THE PROTECTION BY FLAME TRAPS OF PIPES CONVEYING COMBUSTIBLE MIXTURES

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SYNOPSIS

It is common practice throughout the chemical industry to transmit flammable gases and vapours by pipeline, and sometimes combustible mixtures are distributed similarly. If the mixture becomes ignited, flame can spread throughout the pipe layout and the accompanying pressure surge can cause damage. This hazard is eliminated by the use of a flame trap to arrest the travel of the flame.

Flame can propagate as a detonation in a town gas–air mixture and the velocity of propagation depends, amongst other factors, on the pipe diameter.

The design is given of a flame trap that will provide full protection over a range of pipe sizes. This flame trap can be applied to gases other than town gas as long as the velocity at which flame can propagate in those other gases does not exceed the detonation velocity of flame propagation in a town gas–air mixture contained in a pipe of the same diameter.

Introduction

The transport of flammable gases and vapours in pipes is a common feature of many industrial processes. This procedure is safe when the gas contains either no air or air in quantities controlled so that the mixture proportions are always outside the flammability limits. An explosion or fire hazard exists only when these gases or vapours are mixed with sufficient air for the mixture to sustain the propagation of a flame.

It is readily appreciated that if a leak develops in a pipe transporting a flammable gas, for instance if a flange becomes loose or a valve fails, then only a source of ignition such as a spark or hot surface is necessary to start a fire. This hazard can of course be minimised by adequate plant maintenance and by enforcing rigorous fire precautions designed to contain any fire that arises. The ignition, propagation, and suppression of this type of fire does not come within the scope of this paper and thus will not be discussed further.

The hazard with which this paper is particularly concerned arises when air leaks into the pipe and mixes with the flammable gas or vapour being transported; then once sufficient air has entered the pipe a combustible mixture will be formed.

Such a condition can also occur in any plant to which there are piped supplies of both flammable gas and air or other oxidant. Circumstances can be foreseen that could result in a combustible mixture being formed. A simple case would be where gas and air are supplied to a flame spray-gun, for instance, at pressure. Then if a blockage occurs at the burner port, depending on which supply is at the higher pressure either the air will travel back down the gas supply pipe or *vice versa*. Mixing will be enhanced in the compressor and only a source of ignition is necessary to initiate the propagation of a flame with a serious explosion as a possible consequence.

Besides these accidental processes by which a combustible mixture can be formed in a pipe there are industrial plants to which combustible mixtures are supplied by design, and for these the use of suitable protective devices is essential.

In the gas industry, neat town gas is normally transmitted, and, obviously, the procedure is safe. There are, however, a few occasions when flammable mixtures can be present, and in these instances the use of flame traps is advocated.

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Such cases involve the use of pre-mixed gas–air supplies and include, for example, glass working, brazing *etc.*, for which a supply of town gas and air in stoichiometric proportions is supplied from one mixing unit to a number of burners.

Potentially dangerous conditions exist whenever the proportions of air and flammable gas are such as to sustain combustion, since, if the mixture becomes ignited, flame can propagate throughout the system. The potential risk becomes a real danger only when the mixture is ignited, and in practice this can occur when a burner flashes back. It is then possible for flames to travel back through the pipeline to the mixing plant and the pressure generated by the combustion might even destroy the mixing unit. It is clear that the flame must be prevented from travelling back through the pipeline : this is the function of a flame trap.

Propagation of Flame in Pipes

Flame can propagate in a pipe either as a deflagration or a detonation flame front and clearly these modes of propagation are very different in character. In the first case heat is transferred from the flame front to the adjacent layer of unburnt mixture so as to raise its temperature : at the same time ionised radicles diffuse into the unburnt mixture from the strongly ionised flame zone and ignition occurs when the concentration of radicles and temperature are high enough. The interdependance of these two stages is obvious and the level at which ignition occurs is defined by a temperature—the ignition temperature. For a stoichiometric mixture of town gas–air this is about 500°C.

The propagation of a detonation wave on the other hand depends upon the shock wave travelling at the velocity of sound at the flame front sustained by energy received from the flame. The speed of flame travel is so great, however, that complete combustion is not attained for some time after the flame front has passed, thus continued reaction takes place in the wake of the detonation wave.

