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Experimental investigation of spontaneous ignition and flame propagation at pressurized hydrogen release through tubes with varying cross-section

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HIGHLIGHTS

- The effect of varying cross-section has been experimentally investigated.
- The minimum release pressure for ignition is significantly lower.
- The position of initial ignition is closer to the disk.
- A hydrogen deflagration is observed due to partially premixed mixture formed.
- The jet flame shows different morphologies at different release stages.

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ABSTRACT

An experimental investigation of spontaneous ignition and flame propagation at high-pressure hydrogen release via cylindrical tubes with varying cross-section is presented. Tubes with different transverse cross-sections are considered in the experiments: (1) local contraction, (2) local enlargement, (3) abrupt contraction, and (4) abrupt enlargement. The results show that the presence of the varying cross-section geometries can significantly promote the occurrence of spontaneous ignition. Compared to the tube with constant cross-section, the minimum pressure release needed for spontaneous ignition for the varying cross-sections tubes is considerably lower. Moreover, the initial ignition location is closer to the disk in the presence of varying cross-section geometries in comparison with straight channel. As the flame emerges from the outlet of the tube, the velocity of the flame front in the vicinity of the nozzle increases sharply. Then, a deflagration develops across the mixing zone of hydrogen/air mixture. The maximum deflagration overpressure increases linearly with the release pressure. Subsequently, a hydrogen jet flame is produced and evolves different shapes at different release stages. A fireball is formed after the jet flame spouts in the open air. Later, the fireball develops into a jet flame which shifts upward and continues to burn in the vertical direction.

1. Introduction

Hydrogen is one of the promising alternative fuels in the future. Hydrogen has great propensity to cause leaks, fires and explosions due to its unique properties such as high diffusivity and reactivity. It has been known that the sudden release of pressurized hydrogen into air can lead to spontaneous ignition without clearly identified ignition sources [1]. The ignition is very likely to develop into fire and/or explosion accidents [2,3]. Therefore, spontaneous ignition is a potential hazard in the utilization of pressurized hydrogen.

Recently, many studies have attempted to explore the mechanism of spontaneous ignition caused by pressurized hydrogen release. A review of postulated mechanisms of spontaneous ignition was reported by Astury and Hawksworth [1]. The diffusion ignition theory was first proposed by Wolanski and Wojcicki [4], who conducted an experimental investigation using a shock tube technique. It was found that ignition is induced from a high-temperature combustible mixture produced by mass and heat diffusion between the hydrogen jet front and the oxidizer which

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has been heated by a precursor shock wave. Thus the idea of this mechanism is called shock-induced ignition.

Following the pioneer work by Wolanski and Wojcicki, most previous studies focused on the spontaneous ignition that occurred in the scenarios of high-pressure hydrogen release through a tube. Interesting results were obtained in the experimental [5–10] and numerical [11–16] studies. It was found that the release pressure and tube length are two major factors affecting the occurrence of spontaneous ignition in tubes with a constant cross-section. The possibility of spontaneous ignition increases with increasing both the release pressure and tube length. The influence of diaphragm rupture rate on spontaneous ignition was reported by Xu et al. [17] and Golovastov et al. [18]. Oleszczak and Wolanski [9] experimentally investigated the critical conditions for the occurrence of spontaneous ignition. They pointed out that the critical pressure is mainly related to the downstream tube geometry. Bragin and Molkov [11] conducted large eddy simulations of auto-ignition of pressurized hydrogen release and indicated that ignition occurs firstly near the boundary layer of the tube wall.

Hydrogen flame development following auto-ignition in tubes was investigated both by experimental and numerical studies [8,13,19]. It was suggested that shock reflection, shock–shock interactions, shock focusing and turbulence are the main reasons for promoting the growth of the ignition kernel to a flame. After leaving the tube, the flame may be quenched or develop into a jet flame. In addition, hydrogen jet flame was observed in experimental studies [20,21], which suggest that the formation of a complete flame across the tube is important for maintaining a diffusion flame in the open air [7].

