An Experimental Study on Flame Characteristics of Hydrogen Diffusion Flames

Shuichi TORII, Toshiaki YANO
Masatatsu IWASHITA and Hideki NISHINOHARA

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ABSTRACT

An experimental study has been performed on hydrogen jet diffusion flames from vertical circular nozzles burning in free air. The direct photographic method was employed to investigate the influence of fuel flow rate and nozzle diameter, d, on the flame morphology. Emphasis was placed on the determination of the flame length, L_f, over a wide range of the fuel flow rate. It became clear that (i) as the nozzle velocty is increased from zero, the flame burning under conditions of mixing with air is induced and its length is monotonically increased until a laminar-to-turbulent transition occurs, and (ii) after the transition takes place, the turbulent flame length is substantially independent of further increase in fuel jet velocity. A few relationships pertinent to the flame length, i.e. L_f versus u_j, L_f/d versus, Re, and L_f/d versus d, were proposed and examined. In the laminar diffusion flame case, effects of nozzle diameter and Reynolds number on the flame length appear if the experimental data are summarized using the dimensionless flame length, L_f/d. In contrast, a slight effect of the turbulent diffusion flame is observed. The hydrogen diffusion flames, for the burner tube of 1.24mm i. d., are found to be perfectly stable at a nozzle velocity of 300 m/s.

INTRODUCTION

Diffusion flame is generally classified into laminar and turbulent flames. The turbulent diffusion flames have been used in a combustion furnaces for industrial use to get the high thermal output unit chamber volume. A basic understanding of diffusion flame characteristics was required for the design of combustion chamber and burners. Diffusion flame length is one of the important factors when the industrial gas—fired furnaces are designed. It depends on the mixing of fuel gas and surrounding air. The basic information has been obtained for the effects of the fuel flow rate and nozzle diameter on the flame morphology in the wide range of the Reynolds number based on the nozzle diameter. These problems have been studied by many researchers. Burke and Schumann[1] and Rembert and Haslam [2] measured the height of laminar flames in very low gas velocity. Kurt et al. [3] extended these experiments to laminar flames of higher velocity and turbulent flames. Furthermore, Hottle and Hawthorne [4] pointed out the progressive change in flame type with an increase in the nozzle velocity. The actual relationship was established empirically from flame data of carbon monoxide and city gas.

This study is intended to investigate the flame morphology in hydrogen combustion. The hydrogen has recently attracted the special interest for an alternative fuel because it does not produce the greenhouse gas, i. e. carbon dioxide. Emphasis is placed on the influence of fuel flow rate and nozzle diameter on the flame length. In the laminar diffusion flame case, the dimensionless flame length, which is represented as a ratio of flame length to nozzle diameter, is decreased with an increase in the nozzle size. This trend, for the turbulent diffusion flame, becomes minor.

EXPERIMENTAL APPARATUS AND METHOD

The experimental appartus used in the present study is shown in Fig. 1. The vertical burner is a stainless steel tube. Five burner tubes of 1.25, 1.69, 2.40, 3.19, and 4.01mm inside diameter are employed here. The outer wall of the burner is tapered with sufficiently small angle at the tip to a lip thickness of less than 0.08mm in order to prevent the recirculation flow. The end of the burner tube is cut at a right angle to its axis and is placed in a rectangular duct (300 x 300mm), in which straighteners (4mm in diameter, 200mm in length) and screens over the cross sectional area are placed before the nozzle to minimize rotation and turbulence in the secondary gas (air).

