EXPERIMENTAL AND NUMERICAL STUDIES ON A CONTROL OF LIFTED PHENOMENA IN NON-PRIMIXED HYDROGEN JET FLAMES

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ABSTRACT

Stabilization of the non-premixed hydrogen lifted jet flame is investigated experimentally and numerically. Fuel injection velocity is varied to 1300 m/s. In this study, with the visualization technique using a high-speed Schlieren method, effect of shoulder which means the diameter of nozzle rim and influence of fluid dynamic interaction on the lifted phenomena of high-speed jet flames are examined to clarify the control factors of lift-off height and noise level. Over a wide range of fuel jet velocity, three typical flames are observed. Other aspects in this research are noise level, NOx level, and control method for reducing the lift-off flame height. As for the effects of shoulder defined as an external nozzle diameter, the lift-off height of turbulent flames is reduced and noise level is decreased in the cases of high-speed fuel jet conditions. These results are coupled each other. The shoulder is not effective for the reduction of NOx level. As for the influences of fluid dynamic interaction on the lifted phenomena, two types of the control methods are carried out experimentally. One of them is a perpendicularly flow-in type, which is established with the air nozzle injected at right angles from four directions into the main jet. Another is a tangentially flow-in type, where the air is injected tangentially into the main lifted flame. As a result, it is found that the tangentially flow-in type is better than the perpendicularly flow-in type to control the lift-off height due to the effective mixing between fuel and air.

INTRODUCTION

Turbulent diffusion flame is one of the most significant combustion phenomena for industrial applications. Turbulent lifted jet flame is a partially premixed flame, which fundamental and practical studies are extensively necessary to understand the phenomena. However, control of the turbulent lifted jet flame is one of the effective methods to elucidate the lift-off mechanism. For instance, low speed hydrogen jet flames are studied by Vilimpoc and Goss (1988) and Roquemore et al. (1989), and high speed hydrogen jet lifted flames are investigated by Cheng et al. (1992), Brockhinke et al. (1995) for flame temperature, species concentrations using laser systems.

Main subjects of the investigation for lifted jet flames are to clarify the detail structure of combustion field and to elucidate the mechanism of stabilization on lift-off phenomena. Under these circumstances, for instance, Peters and Williams (1983) investigated the quenching phenomenon on diffusion flames, Kiori et al. (1993), research grope of Vervisch (1995, 1998) studied on the triple flame structure. According to the evolution of numerical simulation technique, it can be possible to analyze the detail flame structure and to simulate the reacting flow field. Direct Numerical Simulation (DNS) is effective to examine the non-steady phenomena such as lift-off flame jet. Mizobuchi et al. (2000) obtained a detailed result to simulate the lifted hydrogen jet diffusion flame with three-dimensional time-depending data. Tanahashi et al. (2000) clarified the local flame structure in corrugated flamelets and thin reaction zone.

In this study of lifted hydrogen jet diffusion flame, the stabilization of a flame is investigated with experiment and numerical simulation. Experiments as well as numerical analysis are performed to obtain the control factors for flame stabilization. Using the high-speed Schlieren system, fundamental features of the lift-off flames are shown. NOx measurement system is used to clarify and visualize the phenomena for present study. Furthermore, 2D-numerical simulation is performed to analyze the interaction of flow field under the side jet control.

EXPERIMENTAL DETAI LS

Hydrogen lifted jet diffusion flames are produced using a small size nozzle. Figure 1 shows the apparatus of experimental burner. In this study, the nozzle diameter is 1 mm to perform a high jet velocity condition for the lifted flames. The nozzle has a shoulder whose diameter is varied ranging from 2mm to 100mm. These nozzles are used to examine the effects of air entrainment near the nozzle exit.

To investigate the effects of fuel injection velocity on the lifted height of the flames, the remitted experimental condition of the jet velocity (fuel flow rate; $Q_f = 250$ l/min) is taken to perform the acoustic velocity flow of hydrogen.

Combustion feature is investigated by using Schlieren system. Schlieren method is useful to visualize the reacting flow since the hydrogen flame is difficult to interpret its flame surface due to blue luminescence. High-speed video camera is used to analyze the unsteady behavior of high-speed jet flames. Lifted height of the flame is measured

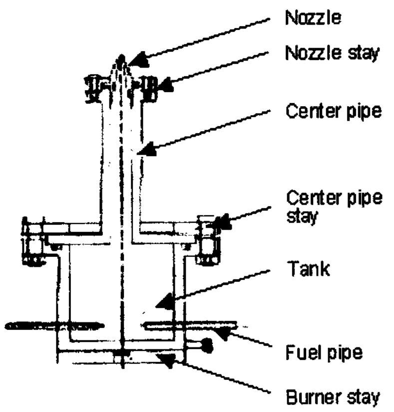


Figure 1. Schematic of experimental burner.

