THE QUENCHING OF PROPANE–AIR EXPLOSIONS BY CRIMPED-RIBBON FLAME ARRESTERS

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SYNOPSIS

Crimped-ribbon flame arresters were subjected to propane–air explosions propagating in ducting of widths 6·4 cm and 30·5 cm, and with the igniter sited near either the open end or the closed end of the ducting. Measurements of flame velocities and explosion pressures showed that an arrester was able to quench flames propagating slower than a certain velocity, and this critical velocity was reduced as the explosion pressure increased. The velocity was related theoretically to the arrester thickness and crimp size, and the explosion pressure.

The application of the results to practical situations is discussed.

Introduction

Flame arresters are used to prevent propagation of flame through flammable gases or vapours in industrial plant and equipment. Most arresters consist of a porous solid mass having apertures to allow the passage of gas during normal working of the plant, but which are sufficiently narrow to quench flame if an explosion should occur. Types of arrester commonly used, and having a relatively low resistance to gas flow, include perforated metal sheeting, wire gauze, and crimped metal ribbon. Other arresters, with a higher flow resistance, include packed towers, sintered metals, and compressed wire packs.

For many applications an arrester with low resistance to gas flow is desirable for technical and economic reasons, and the majority of investigations into flame-arresting capabilities has been concerned with this type of arrester. The performance of wire gauze[1] and perforated sheeting[2] arresters in quenching propane–air explosions has been studied in detail. Provided that the diameter of the apertures in the arrester was less than a critical value, the quenching diameter for the gas mixture, the arrester was able to quench flames propagating at velocities up to a value depending upon the structural dimensions of the arrester; faster flames propagated through the arrester. The aperture diameter and the arrester thickness could be related to the maximum velocity of the flame that the arrester could just quench.

The flame velocity obtained in a pipe or duct system depended upon several factors, including the gas mixture composition, the distance between the point of ignition and the arrester, the presence of bends or obstructions in the pipe, the presence of explosion relief vents, and the extent to which the flame and the unburnt gas mixture were accelerated by the expansion due to the explosion. Single layers of wire gauze and thin perforated sheeting arresters were capable of quenching only relatively slow flames. Finer or thicker gauzes or sheeting are often unsatisfactory because of only limited increase in effectiveness, or high resistance to flow, or difficulty of mass manufacture. The quenching of faster flames can be readily obtained, however, by using crimped-ribbon arresters.

Crimped arresters are attractive from the industrial point of view because they can be made capable of quenching violent explosions and they do not readily sustain mechanical or thermal damage. For instance, Cubbage[3] has shown that crimped-ribbon arresters, of crimp height 0·017 in., are able to quench town gas–air detonations. In many applications, however, the requirements would be much less severe because a slower-burning gas or vapour would be involved and detonation conditions would not be approached. The arresters can therefore safely be made thinner and of coarser crimp; the resistance to gas flow is thereby reduced and can lead to more economic running of plant. The relationship between the structural dimensions of crimped-ribbon arresters and the velocities of flames that were just quenched has been studied in the present investigation. The flammable mixture used was propane–air, which may be taken as representative of a range of saturated hydrocarbons and many solvent vapours mixed with air.

Experiments were carried out in ducting of two sizes, 6·4 cm and 30·5 cm in width, to obtain results with direct application to a range of practical situations.

Experimental

Apparatus and materials

ARRESTERS

Two sizes of arrester were used in the experiments. The smaller arresters were circular and consisted of crimped and flat metal ribbons wound spirally around a central bob (Fig. 1), made rigid by a metal rod inserted diametrically and held in position by an outer casing of brass. The internal diameter of the casing was 6·0 cm. The larger arrester was square and constructed of crimped and flat metal ribbons laid alternately in a rigid metal frame, the internal dimensions of which were $30{\cdot}5 \times 30{\cdot}5$ cm, and which was fitted into a flanged support for insertion in the explosion ducting (Fig. 2). The area of crimped ribbon was subdivided by two flat strengthening bars parallel to the sides of the frame; each bar was 0·8 cm wide and centred 10·2 cm from the parallel inner edge of the frame. Further strengthening of the crimp was provided by two metal rods in holes drilled through the frame and the crimp, at right angles to the strengthening bars. The centres of the rods were 10·2 cm from the parallel edges of the frame. In all arresters the thickness of the metal ribbon was 0·007 cm.

