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An experimental study on shock waves and spontaneous ignition produced by pressurized hydrogen release through a tube into atmosphere

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ABSTRACT

Shock waves and spontaneous ignition produced by pressurized hydrogen release through a tube into atmosphere are studied experimentally. The results showed that the speed of the leading shock wave increases at the initial stage and then decreases when propagating to the downstream inside the tube. The schlieren images of the of the hydrogen jet in the vicinity of the tube exit clearly show various classical flow structures, i.e. Mach disk, barrel shock, reflected shock and shock triple point. Due to the sharp decline of the strength of the shock wave, spontaneous ignition might be difficult to occur or quenched outside the tube. Additionally, Spontaneous ignition is more likely to happen in the downstream tube with small diameter and the possibility of spontaneous ignition increases with increasing the tube length. An accidental explosion was observed when the hydrogen jet was emitted into a semi-closed exhaust chamber. It is found that the rupture process of the diaphragm has an important influence on the formation of shock wave and spontaneous ignition.

Introduction

Hydrogen is one of the most promising alternative fuels due to its high-efficiency and ultra-low harmful emissions. Because of the lower energy density by volume versus other conventional fuels [1], hydrogen storage in the utilization process is a great challenge for the development of a hydrogen economy. Compared with cryogenic hydrogen and metal hydride, high-pressure hydrogen is currently the best choice for hydrogen storage according to the net energy analysis by Sarkar and Banerjee [2]. It is well known that hydrogen has high diffusivity, wide flammability range in air (4–75% by volume) and low ignition energy (the minimum ignition energy only 0.017 mJ) which lead to potential hazards and risk associated with hydrogen leak and combustion. As a result, hydrogen

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leaks, fires and explosions are the main safety concerns in the use of pressurized hydrogen.

Basically, when high-pressure gas is suddenly discharged into air a leading shock wave is produced in front of a jet. And a shock-heated air region can be formed between the leading shock wave and the jet front, where the temperature increases sharply due to shock compression. For pressurized hydrogen release, ignition might be initiated if the temperature of shock-heated air exceeds the temperature of spontaneous ignition of hydrogen in air. Obviously, the shock waves produced by high-pressure hydrogen release are the foundation of ignition. The ignition pattern is known as shock-induced ignition. This mechanism of spontaneous ignition was first proposed and expounded as diffusion ignition by Wolanski and Wojcicki [3] 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 ignition can occur in the front of the hydrogen jet, even if the entire temperature of hydrogen was below the auto-ignition temperature threshold. It was suggested that the ignition was caused by the temperature rise of the combustible mixtures formed between hydrogen jet front and shock-heated oxidizer owing to mass and heat diffusion. Hence, shock waves could play an essential role in the diffusion ignition of high-pressure hydrogen release/leak.

A great deal of experimental [4–8] and numerical [9–16] studies have been performed to investigate the spontaneous ignition of pressurized hydrogen release. Dryer et al. [4] experimentally examined the physical process leading to the spontaneous ignition subsequent to a sudden release of pressurized hydrogen through a tube. It was reported that multi-dimensional transient flows involving shock formation, reflection and interactions could promote the rapid formation of combustible mixture and chemical ignition. Mogi et al. [5] suggested that the strength of the shock waves and the temperature of shock-heated air increases with increasing the burst pressure, which would lead to an increase of the possibility of ignition. Lee et al. [6] pointed out that the hydrogen-air mixing region is produced by multi-dimensional shock–shock interactions. And, shock–boundary layer interaction with the mixing front might also promote the mixing of hydrogen and air [7]. A similar result was obtained in the numerical study by Wen et al. [9]. The formation of shock waves and the process of flow development were simulated by Lee et al. [10] and Yamada et al. [11], when pressurized hydrogen was suddenly discharged into atmosphere through a tube. After leaving the tube, the normal shock rapidly transforms into a semi-spherical shock [12]. Xu et al. [13,14] and Bragin et al. [15] studied the evolution of the flow structures in the downstream of the tube exit. In addition, the conditions required for spontaneous ignition of high-pressure hydrogen release were numerically revealed in Refs. [9–11,16].

Although many studies have been conducted to investigate the spontaneous ignition of pressurized hydrogen release through a tube into the air, most of them were mainly focused on the phenomenon of shock-induced ignition and influencing factors on the ignition. However, the characteristics of the shock waves produced by high-pressure release and their effects on the shock-induced ignition need be explored further. In particular, the distinct flow structures after the shock wave and hydrogen jet spouting from the tube were not experimentally captured and discussed. In present investigation, an experimental study is carried out to investigate shock waves propagation, flow structures and spontaneous ignition produced in the process of pressurized hydrogen release through a tube into atmosphere. Firstly, the characteristics of the shock wave propagating in the tube, such as speed and overpressure, are discussed with different tube dimensions. Secondly, the flow structures in the vicinity of the tube exit are presented and the process of flow development is analyzed in detail. Finally, the physical process of spontaneous ignition and the subsequent explosion are investigated.

Experimental apparatus

A schematic view of the experimental setup is shown in Fig. 1. It is mainly composed of a gas supply system, a high-pressure tank, a diaphragm holder equipped with a downstream tube, a data recording system, a high-speed schlieren photography system and an exhaust chamber.

The volume of the tank is approximately 0.44 L and a pressure transducer (Kulite, ETM-375M-20 MPa) is installed for monitoring the pressure in the tank. The Nickel 201 burst disk is used as a diaphragm, which separates the high-pressure tank from the downstream tube. The designed burst pressure used in the experiments is 5 MPa Fig. 2(a) 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 (*D*) of the ring gasket and the downstream tube. Three types of tube with different diameters of 10, 15 and 20 mm are used. In addition, four tube lengths (80, 160, 240 and 360 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. On the opposite side of the tube, light sensors (Thorlabs, FDS010, Si Photodiode) are mounted to detect the occurrence of the hydrogen spontaneous ignition. The detailed installation positions of pressure transducers and light sensors in different lengths of tube are shown in Fig. 2(b). The high-speed schlieren photography system mainly consists of a line light source, two focusing lenses, two spherical concave mirrors, a vertical schlieren knife edge, and a high-speed video camera. The high-speed video camera

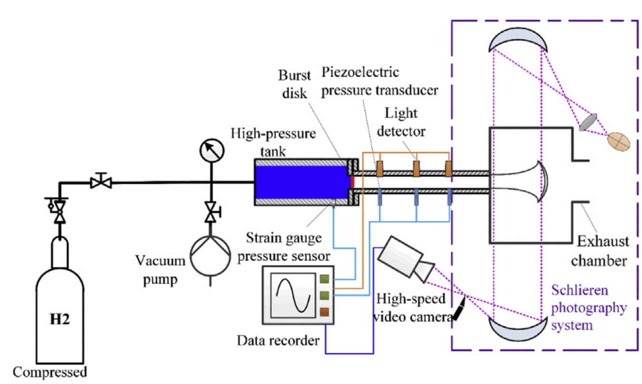

Fig. 1 – Sketch of the experimental apparatus.