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A flow visualization study on self-ignition of high pressure hydrogen gas released into a tube

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Abstract

Hydrogen is known as one of the green energy sources for fuel cells and hydrogen-fueled cars in the next generation. The storage of high-pressure hydrogen gas conditions is preferred to its storage in cryogenic liquid state. However, cases of unidentified self-ignitions were reported, notably when the high-pressure hydrogen gas suddenly leaked out. Only a few of numerical simulations have shown visually the processes of the self-ignition inside a tube. This paper presents a flow visualization study to investigate the self-ignition mechanism in a test tube i.e. how the ignition process is initiated and the flame propagates. In addition to visualization, measurement of a number of pressure and light sensors installed in the tube supported the analysis of the self-ignition and flame propagation. The test result showed that self-ignition takes place at the boundary layer behind the front center of mixing zone at first, and the flame propagates to the front of mixing zone and tail of the mixing zone along the boundary layer. It showed that self-ignition is accompanied with complex mixing induced by shock interaction with the mixing front. It is also suggested that the self-ignition boundary has a certain critical threshold of static pressure at the boundary layer, based on various burst pressures of hydrogen.

Keywords: Hydrogen; Shock compression; Self-ignition; Mixing spot; Visualization

1. Introduction

High-pressure hydrogen gas can be used directly as one of the green energy sources in the next generation. However, high-pressure hydrogen gas leakage can induce a self-ignition and explosions without any ignition sources [1]. Among various plausible reasons for the self-ignition, the diffusion ignition model [2] has been considered as the most influential mechanisms from various experiments [3–11] and numerical simulations [12–15].

Several studies on the diffusion ignition have helped establishing an understanding on the mechanism of the self-ignition of pressurized hydrogen released into air through tubes [3–9,12,13]. Experimental studies of Dryer et al. [3] suggested that multi-dimensional shock interaction induced by the disk bursting may influence mixing of hydrogen and air, which can generate the self-ignition. Lee and Jeung [12] showed the postulation from the numerical simulation

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applying the pressure boundary condition of a spherical shape. They showed that two reaction regions are generated at the core and boundary layer flow inside a tube and that the merge of two reaction regions is necessary in order for the jet-diffusion flame to be sustained at the exit of the tube. Their result suggested that the sufficient tube length is needed to initiate the self-ignition. Mogi et al. [4] and Lee et al. [9] confirmed these results by conducting the experiments using the high-speed photography. They showed that the flame cannot be sustained at the tube exit when the tube is not long enough. In this case, the flame was observed only in the boundary region. Besides these studies mentioned above, many others have been conducted in an objective of finding out the effect of bursting conditions on the self-ignition. The studies showed consistent tendency that the possibility of the self-ignition increases as burst pressure is higher, tube length is longer and tube diameter is smaller [4–10]. Recently, however, experimental result has been reported, which suggests otherwise. That is, if the tube is too long, e.g. exceeding 4.2 m, the flame cannot be sustained, even when the burst pressure is sufficiently high [11]. In addition to that, the research on the effect of tube shape was also conducted. The results showed that the possibility of the self-ignition increases when the rectangular cross-sectional tube was used compared to the experiments which used circular cross-sectional tubes [6,7].

Although many studies have been conducted as mentioned above, however, an understanding on the self-ignition mechanism still remains to be imperfect because it was deduced from the measurements, such as pressure and light signals inside a tube, whereas the visualization images were taken only from outside a tube. The visualization images inside the tube have not been reported yet. Only a couple of numerical simulations have shown the processes of the self-ignition inside a tube. The objective of the present study is to confirm the mechanism from the flow visualization images inside a tube. In order to do so, synchronized shadow and direct photo images obtained using rectangular cross-sectional tube and burst pressure up to 11.3 MPa were analyzed. Additionally, the flow characteristics, such as shock interactions, flow mixing, and flame propagation in the test tube, were also investigated in detail based on the measurements of pressure and light sensors.

2. Experimental setup

Figure 1 shows the experimental apparatus including the test tube assembly. A high-pressure hydrogen cylinder (1) is used to fill up the intermediate cylinder (2) which is enclosed by the diaphragm (4), Mylar polyester film. The intermediate cylinder consists of two regions; the reservoir of $\phi 40 \times \mathrm{L}307$ mm and the throat of $\phi 16 \times \mathrm{L}38$ mm The burst pressure is measured by the pressure transducer (3) (Kulite, ETM HT 375-5000G). The diaphragm thickness was varied in order to control the hydrogen burst pressure, P_B. A test tube (5) with rectangular cross-section was designed, in order to take the shadowgraph and direct photograph images. Two side walls were enclosed with windows, and a series of pressure and light sensors were installed on the top and bottom walls. The visualization region which has the square cross-section of 10×10 mm is located between 37.3 and 278.8 mm from the diaphragm, and the total tube length is 300 mm. Two high-speed cameras (Phantom v710) were used to obtain shadowgraph and direct photograph simultaneously. Shadowgraph was captured at the frame rate of 100,000 fps and the exposure time of 1 μs. In the case of direct photograph images, the frame rate was set at the same level as that of the shadowgraph while the exposure time was extended to 5 μs to get images more clearly. Eight dynamic pressure sensors (PCB 111A26) were flush-mounted on the top wall. Eight light sensors (Hammamatsu photodiodes, S1226-18BQ) were mounted in line with the pressure sensors on the bottom wall. The first pressure and light sensors are located at 57 mm from the diaphragm and the other sensors are spaced out 28 mm apart. All the measurement events were synchronized by the trigger signal obtained from the wall static pressure sensor P_1.

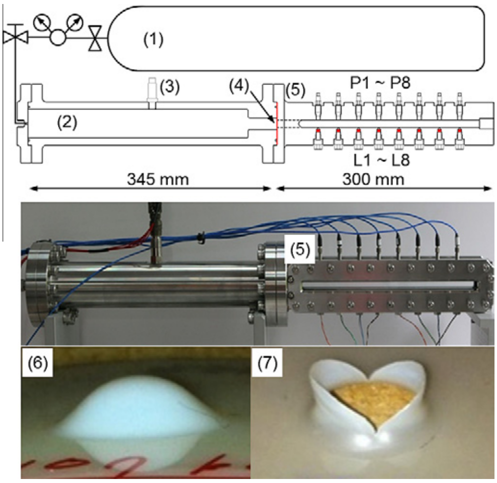

Fig. 1. Test apparatus, (1) high-pressure hydrogen cylinder; (2) intermediate cylinder; (3) Kulite pressure sensor; (4) diaphragm (Mylar film); (5) test tube; (6) deformed diaphragm shape under high pressure; (7) bursted diaphragm shape; P_n: PCB sensor, L_n: photodiode light sensor.