FLAME CHARACTERISTICS OF HIGH-PRESSURE HYDROGEN GAS JET

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ABSTRACT

It is expected that hydrogen will serve as a nonpolluting carrier of energy for the next generation of vehicles, and guidelines for its safe use are required. Hydrogen-gas service stations for supplying fuel-cell vehicles will have to handle high-pressure hydrogen gas, but safety regulations for such installations have not received much investigation. In this study, we experimentally investigated the flame characteristics of a rapid leakage of high-pressure hydrogen gas. A hydrogen jet diffusion flame was injected horizontally from convergent nozzles of various diameters between 0.1 and 4 mm at reservoir over pressures of between 0.01 and 40 MPa. The sizes of the flame were measured, and experimental equations were obtained for the length and the width of the flame. Flame sizes depend not only on the nozzle diameter, but also on the spouting pressure. Blow-off limits exists and are determined by the nozzle diameter and the spouting pressure. Furthermore, the radiation from a hydrogen flame can be predicted from the flow rate of the gas and the distance from the flame.

1. INTRODUCTION

It is expected that hydrogen will serve as a clean source of energy and, in particular, the hydrogen fuel cell is being actively developed. To introduce fuel-cell vehicles that have a high energy efficiency, it is necessary to be able to handle high-pressure hydrogen. The actual proof test for hydrogen-supply stations in Japan requires hydrogen to be handled at a pressure of 35 MPa. Hydrogen is highly combustible and explosive, so that preparing safety regulation for hydrogen-supply stations is very important, and it is necessary to have safety-related data in anticipation of the spread of fuel stations in which high-pressure hydrogen is handled.

The minimum ignition energy of hydrogen is the lowest among the flammable gases, so that there is a possibility of hydrogen leaking through pinholes, narrow gaps, broken pipes, etc. being ignited by ignition sources such as static electricity. In particular, it is possible that a high-speed jet flame could be formed by a high-pressure leakage of hydrogen gas, causing damage to facilities in hydrogen stations and endangering workers and customers. Hence, in terms of ensuring safety, it is important to understand the characteristics of hydrogen jet flames and to organize their basic data in order to evaluate the risk of a disaster involving hydrogen.

Many studies on jet flame have been performed. Hottel et al. showed that the flame lengths and concentration patterns of flames from circular nozzles are determined by the nozzle velocities [1]. Lift-off and blow-off stability for hydrogen diffusion flames have been investigated [2–6]. However, few investigations on flames produced by spouting high-pressure hydrogen have been reported. Iwasaka et al. studied the fire hazard of a rapid leakage of compressed hydrogen [7]. They used hydrogen compressed at pressures of up to 10 MPa and they obtained experimental equations for the relationships of the length and width of the flame to the spouting velocity.

We conducted an experimental study of high-speed hydrogen jet diffusion flames formed by leaking high-pressure compressed hydrogen at up to 40 MPa. Consideration was given to the effects of the nozzle diameter and the spouting pressure on the flame shape. Furthermore, we investigated radiation from hydrogen jet diffusion flames.

2. EXPERIMENTAL APPARATUS AND METHODS

A schematic view of the experimental apparatus used in this study is given in Figure 1. This apparatus consisted of a hydrogen supply system, a nozzle, a pilot burner, and measuring systems. High-pressure hydrogen was stored in four storage tanks each with a capacity of 0.046 m^3 and a maximum pressure of 45 MPa. These tanks combined to form a storage tank with a capacity of 0.184 m^3. Hydrogen gas supplied from the storage tanks was injected horizontally through a circular nozzle, as shown in Figure 2. The nozzle was installed at a header located 1 m above the ground. A premixed burner fueled by liquefied petroleum gas (LPG) was used as a pilot burner. This burner was ignited before the hydrogen was injected, and was extinguished as soon as the hydrogen was ignited.

The pressure in the header was measured by a pressure transducer (Figure 2). In this study, this pressure was assumed to be the spouting pressure P. An aqueous Na_2CO_3 solution of 1 % in concentration was atomized from above the burner and the fuel injection nozzle to permit the hydrogen jet flame to be visualized through the flame reaction of sodium. Flame shapes were recorded by a digital video camera. The flame length and width were read from the video camera images. The spouting pressure was changed from 0.01 MPa to 40 MPa (gage) and the nozzle diameter, d, ranged from 0.1 mm to 4.0 mm. Radiometers (Tokyo Seiko, RE-II, maximum receiving radiation 9000 W/m^2) located at distances of 1.5, 2.5, and 3.5 m from the flame axis were used to measure the thermal radiation from the flame. When radiative energy was measured, the aqueous Na_2CO_3 solution was not atomized.

