PERFORMANCE REQUIREMENTS OF FLAME ARRESTERS IN PRACTICAL APPLICATIONS

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The ability of a flame arrester to stop a propagating flame in a flammable gas-air mixture depends strongly on the flame speed and on the pressure developed upstream of the arrester. These parameters in turn depend on the reactivity of the mixture and on the geometrical configuration of the volume between the point of ignition and the flame arrester. The geometrical configuration of the volume downstream of the arrester is also important as it influences whether or not re-ignition occurs downstream of the arrester. Thus the performance requirements for a flame arrester need to take into account not only the gas mixture to which it will be exposed, but also the practical applications envisaged. The paper discusses the background to this problem , the factors that have to be taken into account in assessing the performance of an arrester and areas where further research is required.

(flame, arrester, arrestor, trap)

INTRODUCTION

A flame arrester is any device that prevents the propagation of a flame, or prevents the transmission of an explosion from one side of the arrester to the other. This definition includes devices like the stone dust barrier and triggered barrier as used in coal mines. It is not the intention of this paper to consider such devices, but rather to concentrate on those flame arresters where the arresting element takes the form of an obstruction to the flow of gas and flame. This latter type of device is often called a flame trap.

A flame arrester was first described by Davy (1) in his famous paper presented to the Royal Society on 9 November 1815 titled "On the Fire Damp of Coal Mines and the Methods of Lighting a Mine so as to Prevent its Explosion". He used a wire gauze to isolate the flame of a miner's lamp from the potentially flammable mine atmosphere. At the same time George Stephenson was also quite independently working on safety lamps. In the course of his experiments he noted that a flame of a particular gas in a given concentration could not pass through a tube smaller than a certain diameter (known as the quenching diameter). He extended this work to

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perforated plates and eventually used these or tubes in his safety lamp to improve the air supply to the flame. Since then many more types of arresting element have been developed for use in a wide range of environments, so that now flame arresters are available for stopping flames or explosions propagating at speeds up to the detonation speed.

A number of papers have appeared in the literature on how a flame arrester works. The mechanisms include heat transfer from the flame and hot gas to the arrester element and cooling and entrainment of the gases passing through the arrester, with consequent prevention of re-ignition downstream of the arrester. Both mechanisms play a part in preventing flame transmission, but they do not explain all the observations reported in the literature. Several reports deal with the calculation of various aspects of flame arrester performance in an attempt to permit prediction. All suffer from the disadvantage of being limited to one type of arrester.

In the UK for most applications in which arresters are used there are no mandatory tests or even recognised test procedures. The two exceptions are for arresters used on oxy-fuel cutting and welding equipment (2) and on diesel engines for use underground in mines (3). To fill this gap Rogowski (4) produced a manual for testing arresters, but the procedures outlined are not suitable for all types of arrester or application. Though the use of arresters is recommended in various industrial safety codes there is in fact no legal requirement in the UK to fit them, except on diesel engines used in mines and on equipment using acetylene above a pressure of 0.62 bar g. There is no comprehensive UK guide on the installation and use of flame arresters. At present the only advice available is that contained in a Health and Safety Executive booklet (5), which is based on work carried out in the late 50's and early 60's.

In most countries the situation regarding codes of practice and standards is broadly similar. In the USA the use of flame arresters by the surface industries is not mandatory. The Underwriters Laboratory does have a standard (6) specifying the construction and testing requirements of arresters for storage tanks and compliance with this standard is one of the conditions of the product appearing in the Underwriters list of approved equipment. West Germany is the exception as flame arrester tests are mandatory by Government order and construction details are specified (7,8). Prototypes of arresters, other than for hydrogen and acetylene, are tested and listed by the Physikalisch-Technische Bundesanstalt (PTB). The International Maritime Organisation (IMO) has also produced a standard on the design, construction, location and testing of devices to prevent the passage of flame into cargo tanks of oil tankers (9).

CLASSIFICATION OF ARRESTERS

The obvious, but not the only way to distinguish between different types of flame arrester is according to the construction of the flame arresting element or matrix. Some of the common types of matrix and their applications are described below.

