quenching ability over a wide range of conditions. For instance, equation (i) holds approximately for flame velocities from under 10^2 to over 10^5 cm/sec, although the equation does tend to overestimate the flame velocity at which the arrester just fails to quench the flame. It is particularly interesting that the results for crimped arresters that can quench town gas /air detonations, for which log (ny) is above 3, (i.e. $ny > 1000$) correlate with the results obtained with much lower flame velocities using crimped ribbon and other types of arrester against propane/air flames. It is also clear from Fig. 6 that the provision of arresters for flame velocities in the range 10^4 to 10^5 cm/sec has received little attention, although estimates of arrester dimensions could be made by interpolation. The number of apertures in unit area of arrester (n) is usually inversely dependent on the area of a single aperture, particularly with crimped ribbon and gauze arresters. It follows that $n \propto 1/d^2$ approximately, where d is the diameter of the aperture, so that Fig. 6 may be regarded as demonstrating that (V + v) is approximately proportional to y/d^2.

CONCLUSIONS

1. The effectiveness of crimped ribbon arresters in quenching propane/air flames increased as the size of the apertures was reduced, provided that the apertures were smaller than the quenching diameter of the gas mixture. The velocity of the flame that was just quenched was inversely proportional to the area of the aperture, approximately.

2. The velocity of the flame that was just quenched was also proportional to the thickness of the arrester.

3. As arresters can be made with small crimp sizes and of considerable thickness they can be much more effective than gauze or perforated sheeting or block arresters.

4. The results obtained with crimped ribbon and other types of arrester against propane/air flames can be correlated with each other, and with results reported for crimped ribbon arresters that quenched town gas/air detonations.

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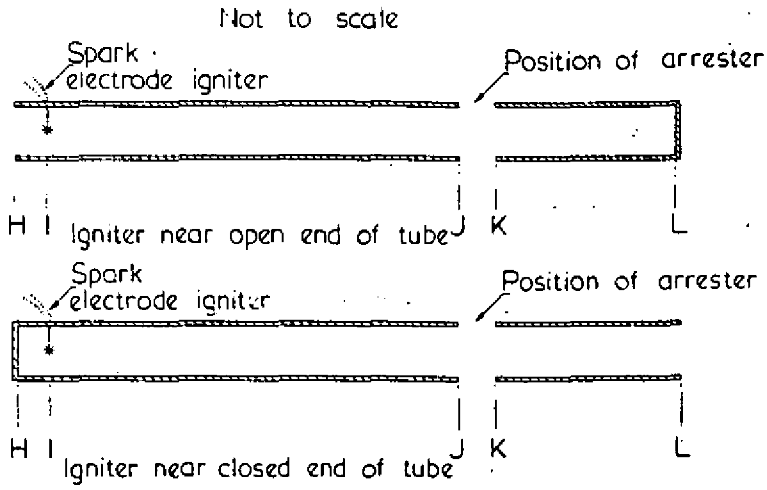

Table 4.

Dimensions in cm of tube systems

	Arrangement	HI	IJ	KL
Igniter near open end of tube	i	12·7	11·4	68·5
	ii	12·7	16·5	63·5
	iii	13·3	34·5	63·5
	iv	12·7	79·0	63·5
	v	12·7	142	63·5
	vi	12·7	158	40·6
	vii	12·7	312	40·6
	viii	29·2	569	119
	ix	30·5	1140	256
Igniter near closed end of tube	x	7·6	11·4	63·5
	xi	8·9	34·5	63·5
	xii	7·6	158	45·7
	xiii	7·6	960	61·0