The jet fluid is the pure hydrogen. The measurement of gas flow is carried out by oriffice meters and its rate is adjusted using the needle valve. In order to visualize the flame, the vessel of NaCl solution (Fig. 2) is placed between the orifice meter and needle valve, because the hydrogen

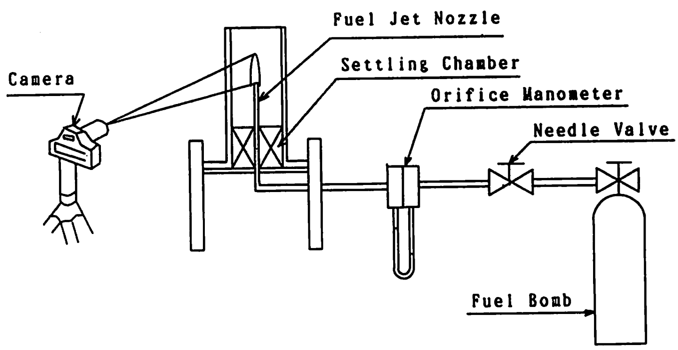


Fig. 1 A schematic of the experimental apparatus

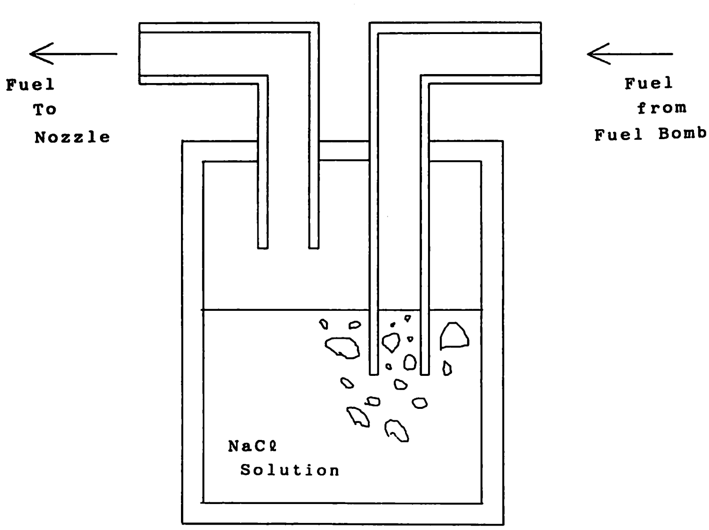


Fig. 2 A schematic of the NaCl solution vessle

is a nonluminous flame.

Direct photography is employed in flow visualization, particularly the flame length measurment. By using a still photograph with the time of exposure of 1／60 second, the distance between the nozzle outlet and the flame tip is measured, which corresponds to the flame length.

RESULTS AND DISCUSSION

Only a few representative results are presented here. The typical experimental data of hydrogen diffusion flames are summarized in Fig. 3 in the form of the fuel jet velocity, u_j, versus the

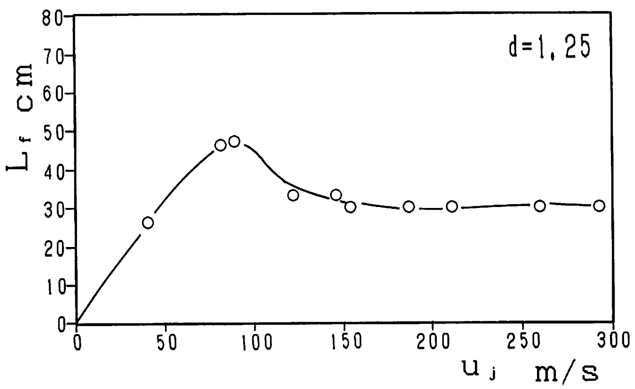
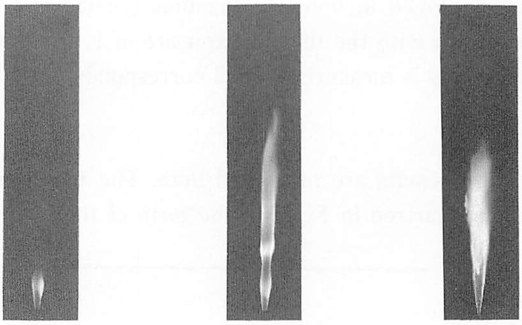