Gauzes

A simple metal gauze to prevent flame propagation was first used by Davy (1) in his miner's safety lamp. In this application if there is a flammable atmosphere present the flame will approach the gauze and heat it until it is hot enough to ignite the gas, as in the school experiment with a Bunsen burner and wire gauze. For this reason advice is given to remove the lamp from the flammable atmosphere should the flame be observed to approach the gauze.

The approach of an explosion is often specified by the speed at which the flame approaches the arrester and its effectiveness is denoted by the maximum flame speed that is successfully arrested. In general, gauzes are effective only for low flame approach speeds (<10 m s^{-1}), although the critical speed can be increased slightly by using several layers of gauze (10). Gauzes are often used to prevent a flame entering a vent in the cargo space of marine tankers, where they are commonly called flame screens. They are easily damaged, liable to become blocked with dirt, paint or corrosion products and the resistance to gas flow is high.

Perforated Plates

Arresters with elements constructed from perforated plates have also been in use for some time. They are more easily constructed and are probably stronger than wire gauze arresters, although no more effective. Their resistance to gas flow is greater than the corresponding gauze.

Expanded Metal

Flame arresters made of layers of expanded metal have been proposed in Japan (11) as a means of venting electrical equipment safely in potentially flammable atmospheres. Expanded metal is made from thin sheet which is slotted and stretched to make an array of diamond shaped holes. Again this type of matrix will only stop slow moving flames.

Sintered Metal

Sintered metal is very effective as an arresting element, but offers a high resistance to the gas flow, so it is suitable only for uses where the gas flow is small. The main uses are for protecting the sensing heads of gas detectors for flammable atmospheres and in flashback arresters for gas welding equipment. One advantage of sintered metal is that it can be produced in a variety of shapes to suit the application. There is a risk that if a flame stabilised on the surface of the arrester, as is likely in welding applications, the flame would eventually burn its way through the sintered matrix. For this reason flashback arresters often incorporate a pressure or thermally activated flow cut-off device.

Metal Foam

A more recent material employed for the matrix of an arrester is metal foam (12). It is made by electro-plating metal onto an open cell polyurethane foam. The material is available in a number of grades (densities), but its density and flame quenching ability can be further modified by compression. Like sintered metal it can be easily shaped and is not suitable for applications where a flame is liable to burn on the surface of the matrix for long periods. It has the advantage over sintered metal in that its resistance to gas flow is very much lower. However, an objection has been raised against its use in that the user or certifying authority cannot guarantee that the sample of foam does not contain a void which would have an adverse effect on its performance.

Compressed Wire Wool

As the name implies these types of matrices are made by compressing a mass of fine wire into an appropriate holder. Alternatively they can be made by compressing knitted wire into a holder. These types of matrices have been effectively used in acetylene filling plant, as protection between the compressor and the cylinder being filled, and in vents for flammable liquid storage tanks. Their resistance to flow is high, which limits their applications, particularly as their effectiveness as an arrester increases with the degree of compression. Questions have, however, been asked about the reliability of arresters with this type of matrix in view of the difficulty of reproducing them with any degree of certainty.

Loose Filling

Loose filled arresters cover a variety of designs, but they all consist of a housing filled with loose discrete objects held in place by restraining screens or by gravity. The effectiveness of such an arrester depends on the size of the filling objects and the depth of the filling. Smaller objects make for a more effective arrester, but of course increase the resistance to gas flow. The shape of the objects also influences the performance of the arrester. Loose filled arresters are inexpensive, but bulky, as to stop fast flames, a considerable depth of filling is required. This type of arrester has been used for many years by the chemical industry. An arrester containing steel balls has been proposed for the air inlet and exhaust of diesel engines used in areas where a flammable atmosphere may be present. The idea is that the vibration of the steel balls would prevent fouling of the arrester with soot and so avoid the need for frequent cleaning of the arrester which is necessary with many other types of matrix.