FIG. 1. DETAILS OF THE EXPLOSION TUBE ARRANGEMENTS

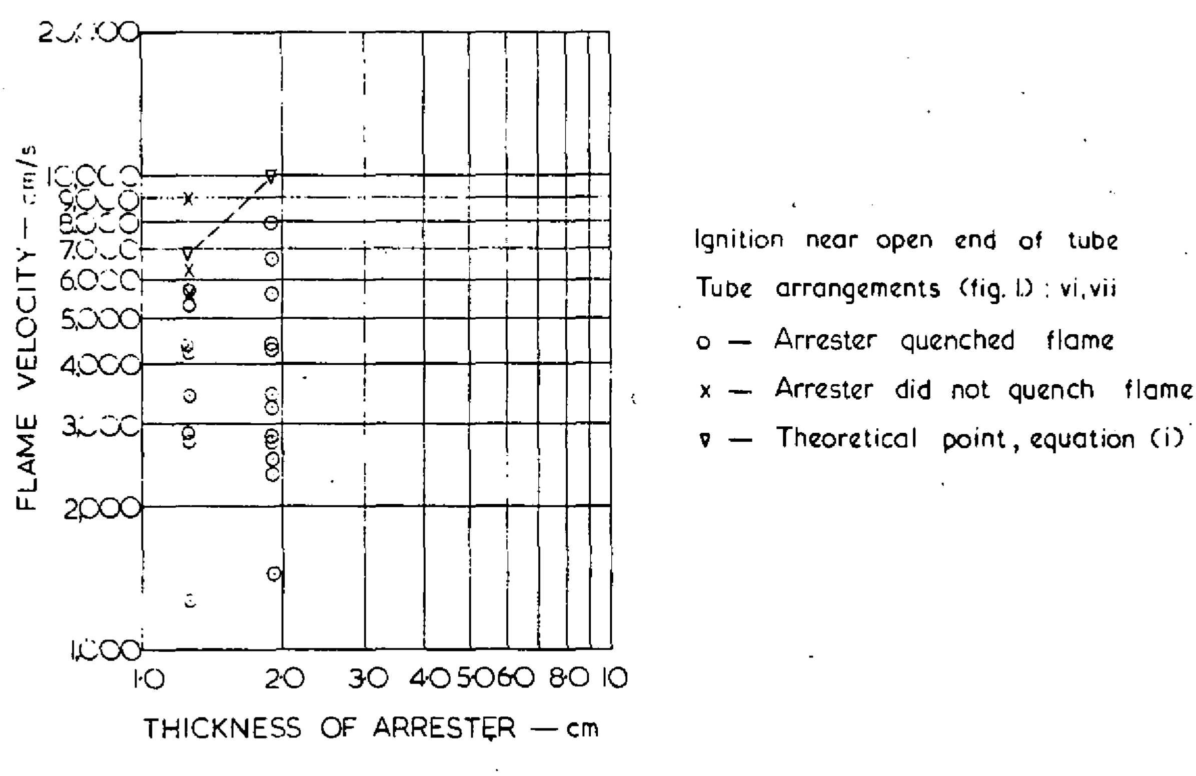

FIG. 2. THE QUENCHING OF FLAMES BY ARRESTERS OF NOMINAL