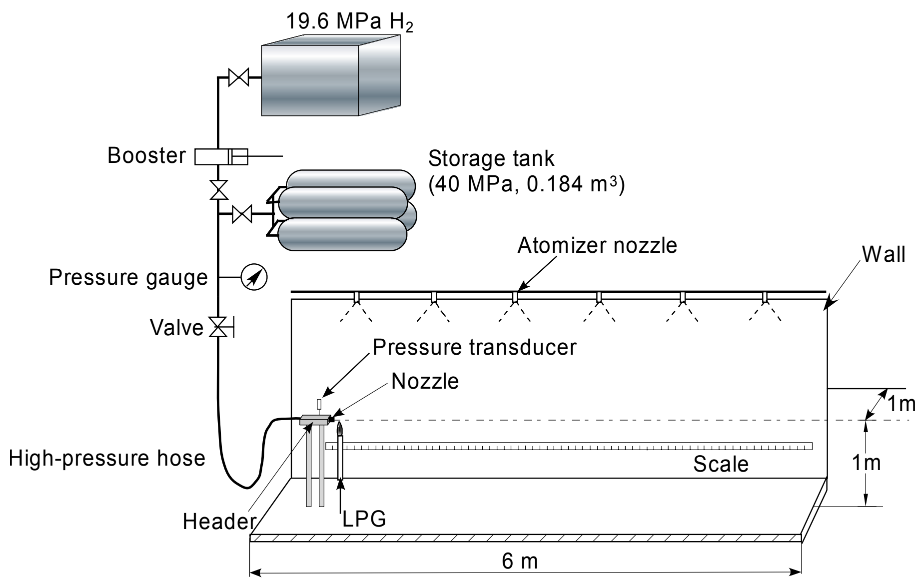


Figure 1. Experimental apparatus.

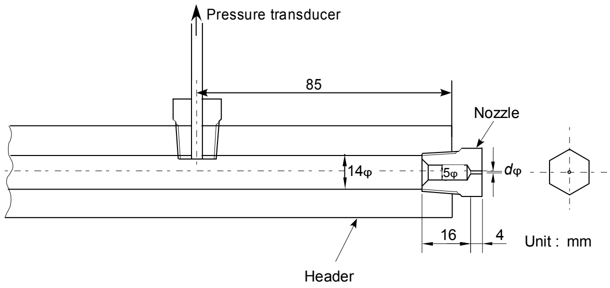


Figure 2. Fuel nozzle and header.

3. RESULTS AND DISCUSSION

3.1 Hydrogen Jet Diffusion Flame and Stability

Figure 3, for P = 35 MPa, shows the hydrogen jet diffusion flame for various nozzle diameters. It is observed that the flames were horizontally formed and were barely affected by buoyancy. Moreover, the flame shape, observed from the direction of the flame axis, was circular like the shape of the nozzle. The flame length was almost 5 m for a nozzle diameter d = 2.0 mm, although it was 1 m or less when d = 0.4 mm.

Figure 4 shows the stability limits of a high-pressure hydrogen diffusion flame. "Blow-off zone" means that the flame blew off as soon as the pilot burner was extinguished. The lower limit of the spouting pressure for blowing off of the flame was constant and independent of the nozzle diameter; however, the upper limit for blow-off was affected by both the spouting pressure and the nozzle diameter. That is, on increasing the nozzle diameter, the spouting pressure when the flame blew off decreased. In the case of d = 0.1 and 0.2 mm, the flame blew off, although the spouting pressure increased up to P = 40 MPa. At d = 2.0 mm or more, the flame showed no blow-off even when the spouting pressure was changed.