Hydraulic Arresters

Hydraulic arresters are filled with a liquid, usually water, so there is no direct passage between the upstream and downstream sides of the arrester. They operate by breaking up the gas flow into discrete bubbles and so quench the flame. A mechanical non-return valve is often incorporated to prevent the displacement of the liquid in an explosion and they are usually effective in quenching flame propagation in one direction only. These arresters are bulky and require the liquid level to be maintained, either automatically or by regular inspection. One of their advantages is that they are not prone to blocking by dirt, some of which is collected by the liquid. Hydraulic arresters are mainly used by the chemical industry and can be very effective.

Stacked Plate

Stacked plate arresters are made by fixing spacers to the edges of metal plates and stacking the plates so that they can just be pushed into the housing. An alternative is to machine the slots into a solid block of metal. The advantage of this type of matrix is its robustness. They can be built to withstand the strongest explosion and can be cleaned without damage. The disadvantages are their weight and cost, as they are usually made from stainless steel. They are capable of arresting moderately fast flames (<100 m s^{-1}), their performance being determined by the plate spacing and plate depth. Their use is almost exclusively limited to the air intake and exhaust of diesel engines used underground in coal mines. In this application their perfomance also depends on the plate temperature. For this use their construction is closely defined (3) and as such is the only type of flame arrester with construction details defined in a UK document having the status of a standard.

Crimped Ribbon

The crimped ribbon arrester is probably the most widely used in industry. The advantages of this type are that they can be constructed to very close tolerances, offer little resistance to gas flow, have good mechanical strength and there is relatively extensive experimental experience to guide their use. The matrix is made by winding on a central pin alternate layers of crimped and plain metal ribbon and surrounding with a suitable housing. This matrix is often reinforced by inserting metal rods radially through the assembly. An alternative construction uses alternate layers of crimped and plain ribbon built into a rectangular frame. In either case this results in a matrix with many approximately triangular shaped channels. The ability of such a matrix to prevent flame transmission depends on the crimp height and the breadth of the ribbon. In the UK, crimped ribbon arresters use a single element with the crimp perpendicular to the ribbon, whilst in Germany they use two or three elements separated by a small gap and the crimp is biased at 45° to the ribbon. There is no evidence to suggest any technical advantage for either construction, though the single element with the perpendicular crimp is easier to manufacture.

Crimped ribbon arresters can be used for many applications, ranging from the atmospheric vent on a storage tank to prevent an external ignition propagating into the tank, to an in-line detonation arrester. In the latter application the matrix has to be supported on both sides with a grid and there is often a baffle, or right angle bend on the ignition side to "de-tune" the detonation before it reaches the crimped ribbon matrix (13,14).

MODE OF OPERATION

With few exceptions the research into the mode of operation of flame arresters has been aimed at exploring the behaviour of one type of arrester in one class of environment. Conclusions are specific to the arrester and the apparatus, although some conclusions might have a wider but not universal truth.

The UK work is dominated by Palmer, sometimes in collaboration with Rogowski. Their work has covered wire gauze, perforated plate and crimped ribbon arresters used to prevent flame propagation in pipes or ducts at atmospheric pressure and to prevent explosion transmission from an enclosure to an external flammable atmosphere.

For wire gauze and perforated plate arresters mounted in tubes it was found there was a critical value of the speed of approach of the flame, above which the flame passed through the arrester (10,15). The results also indicated that the performance of the arresters was independent of the thermal properties of the arresting matrix. In the case of wire gauze matrices it was concluded that for good performance the mesh size must be substantially smaller than the appropriate quenching distance. For perforated plates, provided the perforation diameter was less than the appropriate quenching diameter, the critical flame speed was proportional to the thickness of the plate. This critical flame speed was also found to be inversely proportional to the 1.5 to 2 power of the perforation diameter. A simple theory based upon the assumption that the quenching of the flame was due to the abstraction of heat by the matrix, predicted results which were in reasonable agreement with these experimental observations.