Fig. 3 Nozzle velocity versus flame length for d = 1.25 mm

flame length, L_f, in the case of the nozzle diameter of 1.25mm. As the fuel jet velocity is increased from zero to a critical value (u_j = 85 m/s), there is at first an almost proportional increase in the flame length. The critical value agrees with the velocity of the transition from laminar to turbulent. In these regions, the mixing of fuel gas and surrounding air occurs by molecular diffusion in a thin flame surface which is fixed in space. Therefore, in this case, mass and heat transfer are relatively slow, and diffusion flame has a smooth surface. When the fuel gas discharges at the critical value, the flame becomes unsteady and begins to flutter. With further increase in fuel jet velocity, this unsteadiness develops into a noisy turbulent brush of flame starting at a definite point along the flame where breakdown of laminar flow occurs and a turbulent jet develops. The distance from the nozzle to the point where the turbulent brush begins, is generally called the break—point. However. the break—point did not appear clearly compared with that of propane diffusion flame. With further increase in fuel jet velocity, the flame becomes completely turbulent and its length is held constant. The hydrogen diffusion flame dose not blow off at a jet velocity of 300 m/s. This is a remarkable feature of hydrogen combustion. The same trend was observed in the case of other nozzle diameters.

As shown in the still photograph, the flame morphology is roughly classified into three regions, which are referred to as the laminar, transition and turbulent flames, respectively. The corresponding flames are represented in Figs. 4 (a), (b) and (c). In the laminar case, Fig. 4 (a), the flame has a sharp—edged top and smooth surface, and it keeps the stationary shape. Flame of this type has pale bluish bases and luminous tips. In the region of the transition flame, Fig. 4 (b), the flame with a wave pattern takes place and the swelling with a relatively high brightness appears in a midway of flame. When the fuel jet reaches to a sufficiently high velocity, Fig. 4 (c), the whole flame shows



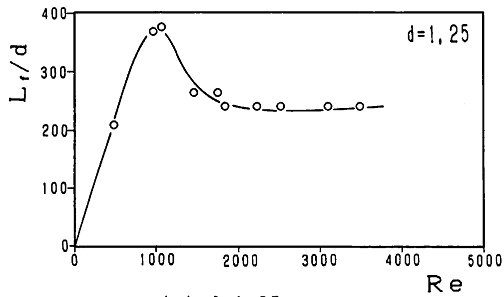
(a) laminar flame (b) transition flame (c) turbulent flame

Fig. 4 Photographs of diffusion flame in the laminar, transition and turbulent regions, respectively

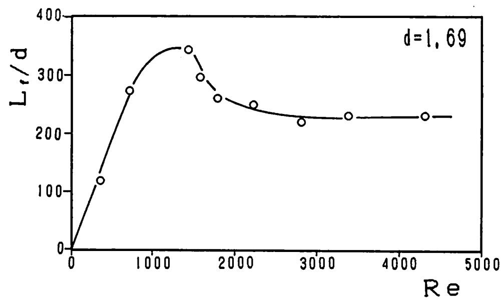
a turbulent appearance and its total length becomes somewhat short. The upper part of the flame becomes brighter with an increase in fuel flow.

An attempt is made to summarize the experimental data using the dimensionless parameters. The results are illustrated in Fig. 5 in the form of the Reynolds number (Re) versus the dimensionless length (L_f/d) represented as a ratio of turbulence flame length (L_f) to the nozzle diameter (d). The Reynolds number given here are calculated with the viscosity and density of nozzle fluids at the room temperature. Figures 5 (a), (b), (c), (d) and (e) correspond to the results of d = 1.25, 1.69, 2.40, 3.19 and 4.01, respectively. In the laminar flame region, the dimensionless flame length, L_f/d, becomes smaller with an increase in the nozzle diameter, when it is compared with the same Reynolds number. Furthermore, the maximum L_f/d is also gradually decreased with a decrease in the nozzle diameter. On the contrary, in the high Reynolds number region, namely for the turbulence flame case, the value of L_f/d is almost independent of the nozzle size and its value is nearly equal to 200. The value obtained in the study is larger than those proposed by Beer et al. [5] and Ida and ohtake [6].