CRIMP HEIGHT 0·048 in

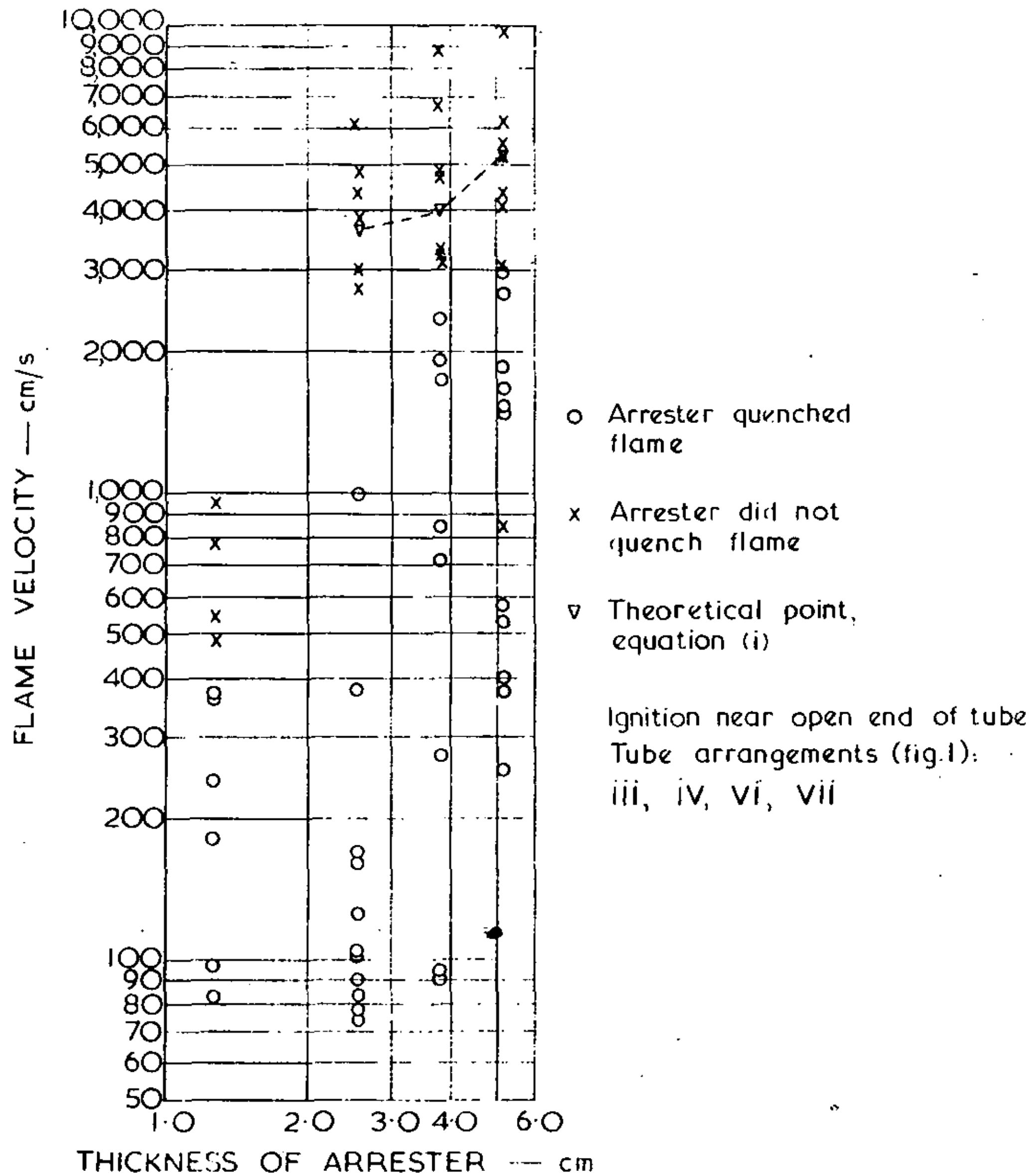

FIG.3. THE QUENCHING OF FLAMES BY ARRESTERS OF NOMINAL CRIMP HEIGHT 0·075 in.