The main conclusions from the work on crimped ribbon arresters (16,17) can be summarised as follows. For a particular crimp size there is a critical speed for the approach of the flame to the arrester, above which the arrester fails to prevent flame transmission. An increase in the depth of the crimp, or a reduction in the crimp height increases the value of this critical speed. The material from which the crimp is made has no significant effect on its ability to arrest flames. Finally more reactive fuel/air mixtures require smaller crimps and/or thicker matrices to quench flames of the same approach speed. A simple heat abstraction theory predicted that the failure flame speed should be given by the following equation:

$$V = 0.95 \; n \; y \; p_o \; / \; p \qquad (1)$$

The predictions given by this formula were found to be in reasonable agreement with the experimental results. Note that in order to obtain agreement with results obtained for an arrester mounted in a duct with a bend or obstruction it was necessary to include the factor p_o/p in the equation to acccount for the effect of the increased explosion pressure. Other limitations of equation 1 are that it is only valid for crimped ribbon elements with apertures which are not more than half as wide as the quenching diameter of the gas mixture and with diameters equal to the test duct or pipe. Strictly speaking it is also only valid for propane/air flames, as it was derived using the combustion properties of propane, but it can be used for other hydrocarbon/air flames with similar combustion properties without modification.

The following empirical equation for the critical flame speed of failure of crimped ribbon, wire gauze and perforated plate arresters:

$$V = 0.38 \; a \; y \; / \; d^2 \qquad (2)$$

is often quoted (5). For crimped ribbons, whose apertures are triangular, the equivalent hydraulic diameter (4 x Area/Perimeter) should be used for d. This equation is derived from the work of Palmer and therefore the same limitations as for equation 1 apply. Equation 2 does not take into account the effect of explosion pressure and thus as given above will be valid only for low failure speeds where the pressure does not rise substantially above atmospheric, for example in short lengths of straight pipe.

Research into sintered metal and metal foam arresters has not been as comprehensive. Work by Davies et al (12,18) indicated that equation 1 is also valid for metal foams, provided the aperture diameter did not exceed half the quenching diameter. However, unpublished work (19) carried out at HSE's research laboratories shows that the performance of a metal foam matrix does not always depend on thickness. For thin metal foam matrices the thickness of the foam was important, a thicker matrix being required for more reactive gas mixtures, but beyond a certain thickness, about 3 mm, a further increase in thickness had no effect on arrester performance. Bartknecht (20) made a similar observation for flame propagation along long capillaries . Metal foam arresters differ from crimped ribbon arresters in that the small tortuous channels through the matrix lead to higher heat transfer rates and also the pressure drop across the matrix is higher. The higher pressures within the foam matrix would allow flame to penetrate to within a short distance of the downstream side and would account for the observed performance of thick matrices. A similar behaviour would be expected for sintered metal arresters.

That the shape of the matrix housing affects the performance of an arrester was demonstrated by the work of Cubbage (21) on detonation arresters for town gas. If a crimped ribbon element was installed in a straight pipe detonation could not be arrested, but a larger diameter element of the same crimp depth and height installed in the same pipe by means of conical shaped housing would stop a detonation. It was concluded that this was due to the housing reducing the flame speed to less than the detonation value before the flame impinged on the element. Conical shaped housings are commonly used on many types of deflagration arrester and would also effect the performance by reducing the flame approach speed.

A number of workers have attempted to calculate either the critical flame speed of failure of an arrester, or the critical aperture dimensions of an arresting element using heat transfer models (29,30). The heat abstraction model developed by Palmer (16) has already been mentioned above. In this model the heat transfer to the matrix was calculated from the velocity, temperature, thickness of the flame and the dimensions of the matrix. The amount of heat abstraction necessary to quench the flame and thus the flame speed at failure was calculated from published combustion properties.

The heat transfer within a flame arrester matrix has also been treated by Hulkanicki (22) and equations are given for calculating the aperture dimensions required to extinquish a flame. The equations are based on a constant Peclet number and show an increased loss of heat from the gases with a reduction in the aperture width, or an increase in its length. An increase in the velocity increases heat transfer, but the corresponding increase in mass flow is sufficient to lead to an increase in the temperature of the gases discharging from the matrix. The validity of these equations was confirmed experimentally for matrices made from spheres, sintered metals, ceramics, gauzes and glass wool for flame speeds not exceeding 15 m s^{-1}.