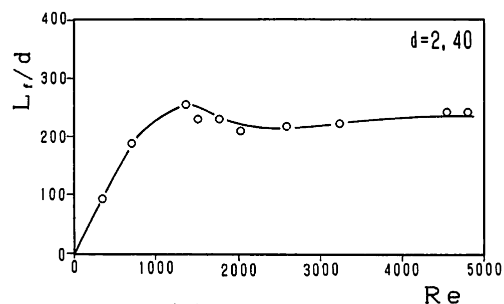
The same data in Fig. 5 are replotted in Fig. 6 in the form of the nozzle diameter (d) versus the dimensionless flame length (L_f/d) with the Reynolds number (Re) as the parameter. In Fig. 6, the results for Re = 500 and 1000 correspond to the laminar flame, and that for Re = 1500 falls under the transition flame case. The turbulence flame data are over Re = 2000. It is observed that in the case of the laminar and transition flames, L_f/d becomes smaller with an increase in the nozzle diameter. When the flame is perfectly turbulent, the corresponding effect of nozzle diameter on flame length is minor. It is found, therefore, that the flame length of the turbulent diffusion flame is increased with an increase in the nozzle diameter, that is, is independent of the Reynolds number. The same result is proposed by Kurt et al. [3].



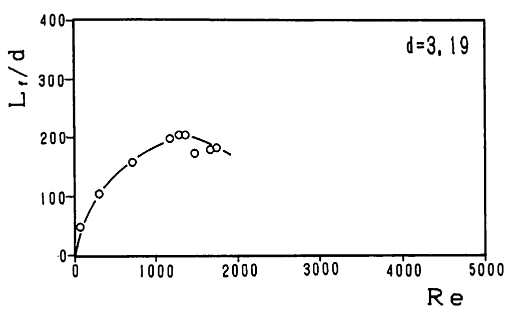
(a) d=1.25 mm



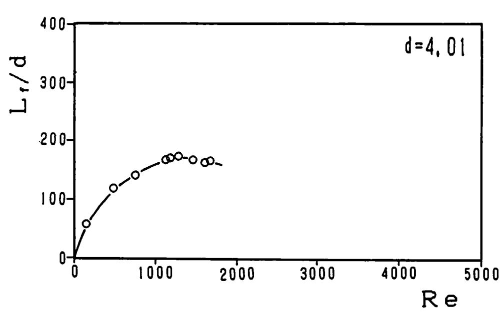
(b) d=1.69 mm



(c) d=2.40 mm



(d) d=3.19 mm



(e) d=4.01 mm

Fig. 5 Comparison of the flame lengths for different nozzle sizes

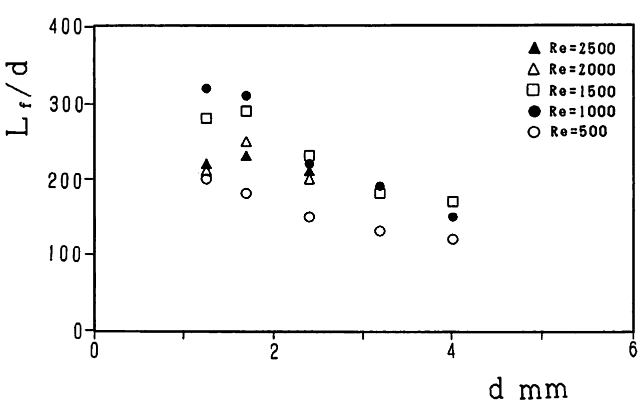


Fig. 6 L_f versus d in the wide range of Reynolds number

SUMMARY

An experimental study has been conducted on the flame morphology of vertical free circular hydrogen jet diffusion flames. Five nozzles with the different size are treated. The results are summarized as follows:

(1) In the case of the laminar flame, the flame length is increased with an increase in the nozzle velocity. In contrast, the corresponding length for the turbulent flame is constant in the wide range of the flow rate.

(2) The flame length, L_f/d, is independent of the Reynolds number and the nozzle size if the flame becomes turbulent.

NOMENCLATURE

- d : nozzle diameter, mm
- L_f : flame length, cm
- Re : Reynolds number, $u_j d/\nu$
- u_j : nozzle velocity, m/s
- ν : kinematic viscosity of fuel, m^2/s

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