Details of the dimensions of the crimps and of the thickness of the arresters are given in Table I. The crimp areas were

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TABLE I.—*Characteristics of the Crimped-ribbon Arresters*

Width of crimp in arrester (cm)	Nominal crimp height (in)	Thickness of arrester (y) (cm)	Fraction of crimped area open to gas flow	Mean area of one aperture (cm^2)	Number of apertures in unit area of arrester (n) (cm^{-2})	ny (cm^{-1})
30·5	0·05	3·2	0·87	$1\cdot8\times10^{-2}$	50	159
6·0	0·017	0·8	0·65	$2\cdot2\times10^{-3}$	295	236
	0·025	0·8	0·78	$4\cdot7\times10^{-3}$	166	133
		1·1	0·78	$4\cdot7\times10^{-3}$	166	183
		1·9	0·78	$4\cdot7\times10^{-3}$	166	315
		2·6	0·78	$4\cdot7\times10^{-3}$	166	432
	0·05	1·3	0·85	$1\cdot5\times10^{-2}$	57	74
		1·9	0·85	$1\cdot5\times10^{-2}$	57	108
		3·2	0·85	$2\cdot0\times10^{-2}$	43	136
	0·075	2·6	0·91	$6\cdot1\times10^{-2}$	15	39
		3·8	0·91	$8\cdot2\times10^{-2}$	11	42
		5·1	0·91	$8\cdot3\times10^{-2}$	11	56

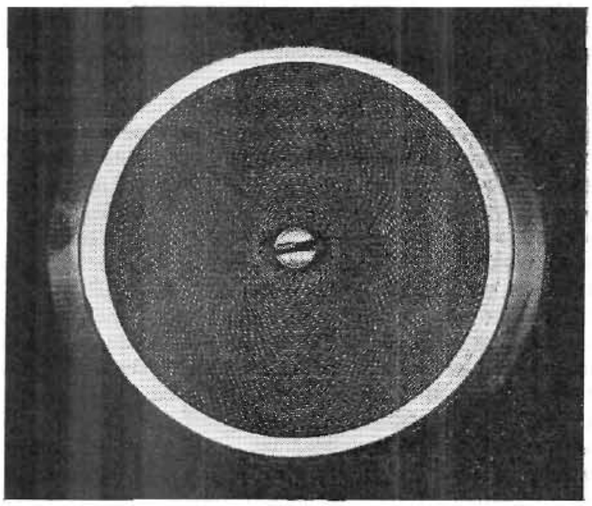


Fig. 1.—*Spirally-wound crimped-ribbon arrester*

determined from measurements of enlarged photographs. For the circular arresters a mean of at least eight determinations was taken, and for the square arrester the mean was of 72 determinations. The variation in values from the means ranged up to ±12%. Table I also gives values of ny, which is the product of the number of apertures in unit area of arrester and the arrester thickness, because it is shown later that the value of ny can be related to the velocity of flame just quenched by the arrester.

