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The quenching of propane deflagrations by crimped ribbon flame arrestors

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ABSTRACT

Experimental studies of deflagration flame quenching by crimped ribbon flame arrestors were performed in a circular ducting with propane-air flammable mixture. The corresponding flameproof velocities were determined systemically. The results showed that the channel length, the expansion ratio and the aperture size must be taken into consideration to predict the performance of the crimped ribbon flame arrestors. To explore the relationship between flameproof velocity and arrestor structure, numerical simulations were carried out. The simulated results showed that with the reduction of the hydraulic diameter of the aperture size, the flameproof velocity is increased, which implies the basic angle must be considered when crimped ribbon flame arrestors are used to quench deflagration flame. In addition, the influence of the expansion ratio is of great significance on the efficiency of flame arrestors. The flameproof velocity can be reduced to be a value related to the expansion ratio. Two empirical formulas were derived to exhibit the relation between the flameproof velocity and the characteristics of the flame arrestor, which can be used to predict the performance of crimped ribbon arrestors.

1. Introduction

Gas transportation can be widely seen in the hydrocarbon process industry (HPI), power generation, pharmaceutical, pulp/paper and other industries, where detonation and deflagration arrestors function as essential safety devices. Catastrophic explosions may occur in some petrochemical plants which are caused by gas leakage or open fire. For example, as a result of poorly designed or improperly applied flame arrestor, approximately 30 separate production-site explosions occurred each year in Alberta Canada in the late 1970s (Mendozs and Smolensky, 1988). To prevent the propagation of the flame, flame arrestors have been used for more than a century since Davy presented his paper to the Royal Society of London entitled "On the Fire-Damp of Coal Mines, and on Methods of Lighting a Mine so as to Prevent its Explosion" (Grossel, 2002). Flame arrestorscan force the flame to be divided into small flamelets, and the apertures can efficiently extract heat from the sides of a flame. Prior to the appearance of arrestors in industry, some research related to flame quenching had been carried out. Payman and Wheeler (1918) found that the ability of a flame crossing a tube with a small diameter depended on the flame speed. Holm (1932) drew a conclusion that the channel size was the most important factor influencing the flame quenching rather than the coefficient of thermal conductivity of the wall. The transient behavior of a flame flowing into a narrow channel from a chamber filled with a propane-air mixture has been studied by Iida et al (1985) using schlieren high speed photography. In recent years, some studies on flame quenching have been conducted with new methods and technologies. To some degree, the narrow passages in flame arrestors can be regarded as micro-channels. Many useful strategies have attempted to improve the flame stability and energy utilization, such as Swiss-Roll (Zhong et al., 2012; Shi and Huang, 2009; Chen and Ronney, 2011; Fan et al., 2011) and Heat-Recirculating (Kim and Kwon, 2011; Shirsat and Gupta, 2012; Kurdyumov and Matalon, 2011; Shirsat and Gupta, 2011; Park et al., 2012) micro-combustors to reduce heat losses. Chemical quenching on the wall surface is another concern for micro-channel. In order to elucidate the effects of wall material on stability limits and chemical quenching behavior, Chen et al. (2012) explored the combustion characteristics in micro-channels with different wall materials by experiments and numerical simulations with detailed chemical kinetics schemes.

The ignition of flammable mixture of hydrocarbons and air or oxygen in pressure piping can produce disastrous result. The use of

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commercial flame arrestors has been suggested as an effective way to reduce the risk of flame propagation within these facilities. Commercial flame arrestors can be divided into two kinds generally, in terms of the location of the pipe where arrestors are installed. One is an end-of-line arrestor and the other is an in-line arrestor. An expansion part is usually designed in an arrestor, which is expected to decelerate the flame. A loud sharp blast and a flash could be heard and seen at the end of a pipe if the flame propagates through the arrestor. Conversely, if the flame fails to pass, the sound is deep. The performance of an arrestor was found to be dependent on the location of the arrestor in the system, the ignition, and the gas velocity in the pipe by Broschka et al. (1983). Lietze (2002) summarized the results of extensive research to determine the limit of safety against flame transmission for flame arrestors of relatively small size fitted with arrestor elements made of crimped metal ribbon, which is the most common elements in arrestors currently.

For the slow moving flames, there is a consistency of the Peclet number for flame quenching in narrow passages in accordance with the quenching theory:

$$P_e = S_L \cdot d_{cr}/\kappa = 65 \quad (1)$$

In this equation, P_e is the Peclet number, S_L is the laminar flame speed of gas/air mixture (m/s), d_{cr} is the diameter of critical passageway (m) and κ is thermal diffusivity of gas/air mixture (m^2/s). The computation is true for very slow flames because the quenching theory considers laminar flow quenching only. For detonation or fast deflagration, the equation does not work in the quenching process as turbulence flow takes the place of laminar flow in narrow channel passageways. Therefore, full-scale teats are required for critical applications.

