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Flame acceleration in pipes containing bends of different angles

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Bend structures are common in process industries. These bends containing three typical angles (90°, obtuse angle and acute angle) are often incorporated into pipes or ducts at different positions. In our experiments, the effect of both the bend angle and bend position on flame acceleration was studied. Flame acceleration in a pipe bend can be divided into three stages. The flame speeds increased before the bend and increased again after decreasing for a short distance in the bend. Flame reversing decreased the flame speeds in the bend and led to additional turbulence, which enhanced flame acceleration after the bend. The flame acceleration in three different pipe bend angles had similar trends. The decreasing amplitude of the flame speed in the bend increased with a decrease in the bend angles. The flame speeds in the bend were ordered such that 52° <90° <145°. However, the maximum flame speeds in the pipe were in the opposite order. Additionally, both the flame speeds in the bends and the maximum flame speeds in the whole pipes increased as the bend's position away from ignition point increased.

1. Introduction

Accidental flame acceleration in pipes or ducts can lead to large economic losses and casualties both in the chemical industry and in underground coal mines. Many researchers have studied accelerating flames in pipelines, tubes, ducts and other industrial processes (Bauwens et al., 2007; Ciccarell and Dorofeev, 2008; Di Sarli et al., 2012a; Di Sarli et al., 2012b; Di Sarli and Di Benedetto, 2011; Zipf et al., 2013; Zipf et al., 2014). Flame propagation in industrial processes that are built from many different constructions can be complex. For example, obstacles in the processes can enhance flame acceleration (Di Sarli et al., 2010; Di Sarli and Di Benedetto, 2013; Kindracki et al., 2007; Park et al., 2008; Silvestrini et al., 2008). Explosions in pipes with a single bend, a U bend, or a Z bend are also quite different than explosions in straight pipes (Blanchard et al., 2010a,b; Frolov et al., 2007; Zhu et al., 2011). Understanding the flame behaviour in these constructions is important for the prevention of gas explosions in industrial processes.

There have been many studies performed in different constructions, especially in bent pipes. In these studies, 90° bends were most commonly used, and the results showed that the bend had a large effect on flame acceleration. Phylaktou et al. carried out experiments in a 3-m long 162-mm diameter tube containing a 90° curved bend and found that the flame moved faster around the inner wall of the bend than the outer wall. This gave rise to an overall acceleration of the flame (Phylaktou et al., 1993). Sato et al. noted that the flame tip speed experienced a short deceleration period in the bend (Sato et al., 1996). Blanchard et al. carried out experiments in closed pipes containing baffles and 90° bends and found that a 90° bend could enhance the flame speed (Blanchard et al., 2010a,b). Ye et al. also observed that the flame speed increased sharply in the bend (Ye et al., 2009). Sulaiman et al. performed work using the CFD tool FLACS and found that the presence of a 90° bend increased the simulated flame speeds by a factor of 2–3 (Sulaiman et al., 2014). Emami et al. provided results that bending was a critical part of the pipeline and can affect the

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maximum overpressure, flame speed and temperature increase in both pure hydrogen/air and methane-hydrogen/air mixtures (Emami et al., 2013). In addition, the effect of the bend on the gas explosion primarily depended on whether the duct was filled with a combustible mixture or not (Zhu et al., 2011).

As mentioned above, the flame speed increased after the bend. This is mainly because the flame front was elongated in the bend, and as a result, the combustion was enhanced. Many research results have revealed this mechanism. Wang et al. developed a parallel code and found that the flame front was enlarged along the bend (Wang et al., 2012). Zhang et al. found that the plane wave span increased with the bend angle (Zhang et al., 2010). Additionally, the heat or temperature loss in the bend also had a great effect on the flame acceleration. Pang et al. found that the bend structure has little influence on the high-temperature flow before the bend and has significant influence on the high-temperature flow after the bend (Pang et al., 2013). Xiao et al. found that the heat loss to the walls in the bend has a significant influence on the combustion dynamics (Xiao et al., 2014).

As mentioned above, most current studies used 90-degree bends. Only few researchers have performed studies in bends with an obtuse angle or acute angle, and their results not involved experimental quantitative flame speeds. However, many industrial pipes, ducts or laneways in industrial processes have different angles that can be divided into a 90-degree, obtuse angle and an acute angle. Flame acceleration may behave quiet differently at different angles. Therefore, this study focused on the effect of different bend angles on flame acceleration in pipes.

