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Full Length Article

Experimental study of pressure dynamics, spontaneous ignition and flame propagation during hydrogen release from high-pressure storage tank through 15 mm diameter tube and exhaust chamber connected to atmosphere

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HIGHLIGHTS

- The pressure inside the tank will not decrease immediately but oscillates around the burst pressure before it drops.
- The pressure depletion rate in the tank increases at first and then decreases because of finite time of diaphragm opening.
- Minimum pressure for spontaneous ignition in a 15 mm tube is between 3.30 MPa and 4.09 MPa for a tube of 360 mm length.
- The velocity of the flame moving downstream outside the tube decreases at first and then remains approximately constant.

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ABSTRACT

Hydrogen is expected to be a promising fuel in the future. However, high-pressure hydrogen is extremely easy to leak, after which spontaneous ignition may occur and causes serious hazards. For the purpose of collecting data to assess the risks and develop mitigation measures, high-pressure hydrogen release through a tube with a diameter of 15 mm and length of 360 mm and subsequent spontaneous ignition and flame propagation are experimentally studied in this work. Piezoelectric pressure transducers and light sensors are employed to detect shock waves and spontaneous ignition inside the tube, respectively. A high-speed video camera is used to record the flame propagation outside the tube. It is found that the pressure in the tank does not decrease immediately after high-pressure hydrogen release. The pressure depletion rate in the tank increases at first and decreases afterwards. Spontaneous ignition of pressurized hydrogen has a tendency to occur with higher burst pressure in the tube with a diameter of 15 mm and minimum pressure for spontaneous ignition in a 15 mm tube is between 3.30 MPa and 4.09 MPa (previous experiments were performed in tubes with diameters of 5 and 10 mm - this is new information). Initial flame detection time of spontaneous ignition is defined and it is shorter for the case with higher burst pressure. The velocity of the flame moving downstream outside the tube decreases at first and then remains approximately constant after the flame splits into two parts. In addition, the flame appears earlier and lasts longer with higher burst pressure. For the cases where spontaneous ignition successfully occurs, the pressure inside the exhaust chamber increases twice and oscillates with a larger amplitude. The pressure does not increase again and it oscillates with a smaller amplitude in other cases.

1. Introduction

Hydrogen is expected to be one of the most promising clean fuel in the future because of its high energy efficiency and its clean combustion products. Nowadays, the safe storage, transportation and utilization of hydrogen are major problems of hydrogen wide adoption. As for hydrogen storage, Sarkar and Banerjee compared compressed hydrogen, cryogenic hydrogen and metal hydride hydrogen storage options using net energy analysis and found that high-pressure hydrogen was the best choice for hydrogen storage [1]. However, as the lightest material in the world, hydrogen is especially easy to leak. Because of its unique properties, such as high diffusivity, low ignition energy which is the energy to ignite the hydrogen-air mixture (the minimum energy is 0.017 mJ [2]) and wide range flammability limits (4–75% by volume in air), there

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Nomenclature

a	Speed of sound (m/s)
M_s	Mach number
T	Temperature (K)
Q	Leak rate (kg/s)
A	Area of leak hole (m^2)
P	Pressure (MPa)
M	Molar mass (g/mol)
R	Gas constant (8.314 J/(mol K))

Greek symbols

γ	Specific heat ratio

Subscripts

1	Low pressure region
2	Shock-affected region
4	High pressure hydrogen

exists a huge risk during hydrogen leakage. In addition, it is well known that spontaneous ignition will occur when pressurized hydrogen is discharged through a tube into atmosphere [3].

Wolanski and Wojcicki [4] studied spontaneous ignition of pressurized hydrogen release and proposed the terminology of diffusion ignition firstly following their experiments in which pressurized hydrogen was suddenly released into a cylindrical chamber filled with pure oxygen or air in a shock tube. It was found that hydrogen could be spontaneously ignited even though the temperature of hydrogen was below the self-ignition temperature which is the minimum temperature required to initiate combustion in a flammable hydrogen mixture when there is no ignition source. The authors suggested that a strong shock wave was produced ahead of the under-expanded hydrogen jet which would increase the temperature of air ahead, generating a shock-heated air region between leading shock wave and hydrogen jet front. Spontaneous ignition might be triggered if the temperature of shock-heated air exceeds the self-ignition temperature of hydrogen in air.