Our experiments[1] showed that detonations could occur in industrial pipe layouts. Thus it is necessary for a flame trap either to be designed to arrest detonations or to be matched to the velocity of flame propagations at the position on the pipeline where the trap is to be installed. To determine the velocity of flame propagation at any point in a pipeline it is necessary to know the position of ignition and in some systems

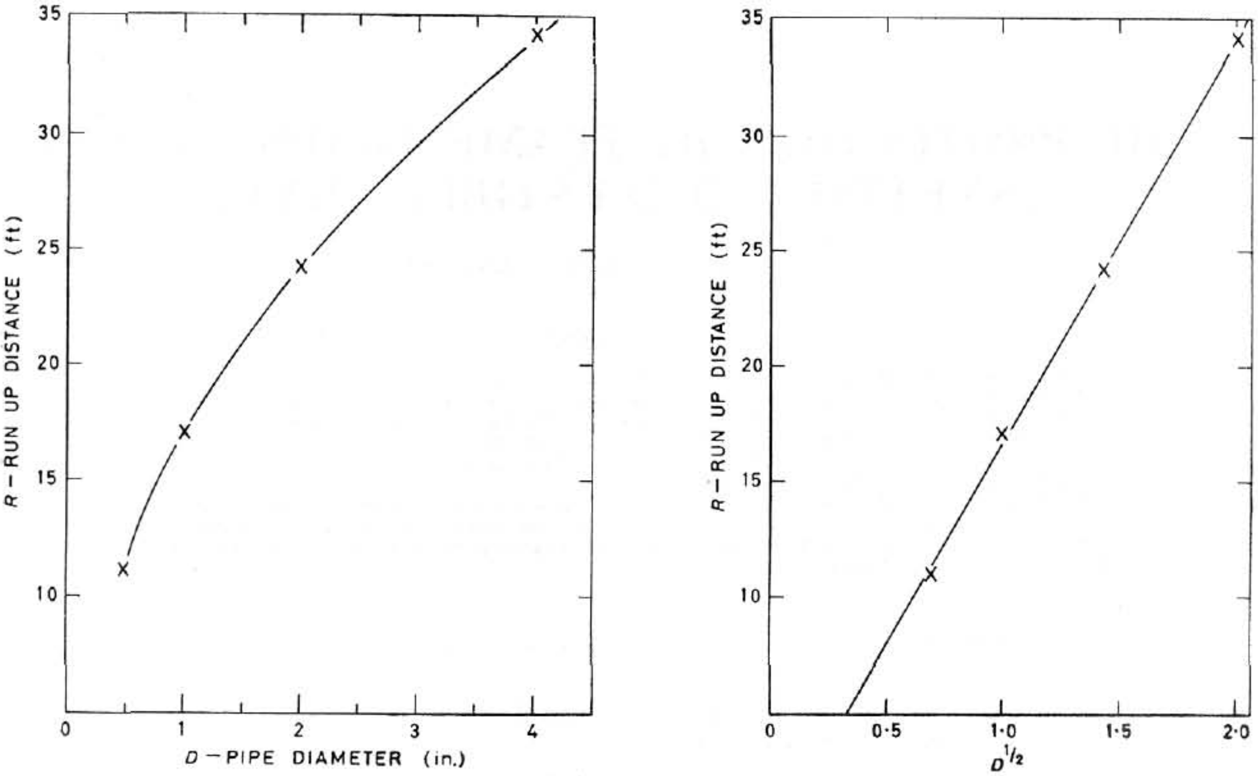


Fig. 1.—*The variation of run up distance (R, ft) with pipe diameter (D, in)*

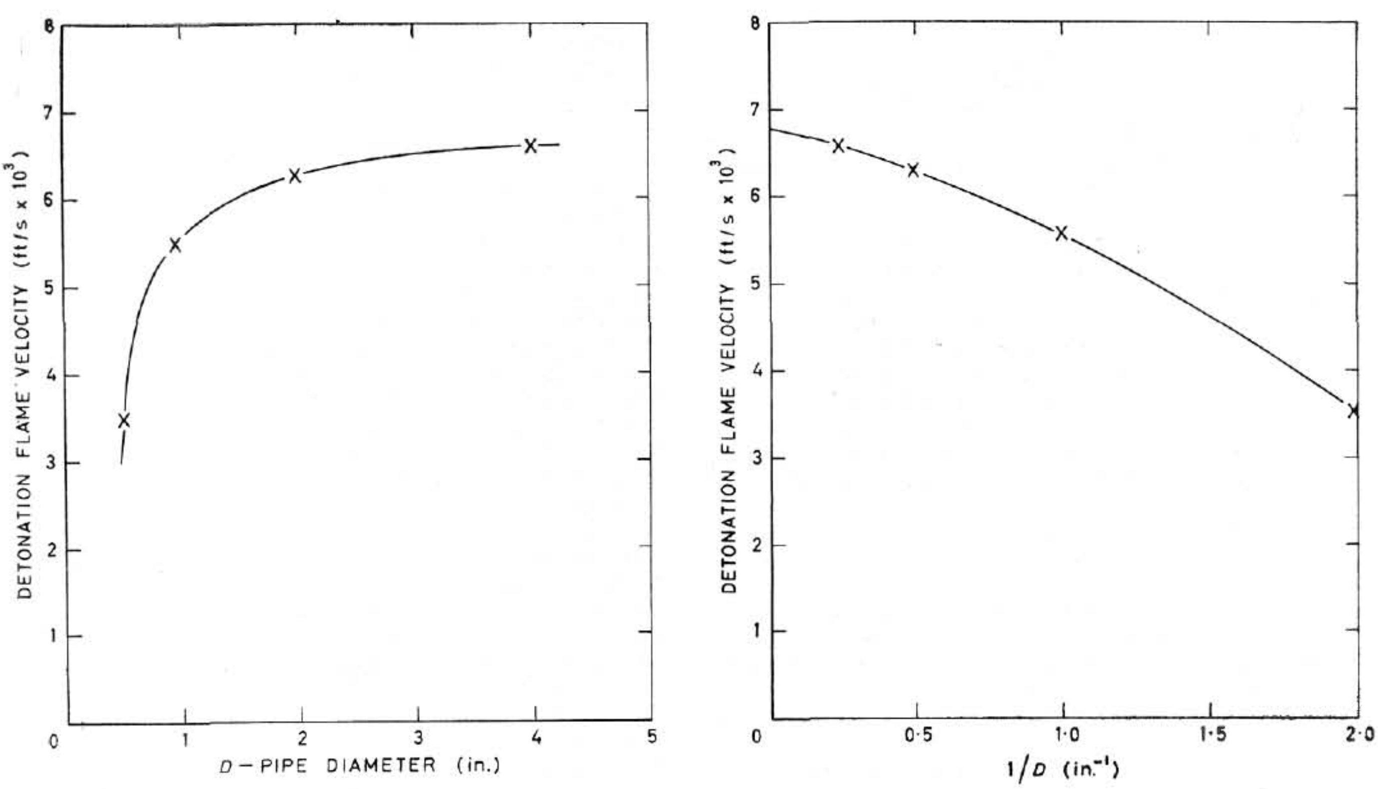


Fig. 2.—*Dependence of the detonation velocity on the pipe diameter*

this is not possible. clearly therefore a flame trap is required that can be fitted at any position in the pipeline without reference to the flame velocity that will be incident upon it, and this implies that the flame trap must be capable of arresting detonations.

In determining the design of the flame trap both the pressure and velocity of the detonation wave must be taken into account because the flame trap itself must be capable of mechanically withstanding the pressure shock loading applied when the detonation reaches the trap. Even with such a flame trap it is possible to increase its useful life by siting it in such a position that it is not necessarily exposed to the mechanical shock of the detonation wave. The fact that the detonation wave builds up as the flame progresses along the pipe can be used to advantage in this case, for if the likely position of ignition is known the trap can be positioned close enough to it so that detonation cannot be attained. For this reason the run-up distances (*i.e.* the lengths of pipe traversed by the flame front before the onset of detonation) must be known. Values of these run-up distances determined in town gas–air mixtures containing 20–25% gas, are plotted in terms of the square root of the nominal pipe diameter in Fig. 1.