2. Methodology

The pipe used in our experiments was 16 m long and had an 8 cm × 8 cm cross section. There were three different bend angles, e.g., 52°, 90° and 145° (Fig. 1), which covered obtuse to acute angles. The long pipe consisted of a series of segments with lengths from 0.5 to 1 m. The bend shown in Fig. 1 was incorporated into the pipe at five different positions, respectively (2 m, 4 m, 6 m, 8 m and 10 m from the ignition point). In addition, the end of the pipe was open in all experiments.

An ignition system was used in our experiments and generated a standard 2-J combustion spark. The flammable methane-air mixture (10% by volume) was prepared in an air pocket. The pipe was pumped first to a vacuum pressure of −0.1 MPa, and then, the prepared mixture flowed into the experimental pipe due to the pressure difference. The flame arrival time was recorded by flame transducers (phototube) validated by a schlieren system. The average flame speed between the two transducers was determined. Additionally, we performed three runs for each experimental condition, and the given flame speed was average value of these three values.

3. Results and discussion

3.1. Comparison of flame acceleration between a straight pipe and a bent pipe

The difference in the flame acceleration between a straight pipe and a bent pipe has been widely studied. Those results show that the bend can significantly affect the flame acceleration. Fig. 2 shows the flame speed in a 90° bend pipe and in a straight pipe in our experiments. The bend is 8 m from the ignition point. As seen from the figure, the flame acceleration can be divided into three stages along the pipe. The flame speeds were quite close before the 90° bend in stage (I). However, the flame speeds were lower in the bent pipe than in the straight pipe at stage (II). Then, the flame speed increased at stage (III). The results are similar to the experimental findings of Sato et al., who used a high-speed cine camera and schlieren techniques (Sato et al., 1996). The flame speed measured by them reached nearly 80 m/s in a square duct (2 cm × 2 cm) with one rounded 90° bend. However, they found that high flame speeds occurred in the bend following by a deceleration period behind the bend, and then the flame propagation speed continuously increased for a while in their experiments. This is mainly due to the

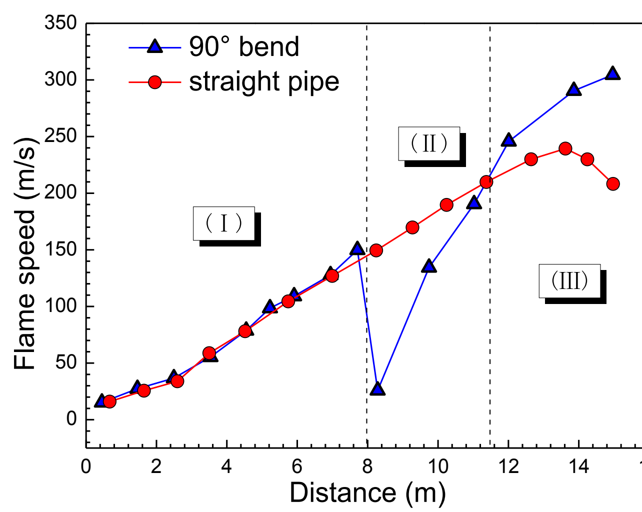
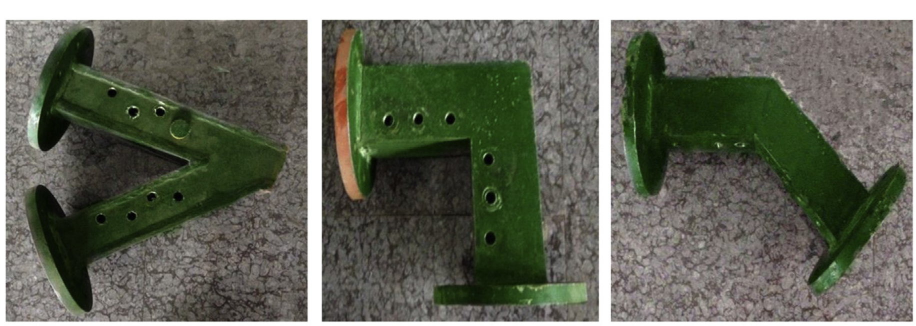


Fig. 2. Comparison of the flame speed in a 90° bend and a straight pipe.



(a) (b) (c)

Fig. 1. Pipes with three different bend angles. (1) 52°; (b) 90°; (c) 145°.