Effects of Porous Structures at Pipe Outlet on Self-ignition of High-Pressure Hydrogen Leakage

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1 Introduction

As the world aims to become 2050 carbon neutral, various energy sources such as hydrogen, ammonia, and biofuels are attracting attention to replace fossil fuels. Among them, hydrogen is attracting attention as a next-generation clean energy source because it has abundant reserves, a wide supply source, and high energy density and does not generate carbon as a combustion product. In addition, due to its high flammability, power generation efficiency, and lightweight, the development of aircraft and automobiles that use hydrogen fuel as a power source is being actively carried out in the aviation and automobile industries. However, hydrogen is generally stored as liquid hydrogen or high-pressure gas because it has a lower volume and density than other fuels. Hydrogen is generally used as the form of high-pressure gas because liquid hydrogen requires expensive storage and transportation technology due to high energy consumption and continuous evaporation in the process of liquefying gaseous hydrogen.

If high-pressure hydrogen gas leaks momentarily, there is a possibility of self-ignition in which flames occur without an ignition source, and secondary damage such as fire and explosion may occur due to the rapid spread of hydrogen. To safely use hydrogen in the form of high-pressure gas, various studies have been conducted on the identification of the spontaneous ignition phenomenon of high-pressure hydrogen and understanding of the tendency to occur [1-7]. As for the self-ignition of high-pressure hydrogen, the temperature of oxygen in the atmosphere rises due to the shock wave generated when hydrogen leaks, hydrogen, and oxygen are mixed and reacted in a contact surface, resulting in self-ignition in a tube [3-5]. Previous studies have shown that the smaller the internal diameter of the tube, the larger the ejection pressure ratio, and the longer the length of the hydrogen ejection tube, the higher the possibility of self-ignition [6-7]. Research has also been conducted to prevent self-ignition. The method of suppressing self-ignition through weakening shock waves has been studied by reducing the ejection area ratio. When the ejection area ratio is reduced, the shock wave speed decreases, and thus self-ignition is suppressed in the same burst pressure, but the possibility of spontaneous ignition at the same shock wave speed increases due to the increase of the mixing effect [8]. The objective of the present study is to observe the effect of the porous structure on the behavior of hydrogen flames through experiments. at the ejection pressure ratio where self-ignition occurs after installing the porous structure designed in consideration of the quenching distance of hydrogen flames at the outlet. The porous structure was designed in consideration of the quenching distance of hydrogen flame, and the experiment was conducted at the ejection pressure ratio at which spontaneous ignition occurred.