Palmer[2] has shown that the relative performance of arrestors could be defined in terms of the flame velocity incident on the arrestor, irrespective of the combustible mixture through which the flame propagates. Thus a flame trap that will arrest the passage of a detonation through town gas–air mixtures can be applied elsewhere provided that the flame velocity is less than or equal to that for which the flame trap is designed.

Before proceeding to evaluate the relative performance of flame traps however, it was necessary to determine the flame velocities that can occur in town gas–air mixtures. In Fig. 2 the highest velocities of stable detonation attained with town gas–air mixtures are plotted against the pipe diameter in which they were determined. The increase in velocity with pipe diameter is in agreement with the considerations of heat loss and fractional resistance at the walls of the pipe.

Commercially Available Flame Traps

There are a large number of different types of flame traps available. The design however of all these flame traps is based on one factor : namely that flame will not be propagated through a mixture if the containing walls are too close. In the case of a capillary tube the maximum diameter through which flame will not propagate is the quenching diameter. The quenching, however, is not a fundamental property of the explosive mixture, but depends as well on such factors as the shape of tube cross-section. Thus the experimental conditions under which quenching diameters have been determined must be taken into account and the values given[3,4] for quenching diameters can only be taken as a guide to the size of aperture that might prove effective. An arrestor extinguishes a flame by removing heat progressively until a condition is arrived at such that propagation is no longer possible. Thus a flame arrestor, being a heat exchanger, must offer a large surface area to the flame, and therefore will contain narrow passages. Since a flame trap must not cause too large a drop in the pressure available (from the fan or compressor) under normal flow conditions, it will consist of a large number of narrow passages in parallel. Most flame traps consist basically of a matrix containing many passages of small cross-sectional area. This can be achieved in a number of ways. Some of the more commonly used flame traps are discussed briefly below and include traps in which the arrestor is made of wire gauze, crimped ribbon, pebble pot, sintered metals, and ceramics, etc.

Flame arrestors of wire gauze are widely used; in general, they consist of several thicknesses of gauze, of either cylindrical or sheet shape, and held in close contact. Palmer[2] has investigated the performance of sheets of gauze using propane–air flame. One of his conclusions, for coarse gauze accurately aligned, was that their effectiveness increases with the number of layers up to about five, but that little improvement is obtained with more. One disadvantage in the use of wire gauze for a flame arrestor is that, although for any gauze the size of the hole is constant, the size of the aperture through a pack of gauzes depends on the manner in which they are stacked together; consequently, it is difficult to guarantee consistant performance.

Another type of flame arrestor is the pebble or gravel pot, which as the name implies, consists of small pebbles so graded that when in close contact with a container there are only small passages between the pebbles. Radier[5] has studied these and suggested the incorporation of bursting discs on the inlets and outlets to the pot to overcome the drawback that, when a detonation wave enters the pebble pot, the pressure rise causes an effect similar to slugging in fluidised beds, resulting in the formation of passages much too large to arrest the flame. The use of water or oil spread on the pebbles in thin layers is said to improve the performance of this type of flame trap. The reason for any improvement would be the resulting reduction in size of the orifice rather than a change in the heat capacity since the amount of heat that has to be removed to quench a flame is relatively small. Miller and Penny[6] have also studied the use of pebble pots for the quenching of acetylene–air flames and shown them to be satisfactory within certain limits.

Porous metal or ceramic discs can be used as flame arrestors, and Egerton[7] has described the use of metal discs with hydrogen–oxygen flames. The size of holes in such compacts can be well below the limiting diameter for any combustible mixture. Their main disadvantage is relatively high pressure loss. The lack of mechanical strength of porous ceramics is also a disadvantage. Nevertheless, where these factors are not important, porous discs can be useful, since a simple and compact trap design is possible.

Another type of flame arrestor is constructed of crimped plate or ribbon. The former consists of a pack of metal sheets corrugated in two directions, the function of one set of corrugations being to space the sheets apart, while the second set provides a tortuous path through which the flame must pass.

The second pattern consists of layers of metal ribbon that are alternately flat and crimped, thus forming a rectangular pack with triangular orifices. Circular flame arrestors are produced by winding two continuous ribbons, one crimped and the other flat, on a central former. This type of flame trap is easily reproducible by the manufacturers to within close limits of tolerance and can be readily made in a number of diameters, depths and crimp sizes. The latter is defined by the spacing between vertex and base of the triangular orifices.