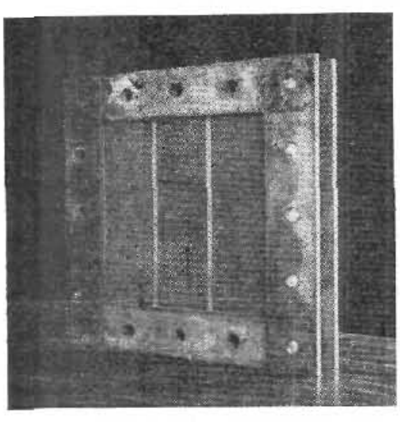


Fig. 2.—*Square arrester in flanged support*

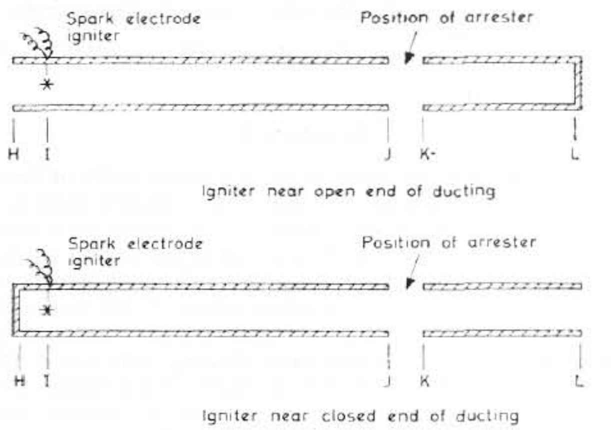


Fig. 3.—*Positions of the igniter in experiments with straight ducting (not to scale)*

EXPLOSION DUCTING

The explosion-ducting systems used with the circular arresters were mounted horizontally and were mainly of perspex, the internal diameter being 6·4 cm and the wall thickness 0·6 cm. The arresters were mounted inside short lengths of perspex, of the same external diameter as the explosion ducting, to facilitate insertion in the test system. The majority of experiments were carried out with straight, smooth ducting free of obstructions. The igniter, a spark electrode, was sited near either the open or the closed end (Fig. 3). The distance IJ between the igniter and the arrester, the "run-up", was varied between 11·4 cm and 11·4 m to obtain a range of flame velocities at the arrester. The distance between the arrester and the further end of the ducting (KL) ranged between 40 and 256 cm.

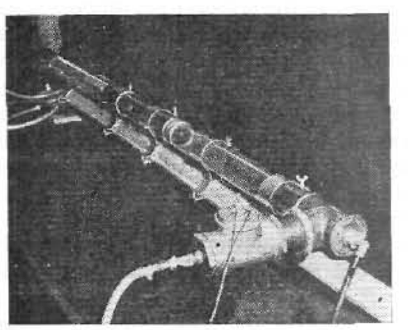


Fig. 4.—*L-shaped explosion ducting*

Fig. 5.—*Large-scale ducting for square arrester*

Some experiments were also carried out with an L-shaped ducting system, with the igniter near the closed end, to obtain greater flame velocities. The arrester was mounted in a tube connected to the bar of a tee-piece, the other end of the bar was blanked off, and the igniter was in ducting connected to the stem of the tee-piece (Fig. 4). The distance between the arrester and the tee was 67 cm, between the tee and the igniter was 17 to 33 cm, and between the arrester and the open end of the tube was 102 cm. An electrical capacity cell for the measurement of the explosion pressure could be mounted in the blanked end of the tee.

The large-scale ducting for the square arrester was 30·5 × 30·5 cm in cross-section and was also mounted horizontally. The ducting was of steel and seven lengths were available, each 1·83 m in length. Flanges were fitted to the ends of each length and also along the fronts to allow the attachment of flat perspex sheets, 0·6 cm thick, acting as windows (Fig. 5). One end of the ducting was closed by a steel plate, bolted to the end flanges. The arrester was bolted in a support between the end flanges of two ducting lengths (Fig. 6). The interior of the ducting was smooth and straight and the igniter was sited near either the open or the closed end (Fig. 3). The run-up distance IJ between the igniter and the arrester could be varied between 20 cm and 10·5 m. A further 1·8 or 3·7 m of ducting (KL) was bolted to the far side of the arrester. Fittings were attached to the ducting for the spark electrode igniter, an inlet pipe for the gas mixture, and a capacity cell for the measurement of explosion pressure. To obtain more violent explosions, in some experiments with the igniter near the closed end of the ducting, a metal strip was mounted horizontally across the centre of the duct at a position 1·83 m from the arrester, towards the closed end. The width of the strip was either 1·3 or 2·8 cm and its thickness was 0·3 cm.