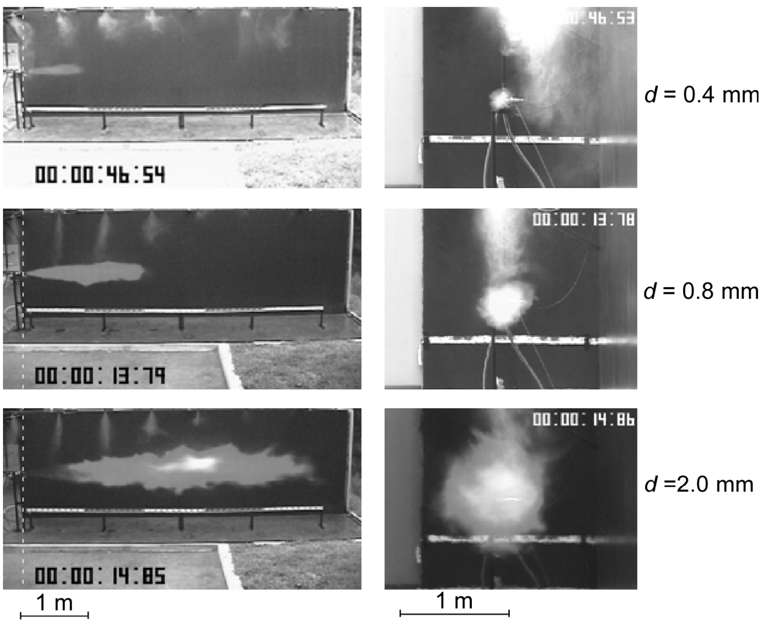


Figure 3. Hydrogen jet flames for different nozzle diameters for P = 35 MPa.

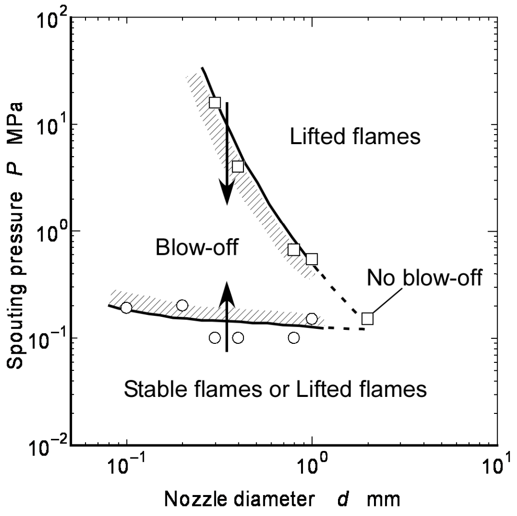
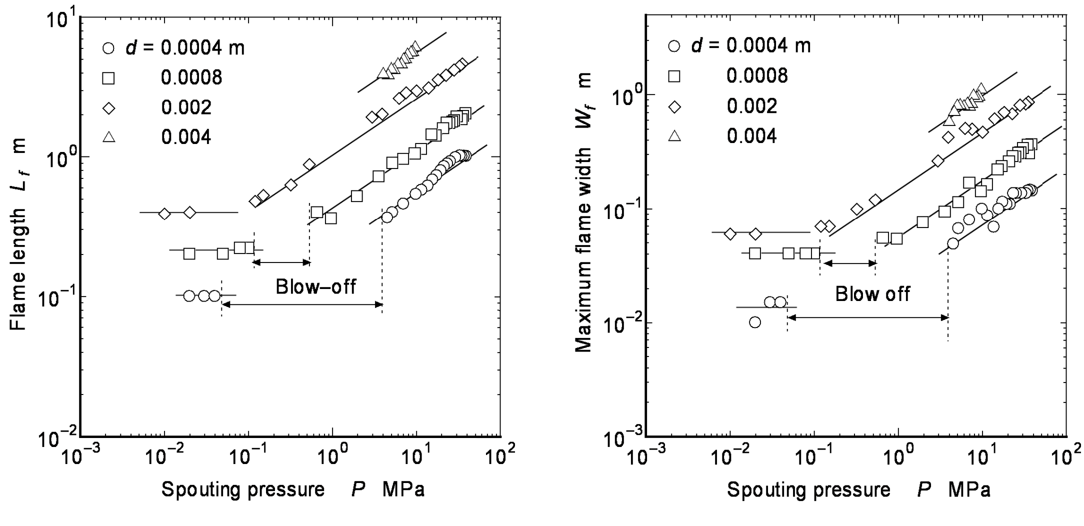


Figure 4. Stability limits of high-pressure hydrogen jet diffusion flames.