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2 Experimental setup

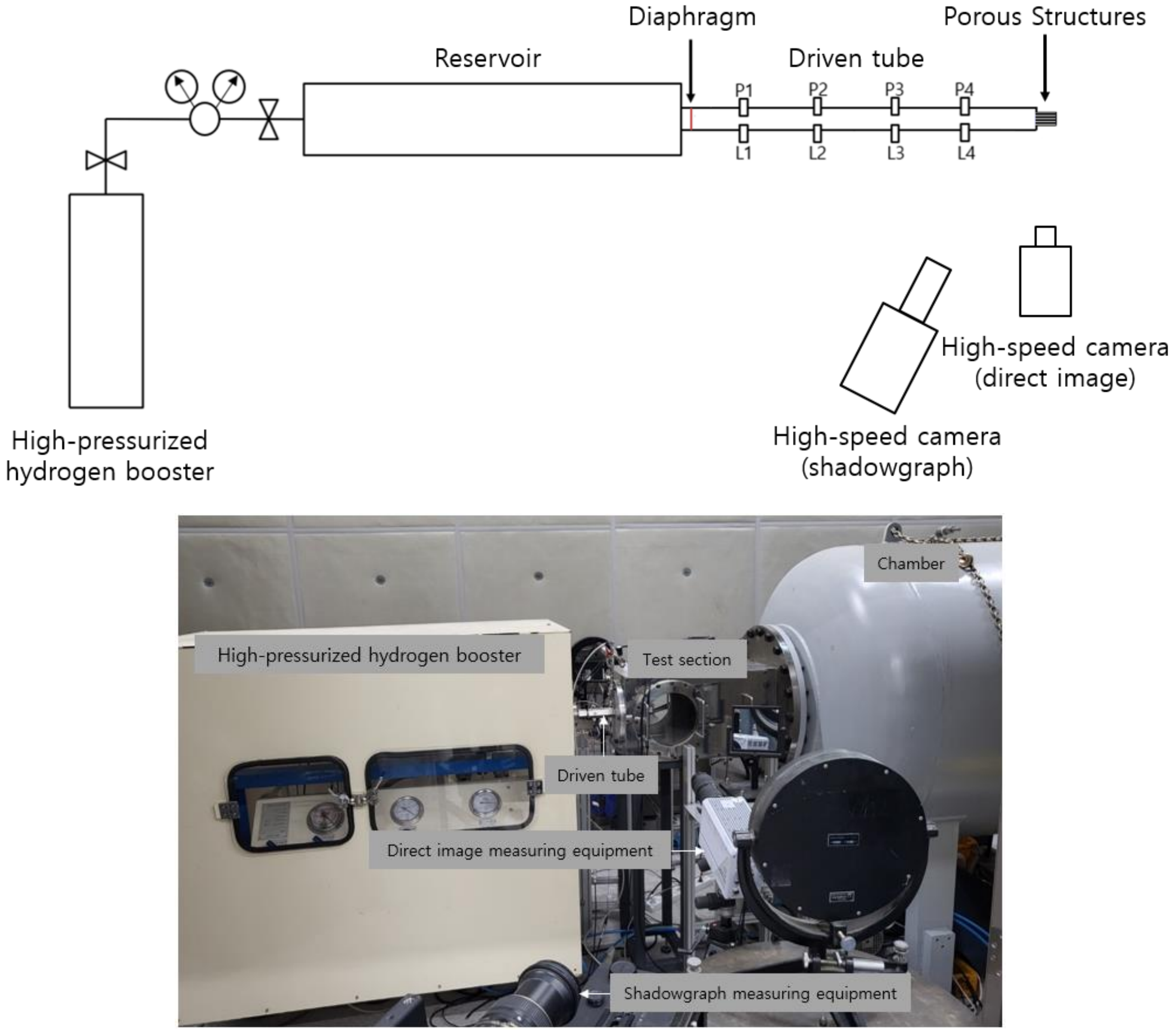
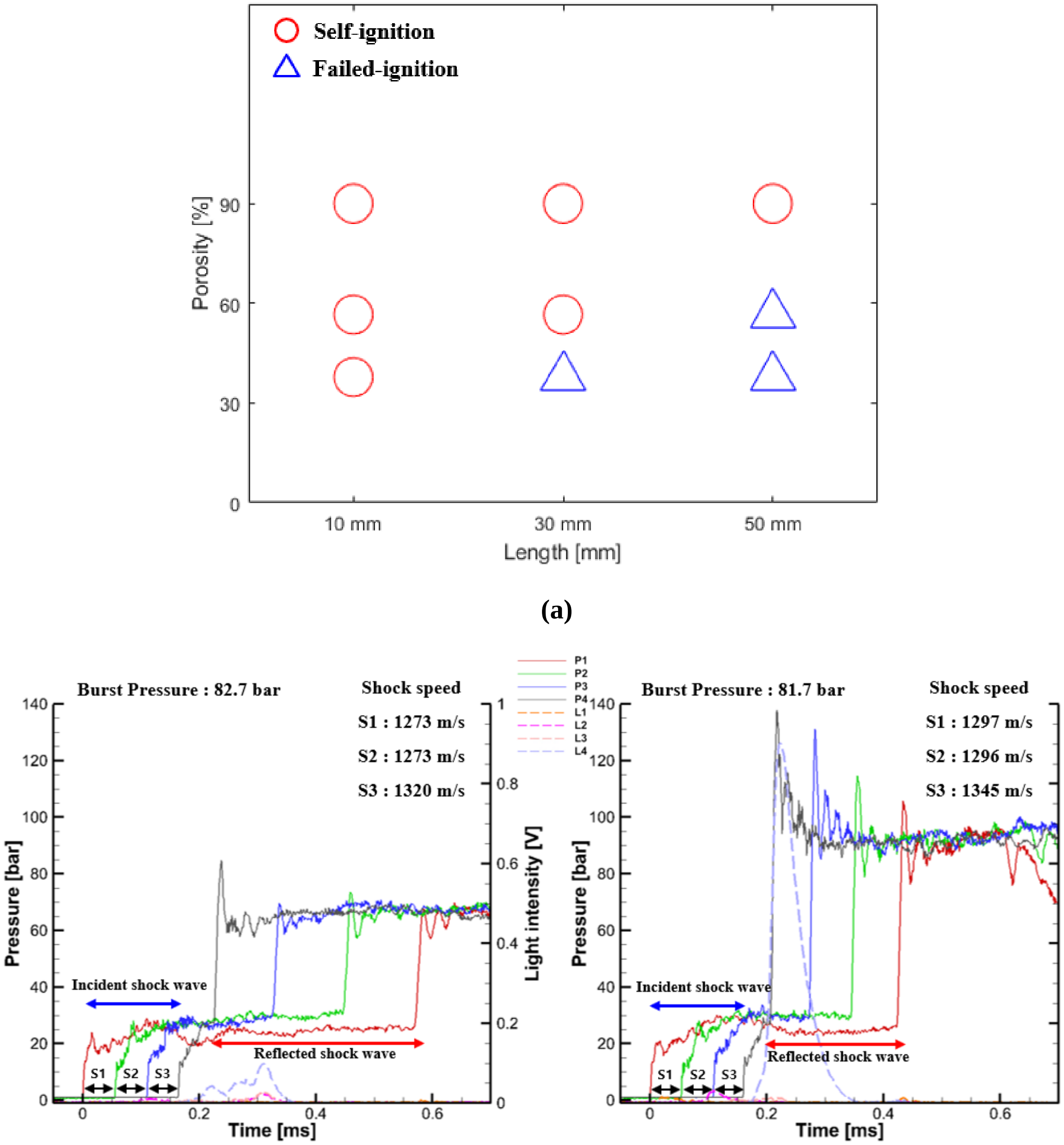