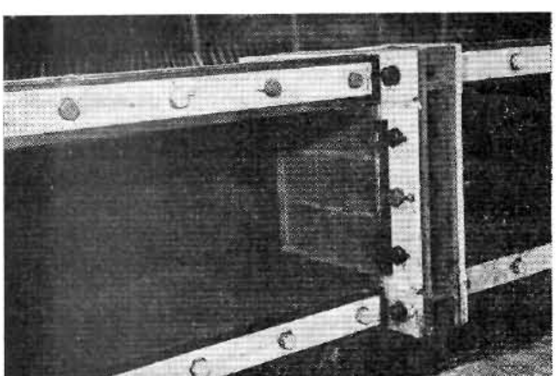


Fig. 6.—*Square arrester in position*

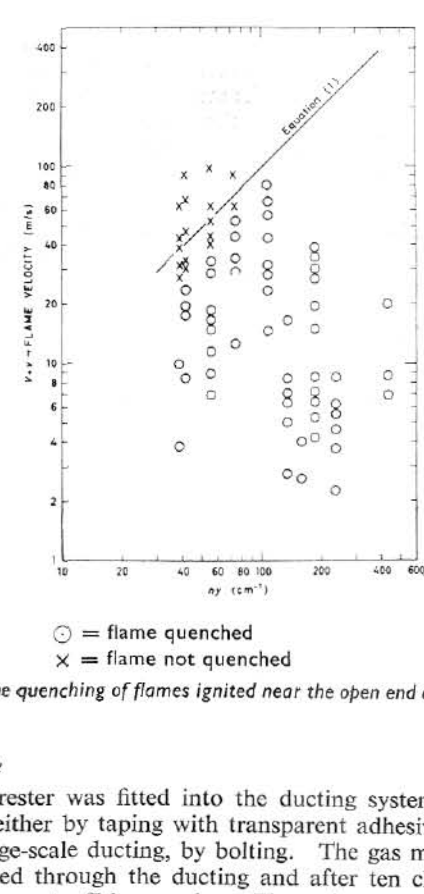
CAMERAS AND PRESSURE GAUGE

Measurements of flame velocities at the arrester were made using a rotating-drum camera with the 6·4 cm dia. ducting and a cine camera with the 30·5 cm ducting; the film records also showed whether the flame passed through the arrester. Both cameras were electrically driven and timed, and the speed of the cine camera was adjustable up to about 280 frames/s.

Explosion pressures were detected by an electrical capacity cell, and after amplication the signal was fed to a cathode ray oscilloscope. A permanent record was obtained by photographing the oscilloscope trace with a drum camera.

GAS MIXTURE

The propane used in the explosive gas mixture had a specified purity of 97% and it was mixed with atmospheric air in the explosive mixture. In all tests a stoichiometric propane–air mixture was used (4·0% by volume) and it was stationary in the ducting before ignition.



⊙ = flame quenched
× = flame not quenched

Fig. 7.—*The quenching of flames ignited near the open end of the ducting*

Procedure

The arrester was fitted into the ducting system and was retained either by taping with transparent adhesive tape or, in the large-scale ducting, by bolting. The gas mixture was then passed through the ducting and after ten changes the supply was cut off by a valve. The quiescent gas mixture was ignited and the flame photographed. The flame velocity at the arrester was subsequently calculated from the photographic record.