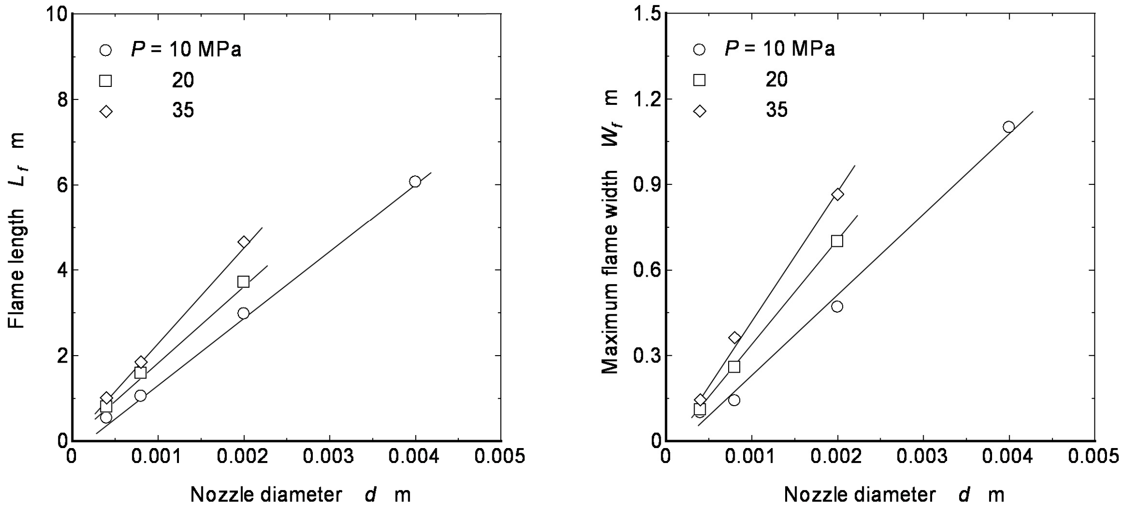
3.2 Flame Size Properties

The results of measuring the length and width of the flame at various spouting pressures and nozzle diameters are shown in Figure 5, where both of the axes are presented as logarithmic scales. In the case of d = 4.0 mm, the measurements were made at P = 4 MPa to P = 10 MPa. When the spouting pressure was low, the flame length and width were almost independent of the spouting pressure; however, when the spouting pressure was larger than 1 MPa, the length and width of the flame increased with increasing spouting pressure. Figure 6 shows the relationship between the nozzle diameter and the flame size. The spouting pressures were 10, 20, and 35 MPa. The flame length and width increased in proportion to the increase in the diameter of the nozzle.



(a) Flame length (b) Maximum flame width

Figure 5. Flame sizes at the various spouting pressures and nozzle diameters.



(a) Flame length

(b) Maximum flame width

Figure 6. Relationship between the flame size and the nozzle diameter.

The scale of the flame is proportional to the nozzle diameter. The dimensionless flame length is defined as L_f/d and the dimensionless flame width is defined as W_f/d. The relationships between L_f/d, W_f/d and the spouting pressure are shown in Figure 7. In these figures, solid lines indicate experimental equations correlated in terms of the spouting pressure as follows ($P > 0.1$ MPa):

$$L_f / d = 524.5P^{0.436} \tag{1}$$

$$W_f / d = 85.1P^{0.436} \tag{2}$$

Dotted lines in these figures represent the equations of Iwasaka et al. [7] as follows:

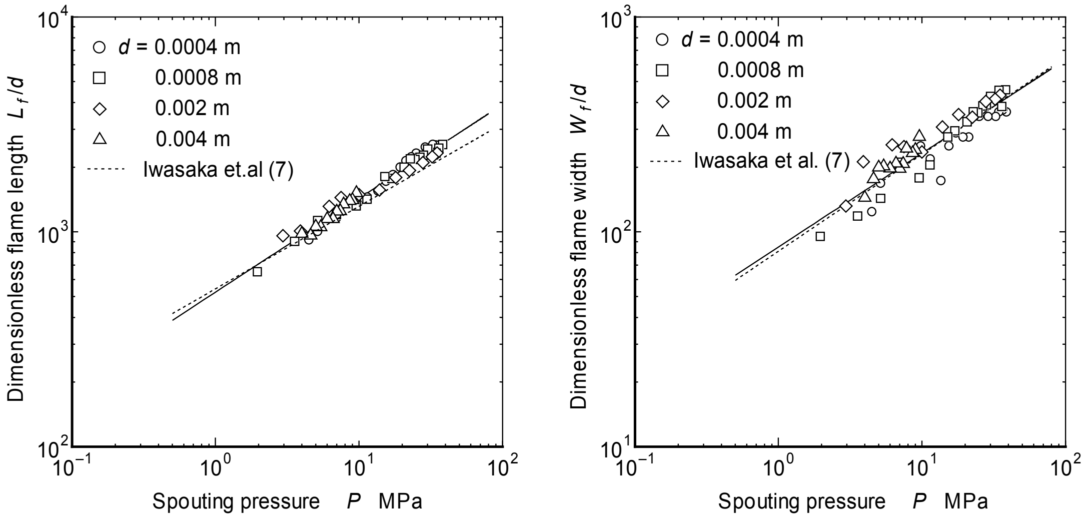
$$L_f / d = 544P^{0.384} \tag{3}$$

$$W_f / d = 78.7P^{0.451} \tag{4}$$

The work of Iwasaka et al. [7] covers only spouting pressures of up to 10 MPa, but it appears that the lines plotted from their results to do not fit those of the present study for the range of pressures up to 10 MPa.

