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Full Length Article

Experimental study on spontaneous ignition and flame propagation of high-pressure hydrogen release via a tube into air

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HIGHLIGHTS

- The critical burst pressure for ignition decreases with tube length increase.
- Higher release pressure reduces ignition delay time.
- The speed of flame front in the air has a sharp increase.
- A strong deflagration is observed and leads to the pressure increase.
- The jet flame shows different morphologies at different release stages.

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ABSTRACT

Spontaneous ignition and subsequent flame propagation of high-pressure hydrogen release via a tube into air are experimentally investigated using pressure records, flame detection and direct high-speed photographs. The study shows that as the burst pressure increases the likelihood of spontaneous ignition increases and the initial ignition is closer to the burst disk. With the increase of tube length, the possibility of spontaneous ignition increases, while the critical release pressure for spontaneous ignition decreases. It is also found that a strong shock wave generated to trigger the ignition and a long tube to promote the growth of the flame are two key factors for the transition from spontaneous ignition inside the tube to jet flame in the air. After the flame exits from the tube, a flame envelope is formed in the front of the hydrogen jet, which gradually splits into upstream and downstream combustion regions. The upstream flame region propagates forward. However, the downstream flame region moves back toward the tube exit. The flame is then stabilized at the tube exit and gradually grows. Noticeable deflagration events were observed to occur successively in the semi-enclosed space. The deflagration leads to a significant increase of pressure in the chamber. And the overpressure of the deflagration is higher than that of the leading shock wave. Both the overpressures of the leading shock wave and the deflagration increase with the release pressure. A stable jet flame is formed outside the tube subsequent to the deflagration. And different jet flame configurations are observed at different controlling mechanisms of flow.

1. Introduction

Hydrogen as an efficient and clean energy carrier, has gained more and more attention. However, compared with the traditional fuels, hydrogen exhibits some unique hazardous properties, for example, wider flammable range in air (4–75% by volume), lower ignition energy (the minimum ignition energy only 0.017 mJ). As a result, released hydrogen from a high-pressure reservoir can be more likely to cause catastrophic fires/explosions. In particular, it is well known that spontaneous ignition can occur when high-pressure hydrogen is suddenly released into air. The spontaneous ignition is a huge potential risk for pressurized hydrogen storage and transport.

There is no consensus for the mechanism of spontaneous ignition of hydrogen, even several postulated explanations have been proposed [1,2]. Among these mechanisms, diffusion ignition is the focus of the current research, which has been confirmed in

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experimental [3–9] and numerical studies [10–15]. The concept of diffusion ignition was first proposed by Wolanski and Wojcicki [16] in 1972, who conducted an experimental study of sudden releases of pressurized hydrogen into a cylindrical chamber filled with pure oxygen or air. It was found that a shock wave was produced in the front of the hydrogen jet, and then the oxidizer after the shock was compressed and heated. Meanwhile, a high temperature flammable mixture could be formed between the hydrogen jet front and the shock-heated oxidizer because of mass and heat diffusion. It was suggested that ignition might be induced even if the entire temperature of hydrogen was below the ignition temperature threshold. Overall, it can be found that this mechanism is a model of shock-induced ignition.

Recently, Dryer et al. [3] experimentally demonstrated the spontaneous ignition from the sudden release of pressurized hydrogen into air. They suggested that downstream flow geometry or objects have important influence on spontaneous ignition. Mogi et al. [17] pointed out that release pressure and tube length are two major parameters affecting the occurrence of spontaneous ignition. The possibility of spontaneous ignition increases with increasing release pressure and tube length. By numerical simulations, Wen et al. [12] extensively investigated the influencing factors of spontaneous ignition of pressurized hydrogen release through a tube into an open ambient environment. They concluded that slower rupture time and lower release pressure will increase the ignition delay time and therefore decrease the possibility of spontaneous ignition. In addition, an experimental research was conducted by Oleszczak and Wolanski [7] to determine the critical conditions for the occurrence of spontaneous ignition. Their results showed the critical pressure is mainly influenced by the extension tube geometry, such as tube length and diameter.

A visualization of the process of the spontaneous ignition and flame propagation in the tube, which was first reported in numerical simulations [11,12,18], was experimentally investigated by Kim et al. [6]. It was suggested that the initial ignition takes place at the boundary layer behind the front center of mixing zone. Then the flame propagates to the front and the tail of the mixing zone along the boundary layer. Flame propagation and transition to jet flame in the open space were observed in some experimental studies [3,5,17,19,20]. Lee et al. [5] proposed that formation of a complete flame across the tube is essential for maintaining a diffusion flame after exiting the tube. The development from a spontaneous ignition into a sustained jet flame was also investigated by Bragin and Molkov [10] using numerical simulations.