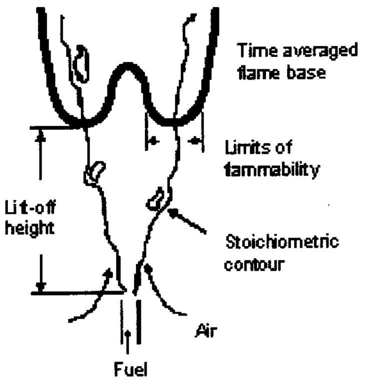


Figure 2. Feature of lift-off flame.

with video images. Figure 2 shows the schematic of lift-off flame indicated the experimental parameter of flame characteristics. In this study, lift-off height is defined as the distance from the nozzle top to the time-averaged flame base.

MODELING AND NUMERICAL METHOD

As for the governing equations, the axisymmetric, time-dependent, compressible Navier-Stokes equations are in the conservative form as follows:

$$\frac{\partial U}{\partial t}+\frac{\partial F}{\partial x}+\frac{\partial G}{\partial z}=\frac{\partial F_v}{\partial x}+\frac{\partial G_v}{\partial z}+B+S \tag{1}$$

where ***U*** is the conservative vector, ***F*** and ***G*** the convective terms, F_v the viscous term, B the body force term, S the source term:

$$U=\begin{bmatrix}\rho\\ \rho u\\ \rho v\\ E\\ \rho_i\end{bmatrix},\quad F=\begin{bmatrix}\rho u\\ \rho u^2+p\\ \rho uv\\ (E+p)u\\ \rho_i u\end{bmatrix},\quad G=\begin{bmatrix}\rho v\\ \rho uv\\ \rho v^2+p\\ (E+p)v\\ \rho_i v\end{bmatrix},$$

$$F_v=\begin{bmatrix}0\\ \tau_{xx}\\ \tau_{xz}\\ u\tau_{xx}+v\tau_{xz}-q_x\\ \rho D_i\dfrac{\partial Y_i}{\partial x}\end{bmatrix},\quad B=\begin{bmatrix}0\\ 0\\ -\rho g\\ -\rho g\left\{\sum_{i=1}^{N}\left(v-D_i\dfrac{\partial Y_i}{\partial z}\right)\right\}\\ 0\end{bmatrix},\quad S=\begin{bmatrix}0\\ 0\\ 0\\ 0\\ \omega_i\end{bmatrix} \tag{2}$$

In Eq. (1), ρ represents density; u and v are the axial and radial components of the velocity vector, respectively; p is pressure; E is the energy; τ_{kl} is the normal or share stress; ω_i is the mass-production rate of the ith species; Y_i is the mass fraction; q_k is the heat flux; D_i is the diffusion coefficient of ith species; and g is the gravitational constant.

The governing equations are transformed from physical space to computational space and are integrated using a finite difference scheme. A multiple-step chemical reaction is assumed for a chemical reaction constituted of nine species (H_2, O_2, O, H, OH, HO_2, H_2O_2, H_2O, N_2) and nineteen elementary reactions. In order to avoid reaction stiffness, a point implicit method is applied by treating the production term implicitly and the other terms explicitly, and a Strang-type fractional step method is used to keep accuracies in time and space. To difference the convective terms the Harten-Yee non-MUSCL modified-flux type TVD scheme, to difference the viscous terms the second order central difference scheme, and to difference the production term the Crank-Nicholson type implicit scheme are used. Physical values on the cell boundaries to calculate the numerical fluxes in the convective terms are provided by the Roe's average.

The boundary conditions for this numerical simulation are the isothermal, non-slip, and non-catalytic on the burner wall, zero radial velocity and other zero radial gradient values on the symmetric axis, fixed pressure and other zero normal gradient values on the other boundaries.

In this simulation, effect of radiation is not considered. However, it could be estimated that radiation heat loss is about 10% - 20% of the calorific value.

RESULTS AND DISCUSSION

Effects of Shoulder

Hydrogen diffusion flame is a basic unit for combustion systems such as boiler and turbine. Hence, its stability is one of the important factors to pursue by active control. Figure 3 shows Schlieren photographs of the flame characteristic. According to an increase in fuel jet velocity, typical flame is divided into three fundamental aspects. In the case of low injection velocity (V_f = 100 m/s), a laminar flame is formed as shown in Fig. 3-a. As a transition flame, a characteristic region of laminar flame is formed: Figure 3-b indicates the transition flame (V_f = 300 m/s). In this case, the flame exists in both regions of laminar and turbulence. It seems that laminar flame region appears due to the large-scale vortex. Figure 3-c is a case of lifted flame (V_f = 850 m/s). The lifted flame is characterized by turbulence.

