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Experimental study of spontaneous ignition and non-premixed turbulent combustion behavior following pressurized hydrogen release through a tube with local enlargement

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Pressure records, flame detection and high-speed photography are used to study the spontaneous ignition and non-premixed turbulent combustion behavior following high-pressure hydrogen release through a cylindrical tube with local enlargement into the semi-enclosed space. The study shows that the leading shock wave is partly reflected when it impacts on the vertical walls in the local enlargement section. The pressure behind the reflected shock wave has a significant increase compared with that behind the leading shock. Moreover, the leading shock wave speed decreases firstly and then increases as it passes through the enlargement. It is found that the presence of the local enlargement structure can significantly facilitate the occurrence of spontaneous ignition. The minimum storage pressure of spontaneous ignition is only 1.98 MPa in the tube with local enlargement, which is lower than that in a constant cross-section tube. The possible positions of initial ignition inside the tube and the delay times of ignition for different burst pressures are obtained. After the hydrogen flame comes out from the tube, a ball of flame is formed around the tube outlet and propagates outward. Then, the noticeable non-premixed turbulent combustion of hydrogen occurs in the semi-enclosed space, which leads to the increase of the pressure in the chamber. Twice peaks of overpressure are observed successively and the second pressure peak has a lower intensity compared with the first peak value. Moreover, the maximum overpressure of non-premixed turbulent combustion increases with the release pressure.

1. Introduction

As a clean and high-efficiency energy carrier, hydrogen is widely regarded as an effective solution for environmental and energy crises caused by excessive use of fossil fuels. However, hydrogen has some unique hazardous properties compared with traditional fuels. The high reactivity of hydrogen is directly related to fire and explosion hazards. In particular, spontaneous ignition can be induced once high-pressure hydrogen is suddenly released into the air. The spontaneous ignition of hydrogen is very likely to develop into fire and/or explosion accidents. It is necessary to understand the physics and conditions of spontaneous ignition during pressurized hydrogen release.

The postulated mechanisms of spontaneous ignition were reviewed by Astbury and Hawksworth (2007), including the reverse Joule–Thomson effect, electrostatic charge generation, diffusion ignition, sudden adiabatic compression, and hot surface ignition. Among these possible mechanisms, the focus of the present study is on the diffusion ignition theory, which was considered as the most likely reason for the occurrence of spontaneous ignition. The diffusion ignition was first proposed by Wolanski and Wojcicki (1972), which is a shock-induced ignition pattern in essence. Immediately after the high-pressure hydrogen is released from a container, a strong shock wave is formed in front of the hydrogen flow, and the air in the shock-affected region is heated. Once the hydrogen jet front mixes with shock-heated air due to mass and heat diffusion, spontaneous ignition can happen if the mixture is flammable and the temperature is high enough.

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Following the pioneer study by Wolanski and Wojcicki (1972), many experimental and numerical investigations have been performed aiming at further understanding the mechanism of the spontaneous ignition during high-pressure hydrogen release. The scenarios of high-pressure hydrogen release through a tube were discussed by most previous works (Dryer et al., 2007; Golub et al., 2009; Mogi et al., 2009; Wen et al., 2009; Oleszczak and Wolanski, 2010; Lee et al., 2011). And some progress has been achieved in recent years. It was found that the release pressure and tube length are two major factors affecting the occurrence of spontaneous ignition (Golub et al., 2008; Mogi et al., 2009; Wen et al., 2009). The possibility of spontaneous ignition increases with higher release pressure and longer tube length (Mogi et al., 2009). The influence of diaphragm rupture rate on spontaneous ignition was experimentally reported by Golovastov and Bocharnikov (2012), as well as was numerically studied by Xu et al. (2009) and Bragin et al. (2013). Oleszczak and Wolanski (2010) experimentally investigated the critical conditions of spontaneous ignition. They pointed out that the critical pressure is mainly influenced by the downstream tube geometry.

Bragin and Molkov (2011) studied the spontaneous ignition of hydrogen using large eddy simulation (LES) and showed that ignition occurs firstly near the tube wall boundary layer. The process of flame development following spontaneous ignition in a tube was investigated by experimental study (Kim et al., 2013) as well as by numerical simulations (Lee and Jeung, 2009; Wen et al., 2009). And it was suggested that multi-dimensional shock formation, reflection, interactions, focusing and turbulence are the main causes to promote the growth of the ignition kernel, which is different with the flame propagation of premixed hydrogen/air in a duct (Xiao et al., 2014; Xiao, 2015). After leaving the tube, the hydrogen flame could quench or develop into a jet flame. Lee et al. (2011) suggested that the formation of a complete flame across the tube is important for maintaining a diffusion flame in the open air. Moreover, the flame propagation in hydrogen jet flow outside the tube was reported in experimental studies (Mogi et al., 2008; Grune et al., 2011).

