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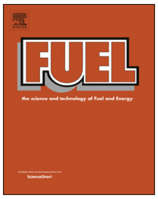

Full Length Article

Effect of burst disk parameters on the release of high-pressure hydrogen

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ABSTRACT

Hydrogen is regarded as an alternative energy carrier in the next decades and high-pressure hydrogen storage is treated as the best option. However, unexpected spontaneous ignition would occur during high-pressure hydrogen sudden release, which induces a severe safety issue. For improving the safety application of hydrogen, an experimental investigation has been conducted. Different diameter ring gaskets are employed to change the opening ratio χ. Pressure transducers and light sensors are used to record the pressure variation and possible light signals inside the tube, respectively. It is found that the burst disk is unable to fully open during high-pressure hydrogen release when $\chi < 1$, resulting in forming a convergent nozzle. This structure leads to the speed reduction for supersonic flow. Consequently, the speed of shock and shock overpressure inside the tube reduce significantly. The spontaneous ignition cannot be initiated even though the initial pressure ratio is as high as 90 when $\chi \le 1/2$. The minimum initial pressure ratio required for spontaneous ignition increases to 64.1 when $\chi = 2/3$. The flame is dimmer for small opening ratio cases. The shock overpressure outside the tube is reduced significantly, which decreases the damage to the facilities and humans to a large extent.

1. Introduction

Nowadays, with the air pollution and energy shortage becoming more and more serious, the value of hydrogen draws our attention. However, the safety issue associated with high-pressure hydrogen blocks its wide application [1]. It is well known that spontaneous ignition would occur during high-pressure hydrogen sudden expansion from a high-pressure tank [2]. This spontaneous ignition will lead to unexpected fires and explosions in the end, which causes casualties and loss of properties.

Based on the diffusion ignition theory proposed by Wolanski and Wojcicki [3], the incident shock wave is responsible for the occurrence of the spontaneous ignition. Ahead of the released high-pressure hydrogen, the produced multi-dimensional incident shock wave propagates downstream with reflection and interactions, heats the air and mixes the heated air and cold hydrogen. The heat and mass transfer between the air and the hydrogen finally contributes to the spontaneous ignition.

So far, a number of experimental studies have been conducted to investigate this phenomenon [4–18]. Dryer et al. [4] stated that in addition to the molecular diffusion between hydrogen and air, the pressure failure boundary and multi-dimensional shock reflection and shock-shock interaction could provide extremely short mixing time scales. Chemical ignition time was the limiting factor for lower burst pressure cases, while for higher burst pressures cases, the mixing time was the limitation. Golub et al. [5] suggested that the maintenance of high temperature for a long time in the area where hydrogen and air mix was the required condition for spontaneous ignition. Mogi et al. [6] confirmed the spontaneous ignition inside the tube using the light sensors. The flame outside the tube was not lifted and the ignition was initiated at the outer edge of the jet. In Golub et al. [5] and Mogi et al. [6]'s investigations, they employed tubes with different diameters and lengths and hydrogen were released at different burst pressures. It was found that the possibility of the spontaneous ignition increased with the increasing of the burst pressure and the tube length. However, a critical length for the extinction was determined as 1.2 m by Kitabayashi et al. [7], who used tubes of length 1.0–4.2 m in their experiments. Golovastov et al. [8] investigated the effects of the burst disk rupture rate on the high-pressure hydrogen spontaneous ignition and found that the possibility of the spontaneous ignition was influenced not only by the initial pressure of hydrogen and tube length but also by the rupture rate of the burst disk. The faster rupture rate, the easier for spontaneous ignition to take place. Ducts with windows on the two sides were employed in [9–11]. The visual process of the spontaneous ignition inside the tube was shown. It is found that the spontaneous ignition firstly took place at the boundary of the tube and then propagated along the boundary layer [9]. The spontaneous ignition was accompanied with the complex mixing which was induced by the multi-dimensional shock

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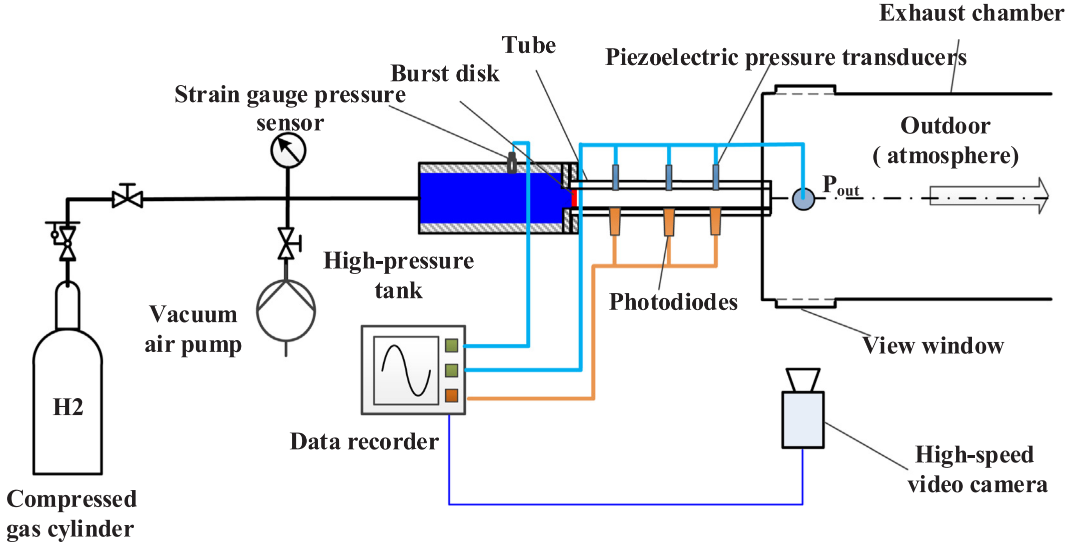