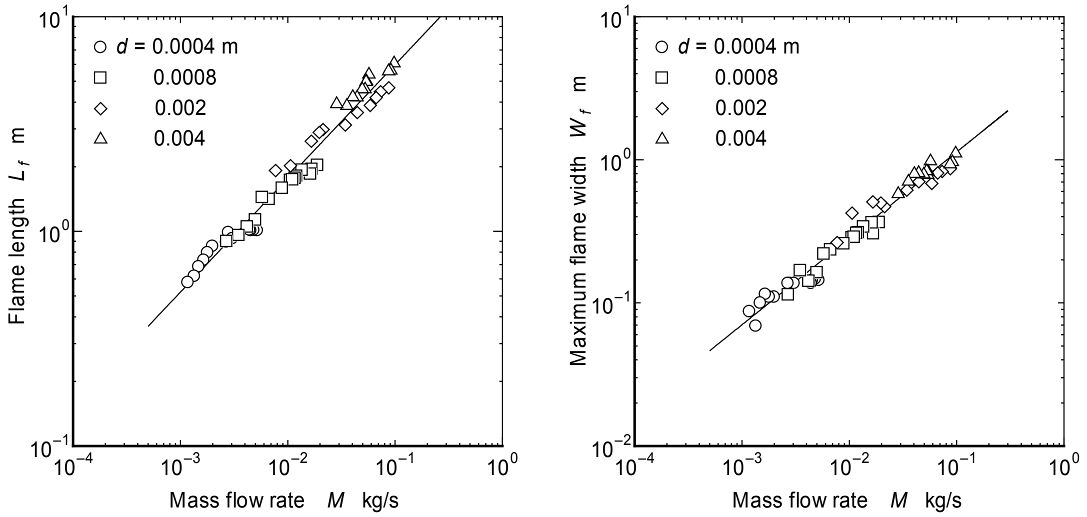
The mass flow rate was calculated from the difference in pressure in the storage tank before and after spouting and from the volume of the storage tank. The density of hydrogen at each pressure was taken from the tables of McCarty et al. [8]. Figure 8 shows the relationship between the flame length and mass flow rate of hydrogen. The flame size was proportional to the mass flow rate regardless of the nozzle diameter. The flame length is correlated in terms of the mass flow rate as follows:

$$L_f = 20.25M^{0.53} \tag{5}$$



(a) Flame length (b) Flame width

Figure 7. The relationship between the dimensionless flame size and spouting pressure.



(a) Flame length (b) Flame width

Figure 8. The relationship between the flame size and mass flow rate of hydrogen.

Similarly, the maximum flame width is correlated in terms of the mass flow rate as follows:

$$W_f = 1.52M^{0.604} \tag{6}$$

The spouting velocity is constant and independent of the spouting pressure, because the flow at the exit of the nozzle is choked. When the spouting pressure increases, the density of hydrogen and hence the mass flow rate also increase, so the flame becomes longer and wider.

3.3 Radiation from a Hydrogen Jet Diffusion Flame

The emissivity coefficient of a hydrogen flame is smaller than that of other gaseous fuel flames. However, we cannot ignore the fact that radiation from a hydrogen flame affects its surroundings in the case of a large flame. The thermal radiation from the flame was measured in order to investigate its thermal effect on its surroundings. In the case of d = 2.0 mm and P = 35 MPa, the thermal radiation was about 7000 W/m^2 at a distance of 1.5 m from the axis of the flame. The results for the thermal radiation from the flame at each position are shown in Figure 9, where the abscissa is the mass flow rate. The result shows that the thermal radiation from the flame increases proportionally with increasing mass flow rate, because the flame size also increases.

The radiation heat flux decreases in inverse proportion to the square of the distance. Hence, the product of the radiation flux, E, and square of the distance between the detector and the flame axis, L, is obtained. Figure 10 shows the relationship between EL^2 and the mass flow rate. E and L^2 are correlated in terms of mass as follows:

$$EL^2 = 6.41 \times 10^5 M^{1.31} \tag{7}$$

It seems that it is possible to predict the thermal risk of a hydrogen jet flame to its surroundings from this equation.

