Study on the Effect of Bifurcation Position on Spontaneous Ignition and Shock Wave Propagation Characteristics in High-pressure Hydrogen Leakage Tubes

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Abstract. Hydrogen safety issues constrain the development and diffusion of hydrogen energy technologies. The current research on tube types in high-pressure hydrogen storage and transportation links is insufficient. In this paper, the spontaneous combustion law and the propagation characteristics of the shock wave in the tube after accidental leakage of high-pressure hydrogen in a bifurcated tube with a blocking structure are investigated by experimental means. By changing the relative position of the bifurcation structure, it is found that moving the bifurcation position upstream can effectively reduce the intensity of the shock wave at the nozzle of the tube, the propagation velocity of the shock wave inside the tube and the critical ignition pressure. There are three ignition possibilities in the bifurcated tube with blocking structure, and quenching can be realized in the tube under lower pressure.

Keywords: accidental leakage of high-pressure hydrogen; bifurcated tube; blocking structure; shock wave; ignition.

1. Introduction

While hydrogen energy technology is developing at a high rate, hydrogen safety issues can no longer be taken lightly. At present, the main way of hydrogen storage and transportation is still through high-pressure gaseous hydrogen. Hydrogen has a very low ignition energy (0.017mJ), wide combustion limit and other physicochemical properties, and easy to react with metals to produce hydrogen embrittlement phenomenon, easy to trigger hydrogen leakage, which may produce accidental fire, jet flame, explosion will be a threat to the safety of people and property. In addition, the diversity of tube applications and endpoints will make hydrogen safety accidents even more complex.

Bifurcated tube structures are widely used in hydrogen storage and transportation because of their flow diversion function. Compared with ordinary straight tubes, the bifurcated tube structure is special, and the special corner structure and tube cross-sectional area changes make the study of hydrogen spontaneous combustion, shock wave evolution, and flame propagation more special and complicated. Wang et al. [1] conducted experiments on T-tubes, and found that by changing the length conditions, the existence of a critical length was found, which led to the lowest critical ignition pressure in the tube. Ta et al.[2] investigated the effect of different angles of T-tube and proposed the self-ignition mechanism of bifurcated tube under different angles (60°,120°,180°).Jiang et al.[3-5] systematically summarized the ignition pattern and flame propagation of tee tube under different flow directions and analyzed the bifurcation position by numerical simulation. Experimentally, it was proved that the length of downstream tube, the bifurcation structure location in the downstream tube all have an effect on the shock wave propagation and spontaneous ignition development.

The existence of the special downstream tube may be easier to trigger the obvious reflected shock wave compared with the ordinary straight tube, and the reflected shock wave has the effect of compression and heating on the hydrogen jet, which may promote the spontaneous combustion; on the other hand, due to the special characteristics of the tube structure, the shock wave attenuation will be more intense, thus suppressing the spontaneous combustion in a shorter period of time. In this paper, two types of bifurcated tubes with blocking structures are designed by combining the blocking and non-stopping process of high-pressure hydrogen delivery tubes in production practice. By changing the relative position of the bifurcation structure, experimental research and analysis on the evolution of the shock wave and flame development in the tube are carried out.

2. Experimental setup

This experiment relies on the high-pressure hydrogen leakage simulation experimental platform to conduct experiments, the specific details are shown in Fig. 1. The experimental setup contains a high-pressure hydrogen cylinder, a high-pressure nitrogen cylinder, a storage tank (1 L), a vacuum pump, a booster pump, a pressure gauge, a rupture disc, and the necessary piping and valves. The specific details have been described[3]. In this paper, two types of bifurcated tubes with blocking structures are designed, and the sensor distribution is shown in Fig. 2. The distance from the rupture disc to the nozzle of the tube is 810 mm, and both types of tubes are designed with axial blocking, and the tube outlets are set in the downstream branch tubes of the bifurcation position.