Comparisons with experiment and calculated quenching distances indicate that for higher flame speeds (even when the flame is quenched in the matrix) the arrester does not stop flame transmission, as the hot gases passing through the matrix ignite the unburnt gas on the downstream side. Thus in many cases the performance of an arrester is primarily determined by whether re-ignition of the gases occurs. Streak photographs taken of experiments by Davies et al (18) on metal foam arresters showed that the hot gases flowing through the arrester re-ignited the unburnt gases downstream of the arrester. A Schlieren investigation (23) of the region downstream of a flat-plate flame arrester has also shown re-ignition by the hot gases discharged from the arrester. A self-propagating flame was observed to form a short distance downstream from the arrester after a delay time, the length of the delay depending on the reactivity of the unburnt gas.

Research into this re-ignition mechanism has not been very widespread. The first attempt to model this mechanism was by Phillips (24,25) who showed that an arrester in the wall of an enclosure acted in the same way as a single orifice. In the model it was assumed that the flame was quenched within the arrester matrix. The hot combustion products passing through the matrix then entrained fresh unburnt gas from the external atmosphere and so were cooled even further. At the same time the unburnt fuel entrained could begin to react. Whether flame transmission occurred depended on the balance between cooling by entrainment and heating by combustion of the entrained gases. If the heating dominated then re-ignition occurred at some distance downstream from the arrester. This model is restricted to the situation that occurs when the hot gases from the arrester matrix discharge into a large volume. In a pipe or duct, where unburnt gas cannot be entrained into the side of the discharge it does not apply.

In unpublished work carried out by Lunn (26) a model of the re-ignition process occurring downstream of an arrester in a pipe or duct was developed. It was assumed that the mixing zone could be treated as a perfectly stirred reactor and the heat release rates were computed for different rates of entrainment, combustion and cooling by wall contact. The model predicts that ignition might occur in a mixing zone that is moving along the pipe and that for the reaction mechanism assumed, heat loss to the walls prevents slow reactions becoming active flames. A zone of mixed, but unreactive gas is created to separate the unburnt from the burnt gas. These predictions were confirmed by Schlieren photographs of the mixing zone (23).

ARRESTER ENVIRONMENT

It is clear from the research carried out on flame arresters that the performance of an arrester does not depend solely on the reactivity of the gas mixture and the dimensions of the arresting matrix, but that it is also strongly dependent on the environment in which it is used. The environment in this context is taken as the upstream and downstream volumes connected to the arrester as well as the housing in which the matrix is held. The traditional model of a flame arrester based on quenching distance and heat loss from a moving flame front, has resulted in the maximum flame speed quenched being taken as the sole measure of the performance of an arrester. This is valid only in a limited number of applications. In most practical applications of arresters the apertures in the matrix are much smaller than the appropriate quenching distance and whether or not an arrester is effective depends on whether re-ignition occurs in the downstream volume.

An arrester system can be considered as comprising of three regions:

1) The upstream volume - through which a flame travels towards the arrester.

2) The arrester matrix - through which pass hot burnt gases which are subjected to heat transfer and frictional effects.

3) The downstream volume - in which hot burnt gas and ambient unburnt gas intermix and react.

Note that these regions have been defined in terms of the direction of flame propagation which may not necessarily be the same as the gas flow.

The physical and chemical processes in each of these three regions determine the performance of the arrester.

The Upstream Volume

This comprises the volume containing the flammable gas between the point of ignition and the arrester matrix. The flammable gas may be unconfined, for example in the case of an end-of-line arrester on a storage tank vent, or be contained in a pipe or vessel. The flame speed at the arrester matrix and the pressure will depend on the initial ambient conditions of gas flow, pressure and temperature, the gas composition, the distance between the matrix and the point of ignition (the run-up distance) and the shape of the volume. Bends or obstacles in an upstream pipe or duct will create turbulence and lead to an increase in flame speed and pressure at the matrix. The upstream volume also includes the upstream part of the matrix housing and items such as weather cowls, which are often fitted to end-of-line arresters. Thus housings, weather cowls and other equipment within the upstream volume can have a significant influence on an arrester's performance.

