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Effect of bifurcation on premixed methane-air explosion overpressure in pipes

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ABSTRACT

It is well known that bifurcation structures have a significant influence on gas explosions in pipelines or roadways. In this work, three different types of bifurcation, namely, bifurcation with two right angles (BTRAs), bifurcation with two obtuse angles (BTOAs), and bifurcation with an obtuse angle and an acute angle (BOAA), were used to study the effect of bifurcation on premixed methane–air explosion overpressure in pipes. The effect of the position of bifurcation on gas explosions was also discussed. Our results suggest that the peak overpressure evolution in pipes exhibits a downtrend before the bifurcation, a sharp increase after the bifurcation until reaching the maximum, and a downward trend when propagating into the pipe end. It was also found that gas-explosion propagation was affected by the joint action of turbulence induced by obstacles and the abrupt increase of the cross-sectional area. In addition, the bifurcation's position had only a small effect on the maximum peak overpressure in pipes.

1. Introduction

Gas explosions are a major threat to chemical production, gas transportation, and underground coal mining industries (Msiza, 2003). Pipelines or roadways with bifurcation structures are widely used in these processing industries as gas-flow channels. The gas flow path of a pipe that includes a bifurcation divides into two or more pipes via branches after the bifurcation. Gas explosions usually occur in these bifurcations and can negatively impact industry safety (Huang et al., 2012; Jeffery, 2015).

Studies on the effect of bifurcation on premixed methane–air explosion overpressure in pipes, which are helpful in the design and layout of gas-explosion–suppression systems in coal mines, can play an important role in preventing gas explosions or alleviating the consequences. In recent years, many studies have been conducted on the propagation characteristics of gas explosions in different pipeline structures.

Some experts and scholars conducted experimental studies on the gas explosion process in 90°-bend pipelines using high-speed cameras and schlieren optical technology (Sato et al., 1996; Zhou et al., 2006; Zhai et al., 2009; Robert et al., 2010; Zhu et al., 2011); they reported distortion of the flame front and fluctuation of the flame speed. Xiao Huahua (Xiao et al., 2013) also conducted an experimental and numerical investigation of flame propagation for a propane/air mixture in a closed duct with a 90° bend. The outer flame skirt was suggested to significantly influence the flame dynamics. Andrade (Andrade and Zaparoli, 2001) and Wang Yunyan (Wang et al., 2007) studied the flow of an explosion wave in the bend tube using the method of finite-element analysis. It was found that the regular distribution of speed and temperature changed after the propagation of the air-shock wave through the bend. Some scholars also carried out studies on the U-bend, Z-bend, and continuous bend pipe or tube (Cha et al., 2003; Yang et al., 2006; Frolov et al., 2007a, 2007b). Previous studies have suggested that a bifurcation in parallel pipes could produce a turbulent flow that enlarges the flame area (Zhu et al., 2012). Zhang Qi et al (Zhang et al., 2010). performed a numerical simulation on gas explosions in laneways and reported that when the air shock wave went through the laneway bend, the attenuation of peak overpressure with distance did not obey the exponent law. In addition, Nie (Nie et al., 2011) conducted experimental investigations of the influence of foam ceramics on gas explosions and demonstrated that the foam ceramics could drastically attenuate the maximal explosion overpressure by up to fifty percent.

In all of these studies, gas explosions were studied in pipes with a bend. However, only limited studies were carried out on gas

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explosions in pipes with a bifurcation, and therefore, the effect of bifurcation on the propagation of gas explosions is unclear. In addition, most of the studies on bifurcation were carried out on pipes or roadways with a fixed shape and position; however, it is well-known that the shape and position of the bifurcation in actual process industries can be quite different, and studies in this area are rarely reported. Therefore, in this study, gas explosions were conducted in test pipes with bifurcations of different angles at different positions. The propagation law of gas explosion overpressure in pipes containing bifurcations was then studied, which is of great importance to the prevention of gas explosion and the design of explosion-protection facilities.

2. Experimental apparatus

The apparatus in our study mainly consisted of a test pipeline system, an ignition system, a circulating pump, a vacuum pump, a data-acquisition system, and a gas-preparation system. The experimental setup is shown in Fig. 1. The test pipeline system consisted of several steel pipes ($8 \times 8\ cm^2$) at the cross section. The ignition source end of the straight pipe was closed, and the outlet ends of the bifurcation pipes were open. The ignition system was set at the straight pipe end, which can generate a 2-J combustion spark. Pressure sensors (model No. YD205) were set on the pipeline to measure the explosion overpressure. The measuring range of these sensors were 0–2 MPa, and their data-acquisition speed was less than 1 μs We calibrated these sensors before the experiments. Experimental data measured by the dynamic data acquisition system were transmitted to the computer. The concentration of the premixed methane–air was 10% v/v; the mixture was prepared in the air pocket using the partial pressure method. The initial temperature and pressure of the mixture was 25 Celsius and 101.32 KPa, respectively.