The gas industry required a flame trap that in addition to stopping flames, would be sufficiently robust to withstand the effect of successive flames impinging on it and would not involve too great a pressure loss during normal mixture flow. Clearly the pressure loss that would be acceptable must be related to the working pressure of the system. Since this can vary over an appreciable range it is rather difficult to define quantitatively the pressure loss for which the flame trap should be designed. Premixed town gas–air supplies can be provided by a positive displacement compressor having a delivery pressure of up to 5 lb/in^2 or from a fan with a delivery pressure from a few inches water gauge up to about 2 lb/in^2 g or from an injector providing a mixture pressure of about

6–10 in. w.g. Making allowance for the pressure loss throughout the rest of the system, it would seem reasonable that a flame trap having a pressure loss of only 1–2 in. w.g at the maximum throughput would be acceptable for the large majority of applications.

Various commercial forms of the above types of flame traps were tested[1] and it was found that of those that had an acceptable flow resistance, all but the last of the types discussed above failed when the flame velocity exceeded 350 ft/s. One version of the crimped ribbon type trap in fact successfully stopped detonation where the flame speed was 5600 ft/s. This type was therefore developed to provide a range of sizes.

Flame Trap Design

One important property of detonation waves which was reported by Laffitte[8] was that on passing into a wider pipe the detonation degenerates, reducing the flame speed, and then reforms at some distance from the change in section. Thus the possibility arises of siting a flame arrestor so that the flame speed incident upon it is a minimum. Our experiments showed that a detonation on passing from a 1 in. to a 4 in. diameter pipe degenerated and the flame velocity decreased to about 800 ft/s. After traversing about 8 ft of the wider pipe the flame speed increased again and stable detonation was re-established after a further 14–17 ft.

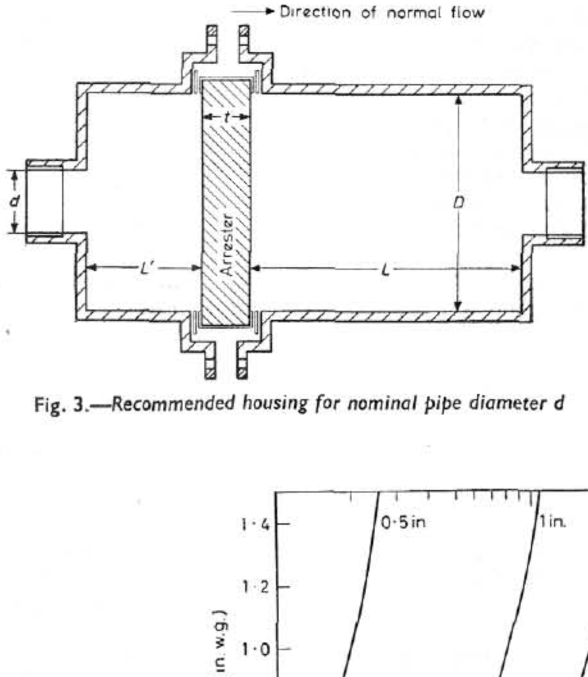


Fig. 3.—*Recommended housing for nominal pipe diameter d*

This property clearly can be applied to the flame traps although the presence of the arrestor in the pipe could affect the lengths of pipe and minimum velocities attained so that experimental investigation of this arrangement was important. By experiment, it was found that the crimped ribbon could effectively stop detonations if inserted in a housing that enlarged from the diameter of the pipeline to about four times this size.

For this case the dimensions of the flame arrestor and housing shown in Fig. 3 are given in Table I.

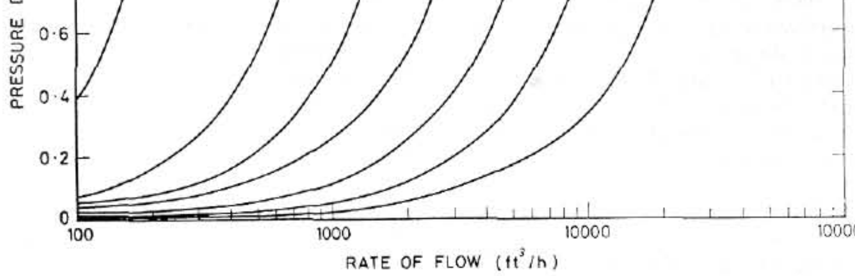
TABLE I.—*Dimensions of Flame Arrestor and Housing (see Fig. 3)*