Results

GAS IGNITED NEAR OPEN END OF DUCTING

During the explosions the hot combustion products were able to escape to atmosphere from the open end of the ducting, whilst the unburnt gas mixture was retained within the ducting by the closed end. Apart from acoustic vibrations which developed particularly in the 6·4 cm dia. ducting, there was little movement of the gas ahead of the flame

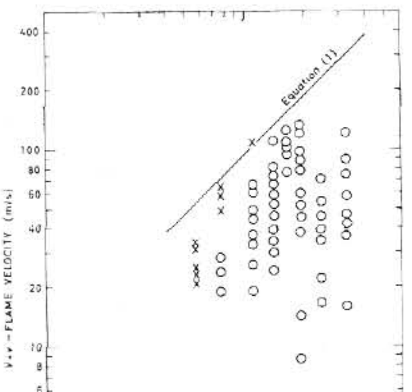
In consequence the explosion pressures were negligible compared with atmospheric pressure, and the velocities of flames relative to the ducting, which were measured by the cameras, were not as high as when ignition was near the closed end of the ducting.

The results obtained with various sizes of crimp, arrester thicknesses and diameters are shown in Fig. 7. The velocities of the flame relative to the ducting ($V+v$), as recorded by the cameras, are plotted against values of ny from Table I. Distinction is made as to whether or not the flame passed through the arrester. In all experiments the ducting was straight and without internal obstructions. The maximum run-up lengths (IJ, Fig. 3) were 3·1 m for the finest and coarsest crimps, 11·4 m for the 0·025 in. crimp, and 9·6 m for the 0·05 in. crimp arresters.

The relatively slight acoustic vibrations that developed in explosions in the 30·5 cm ducting are illustrated in Fig. 7 by the low flame velocities, up to 4 m/s, obtained with the arrester for which $ny = 159$. Much higher velocities were obtained with the narrow ducting, where acoustic vibrations of the flame were more pronounced.

GAS IGNITED NEAR CLOSED END OF DUCTING

In explosions under these conditions the expansion of the gas caused by the combustion resulted in the unburnt mixture being accelerated through the arrester and out of the ducting. When the flame arrived at the arrester it was propagating through a moving gas mixture, and hence faster flame velocities, measured relative to the ducting, could be obtained than when ignition was near to the open end of the ducting. In addition, with ducting having a bend or an obstruction, increased turbulence was generated in the unburnt gas and when the flame propagated into the region of increased turbulence both the velocity and the explosion pressure were increased further.

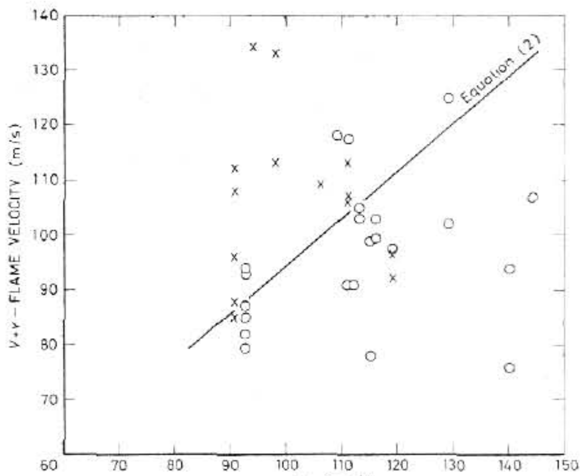


⊙ = flame quenched
× = flame not quenched

Fig. 8.—*The quenching of flames ignited near the closed end of the straight ducting, without obstructions*

The results obtained with straight explosion ducting, with no obstructions, are represented in Fig. 8 for various crimp sizes and arrester thicknesses and diameters. The flame velocities relative to the ducting ($V+v$) are again plotted against values of ny from Table I. The maximum run-up lengths used were 1·6 m for the finest crimp, 9·6 m for the 0·025 in. crimp, 10·5 m for the 0·05 in. crimp (ducting width 30·5 cm), and 11 cm for the coarsest crimp.