Figure 1: Test apparatus

The experimental setup was constructed as shown in Figure 1. Hydrogen in the reservoir is compressed to high pressure using a high-pressure hydrogen booster and an air compressor. Nine types of porous specimens having a porosity of 90%, 57%, and 38% of the length of 10 mm, 30 mm, and 50 mm, respectively, were mounted at the outlets of the ejection tube having an inner diameter of 10 mm and a length of 300 mm. To generate self-ignition in a tube with a diameter of 10 mm, hydrogen having a driver pressure of 80 to 85 bar should be ejected into the atmosphere, and for this purpose, Mylar Film having a thickness of 175 μm was used. Four PCB pressure transducers are installed to measure the strength of shock waves formed when high-pressure hydrogen leaks and a photodiode sensor is installed to measure the ignition position inside the tube. In addition, direct image and shadowgraph images were obtained to measure the flow field ejected from the tube outlet and obtain the shape of the flame.

3 Results and discussion



(a)

(b)

Figure 2: Experiment result, (a) Self-ignition boundary concerning Flame Arrester (Diaphragm Burst Pressure: 81 ~ 85 bar) (b) Measurement result of Pressure and Light intensity In tube (P1 – P4: Pressure data, L1 – L4: Light intensity data)

Hydrogen was leaked under Driver Pressure 81–85 bar conditions to understand the effect of porous structures on the behavior of hydrogen flames generated by spontaneous ignition. As for the porous structure, a total of three types of honeycomb structure specimens were used, with a porosity of 47%, 36%, and 27% and their lengths of 10 mm, 30 mm, and 50 mm, respectively. The experimental results are shown in Fig. 2(a). Regardless of the length of the 47% porosity specimen, the flame spread to the pipe outlet, and the 36% porosity length 50 mm, 27% porosity length 30 mm, and 50 mm specimen were observed to have a failed position in which the flame could not be maintained at the pipe outlet. (b) in Figure 2 is the result of measurement of the internal pressure and light signal of the experiment equipped with a 50 mm length, 47% porosity, and 27% specimen. In both cases, hydrogen was ejected at a similar rupture pressure, indicating that the strength of the incident shock wave was also similar, as the shock speed described in the upper right corner of each plot was similar. The left graph of Figure 2 (b) shows a lower result than the experiment in which the pressure and speed of the reflected shock are mounted on a relatively high porosity specimen at the end of the pipe. In addition, the graph on the right side of Figure 2 (b) showed that the flow path was blocked a lot due to the low porosity specimen mounted at the pipe outlet, and the flame was stagnated at the end of the pipe. This was inferred as the voltage of L4 in the plot was measured high. (a) in Figure 3 is the result of the left side of Figure 2 (b), and (b) is the result of visualization of the flow of the pipe outlet of the right side of Figure 2 (b). (a) can be seen that the flame generated by spontaneous ignition inside the tube develops into a diffusion flame at the tube outlet, and (b) can be confirmed that the flame in the tube is converted into a failed-ignition by a porous structure.