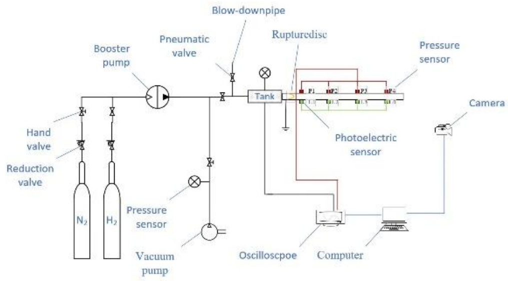
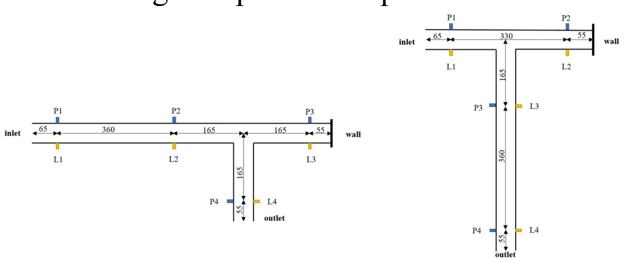


Fig.1 Experimental platform



(a) Type I (b) Type II

Fig. 2 Tube types

3. Shock wave evolution

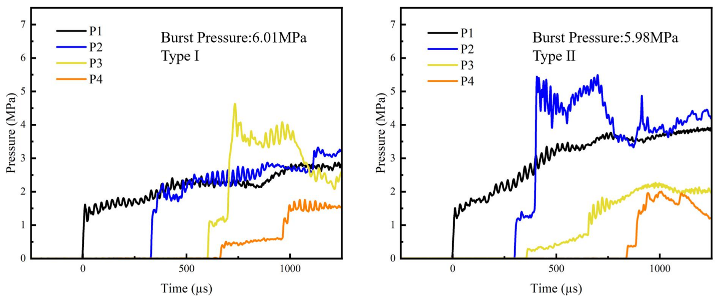


Fig. 3 Evolution of shock wave in the tube

Fig. 3 compares the typical pressure change curves in the bifurcated tube of Type I and Type II axial blocking structures, for example, with an initial release pressure of 6 MPa. The time when the pressure signal is detected at P1 is defined as 0 μs. At 0 μs, the pressure increases steeply at P1, and a strong discontinuity appears with a huge pressure gradient between the wave front and the wave back. The pressure value corresponding to the pressure rise is the intensity of the leading shock, which tends to decay as the hydrogen jet propagates downstream in both Type I and Type II tubes, but there is a significant difference. The two types of tubes have the same intensity of P1, and with the propagation of the wave downstream, the tube structure changes, and the intensity of the wave monitored by the pressure sensors P2, P3, and P4 is different, which is mainly manifested in the two aspects of the blocking end and the branch tube. In the two types of tubes, the evolution trend of the shock wave at the blocking end is similar, and obvious pressure elevation is observed, originating from the reflected shock wave generated at the blocking end. However, Type II P2 is closer to the rupture disc, and its pressure attenuation is relatively weak.