In the procedure of the design and manufacture of arrestors, a contradictory problem has been existing, which is not solved properly. On the one hand, the arrestor is expected to stop a flame with the velocity. On the other hand, to ensure that the gas can be transported with high-efficiency, the flow resistance is expected to be low. Some findings indicated that the best quenching performance for the least flow resistance was offered by flame arrestors of the crimped ribbon type (Grossel, 2002). In the work reported in this paper, crimped ribbon flame arrestors were tested to determine the flameproof velocities in a ducting system containing flammable propane mixtures. The results of numerical simulations illustrate that with the reduction of the hydraulic diameter of the aperture and the increasing of the expansion ratio, the flameproof velocity can be increased. The flameproof velocity can be predicted by the equations derived in this paper. The results can give guidance on the performance of crimped ribbon flame arrestors.

2. Testing flame arrestors

Six DN50 flame-arrestor configurations belong to Group IIA (A_1, B_1, A_2, B_2, A_3,B_3) were measured and tested. A flame arrestor consists of an arrestor element, an arrestor housing and associated fitting, which is shown in Fig. 1. The test typeA flame arrestor is fitted with only one crimped metal ribbon element (Fig. 1(a)). Test type Bflame arrestor is fitted with two elements with the identical parameters except the inverse inclined direction of narrow passages, with the gap of 2.2 mm (Fig. 1(b)). The array mode can increase the viscous force, which will extinguish the flame effectively. $D$is the diameter of the arrestor element while b is the thickness.

The diameter of the ducting$d$ can be measured directly, as is shown in Fig. 1. In the experiments reported in this paper, $d = 50$ mm. Because the arrestor elements made of crimped metal ribbon is bolted between two cast stainless flanged ends to form

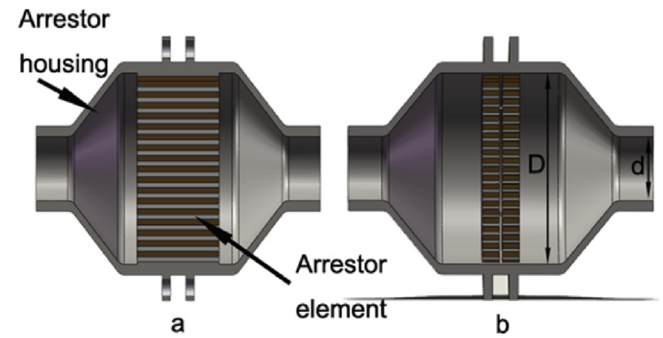

Fig. 1. Sketches of two types of flame arrestors. a: Test type A flame arrestor with one crimped metal ribbon element; b:Test type B flame arrestor with two crimped metal ribbon elements.

the complete unit, the elements can be taken out to be measured. Fig. 2(a) shows the configuration of a flame arrestor. The expansion ratioβ can be calculated with$\beta = D/d$. The narrow passages of the arrestor element is not perpendicular to the section of the crimped ribbon actually, but deflecting. In other words, there is an angle,α, between the narrow channel and vertical direction (Fig. 2(b)). The cross-section of the apertures can be regarded as an isosceles triangle approximately, and the parameters can be determined with reading the microscope, which can be seen in Fig. 2(c). In which a and h are the bottom side length and the height of the isosceles triangle, γ is the basic angle. The results are shown in Table 1.

3. Experiments and procedure

The experiments of testing the flameproof velocity V were carried out in a circular ducting of the inner diameter 50 mm with the thickness 5 mm. Here, the flameproof velocity is defined as the maximum velocity of flame that a flame arrestor is able to quench. Fig. 3 shows the experimental system of testing the flameproof limits. The location of flame arrestors was 6 m downstream from the spark igniter and 2 m upstream from the end. To test the flame arrestors, commercial propane with the purity of 99% was selected. The flammable stoichiometric mixture was prepared by the method of partial pressures (with a mercury gauge) in a mixing chamber and was allowed to mix in the chamber for more than 4 h in order to ensure mixture homogeneity, in which the percentage of commercial propane is 4.3 ± 0.2% (in volume). Prior to an experiment, the pipe was evacuated by a rotary vacuum pump. Then the flammable mixture was filled into the pipe until the pressure reached the ambient pressure, and was left 10 min till the mixture

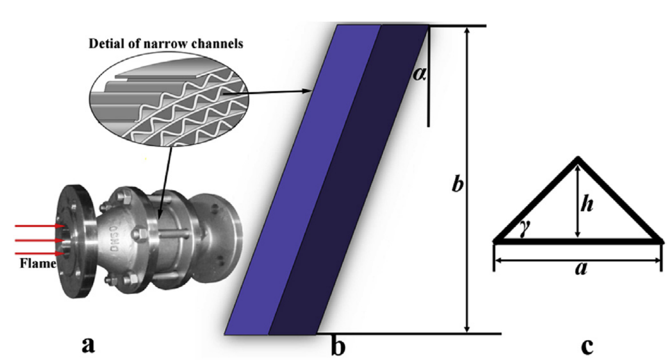

Fig. 2. Sketch the crimped metal ribbon element. a: Sketch of a crimped ribbon flame arrestor and the detail of narrow channels. b: Sketch of a narrow channel. c: Cross-section of a narrow channel.