The majority of previous studies have been concentrated on the spontaneous ignition at pressurized hydrogen release through a tube with constant cross-section. However, the tube with varying cross-section is often encountered in the practices of utilization of high-pressure hydrogen. Dryer et al. [5] suggested that downstream flow geometry has an important influence on spontaneous ignition. Golub et al. [22] reported that with the release of hydrogen in a T-shaped tube, the ignition delay was reduced in comparison with the release into the straight open tube. In addition, the effect of the tube internal geometry on spontaneous ignition was numerically investigated by Xu and Wen [23]. They thought that the presence of internal geometries can significantly increase the propensity to spontaneous ignition. Although qualitative results were obtained in the numerical simulations using small-size tubes, experiments are necessary to provide further understanding of the effects of internal geometry on self-ignition. Moreover, the critical conditions for spontaneous ignition and flame propagation outside the tube have not been reported yet.

The purpose of the present study is to further understand the effect of the tube internal geometry on the spontaneous ignition. Experiments are carried out to study spontaneous ignition and flame propagation caused by pressurized hydrogen release through four types of tubes with a transverse cross-section varying along axial direction: (1) Local contraction (LC), (2) Local enlargement (LE), (3) Abrupt contraction (AC) and (4) Abrupt enlargement (AE). The minimum release pressure of spontaneous ignition is examined for each type of tube with varying cross-section.

2. Experimental apparatus

A schematic diagram of the experimental set-up is illustrated in Fig. 1, which is mainly composed of a high-pressure tank, a diaphragm holder, a downstream tube, a visualization exhaust chamber, a data recording system, and a camera system. The volume of the high-pressure tank is 0.44 l. The nickel burst disk equipped in the holder is used as a diaphragm separating the high-pressure tank and the downstream tube. The burst pressure (*Pb*) is varied from 2 to 5 MPa. Four types of cylindrical tubes with varying cross-section are schematically shown in Fig. 2(a). The tubes have a length (L) of 360 mm and a diameter (D_0) of 15 mm for the portion on the left-hand side ($x < 120$ mm, where x is the coordinate in the longitudinal direction). The tube cross-section begins to vary from the position of 8 times of the diameter D_0 to the diaphragm. According to our previous study [24], the speed of the leading shock wave has reached nearly a constant before the tube cross-section begins to change at the position of $x = 120$ mm. The visualization exhaust chamber is a rectangular cavity with a size 1200 mm × 470 mm × 500 mm. The right end of the chamber is open to the atmosphere. The view windows (230 mm × 230 mm) are mounted on the two sides of the chamber.

The experimental procedures of this study are described as follows. Firstly, the air in both the supply gas pipeline and the high-pressure tank is evacuated by a vacuum pump. Then, hydrogen gas is gradually supplied to the tank until the disk ruptures. Immediately, a significant pressure rise is detected in the downstream tube, which is used to trigger the high-speed video camera and the data recording system.

The burst pressure is measured by a pressure transducer (Kulite, ETM-375M–20 MPa), which is installed in the high-pressure tank. Several pressure transducers (PCB Piezotronics, 113B22) and light sensors (Thorlabs, Si Photodiode, FDS010) are used to record the

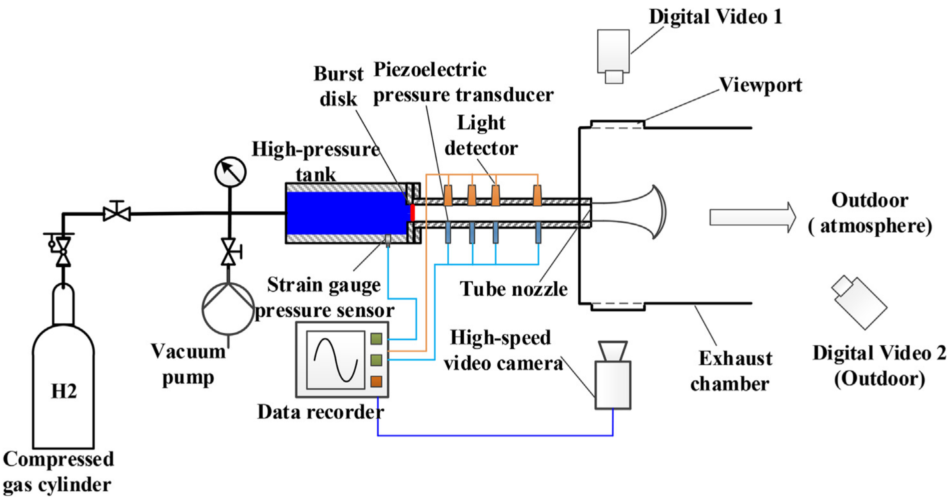

Fig. 1. Sketch of the experimental apparatus.