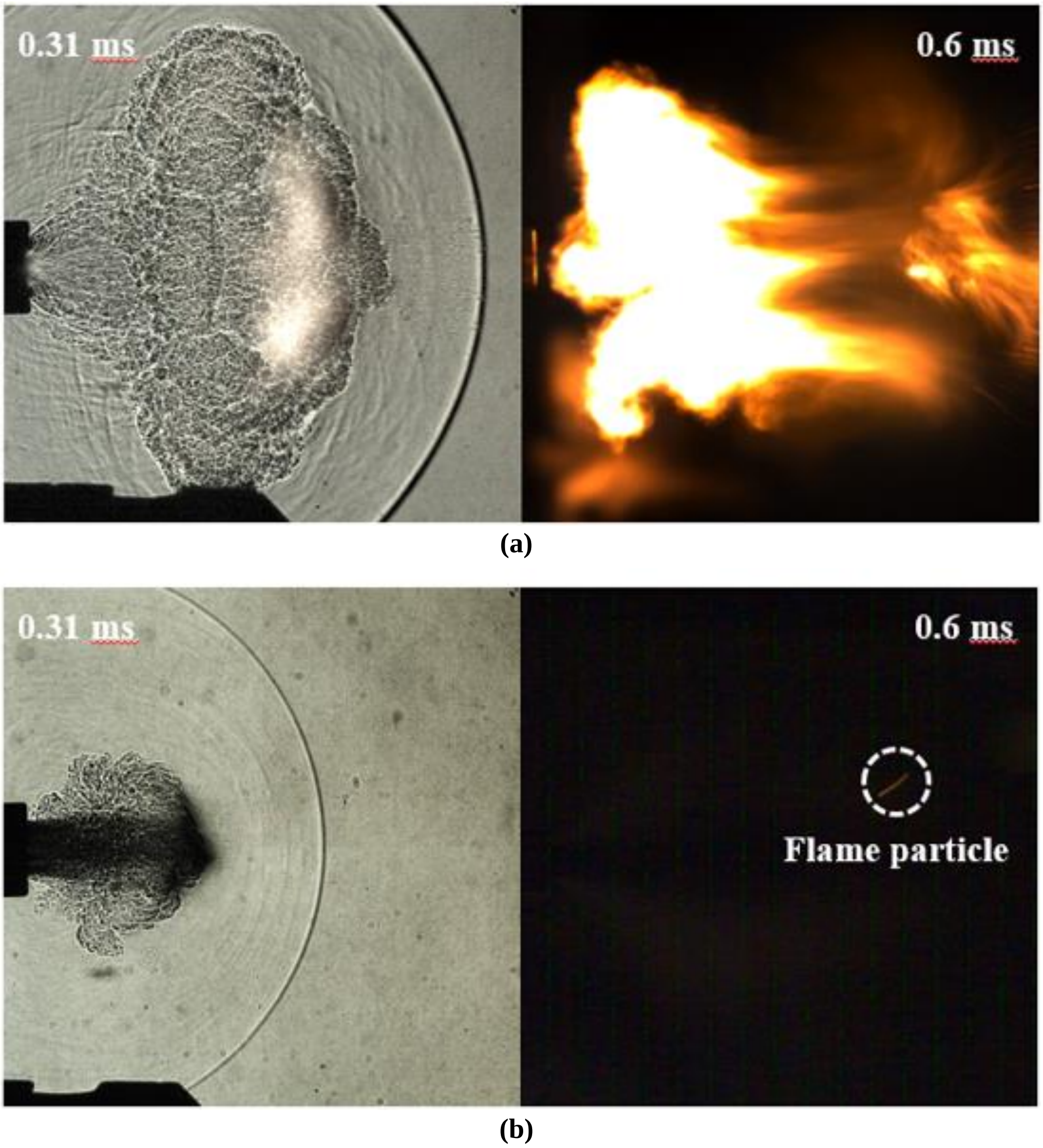


Figure 3: Flow visualization result, (a) Self-ignition case (left: shadowgraph, right: direct image) (b) Failed-ignition case (left: shadowgraph, right: direct image)

Through experiments on the porosity and length of the porous structure, it was confirmed that failed-ignition occurred as the length of the pipe outlet structure increased and the porosity decreased. Through this, it was confirmed that there is a possibility of preventing spontaneous ignition when a porous structure suitable for the vent tube outlet of a high-pressure hydrogen storage system is used.

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