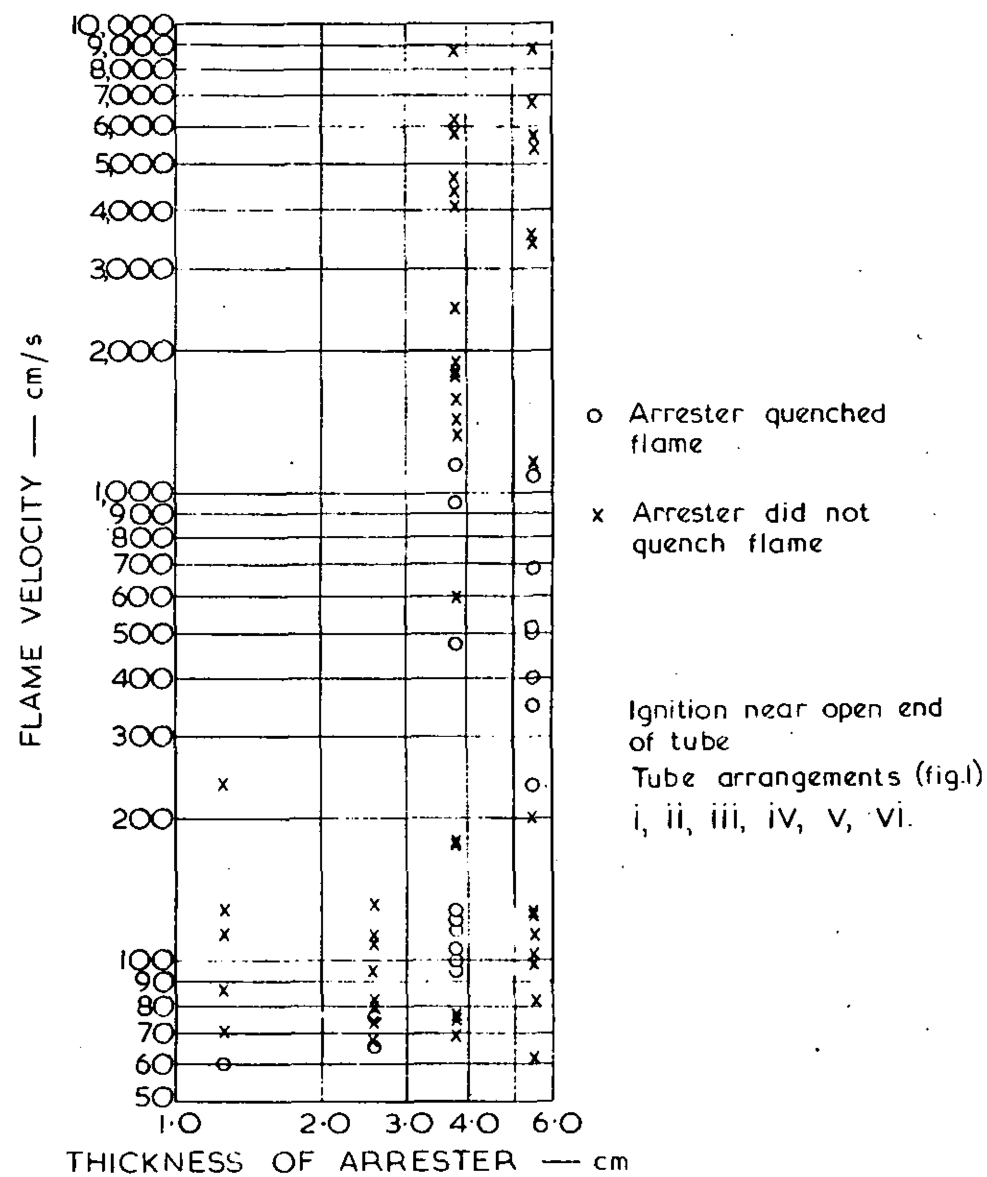

FIG 4. THE QUENCHING OF FLAMES BY ARRESTERS OF NOMINAL CRIMP HEIGHT 0·100 in.