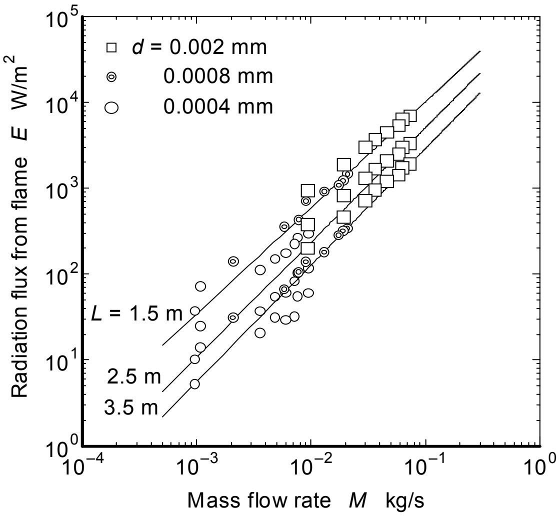


Figure 9. Radiation flux from the flame.

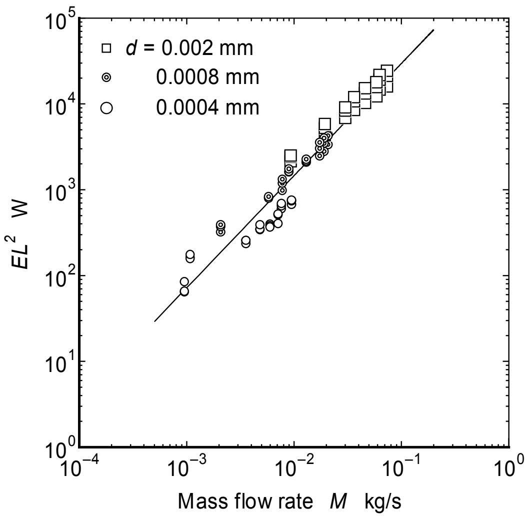


Figure 10. Relationship between EL^2 and mass flow rate.

We can calculate the emissivity coefficient of the hydrogen flame from the experimental results. The radiation flux can be described by the following relation:

$$E = \phi \varepsilon \sigma T^4 \tag{8}$$

where E is the radiation flux, W·m^{-2}; ϕ is the form coefficient; ε is the emissivity coefficient; σ is the Stephan–Boltzmann constant, W·m^2·K^{-4}; and T is the flame temperature. In the case of d = 2.0 mm and P = 35 MPa, the flame length is 4.94 m and the flame width is 0.802 m. Furthermore, the radiation flux is 7000 W/m^2 at L = 1.5 m. The flame is assumed to be a cylinder and the form coefficient is calculated from the following equation [9]:

$$\phi = \frac{1}{180Y}\tan^{-1}\left(\frac{X}{\sqrt{Y^2-1}}\right) + \frac{X}{180}\left[\frac{(A-2Y)}{Y\sqrt{AB}}\tan^{-1}\left(\sqrt{\frac{A(Y-1)}{B(Y+1)}}\right) - \frac{1}{Y}\tan^{-1}\left(\sqrt{\frac{(Y-1)}{(Y+1)}}\right)\right] \tag{9}$$

where R is the flame radius, m; L is the distance from flame axis to the detector, m; $X = L_f / R$, $Y = L/R$, $A = (1+Y)^2 + X^2$, $B = (1-Y)^2 + X^2$. If the flame temperature is assumed to 2318 K (the adiabatic temperature), the emissivity coefficient is calculated to be 0.03. The value is smaller than other reports (for example, ε = 0.10 [10]).

4. CONCLUSIONS

The experimental investigations of properties of high-pressure hydrogen jet diffusion flame revealed the following results.

(1) Blow-off occurs at specific spouting pressures and nozzle diameters.

(2) The flame size is in proportion not only to the nozzle diameter, but also to the spouting pressure (P > 0.1 MPa), and it can be predicted from the following equations:

$$L_f / d = 5245P^{0.436}$$

$$W_f / d = 85.1P^{0.436}$$

(3) Because the density of hydrogen increases with increasing spouting pressure, the mass flow rate also increases, leading to increases in the flame length and the flame width.

(4) An experimental equation has been obtained for the radiation from a hydrogen jet flame. Furthermore, the emissivity coefficient of the hydrogen diffusion flame has been also obtained.

ACKNOWLEDGMENTS

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