So far, a great number of experimental studies [5–11] have been performed to study the spontaneous ignition of pressurized hydrogen release. Dryer et al. [5] experimentally demonstrated the hydrogen self-ignition from a sudden release and pointed out that the flow geometry structures downstream of the diaphragm had a strong influence on the occurrence of the hydrogen spontaneous ignition. Golub et al. [6,7] suggested that the required condition for hydrogen spontaneous ignition was to maintain the high temperature in the area for a long time so that hydrogen and air could be mixed well. Mogi et al. [8,9] demonstrated that the hydrogen had an increasing tendency to ignite in the tube if the tube which is downstream of the diaphragm is longer and the burst pressure is higher. Kim et al. [10] investigated the hydrogen self-ignition using a tube with rectangular cross-section whose two side walls were enclosed with windows and took the shadowgraph and direct photograph images. The tests showed that spontaneous ignition took place at the boundary layer behind the front center of mixing area firstly and then the flame propagates to the front and the tail of the mixing area along the boundary layer. Kitabayashi et al. [11] experimentally studied the spontaneous ignition of compressed hydrogen release and found that the minimum burst pressure at which spontaneous ignition occurs is to be between 1.0 and 1.2 m of the extension tube length.

Numerical studies [12–16] have also been conducted. Wen et al. [12] used implicit large eddy simulation (ILES) with 5th-order weighted method to study pressurized hydrogen release and revealed that the finite rupture process of the diaphragm had an important influence on hydrogen self-ignition. The rupture process induced significant turbulence at the contact region mixing the air and hydrogen via shock reflections and shock-shock interaction. Xu et al. [13,14] suggested that molecular diffusion between the shock-heated air and hydrogen might be a possible mechanism for hydrogen self-ignition. In addition, an obstacle plate placed downstream of the release hole performed the function to quench the flame following spontaneous ignition. Bragin et al. [15,16] described a large eddy simulation model of hydrogen spontaneous ignition in a T-shaped channel filled with air, where 3D model was firstly used to investigate the phenomenon of high-pressure hydrogen release. And most importantly, it reproduced experimental results.

Even though a lot of studies have been performed to investigate the spontaneous ignition of pressurized hydrogen release through a tube, many of them were focused on the phenomenon of hydrogen spontaneous ignition and influencing factors. However, the features of hydrogen release process and flame propagation outside of the tube need to be further studied. In present study, an experimental study is conducted to study the hydrogen release process and flame propagation. At first, the change of pressure profile in the tank is discussed. Then, the features of the spontaneous ignition are presented. Finally, the flame propagation outside the tube is analyzed.

2. Experimental apparatus

A schematic view of the experimental setup is shown in Fig. 1a. The experimental setup consisted of six parts: a gas supply system, a high-pressure tank, a diaphragm holder, a downstream tube, an exhaust chamber and a data recording system.

The volume of the tank is approximately 0.44 L and a pressure transducer (Kulite, ETM-375 M-20 MPa) is installed for monitoring the pressure in the tank. The diameter and the length of the pressure chamber are 40 mm and 320 mm, respectively. The distance between the membrane and pressure sensor located inside the chamber is 80 mm. The Nickel 201 burst disk is used as a diaphragm, which separates the high-pressure tank from the downstream tube. The detailed geometry of the high-pressure tank and location of burst disk are shown in Fig. 1b. The designed burst pressure used in the experiments is varying from 2 MPa to 9 MPa. Fig. 2a shows the assembly of the diaphragm holder, burst disk, ring gasket and downstream tube. The discharge caliber of the burst disk is equal to the internal diameter of the ring gasket and the downstream tube. Eight types of burst disk with different designed burst pressure varying from 2 MPa to 9 MPa are used. In addition, the tube length 360 mm and tube diameter 15 mm are employed. To record the propagation of pressure wave inside the tube, piezoelectric pressure transducers (PCB Piezotronics, 113B22) are installed on the lower wall of the tube. P1 is located 90 mm away from the burst disk and the distance between three pressure transducers is 90 mm. On the opposite side of the tube, light sensors (Thorlabs, FDS010, Si Photodiode) are mounted to detect the occurrence of the hydrogen spontaneous ignition. L1 is located 90 mm away from the burst disk and the distance between three light sensors is 90 mm. The detailed installation positions of