Fig. 1. Schematic of experimental facility.

wave reflection and interaction at the contact surface. In addition, a branching of the flame was observed in [10], with one coupled with the shock wave and the other followed the position of the contact surface. A cylindrical flame was captured in [11] and it was found that the mixing of hydrogen and air at the boundary layer was enhanced until it satisfied the required condition for spontaneous ignition. The effects of doping to hydrogen had also been investigated [12–14]. The additions of methane and nitrogen significantly increased the minimum burst pressure at which spontaneous ignition occurred. Duan et al. [15] investigated the combined effects of tube dimensions (*L/D*) and burst pressure on the spontaneous ignition and found that that the influence of tube diameter on spontaneous ignition shows complex behavior. Liu et al. [16] presented an integrated model to predict the flame length during high-pressure hydrogen release. Makarov et al. [17] proposed a model of pressure peaking phenomenon of unignited and ignited release of hydrogen.

Our previous studies [19–21] focused on the effects of geometry of tubes on the spontaneous ignition and it was found that different geometries of tubes could induce significant shock reflection, which increased the possibility of spontaneous ignition.

Numerical studies are also reported [22–27]. Wen et al. [22] simulated the high-pressure hydrogen release and found that the mixing of hydrogen and air at contact surface was affected by the shock reflections and shock-shock interactions significantly. Large amount of shock heated air and well developed partially premixed mixtures were two major limitations. Xu et al. [23] numerically studied the effect of internal geometries on high-pressure hydrogen spontaneous ignition using four types of tube: local contraction, local enlargement, abrupt contraction and abrupt enlargement. It was found that shock reflections from the internal surfaces and subsequent shock interactions increased the temperature of mixture at contact surface and increased the possibility of spontaneous ignition. Lee et al. [24] and Terashima et al. [25] both investigated the effects of pressure boundaries on spontaneous ignition numerically. Lee et al. [20] used spherical and flat shapes while Terashima et al. [21] employed pressure boundaries with different amplitude of initial burst disk shape. They all stated that there existed a significant relevance between spontaneous ignition and the burst conditions. Bragin et al. [26,27] compared the simulation against experimental studies using LES model and reproduced the flame separation outside the tube and spontaneous ignition conditions in a T-shaped tube. The membrane rupture showed that a layer of hydrogen-air mixture appeared at the boundary at which spontaneous ignition subsequently took place.

Despite the observations discussed above, the understanding of high-pressure hydrogen release process is still imperfect. Actually, the ignition conditions are not always identical even though the burst pressure and tube length are the same. This is mainly because of different opening behaviors of the burst disk. In fact, the burst disks employed in previous studies can form different shapes and open different areas after rupture. This leads to the fact that different intensity shock waves are produced inside the tube. The observations of Lee et al. [28] showed that even though the burst pressure is high enough, the spontaneous ignition is unable to be initiated if the opening ratio of burst disk is reduced sufficiently. However, the characteristics of effects of opening ratios on shock waves and spontaneous ignition of high-pressure hydrogen release still needs further exploration. In present investigation, the effects of opening ratios on the shock waves and spontaneous ignition of high-pressure hydrogen release are conducted. The effects of opening ratios on shock waves, such as mean shock speed and shock overpressure, are discussed under different opening ratios. Furthermore, the conditions of spontaneous ignitions under different opening ratios are discussed as well as the flame propagation behavior and shock overpressure outside the tube.

2. Experimental facility

A schematic of the experimental facility is shown in Fig. 1. The experimental facility consists of a high-pressure hydrogen cylinder, a high-pressure tank, a nickel 201 burst disk, a tube, an exhaust chamber and a data recording system. The high-pressure hydrogen cylinder can supply hydrogen into the high-pressure tank up to 12 MPa. The diameter and length of high-pressure tank are 40 mm and 320 mm, respectively. Different thicknesses of nickel 201 burst disks are used to control the burst pressures. A x-mark is on the surface of the burst disk which is used to increase the producibility of the experiments just like what Kaneko et al. [29] did in their investigation. The parameters of the burst disk used in the experiments, i.e. the thickness and the notching depth on the surface, are listed in Table 1. The tube has a 15-mm diameter and a 360-mm length. The high-pressure hydrogen is eventually released into atmosphere through an exhaust chamber which is a rectangular cavity (1200 mm × 470 mm × 500 mm). Two view windows with a size of 230 mm × 230 mm are mounted on the side walls of the exhaust chamber. The data recording system includes the data about pressures, lights and videos. A pressure transducer (Kulite, ETM-375M-20 MPa) is installed on the high-pressure tank wall to measure the burst pressures. Three pressure transducers (PCB Piezotronics,