Pipe diameter d (in.)	Housing diameter D (in.)	Thickness of arrester t (in.)	Run up length L (in.)
1	3·5	1·25	1–2·75
1½	7	1·5	2–8
2	7	1·5	3–9
3	14	1·75	6–15
4	14	1·75	9–24

The length L^1 of the housing on the upstream side of the arrestor does not affect the performance of the flame trap and is determined only by consideration of keeping the pressure loss for normal mixture flow small. For this purpose it is necessary that L^1 should be of sufficient length to allow the normal mixture flow to occupy the full area of the arrestor. A value of L^1 between $0{\cdot}5D$ and D has been found satisfactory.

The crimp size, *i.e.* the internal height of the triangular orifices, must be 0·017 in. It is also strongly emphasised that this trap must be regarded as a unit since the performance of the arrestor depends on the effect of the housing in decreasing the speed of the flame incident on it.

The pressure loss through this trap which can be obtained from Fig. 4 is low enough for most applications. However, where an even lower pressure loss is required a flame trap designed for a larger pipe diameter can be used bushed down to the pipe in which it is to be sited.



4 : 1 air–town gas mixture

Fig. 4.—*Pressure loss through the flame trap for different pipe diameters*

Alternative Flame Trap Designs

Conical housing

An alternative form of housing, which has been proved satisfactory on pipelines ranging from $\frac{1}{2}$ in. to 4 in. dia, consists of two conical sections expanding from the pipe diameter to about four times this at an angle such that the position of the arrestor is within the safe limits given above for a sudden-enlargement housing. The arrestors already specified are effective in conical housings of this design.

In-line trap

Where the pressure loss can be large, about 20 times that of the sudden enlargement type of flame trap given above, it may be possible to install an arrestor of the same diameter as the pipeline directly in the pipe. The housing is then the pipe and the only design data required are the dimensions of the arrestor.

For town gas–air mixtures Table II gives the relevant depths (t in.) for 0·017 in. crimp size arrestors that can be used with confidence to arrest detonation in a pipe of diameter d in.

TABLE II.—*Depth of* 0·017 *in. Crimp Arrestors to Arrest Detonation in pipes of Diameter d.*

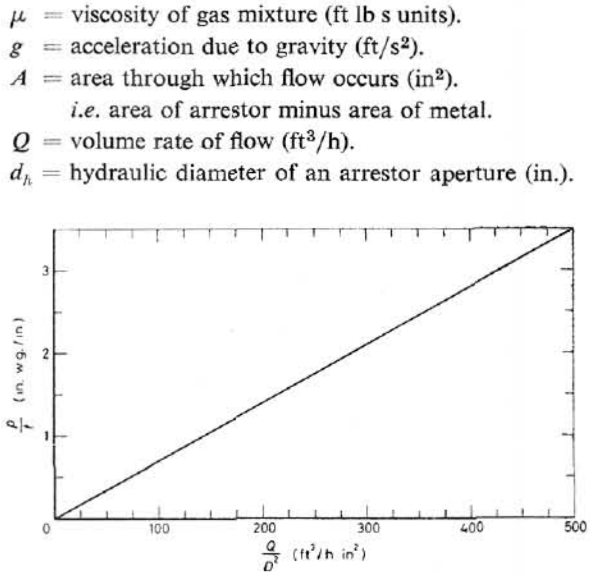
Pipe diameter d (in.)	Depth of arrestor t (in.)
$\frac{1}{2}$	2·5
1	3·0
$1\frac{1}{2}$	3·0
2	3·25
4	3·5

Since the flow through the arrestor apertures is streamline, the pressure drop can be calculated from:

$$\frac{p}{t} = \frac{3{\cdot}76\mu Q}{gA\, d_h^2}$$

where:

p = pressure loss (in. w.g).
t = thickness of arrestor (in.).
μ = viscosity of gas mixture (ft lb s units).
g = acceleration due to gravity (ft/s²).
A = area through which flow occurs (in²).
i.e. area of arrestor minus area of metal.
Q = volume rate of flow (ft³/h).
d_h = hydraulic diameter of an arrestor aperture (in.).