The Arrester Matrix

The flow velocity through each aperture in the arrester matrix will depend, as it does with any orifice, on the pressure differential across the matrix, which in turn will depend on the pressure generated in the upstream volume. In the majority of matrices used in industry the aperture dimensions are much smaller than the appropriate quenching, so the flame is rapidly quenched once it enters the matrix. The temperature and velocity of the hot burnt gases will be modified by heat transfer and frictional effects within the arrester matrix and so influence the conditions in the downstream volume. However, in many cases this influence may not be as significant as might at first be thought. For example, for crimped ribbon arresters the thermal properties of the crimp material were found (21) to have no discernible effect on the flame quenching performance of the arrester.

Downstream Volume

The ability of an arrester to prevent flame transmission comes down to whether re-ignition occurs in the downstream volume. The conditions in the downstream volume are primarily determined by the conditions in the upstream volume following ignition, with some secondary influences due to the arrester matrix. The hot burnt gases discharging from the matrix are cooled by mixing with cold unburnt gases. At the same time the unburnt gases begin to react and generate heat. The balance between the cooling by entrainment and heating by reaction determines if re-ignition will occur. It is clear that this balance will be altered by such factors, as the gases discharging into a large downstream volume, where entrainment can occur from the side. Turbulence generated by obstacles, bends or changes in cross-section in the downstream pipework will alter the mixing rate and hence the possibility of re-ignition. Again the conclusion is that this part of the environment of the arrester may influence its performance.

A possibility that up to now has only been briefly mentioned is the failure of an arrester due to continuous burning on the matrix. If there is a continuous flow of flammable gas from the downstream side of an arrester to the upstream side (remember the sides are defined in terms of the direction of flame propagation) then even though the arrester prevents flame propagation initially a flame may stabilise on the upstream side. The arrester could eventually fail by the flame literally burning through the matrix or the matrix becoming hot enough to ignite the gas on the other side. In the latter case the important factors determining the performance of the arrester would be the thermal properties of the matrix and its immediate environment and the auto-ignition temperature of the flowing gas mixture.

TESTING OF FLAME ARRESTERS

It is evident from the above discussion that in testing a flame arrester the environment in which it will be used must be taken into account. It cannot be assumed that because a flame arrester has been tested and passed for use in one environment it will perform equally well in all environments. With our present incomplete understanding of the mechanism of operation it is necessary to simulate as closely as possible in the tests the environment in which it will be used.

Tests for flame arresters can be classified as follows:

1) End-of-line arrester tests

2) Deflagration arrester tests

3) Detonation arrester tests

4) Endurance burning tests

The question of a margin of safety in the test methods, to ensure that the test conditions are more stringent than the intended service conditions, also needs consideration. A margin of safety is also important in the type testing of arresters. Due to the statistical nature of type testing it is necessary to eliminate the possibility of an arrester, with a borderline performance, passing the type test, but failing in service.

End-of-line Arresters

These type of arresters are fitted, for example, to the vents of storage tanks and are intended to prevent an ignition in an external unconfined flammable cloud from propagating into the storage tank. They are, therefore, required to prevent flame transmission at low flame speeds and pressures. The traditional method, described by IMO (9) and Rogowski (4), of testing this type of arrester is with a large plastic bag containing a flammable mixture, to simulate the upstream volume, and a vessel, with some form of pressure relief to simulate the downstream volume. It is a satisfactory test method, provided the arrester is tested with any accessories (eg weather cowl) fitted and several tests are carried out with different points of ignition within the bag. This is to ensure that the range of flame speeds and pressures that the arrester could be subjected to in use are simulated in the testing. A vented vessel can be used instead of a plastic bag, but this can lead to a more stringent test as the pressure generated by the flame may be higher.

For some time it has been the custom to classify the suitability of this type of arrester, and also deflagration and detonation arresters, for a given gas or vapour according to the gas grouping used for electrical apparatus in potentially explosive atmospheres (27,28). These groupings are based on the maximum experimental safe gap or the minimum ignition current. In testing an arrester it is usual to use a gas representative of the appropriate group, that is methane for Group I, propane for Group IIA and ethylene for Group IIB. For Group IIC the actual gas is used. The use of this classification is reasonable for rating the performance of an end-of-line arrester in preventing flame transmission, but is not appropriate for rating its performance in an endurance burning test (see below).

