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Experimental study on the hazards of high-pressure hydrogen jet diffusion flames

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ABSTRACT

The present paper reports the hazards of a hydrogen jet diffusion flame formed by high-pressure hydrogen gas. Hydrogen jets were horizontally released from circular nozzles with diameters ranging from 0.1 to 4 mm, and the release pressure varied from 0.01 to 40 MPa (gauge). The blow-off limits were determined from the nozzle diameter and the release pressure. The flame sizes were measured, and experimental equations were obtained for the length and width of the flame. The flame sizes depended not only on the nozzle diameter but also on the release pressure. In the case of slit nozzles, the flame length depended on the length of the shorter side of the slit nozzle. The radiation from the hydrogen flame could be predicted from the flow rate of the gas and the distance from the flame.

1. Introduction

Hydrogen is expected to serve as a clean energy carrier, and hydrogen fuel-cell vehicles have been actively developed. The introduction of fuel-cell vehicles that have a high energy efficiency requires the handling of high-pressure hydrogen. Hydrogen is highly combustible; therefore, the preparation of safety regulations for hydrogen supply stations is very important, and it is necessary to obtain safety data owing to the increase in the number of fuel stations that handle high-pressure hydrogen. Several studies have been performed on the safety regulations for handling hydrogen (e.g., Howard, Tchouvelev, Cheng, & Agranat, 2005).

The minimum ignition energy of hydrogen is the lowest among flammable gases; hence, hydrogen leaking through pinholes, narrow gaps, or broken pipes may be ignited by ignition sources such as static electricity. Furthermore, hydrogen flames enable an increase in the flame strength, even when the jet velocities exceed 1300 m/s. If a high-speed jet flame is formed by the high-pressure leakage of hydrogen gas, it damages the facilities of hydrogen stations and cause injury to the employees and customers at hydrogen stations. Hence, from the viewpoint of safety, it is important to understand the characteristics of the hydrogen jet flame and to evaluate the risks of disasters involving hydrogen.

The jet flame has been examined in several studies. Hottel and Hawthorne (1949) reported that the flame lengths from circular nozzles are determined from the nozzle velocities. Becker and Liang (1978) and Kalghatgi (1984) developed the formulae for flame length. However, few investigations have examined the flames produced by the release of high-pressure hydrogen. Iwasaka, Urano, and Hashiguchi (1979) studied the fire hazards associated with the rapid leakage of compressed hydrogen. They used hydrogen compressed at pressures of up to 10 MPa and obtained the experimental equations for the relations between the length and width of the flame and the release velocity. Takeno, Okabayashi, Hashiguchi, Noguchi, and Chitose (2005) obtained the experimental formula for the flame scale. They conducted experiments under release pressures of up to 40 MPa. However, the thermal radiation hazards were not investigated in these experiments.

We conducted an experimental study on the high-speed hydrogen jet diffusion flame formed by the leakage of high-pressure compressed hydrogen at up to 40 MPa. We also considered the effects of the nozzle diameter and release pressure on the flame scale. In addition, in order to investigate the flame characteristics of hydrogen leaking from a crack, we observed the hydrogen jet flame formed by a slit nozzle. Furthermore, we investigated the radiation from hydrogen jet diffusion flames. Herein, we present a simplified equation for determining the area that could be affected by the fire caused by high-pressure hydrogen.

2. Experimental

A schematic diagram of the experimental apparatus used in the present study is shown in Fig. 1. High-pressure compressed hydrogen was stored in four storage tanks, each having a capacity of 0.046 m^3 and a maximum pressure of 45 MPa. The combined capacity of these storage tanks was 0.184 m^3. Hydrogen gas

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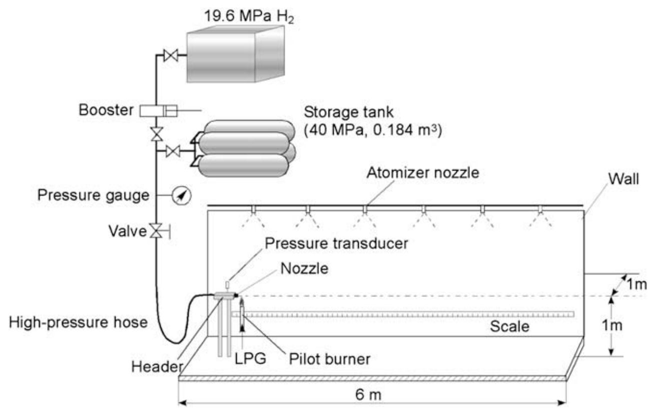

Fig. 1. Experimental setup.

supplied from the storage tanks was ejected horizontally through a circular nozzle made of a stainless steel plug, as shown in Fig. 2. The nozzle was installed at a header that was located 1 m above the ground. A torch burner fueled with liquefied petroleum gas (LPG) was used as a pilot burner. This burner was ignited before the hydrogen gas was spouted and was extinguished as soon as the gas was ignited.