4 : 1 air–town gas mixture
Q = Rate of flow of mixture (ft/h³)
D_a = Arrestor diameter (in.)

Fig. 5.—*The pressure loss/unit depth P/I of 0.017 in. crimp arrestors*

For a fixed crimp size:

$$\frac{p}{t} \propto \frac{Q}{A} \propto \frac{Q}{D^2}$$

where: D = diameter of arrestor.

Thus the pressure loss of an arrestor with 0·017 in. crimp can be found for any flow rate and mixture. From Fig. 5 the pressure loss per unit depth of arrestor can be found directly from the diameter of the arrestor and the flow rate of mixture consisting of four parts of air to one of town gas.

For mixtures with flame speeds in excess of that for town gas–air then, although no experimental verification has yet been obtained, there is the possibility of designing effective flame traps. Since flame speed is reduced in the housing, the actual speeds of the flames incident on arrestors in many of our experiments were not known, although the speed of the flame in the pipe was measured. However, the actual incident flame speed was known in a few cases and, from these it was found that, for a given aperture size in a crimped ribbon flame trap, the thickness of arrestor, t in., necessary to stop a flame travelling with speed V ft/s was given by:

$$t = KV^{1/5}$$

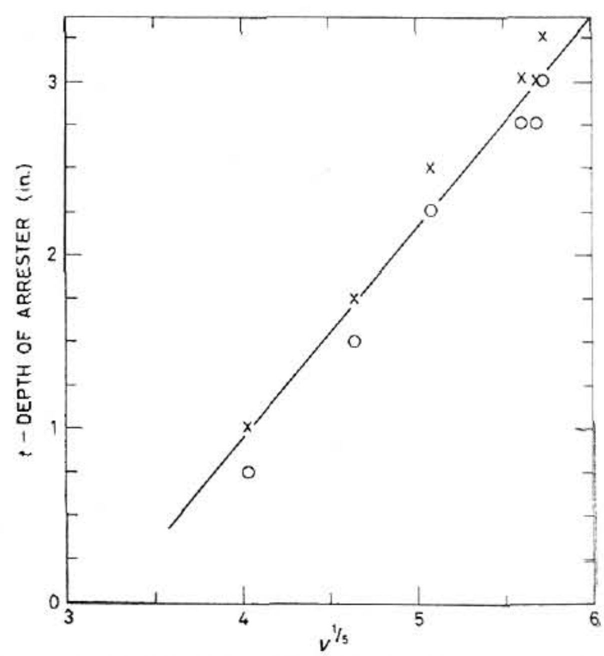


Fig. 6.—*Correlation of the depth* (t) *of an arrestor with its flame-stopping performance*

In Fig. 6 the thickness of 0·017 in. crimp arrestor that just failed to stop, ⊙, and the thickness that stopped, ×, flames travelling with speed V ft/s are plotted against $V^{1/5}$. It can be seen that for flame speeds greater than 1000 ft/s the depth of arrestor necessary to stop any flame speed can be calculated. Since it has already been shown that the maximum detonation velocity of town gas–air mixtures for any pipe diameter is less than 7000 ft/s it can be deduced that a 0·017 in. crimp size arrestor 3·5 in. deep will stop detonations in any diameter of pipe.

Construction and Maintenance of Flame Traps

Most of the work reported has been based on the use of ribbon 0·0020–0·0023 in. thick. However, there is some evidence that the ribbon thickness is not important; in any case, there is a limited range of thickness suitable for the manufacturing process, since the ribbon must be thick enough not to break and thin enough to crimp.

Crimped ribbon arrestors are readily available made of cupro-nickel, copper, stainless steel, aluminium and brass, and can be manufactured in any material that is obtainable in a suitable ribbon form.

It has been shown[1] that the temperature rise of an arrestor in extinguishing a flame is small. Experimental proof of this was obtained with a crimped ribbon arrestor made by Mr. M. Roper of Amal Ltd., using gummed brown paper. This arrestor was successfully employed to arrest detonations. After five tests the only visible damage was that the edges of the paper that faced the flame front were bent over thus partially blocking the passageways. No charing of the paper was visible. Tests using an arrestor made of p.v.c. tape were similarly successful. Thus the thermal properties of the material used are not important, and, consequently the material should be chosen on a basis of cost and mechanical and corrosion resistant properties.