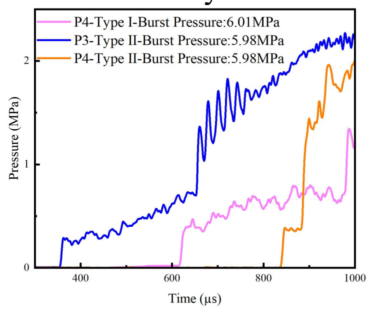


Fig. 4 Shock wave evolution of downstream branch tube after bifurcation

Fig. 4 demonstrates the comparison of the wave evolution in the downstream branch tube. At the initial discharge pressure of 6 MPa, the leading wave pressures of Type IP4, Type IIP3 and Type IIP4 are 0.39 MPa, 0.28 MPa and 0.37 MPa, respectively. Although the supersonic hydrogen jet passes through the same bifurcation structure and has the same downstream propagation path, the Type I bifurcation is closer to the rupture disc and has a higher wave incidence velocity before entering the bifurcation structure. higher incidence velocity of the wave. Based on the expansion properties of the Plante-Meyer flow, this means that less of the flow is diverted into the branch ducts. Therefore, the intensity of the pilot wave measured at P3 in Type II is lower than the intensity of the pilot wave measured at P4 in Type I. The intensity of the pilot wave measured at P3 in Type II is lower than the intensity of the pilot wave measured at P4 in Type I. Besides, the intensity of P4 leading shock in Type II is higher than that of P3 leading shock in Type II, which means that the shock wave is gradually enhanced in the branch duct, which is mainly related to the propagation of leading shock wave in the branch duct after the bifurcation. After the bifurcation of the flow at the bifurcation position, the lesser hydrogen jet flow inside the branch tube is insufficient, and the wave pressure gradually decays. However, with the large accumulation of hydrogen jet flow at the blocking end, the rearward hydrogen jet flow starts to inject into the branch tube and increase its velocity and pressure.

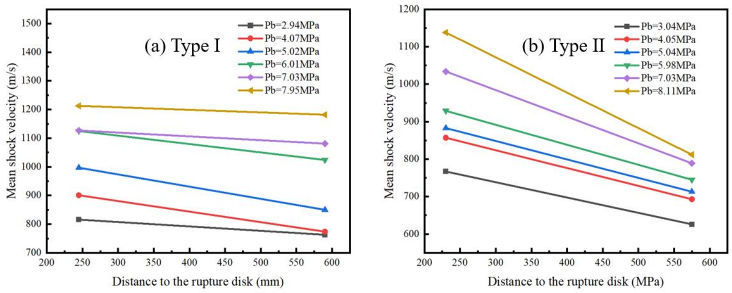


Fig. 5 Variation of the propagation velocity of the shock wave in the tube section

Fig. 5 illustrates the variation of the average velocity in each pipe section in Type I and Type II. The average velocity in the tube is calculated as follows:

$$v = \frac{\Delta L}{\Delta t} \#(1)$$

Where ΔL is the distance from pressure sensor P1 to pressure sensor P4, and the distance from P1 to P4 is 690mm; Δt is the time difference between the pressure signals recorded by pressure sensors P1 and P4, and the time for P1 to record the pressure signal is 0μs. The average velocity of the wave in the two types of tubes rises with the increase of the initial discharge pressure, and the average velocity change shows a decay trend along with the propagation process of the wave. Comparing the upstream section of the two types of tubes, it is found that the propagation velocity of the wave in Type I is higher than that in Type II, and the velocity change of the wave from the upstream section to the downstream section of the tube is much higher in Type II than that in Type I. After diverging at the bifurcation location, most of the supersonic flow will continue to follow the original propagation path, while the flow volume propagating toward the branch tube is relatively small. In the Type II tube, the bifurcation location is closer to the rupture disc, and the higher incident velocity at the bifurcation location implies a smaller deflection angle in the Plante-Meyer flow, so the flow into the branch tube is lower relative to Type I. The degree of velocity decay downstream of Type II is drastic because of the lower flow and lack of momentum.

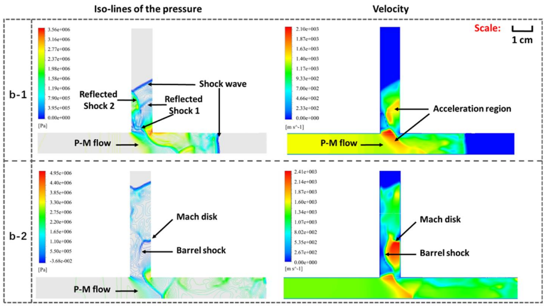


Fig. 6 Pressure and velocity cloud at bifurcation position[5]

Fig.6 illustrates the numerical simulation of the bifurcated tube. In the branch tube downstream of the bifurcated tube, a reflected wave is formed by the effect of the wedge angle oblique wave. This can also well explain the pressure lift observed in the branch tube in Fig. 4. In addition to this, it can be seen that a Mach disk structure is formed inside the branch tube based on the velocity section. The velocity of the jet decreases after passing through the Mach disk, which is not favorable for the propagation of the hydrogen jet. In addition, the propagation velocity of the branch tube wave in the simulation is lower than the propagation velocity of the main tube wave, which is consistent with the phenomenon in the experiment.