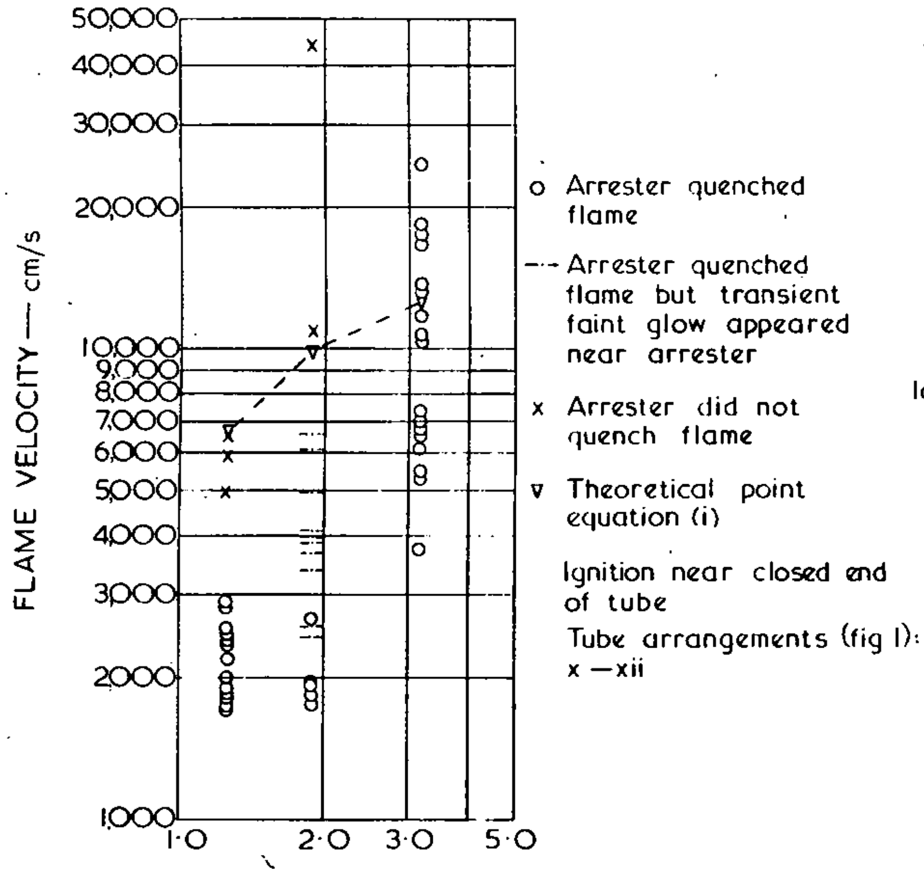

FIG. 5 THE QUENCHING OF FLAMES BY ARRESTERS OF NOMINAL CRIMP HEIGHT 0·042 in.