Numerical simulation is one of the useful ways to clarify the detail of physical distributions for combustion. Figures 4 and 5 show numerical results in the same conditions with the experiments shown in Fig. 3. From the results of Schlieren images, fundamental effect of fuel jet velocity on the flame stability was clarified. However, analysis of flow field such as velocity, vorticity, mixture state of fuel and oxygen is important to investigate flame stability of high-speed jet.

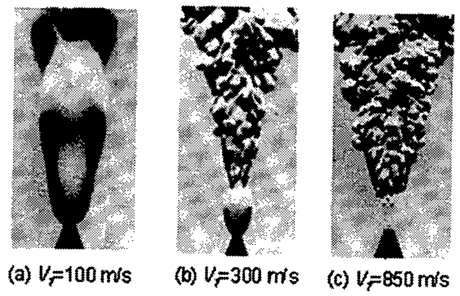

(a) V_f=100 m/s (b) V_f=300 m/s (c) V_f=850 m/s

Figure 3. Schlieren images of hydrogen jet diffusion flames.

Figure 4 is the result of transition flame. In this result, physical distributions shown by temperature, velocity (contour rang and vector), and vorticity are indicated with the same phase of calculation step. From the result of temperature distribution, the local extinction regions of flame surface are observed at the downstream of fuel jet. The region is caused by a strong vorticity as shown in the result of vorticity magnitude. Furthermore, the velocity magnitude of fuel jet is kept downstream. It seems that the distance affected with the magnitude of fuel jet velocity is comparable to the laminar region discussed with the Schlieren image of transition flame (see. Fig. 3-b).

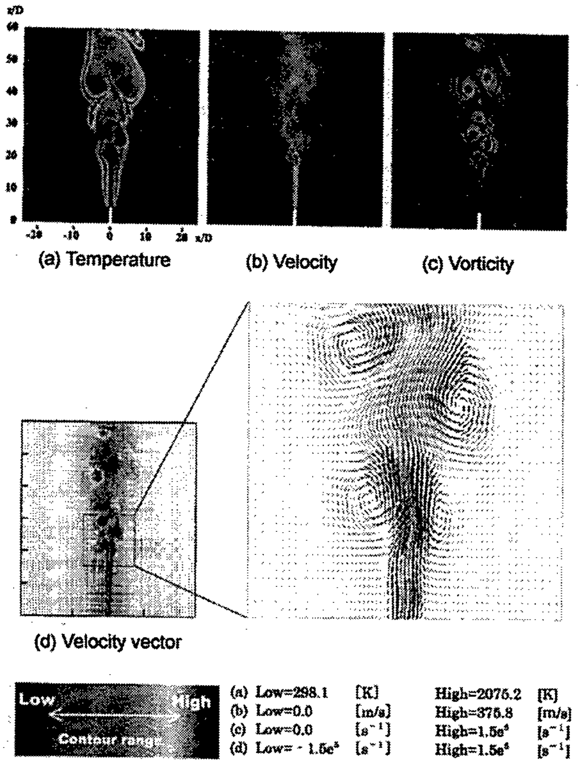


Figure 4. Physical distributions (V_f= 300 m/s).

In the case of lift-off flame (V_f = 850 m/s), the physical distributions are shown in Fig. 5. From the temperature distribution, a lifted flame is simulated successfully. In this case, the lift-off height is about 15 mm with almost the same value of the experiment. When the fuel jet velocity is increased, the local extinction region appears at all over the flame surface. Comparing the result of velocity magnitude with that of vorticity, the potential core of initial fuel jet corresponds to the high vorticity distribution caused by the share effect between the injection velocity and static air. At the downstream of fuel jet, the large-scale of vortices are formed and local extinction appears due to the large-scale roll-up phenomena of the vortex.

Magnitudes of fuel jet injection and air entrainment are one of the important factors for the flame aspect. Considering the results of Schlieren images and simulations as shown in Figs. 3, 4 and 5, the air entrainment gives an influence on the