4. Spontaneous ignition development in tubes

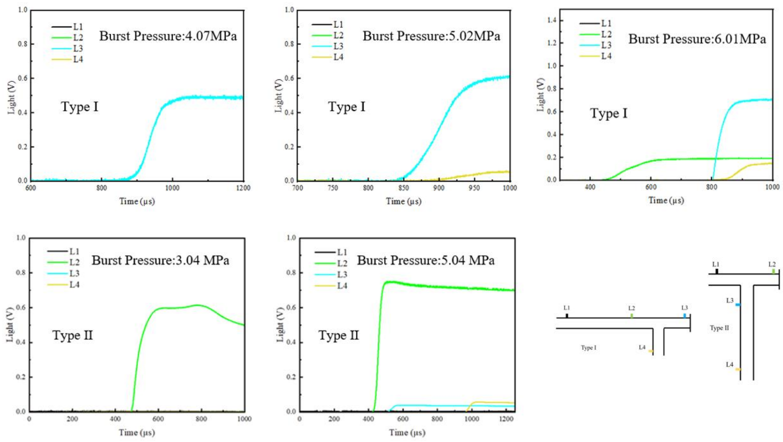


Fig. 7 Evolution of the light curves in the tubes

Fig. 7 demonstrates the evolution of the light curves inside the two types of tubes. The largest photoelectric signal is observed on the blocked end side of the two types of tubes, which is mainly due to the large reflected shock wave generated at the blocked end position, which promotes the mixing of the hydrogen jet with air inside the tube and thus combustion occurs. At 4.07 MPa, Type I only observed the photoelectric signal on the side of the blocked end, and the other photoelectric sensors had no signal. This is mainly because the cooling effect of the hydrogen jet also played a key role, resulting in the ignition in the tube did not propagate upstream. Similarly, a similar phenomenon was observed in Type II at 3.04 MPa. At 5.02 MPa, photoelectric signals were detected at L3 and L4 in Type I, which indicated that the reflected shock formed at the location of the bifurcated structure heated up the hydrogen jet and triggered the spontaneous ignition. A similar phenomenon was observed in Type II at 5.04 MPa. When the initial relief pressure reaches 6.01 MPa, the photoelectric signal has been observed at L2 in Type I. The spontaneous ignition occurred between L1 and L2, and the boundary layer effect heated the hydrogen-air mixture to induce the spontaneous ignition to occur.

Fig. 8 Spontaneous ignition in tubes

Fig. 8 illustrates the in-tube self-ignition of the two types of tubes and discusses the in-tube self-ignition into three categories: non-ignition; quenching in the tube; self-ignition. The critical ignition pressure for Type I is 4.07 MPa, and that for Type II is 3.04 MPa , and Type II is more prone to ignition than Type I . However, in-tube quenching occurs at less than 6 MPa for both types of tubes. When the initial relief pressure is higher than 6 MPa, the two types of bifurcated tubes form a jet fire outside the tube.

5. Summary

In this paper, two types of bifurcated tubes with blocking structures are designed to study the propagation characteristics of shock waves and the development of spontaneous ignition for accidental leakage of high-pressure hydrogen under different types of tubes by changing the relative positions of the bifurcated structures. The forward shift of the bifurcation position can effectively reduce the intensity of the shock wave at the nozzle of the tube and suppress the propagation speed of the shock wave inside the tube. Three ignition modes are analyzed: the ignition under the reflected shock wave from the blocking structure, the ignition under the reflected shock wave from the bifurcation wall, and the ignition dominated by the boundary layer effect. The forward shift of the bifurcation location reduces the critical pressure for ignition. Both types of bifurcated tubes can limit the ignition under initial relief pressure lower than 5MPa, so that spontaneous combustion can be extinguished inside the tube.

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