The majority of previous studies have focused on the spontaneous ignition of pressurized hydrogen release through a tube with constant cross-section. In practice, the tube with varying cross-section is often encountered in the utilization of pressurized hydrogen, such as abrupt contraction and enlarging circular orifice. Dryer et al. (2007) suggested that downstream flow geometry can play a role in spontaneous ignition. Xu and Wen (2012) numerically investigated on the effect of tube internal geometry on spontaneous ignition and thought that the presence of internal geometries could significantly enhance the propensity to spontaneous ignition. Bragin et al. (2013) firstly conducted 3D numerical simulations of the hydrogen spontaneous ignition in a T-shaped channel. Their results showed that the “sustainable” ignition was achieved at relatively low pressure of 2.9 MPa. Nevertheless, previous studies mainly provided some qualitative numerical results using small-size tubes. The experimental investigation is necessary to for deep understanding of the effects of internal geometry on self-ignition and subsequent flame propagation.

In this work, an experimental investigation is carried out to further reveal the effect of the internal geometry of a tube on spontaneous ignition following pressurized hydrogen release. The release tube is a cylindrical tube with local enlargement which can facilitate producing multi-dimensional flow features, such as shock reflection, interaction and flow divergence. Shock propagation and spontaneous ignition inside the tube are discussed. Further, flame development and non-premixed turbulent combustion behavior of the hydrogen jet in a semi-enclosed chamber are also investigated.

2. Experimental setup

The experimental apparatus is illustrated in Fig. 1. It mainly consists of a high-pressure tank, a diaphragm holder, a tube with local enlargement, a visualization exhaust chamber, a data recording system, a camera system.

The high-pressure tank has a volume of 0.44 l. The nickel burst disk equipped in the holder is used for the diaphragm separating the high-pressure tank and the downstream tube. The burst disk is designed with a cross scored line built on one of the surfaces of the disk. The burst pressure (*Pb*), which is measured by a pressure transducer (Kulite, ETM-375M-20 MPa) installed in the tank, is varied from 2 to 5 MPa. The schematic of the tube with axially local enlargement is shown in Fig. 2a. The total length (L) of the tube is 360 mm and the initial diameter (D_0) of the tube (Section 1) is 15 mm. The local enlargement (Section 2), which has a diameter of 20 mm and a length of 30 mm, is located at 8 times of the initial diameter (120 mm) from the diaphragm. In our previous study (Duan et al., 2015a), it was found that the velocity of the leading shock wave has reached the maximum and kept nearly a constant value before the position where the tube cross-section begins to change. In the subsequent portion of the tube (Section 3), the tube diameter equals to the value of the initial diameter (15 mm).

Several pressure transducers (PCB Piezotronics, 113B22, P*n*) and light sensors (Thorlabs, Si Photodiode, FDS010, L*n*) are installed on the tube wall to detect the propagation of the pressure wave and the occurrence of the hydrogen spontaneous ignition, respectively. Moreover, a pressure transducer and a light sensor are mounted on the local enlargement section in order to explore the effect of varying cross-section on the shock wave propagation and the occurrence of spontaneous ignition. Positions of pressure transducers and light sensors on the tube are also shown in Fig. 2a. The tube end is connected to a visualization exhaust chamber which is a rectangular cavity 1200 mm × 470 mm × 500 mm. The end of the chamber is open to the atmosphere. The observation windows (230 mm × 230 mm) are mounted on the two sides of the chamber. The flame propagation outside the tube is recorded by a high-speed video camera (Phantom, v710) through the observation windows. The operating speed of the high-speed video is 80,000 fps. In order to detect the variation of the pressure, three pressure transducers (PCB Piezotronics, 113B22, Po*n*) are mounted in the top of the chamber, as presented in Fig. 2b.

The experimental procedures are as follows: (1) the air is evacuated from the high-pressure tank and the supply gas pipeline using a vacuum pump. (2) Hydrogen is gradually fed into the high-pressure tank until the diaphragm ruptures. (3) A rising pressure signal is detected by the pressure transducer P1 as the released hydrogen moves downstream, which is used to trigger the data recording system and the high-speed video camera.

3. Results and discussion

3.1. Shock wave propagation in the tube

Table 1 lists eleven experiments conducted under different burst pressures. The burst pressure is varied by changing the thickness of the burst disk. Once the disk is broken, hydrogen is rapidly discharged into the air through the tube. The typical pressure variation versus time inside the tube is shown in Fig. 3. In order to show the effect of the local enlargement structure on the flow development, the pressure profile in the same length tube with constant cross-section is presented in Fig. 3b as a comparison experiment. Two cases have similar burst pressure values. Time zero indicates the time when a rapid increase in pressure is detected by the transducer P1. The pressure transducers mounted in different positions

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