Further results were obtained with arresters of 0·05 in. crimp and explosions increased in violence by using L-shaped ducting (6·4 cm dia.) or installing an obstruction in the wider ducting (30·5 cm width). The results for both sets of ducting are represented in Fig. 9, where the flame velocities



⊙ = flame quenched
× = flame not quenched
Crimp height of arresters = 0·05 in.
Thickness of arresters = 3·2 cm

Fig. 9.—*The quenching of flames ignited near the closed end of ducting with a bend or obstruction*

relative to the ducting ($V+v$) are plotted against nyp_0/p, for which values of ny were taken from Table I, p_0 was the atmospheric pressure, and p was the explosion pressure (absolute) when flame reached the arrester. The results for the L-shaped ducting include experiments in which parts of the arrester of width 30·5 cm ($ny = 159$, Table I) were exposed in turn to explosions in the narrow ducting. In all experiments with the L-shaped ducting the explosion pressures were within the range 20–25 lb/in^2 abs. The explosion pressures with obstructions mounted in the wider ducting were in the range 20–24 lb/in^2 abs, and the run-up was 3·2 m. For comparison the pressures without obstructions were only up to 18 lb/in^2 abs for run-ups up to 10·5 m; these results are also included in Fig. 9.

When the arresters failed to quench the flame in explosions of increased violence, in either set of ducting, there were occasions during which no photographic record was obtained of flame emerging from the arrester, although flame was subsequently to be seen propagating in the ducting 30–100 cm downstream of the arrester. Thus either the flame ceased to emit light on emerging from the arrester, because of cooling, or the flame was quenched and then the unburnt gas mixture was reignited by hot combustion products passing through the arrester. Insufficient evidence was obtained to enable a decision to be made between these explanations.

Discussion

Relation between arrester structure and flame quenching

In a previous paper[2] an equation was derived which related the maximum velocity of flame that an arrester was able to quench to the size of the apertures and the thickness of the arrester. In the derivation of the equation it was assumed that the quenching of the flame was due to transfer of heat from the flame to the arrester, and if more than a certain critical amount of heat were removed the flame would be quenched. The heat transfer to the arrester was calculated from the velocity, temperature, and thickness of the flame, and the dimensions of the arrester. The amount of heat abstracted from the flame for it to be quenched was calculated from published experimental values. The resulting equation may be represented as:*

$$(V+v) = \frac{2{\cdot}4\,\pi k(T-T_0)\,ny}{Q/x_0} \quad . \quad . \quad (1)$$

Equation (1) is not independent of the aperture diameter, which is an inverse function of n. The equation is independent of the diameter of the ducting because the area of the arrester and the cross-section of the ducting increase in proportion. As $(V+v)$ is the flame velocity relative to the ducting the equation should be applicable whether ignition was at the open end or at the closed end of the ducting.

The following values were taken for the constants in equation (1), for stoichiometric propane–air flames:[2]

$$K = 1{\cdot}7\times10^{-4}\ \text{cal cm}^{-1}\,\text{s}^{-1}\,{}^\circ\text{K}^{-1}$$

$$T = 2000^\circ\text{K}$$

$$T_0 = 290^\circ\text{K}$$

$$Q/x_0 = 2{\cdot}32\times10^{-2}\ \text{cal cm}^{-3}$$

Equation (1) then becomes:

$$(V+v) = 0{\cdot}95\,ny$$

when $(V+v)$ is in m s^{-1}, and is represented by a line in Figs 7 and 8. In theory the line should separate points representing quenched flames from those representing failure of the arrester, whether ignition was at the open or the closed end of the ducting. In practice the arresters were capable of quenching flames propagating below a certain critical velocity but equation (1) overestimated the velocity for arresters of coarse crimp, with which $ny < 100$, but appeared to give a better approximation for the remaining arresters. The equation indicated that the finest crimp should quench considerably faster flames than those obtained in the experiments.

In the derivation of equation (1) the pressure of the flame gases was assumed to be atmospheric, and this was a reasonable assumption for explosions in straight ducting open at one end and without obstructions. When the explosion pressure rose appreciably above atmospheric, as in experiments with L-shaped ducting and straight ducting with an obstruction, equation (1) needed modification to allow for the effect of increased pressure on the performance of the arresters.