Deflagration Arresters

These arresters are used in-line, for example in pipes or between vessels, and also to prevent explosions propagating from a pipe or vessel into an external atmosphere. Thus, depending on their location they may have to arrest flames travelling at relatively slow speeds of a few metres per second to speeds of hundreds of metres per second.

The method usually adopted for testing this type of arrester is to use a pipe or duct as the upstream volume and to vary the run-up distance to determine the flame speed at which the arrester fails. The arrester is then regarded as suitable for use for a given gas or group of gases provided the flame speed does not exceed this failure value. This practice is adequate when the arrester is used with a straight duct or pipe, but when used with other geometries experience has shown that caution must be exercised. It is not just a case of using an arrester with a higher flame speed rating than the run-up distance warrants, to compensate for the increase in flame speed. Account must also be taken of any difference in pressure. For a given arrester there is not an unique relationship between flame speed and pressure in the upstream volume, as this also depends on the geometry of the upstream and downstream volumes. Surprisingly there is virtually no data in the open literature on the flame speeds and pressures generated in different configurations and sizes of pipework and vessels, that could be used in assessing the suitability of an arrester from the test results in straight pipes. Therefore, at present deflagration arresters have to be tested under conditions that simulate as closely as possible those of the system in which they will be used.

In the test procedure suggested, by Rogowski (4), for this type of arrester a sleeve of thin polyethylene plastic may be attached to the outlet of the arrester to facilitate observation of flame transmission. In view of the fact that flame transmission is due to re-ignition downstream of the arrester it is felt that the use of a plastic sleeve, or nothing at all attached to the outlet, is not a realistic test. The pressure pulse travelling ahead of the flame may rupture the sleeve and disperse the flammable mixture. It is, therefore, recommended that a pipe of length at least ten times the nominal bore of the arrester be fitted downstream if the device is to be used in-line, or a large plastic bag be fitted to the outlet if the device is intended to discharge directly into an external atmosphere.

Detonation Arresters

The traditional method adopted for detonation arresters is to test against a stable detonation, that is a detonation propagating at a constant velocity (the Chapman-Jouguet velocity). For the test, a long pipe of sufficient length to establish a stable detonation, and of the same nominal diameter as the arrester is used. The length of pipe required can be shortened by inserting turbulence generating obstacles and by increasing the strength of the igniter. The arrester must be tested with any pipework or baffles which have been included to deflect the detonation wave before it impinges on the arresting element. Similar arguments as advanced for the deflagration arrester test apply to the choice of the downstream volume for the test rig.

In the transition from a fast deflagration to a stable detonation an over-driven detonation can be produced. An over-driven detonation can also be produced by a strong ignition source. The detonation pressure and velocity of these detonations can be appreciably greater than the values for a stable detonation. This raises the question of whether a detonation arrester should also be expected to prevent the propagation of an over-driven detonation. If so it should also be tested against over-driven, as well as stable detonations. In practical situations it would be difficult to guarantee that a detonation arrester was not subjected to an over-driven detonation. For similar reasons a detonation arrester would also have to be capable of arresting deflagrations.

Endurance Burning Test

It has already been mentioned that in some cases a flame may stabilise on the matrix of an arrester and eventually lead to failure of the arrester. The procedure to assess the endurance burning performance of an arrester involves allowing a flame to burn on the arrester element and varying the gas composition and flow to achieve the maximum temperature on the other side of the element Once the maximum stable temperature has been achieved the flame is then allowed to burn for a further specified period. Flashback of the flame should not occur during the test, or when the gas flow is turned off at the end of the test.

The practice of classifying the suitability of arresters according to the gas group for electrical equipment is not adequate when it comes to endurance burning performance. This group is based on values for the maximum experimental safe gap or minimum ignition current, while the resistance to endurance burning depends on the auto-ignition temperature of the gas mixture. For example, propane which is the gas usually used in assessing the suitability of an arrester to prevent flame transmission in Group IIA gases has an auto-ignition temperature of 470°C, whilst pentane, which is also classed as Group IIA, has an auto-ignition temperature of 300°C (28). Thus an arrester may be suitable for preventing flame propagation in Group IIA gases, but not be able to prevent flashback, if burning on the element occurs, for all the gases in Group IIA. A temperature classification and a gas group classification is thus required.