A number of studies have been performed to investigate the spontaneous ignition caused by high-pressure hydrogen release. Still, many scientific issues remain unsolved in the understanding of the mechanisms of spontaneous ignition and flame development, such as the critical conditions for ignition, flame propagation after exiting the tube, and the dynamics of jet flame. In the present study, experiments are conducted to gain an insight of the spontaneous ignition mechanism and flame propagation when pressurized hydrogen is suddenly discharged into air through a tube.

2. Experimental

A schematic view of the experimental facility is depicted in Fig. 1(a), which is mainly composed of a high-pressure tank, a diaphragm holder, a downstream tube, a visualization exhaust chamber, a data recording system, a camera system.

The high-pressure tank has a volume of 0.44 l. The diaphragm holder equipped with a burst disk is connected with the tank in upstream and with the tube in downstream, respectively. The burst disk is designed with a cross scored line building on one of the surfaces of the disk. The burst pressure (P_b), which is measured by a pressure transducer (Kulite, ETM-375 M-20 MPa) installed in the tank, is varied from 2 to 11 MPa. The tube has a diameter (D) of 15 mm. Five variable tube lengths (L) are employed, as shown in Fig. 1(b). Several piezoelectric pressure transducers (PCB Piezotronics, 113B22, Pn) and light sensors (Thorlabs, FDS010, Si Photodiode, Ln) are installed on the tube wall to detect the propagation of the pressure wave and the occurrence of the hydrogen spontaneous ignition, respectively. The installation positions of pressure transducers and light sensors in tubes with different lengths are also shown in Fig. 1(b). The tube end is connected to the visualization exhaust chamber which is a rectangular cavity (1200 mm × 470 mm × 500 mm). The end of the chamber is open to the atmosphere. Observation windows (230 mm × 230 mm) are set up in the two sides of the chamber. The flame propagation outside the tube is recorded by the high-speed video camera (Phantom, v710) and the DV camera (Sony, HDR-PJ790E) through the observation windows. To record the variation of the pressure, the pressure transducers (PCB Piezotronics, 113B22, $P_o n$) are mounted in the top of the chamber and the installation positions are presented in Fig. 1(c). The operating speed of the high-speed video camera depends on the resolution, which is from 20,000 to 150,000 frames/s (fps) in the experiments. The operation rate of the DV camera is 25 images per second.

Before each experiment, the air is evacuated from the high-pressure tank and the supply gas pipeline using a vacuum pump. Then, hydrogen is gradually fed into the high-pressure tank until the diaphragm ruptures. Finally, a rising signal is detected by the first pressure transducer (P1) when the pressure wave passes through it, which is used to start the data recording system and the high-speed video camera.

3. Results and discussion

3.1. Conditions of spontaneous ignition inside the tube

Following the theory of diffusion ignition, there are several requirements for auto-ignition inside the tube, including a strong enough shock wave and sufficient combustible gas volume heated by the shock. Moreover, continuous pockets of combustible hydrogen–air mixture for the flame to continue burning are necessary to ensure the ignition nucleus to develop into a flame. Depending on the occurrence and development of ignition, three typical experimental phenomena can be observed, namely non-ignition, failed ignition, and self-ignition. Non-ignition means that no ignition is detected in the whole process of pressurized hydrogen release. Failed-ignition refers to the phenomenon that spontaneous ignition is observed in the early stage and then quenches in a short time, that is, the ignition cannot develop into a sustained flame. Self-ignition describes the observation that ignition not only occurs inside the tube but also successfully develops into a jet flame in the open space.

Fig. 2 shows three typical pressure profiles and light signals inside the tube at different positions (90/180/270 mm). These cases, which are conducted using the same tube length (L = 360 mm) but at different burst pressures, represent three different experimental phenomena as described above. The time when a rapid increase of pressure is detected by P1 transducer is defined here as time t = 0 μs. It is shown from the pressure profiles that a shock wave is generated and propagates along the tube. And the pressure has a sharp increase when the shock front impacts on the transducers. The pressure in the shock-affected region is greater than the value calculated by the shock tube flow theory [21], and this is inferred to be due to the presence of shock reflection and interactions [3,6]. It can be seen that the overall pressure inside the tube after pressurized hydrogen release increases with