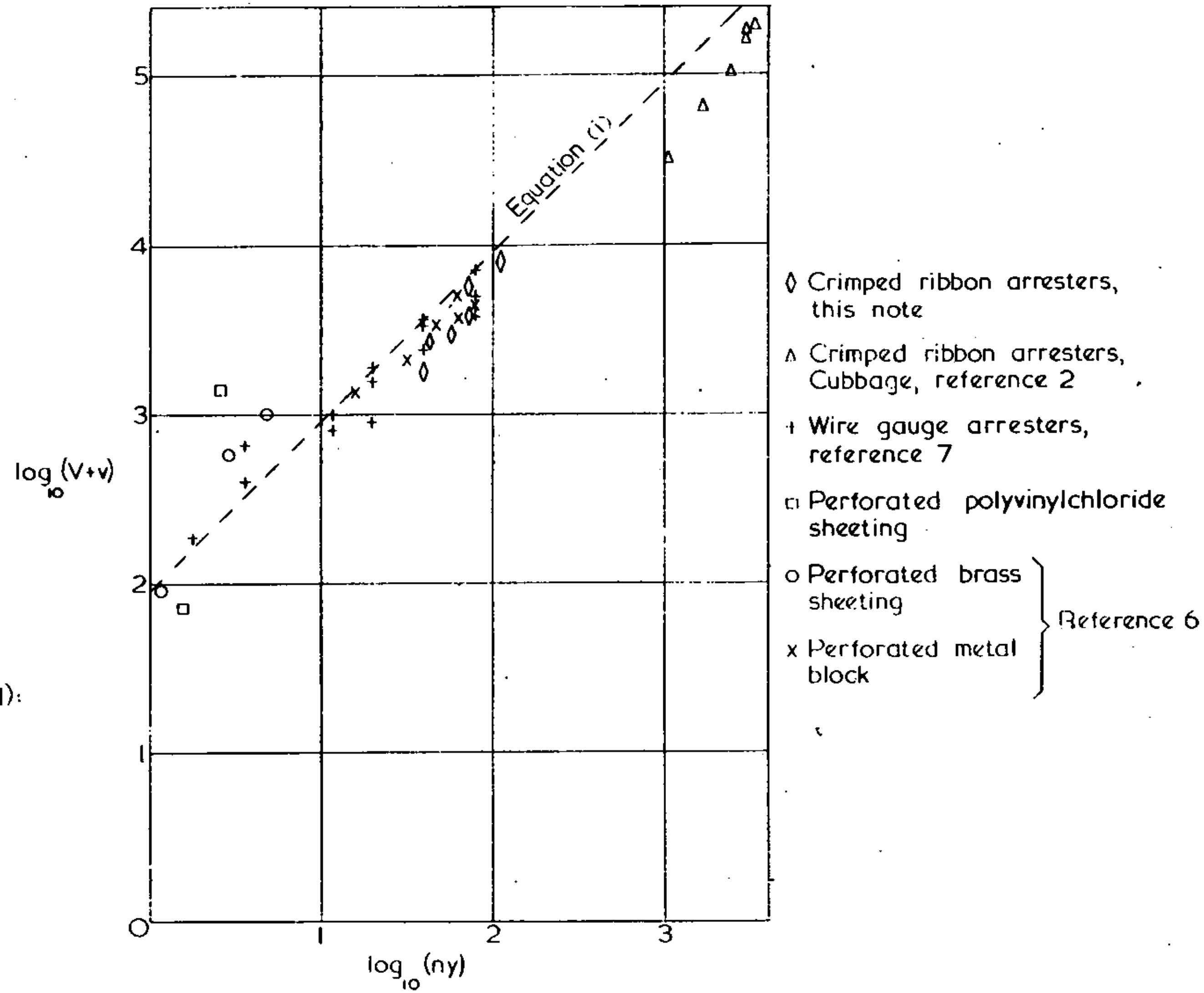

FIG 6 THE PERFORMANCE OF DIFFERENT TYPES OF ARRESTER CORRELATED BY EQUATION (i)