A temperature classification similar to that used for electrical equipment could be used (28). This could be based upon the maximum stable temperature recorded in the endurance burning test, using the gas representative of the gas group. The arrester would then be suitable for use for any gas in that group with an auto-ignition temperature below the measured temperature. In the case of arresters fitted with a device to cut-off the flow if a flame burning on the element is detected, then the temperature of the element when the cut-off operates would be the appropriate temperature to use.

Margin of Safety

A certain margin of safety is built into the test methods described above, in that the worst possible conditions are used in the tests and the probability of these occurring in practice is low. For example, the gas composition used is that which gives the highest flame speed and pressure (for most gases just slightly fuel rich). The margin of safety can be further increased by various means. The reactivity of the test gas can be increased and hence the flame speed, pressure and ease of re-ignition, by adding oxygen. This would also decrease the quenching distance. Another approach is to test an arrester which has the maximum allowed dimensions, according to the manufacturing tolerances, for the matrix apertures, gap between the matrix and housing, etc. An even more stringent approach would be to deliberately increase these dimensions.

The margin of safety could also be altered by changing the initial conditions of pressure and temperature in the test. Unfortunately, to date, virtually no work has been done on the effects of initial temperature and pressure on the performance of an arrester, so it is difficult to know with any certainty whether the changes are increasing or decreasing the margin of safety. It is often the case that arresters are tested at one initial temperature and pressure, usually ambient conditions, and then used on plant where the conditions are very different. Even if it is used at ambient conditions it should be kept in mind that ambient conditions can vary significantly. An arrester may be expected to work equally well on a chemical plant whether it is used in arctic or desert conditions, when the difference in ambient temperature could easily be as high as 100° C. For example calculations have shown that the detonation pressure would change significantly over such a range of temperature and, therefore, a detonation arrester may well not be effective over the whole temperature range.

CONCLUSIONS

In spite of much study in the UK and elsewhere there is no complete or universal description of the way flame arresters are effective in all environments. In part this is due to the diversity of arrester elements in use and the variety of housings and environments. A better understanding of the operating mechanism of arresters will pave the way for improvements in arrester design and lead to more concise guidance on the installation and testing of arresters.

From the review of the influence of environment on arrester performance and test methods the following requirements have been identified:

1) Basic data on the flame speeds generated in various sizes and geometries of upstream volume. This would enable the suitability of a given arrester to be assessed for different environments without having to resort to an extensive series of tests.

2) Work on over-driven detonations to resolve the question of whether detonation arresters are suitable for arresting this type of detonation.

3) A programme to study the effects of temperature and pressure on arrester performance. This is particularly important as many arresters are used in industry in conditions significantly different from the ambient in a test laboratory.

4) Fundamental research into the re-ignition mechanism downstream of the arresting matrix. The results of this work would have implications

for the way in which arresters are tested, as well as possibly leading to the design of more effective arresters.

There is still a tendency to fit an arrester, without giving any thought to whether it is really suitable for the application. The need for regular maintenance is another requirement that is often overlooked. The fitting of an arrester by an unknowledgeable user can lead to a totally false sense of security. A set of standards covering the testing, installation and use of flame arresters is clearly required. Before this can be done the results of some of the further research work detailed above are needed. Current work at HSE's Buxton Laboratories is aimed at filling these gaps in our knowledge. In the meantime it is hoped that this paper will provide some guidance on the testing and selection of flame arresters.

SYMBOLS USED

a - fractional free area of arrester surface

d - diameter of aperture (cm)

n - number of apertures per unit area of arrester surface (cm^{-2})

p_o - atmospheric pressure

p - explosion pressure when the flame front reaches the arrester

V - flame speed at which the arrester fails ($m\ s^{-1}$)

y - thickness of the arrester element

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