Since an arrestor is liable to be damaged by repeated explosions or detonations and, over long periods, may in addition become blocked by dust or carbon deposited when flames are extinguished, some form of regular maintenance is necessary. In view of the well-known difficulty of ensuring that regular maintenance is carried out, it is essential to make this as easy as possible by arranging that the arrestor can be readily extracted from the housing, without any major dismantling of the pipework. This consideration is an important feature in determining the final design of a housing.

Regular maintenance would be facilitated if two arrestor elements were obtained with each trap and interchanged at each inspection period. The extracted arrestor could then be cleaned and examined both for general deformation and for damage to the edges of the crimped ribbon.

Sealing

It is of vital importance whenever an arrestor is inserted in a housing that a good seal should be obtained all round the circumference. This can be readily appreciated from the following. The mesh size of a passage that will stop a flame decreases as its length decreases; therefore, if a gap is left between the outside of an arrestor and its housing in such a position that the depth of the gap is much less than the thickness of the arrestor, a flame stopped by the arrestor will still propagate through the gap even if this is narrower than the crimp size *i.e.*, less than 0·017 in. Such gaps can easily occur in practice; for example if an arrestor is a loose fit in a housing and sealed to the housing at the front shoulder, a gap in any part of the circumference will have only a small depth. Evidence regarding the importance of sealing was obtained during the experimental work, both from the poor performance of some of the commercial traps tested, which were almost certainly due to inadequate sealing, and also from the difficulty with sealing experienced from time to time in adapting crimped ribbon arrestors to various housings.

Fuel cut off

A further point that required attention arises because a flame arrested by a flame trap need not necessarily be extinguished and so the flame will continue to burn on the arrestor. It is necessary therefore to cut off the fuel supply before the arrestor is heated sufficiently to ignite the mixture on the upstream side of the trap This is affected by fitting a suitable fuel cut-off valve in the upstream pipe, the valve being operated by a heat sensitive device placed in the flame trap housing and adjacent to the downstream face of the arrestor element. Suitable heat sensitive devices include fusible links, bimetallic strips, and thermocouples. Satisfactory devices are commercially available.

Siting

Although these flame traps stop detonations and consequently are effective at any position in pipelines, it is advisable to insert the traps as near as possible to the source of possible ignition such as burners. In this way the arrestor elements will not necessarily be exposed to the severe conditions of detonation and hence their life can be increased. In practice, however, when siting the trap close to the burner the possibility of ignition upstream of a trap, due, for example to unauthorised tampering with the pipeline, must be considered, and if necessary, a second trap should be inserted near the other end of the line.

Conclusion

The explosion hazards which can arise from the transport of combustible gas–air mixtures may be eliminated by an effective flame trap, which should, therefore, always be inserted into pipelines conveying mixtures when it cannot be guaranteed that the mixture proportions will always be outside the flammable range, *i.e.* for town gas this range is when the gas concentration is 10–30% by volume of the mixture.

Although the design of flame traps set out in the paper provides full protection against detonations of town gas–air mixtures it is advisable to insert the trap in the pipeline as near as possible to the likely source of ignition.

It must be stressed that, since the housing dimensions affect the speed of the flame incident on the arrester, the housing and arrester must be treated as a single unit. Furthermore it is essential that particular attention is paid to the sealing of the arrester in the housing.

It can be pointed out that, although the flame trap has been specifically designed for use with gas–air mixtures, the work of Palmer[10] shows that the flame-arresting properties of gauzes is a function of the speed of the incident flame and does not otherwise depend on the type of fuel gas used. On this basis, the flame trap may be applied to the mixtures of air with any flammable gas or vapour, providing these have the same or lower flame speeds than town gas–air mixtures.

In the past two years over **100** flame traps of the design given in this paper have been supplied by Amal Ltd. for use in town gas–air pipes and the rest for use in pipelines conveying flammable gases having a flame velocity equal to or less than that of town gas–air mixtures. So far there have been no reported failures and thus it is possible with confidence to recommend the use of this type of flame trap.

Acknowledgments

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