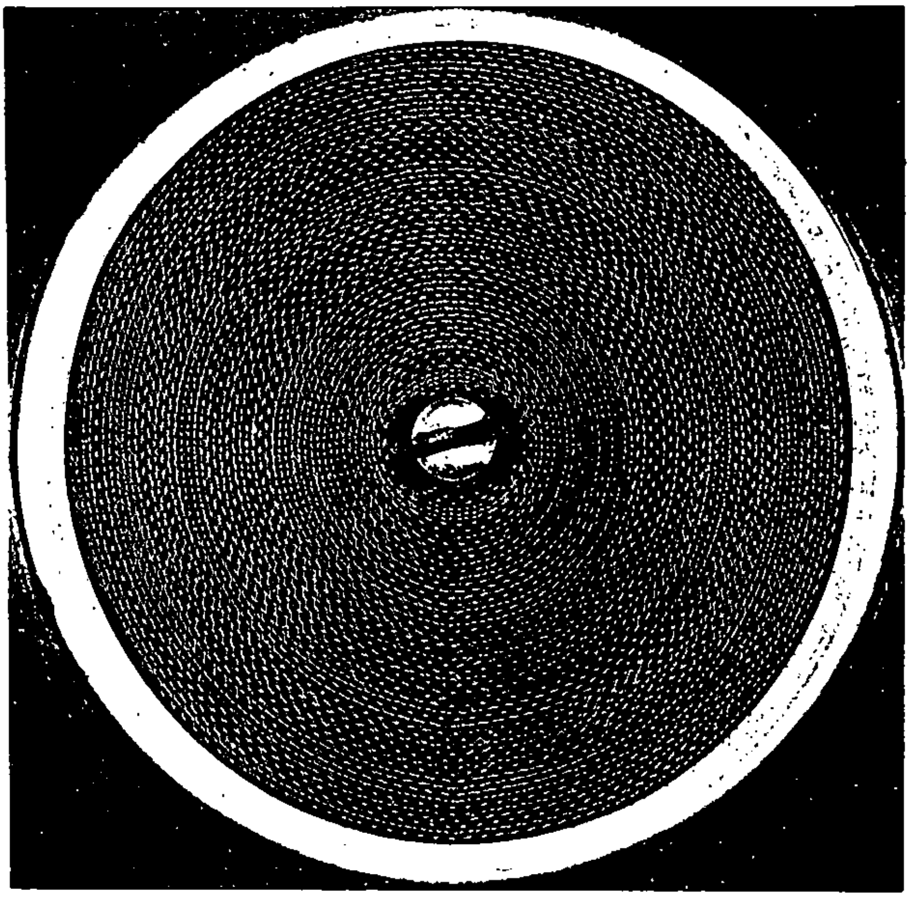

PLATE 1. CRIMPED RIBBON ARRESTER, NOMINAL CRIMP HEIGHT 0·017 IN. (ENLARGED PHOTOGRAPH)

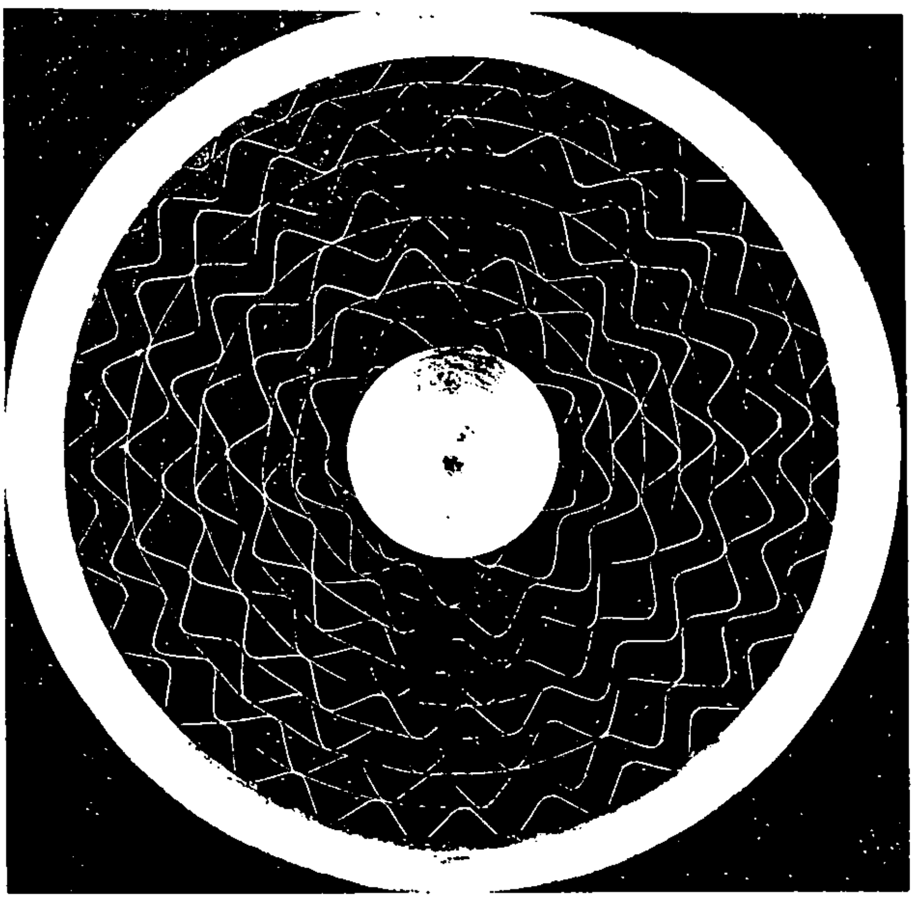

PLATE 2. CRIMPED RIBBON ARRESTER, NOMINAL CRIMP HEIGHT 0·100 IN. (ENLARGED PHOTOGRAPH)