Before the experiment, the open ends were sealed by flange plates. Then, a vacuum pump was used to exhaust the pressure within the pipeline to −0.1 MPa. The inlet valve was opened, and the gas mixture (methane–air) flowed into the pipeline due to the pressure difference. To ensure even distribution of the gas mixture, a circulation pump was used for 20 min. Finally, upon opening the flange plates by the testers, the gas was ignited. The opening of the flange plates and subsequent ignition was so quick that the experimental error was negligible. In addition, we measured data for each set of tests thrice to improve the accuracy of experimental results.

Experiments were carried out in different pipeline systems with three different bifurcations, that is, bifurcation with two right angles (BTRAs), bifurcation with two obtuse angles (BTOAs), and bifurcation with an obtuse angle and an acute angle (BOAA), as shown in Fig. 2.

3. Results and discussion

3.1. Comparison of overpressure between straight pipe and bifurcate pipe

Fig. 3 presents a comparison of peak overpressure in a straight pipe and a BTRAs pipe. The straight pipe was 12 m long and the BTRAs pipe was set at the distance of 6 m from the ignition source. By adding the length of the bifurcation, the distance from the ignition source to the turning point is 6.3 m. The sensor arrangements of the two pipelines are shown in Fig. 4a and b. For easy comparison, only data from the T1 branch of the BTRAs pipe is presented in Fig. 3.

Fig. 3 shows that the existence of the bifurcation will affect the peak overpressure of explosion. When the ends of branches T1 and T2 were open, the peak overpressures in both the straight pipe and the straight section of the BTRAs pipe showed a decrease with increasing propagation distance. Because of the influence of the reflection and diffraction of BTRAs, the peak overpressures in the straight section of the BTRAs pipe were slightly larger than that in the straight pipe at the same condition, although not by much. The peak overpressure increased rapidly from 39.75 to 63.99 kPa at, before, and after the bifurcation point, increasing by about 61%. Beyond the bifurcation point, the peak overpressure value increased until it reached the maximum value (72.63 KPa), which was far greater than the peak overpressure in the straight tube under the same conditions.

It can be seen that the bifurcation structure would increase the peak overpressure of explosion. Because the pipeline ends were open, large amounts of gas rushed out of the pipe. The shock wave entered the open space, and the peak overpressures plunged.

Fig. 5a shows the simplified model of BTRAs. Some experts recognized that in a pipe with a bend, the bend could generate strong turbulence which induced flame tip wrinkle and a following enhanced combustion process (Phylaktou et al., 1993; Sato et al., 1996; Jo and Crowl, 2009). Similarly, relative to the straight pipe, wall *C* was similar to a plane obstacle, which was directly in front of the straight pipe's exit. As a result, the disturbance of air flow was very strong. In addition, points *A* and *B* were equivalent to the two disturbance sources of airflow. When the shock wave entered the BTRAs, the pipeline's cross-sectional area increased suddenly, like a sudden expansions pipe with a plane obstacle. This is well concordant with numerical results (Ma et al., 2014).

3.2. Effect of bifurcation form on overpressure

Many kinds of bifurcations exist and the propagation laws of gas explosion in pipes with different bifurcations vary. To study the influence of the bifurcation on gas explosion, a piping system with the BTRAs, BTOAs, and BOAA was used, respectively, at the distance of 6 m from the ignition source. The length of each branch pipe was 6 m as well. The sensor arrangement of the piping system with the BTRAs, BTOAs, and BOAA are shown in Fig. 4b, c, and 4d, respectively.

The relationship between peak overpressure and distance in different pipes are shown in Figs. 6–8.

Figs. 6–8 show that the change of peak overpressure in different bifurcation pipes was similar. The overpressures showed a decreasing trend with the increase of the propagation distance before the bifurcations; however, the ranges of decrease are different. In the BTRAs pipe, the decreasing amplitude of peak overpressure was 7.1 KPa from the ignition source to the bifurcation, whereas the amplitude of peak overpressure at the BTOAs and BOAA was 10.74 and 8.39 KPa, respectively. The initial pressures of the three, however, were close to each other, and their order is as follows: BTRAs (largest) > BOAA > BTOAs (smallest). This result indicated that the overpressures in the straight pipe before the BTRAs were generally larger than the other two (i.e., BOAA and BTOAs).

At the point of bifurcation, the peak overpressure of all three pipes showed a rapid increasing trend. The peak overpressure of BTRAs increased from 42.4 to 63.99 KPa, and the rising range was 50.92%. The peak overpressure of BTOAs increased from 34.52 to 48.25 KPa, and the rising range was 39.78%. The BOAAs increased from 38.28 to 62.46 KPa, and the rising range was 63.17% in the obtuse branch. Thus, the increase in pressure follows the following order (from large to small): BTRAs > BTOAs > BOAA.

After the bifurcation, the peak overpressures in both branches T1 and T2 in all three pipes increased rapidly. The maximum peak overpressure in the pipe with BTRAs was 72.69 KPa, whereas those