The burning of propane–air flames at ambient pressures within the range 0·5–2·0 atm was investigated by Botha,[4] using a water-cooled flat-flame burner. The amount of heat to be extracted from unit volume of propane, measured at n.t.p., that was necessary to reduce the burning velocity of a stoichiometric propane–air mixture to 4 cm/s was approximately constant over the pressure range. A reduction of this amount in the burning velocity was previously assumed sufficient to quench the flame.[1] If the pressure of the unburnt propane–air mixture were raised the heat released on combustion of unit volume of mixture would be raised proportionately, but the volume of flame would stay approximately constant, because the flame temperature and the dissociation of product molecules would change little with pressure over the range in question. Hence the heat to be abstracted from unit volume of flame in order to quench it (Q/x_0) should be approximately proportional to the pressure, and equation (1) should become:

$$(V+v) = \frac{2{\cdot}4\,\pi k(T-T_0)\,ny}{Q/x_0}\,\frac{p_0}{p} \quad . \quad . \quad (2)$$

Equation (2) is represented by a line in Fig. 9, which shows the results for some arresters of crimp size 0·05 in. mounted in ducting with a bend or obstruction. The agreement with experiment was reasonably good, for both wide and narrow ducting. It is clear that when crimped-ribbon arresters are used to quench violent explosions, due account must be taken of the effect of explosion pressure as well as the effect of flame velocity. Similar requirements would of course hold for most other types of arrester.

Practical considerations

Earlier work[1, 2] has shown that simple arresters, such as wire gauze and perforated sheeting, are suitable for only relatively mild explosions, as with ignition near the open end of the ducting and short run-up lengths. For more vigorous explosions, particularly in larger-scale plant, a more effective type of arrester would be required, such as crimped-ribbon arresters. The present work includes derived equations which indicate that arresters of small crimp size and substantial thickness would be expected to quench fast-moving flames, accompanied by substantial explosion pressures, in general accordance with the results obtained by Cubbage.[3] For example, an arrester of 0·05 in. crimp height and thickness 1·3 in. quenched propane–air explosions propagating with a run-up distance of over 30 ft from the open end of the ducting. Crimped-ribbon arresters also have the advantage that they are less susceptible to mechanical damage or overheating than are gauzes.

The equations derived in this paper give guidance on the performance of crimped-ribbon arresters, but some care is needed in their interpretation. In particular, large values of y (the thickness of the arrester) would not always compensate for small values of n (*i.e.* wide aperture diameters). A sound practical rule is not to have the crimp height exceeding half the minimum quenching diameter for the gas–air mixtures involved (*i.e.* not more than 0·05 in. for propane–air). In addition the arrester should be at least 1·3 cm (0·5 in.) thick to give sufficient mechanical strength and rigidity.

It is generally advantageous to ensure that explosion flame velocities are kept as low as possible, because this enables an arrester of coarser aperture size to be used and hence reduces the resistance to gas flow during normal running of the plant and reduces the danger of blockage of the arrester. Estimates of the resistance to gas flow, for several types of arrester, may be obtained from a paper by Quinton.[5] Ways of keeping flame velocities down include: the siting of the arrester near the probable source of ignition (if known); avoiding intensely turbulent flames at the arrester by siting it away from bends, obstructions, or fans in the ducting; and installing explosion-relief vents preferably so that they open closely behind the flame as it approaches the arrester.[6]

The results given for propane–air may be taken as applicable to other saturated hydrocarbons, and to many solvent vapours, mixed with air.

Acknowledgments

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* *Symbols have the meanings given them on page 20.*

Symbols Used

k = thermal conductivity of flame gases.

n = number of apertures in unit area of arrester surface.

p = explosion pressure (absolute) when the flame reaches the arrester.

p_0 = atmospheric pressure.

Q = heat lost by unit area of flame.

T = mean temperature of flame gases in arrester.

T_0 = temperature of arrester.

V = flame velocity, relative to the unburnt gas.

v = gas velocity along explosion ducting.

x_0 = thickness of flame propagating at standard burning velocity.

y = thickness of arrester.

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