The release pressure p_0 in the header was measured by using a pressure transducer (KYOWA, PG-500KU) that was connected to a dynamic strain amplifier (KYOWA, CDV-700A). An aqueous Na_2CO_3 solution (1%) was atomized from above the fuel injection nozzle so that the hydrogen jet flame can be visualized through the flame reaction of sodium. Flame shapes were recorded by two digital video cameras (Sony, DSR-PD170A). One camera was placed at one side of the apparatus, and the other camera was placed at the front of the apparatus. The flame length and flame width were determined from the video camera images. To evaluate the thermal radiation from the hydrogen jet flame, radiometers (Tokyo Seiko, RE-2, maximum radiation received: 9000 W/m^2) located at 1.5, 2.5, and 3.5 m from the flame axis were used. The radiometers were of thermopile-type, and a filter (KRS-6, 0.5–27 μm) was attached to the detector front in order to prevent the airflow. The recorded voltage was converted to irradiance. The radiative energy was measured, but the aqueous Na_2CO_3 solution was not atomized.

The release pressure p_0 was changed from 0.01 to 40 MPa, and the nozzle diameter d ranged from 0.0001 to 0.004 m.

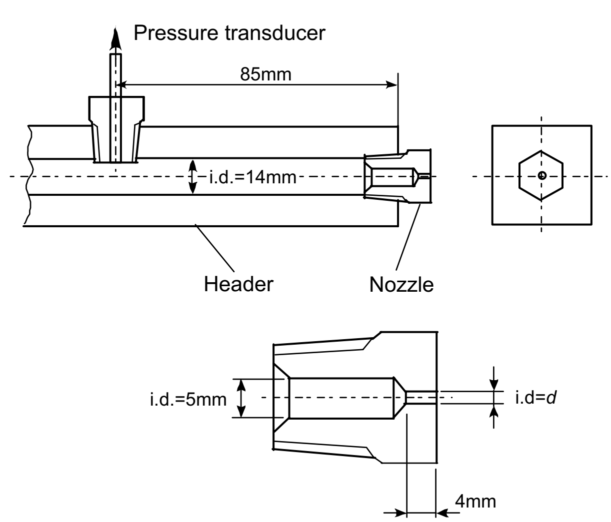

Fig. 2. Schematic diagrams of the header and nozzle.

3. Results and discussion

3.1. Flame of released high-pressure hydrogen and its stability

The hydrogen jet diffusion flame obtained with various nozzle diameters when $p_0 = 35$ MPa is shown in Fig. 3. The flame length was approximately 5 m when $d = 0.002$ m, although it was 1 m or less when $d = 0.0004$ m. The flame extended horizontally if the release pressure was greater than $p_0 = 0.1$ MPa owing to buoyancy.

The combustion states of the flame were investigated under various nozzle diameters and the release pressures of hydrogen. Fig. 4 shows a map of the combustion states and the stability limit of the hydrogen jet diffusion flame. Blow-off implies that the flame extinguishes as soon as the pilot burner is extinguished. By increasing the release pressure, the combustion state changed from laminar to turbulent. Furthermore, when the release pressure was less than the critical pressure, which is 1.9 times greater than the atmospheric pressure, the flame was found to be lifted, irrespective of the nozzle diameter.

The lower limit of the release pressure for the blow-off of the flame is approximately constant and is independent of the nozzle diameter. However, the upper limit for blow-off is affected by both the release pressure and the nozzle diameter. In other words, upon blow-off, the release pressure decreases with an increase in the nozzle diameter. For the cases of $d = 0.0001$ and 0.0002 m, blow-off occurs, although the spouting pressure increases up to $p_0 = 40$ MPa. At $d = 0.0015$ m or more, the flame shows no blow-off, even when the release pressure is changed.

3.2. Jet flame length

The results of measuring the flame length, L_f, at various release pressures and nozzle diameters are shown in Fig. 5, where both the axes are presented as logarithmic scales.

In the present study, the flame length is defined as the distance from the nozzle top to the visible flame top. In the case of $d = 0.004$ m, the measurements are made in the pressure range of 4–10 MPa. The blow-off region exists for $d = 0.0004$ and 0.0008 m. When the release pressure is lower than the critical pressure, the flame length remains approximately constant, irrespective of the release pressure. However, the flame length is proportional to the release pressure when the release pressure is higher than the critical pressure.

Fig. 6 shows the relations between the dimensionless flame length and the release pressure. The dimensionless flame length is defined as L_f/d. L_f/d is proportional to the power of p_0, and the following experimental equation is obtained ($p_0 > 0.1$ MPa):

$$\frac{L_f}{d} = 530 p_0^{0.43} \tag{1}$$

The empirical formulae (Iwasaka et al., 1979; Takeno et al., 2005) are plotted together for comparison. Iwasaka's results cover only release pressures of up to 10 MPa, but it appears that the lines plotted on the basis of their results to do not fit those in the present study for pressures up to 10 MPa. Since Takeno's results are approximated by the 0.5 power, the flame scale is dependant on the release pressure. This is attributed to the variation in the proportional coefficients of empirical formulae due to the changes in the fluid resistance, which was caused by factors such as differences in the nozzle diameter (Takeno et al., 2005). However, it is confirmed that the dimensionless flame length is proportional to the 0.4 ∼ 0.5 power of the release pressure.

Fig. 7 shows the relations between the flame length and the mass flow rate of hydrogen. The mass flow rate is calculated from the difference between the pressures in the storage tanks before