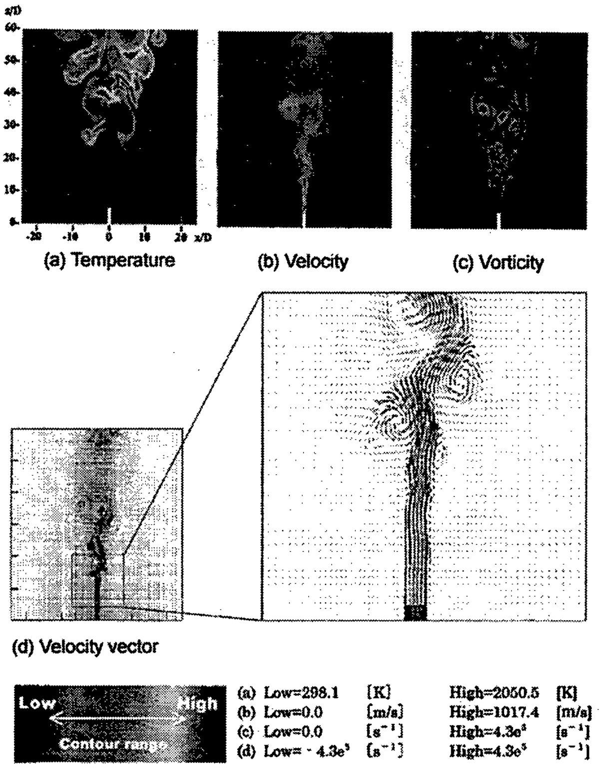


Figure 5. Physical distributions (V_f= 850 m/s).

lift-off phenomena. Hence the effect of shoulder defined as an external nozzle diameter is examined.

Figure 6 is the result of lift-off height of the flame. In the case of medium fuel jet velocity ($\sim V_f$ = 600 m/s), the transition flame is formed and the laminar region existed near the nozzle exit is decreased with an increase in fuel jet velocity. Under the high-speed injection conditions where the lift-off phenomena are observed, the lift-off height is reduced with a large shoulder nozzle. With averaged, about 20% of the lift-off height is controlled by the shoulder.

Figure 7 shows the noise level configurations of jet flames depending on the fuel jet velocity. The pressure fluctuation of gas is varied dramatically since it occurs due to the dramatic change of local heat release. Hence the frequency of noise becomes random. From the data plots shown in the figure, the difference in the shoulder effects is observed as shown at the critical point (V_f = 900 m/s). This point corresponds to the condition where the lift-off height becomes higher. Then to reduce the noise level caused by high lift-off flame, the control of the air entrainment such as the attachment of the shoulder is effective.

To achieve clean combustion, the reduction of NOx emission level is desired. From the result of Fig. 7, the attachment of the shoulder performs well for controlling the noise level. Thus, it is important to examine the level of NOx emissions with the same conditions.

Figure 8 is the result of NOx concentration. NOx is measured in the duct after the burnt gas is collected through the hood above the jet flame. NOx level continuously decrease as the hydrogen non-premixed jet flame velocity increases although there is a small jump which is hardly recognized in Fig. 8 when the jet flame transfers from the lower stable lifted position to the higher unstable lifted position. In this case, shoulder effects are not so effective due to the production of thermal NOx. Thermal NOx is caused by an increase in flame temperature. Since the shear effect is reduced due to the shoulder effects, the air entrainment based on buoyancy becomes strong. Hence it is considered that the flame temperature is increased due to an increase in partial pressure of oxygen in the flame. Concerning about the reduction of NOx emissions, to equip the shoulder is not effective on high-speed hydrogen jet flames.

Effects of Fluid Dynamic Interaction

To investigate the mechanism of lift-off flame and its control methods, two types of the control methods are carried out experimentally. One of them is a perpendicularly flow-in type, which is established with the air nozzle injected at right angles from four directions into the main jet flow (see. Fig. 9-a). Another is a tangentially flow-in type, where the air is injected tangentially into the main lifted flame (see. Fig. 9-b). For both cases, the main jet velocity is 900 m/s with the nozzle of 1 mm diameter and the side air jet velocity is fixed at 20 m/s.

Figure 9-a shows the Schlieren images of the lifted non-premixed hydrogen jet flame in the case of perpendicularly flow-in type. It is clarified that the airflow injected at right angle to the main jet flow is involved in the

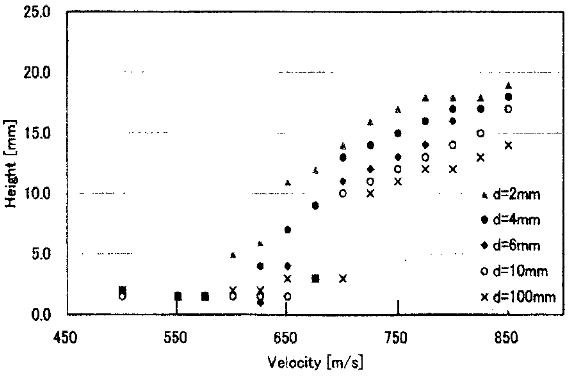


Figure 6. Behavior of lift-off flame height under various fuel injection velocities.

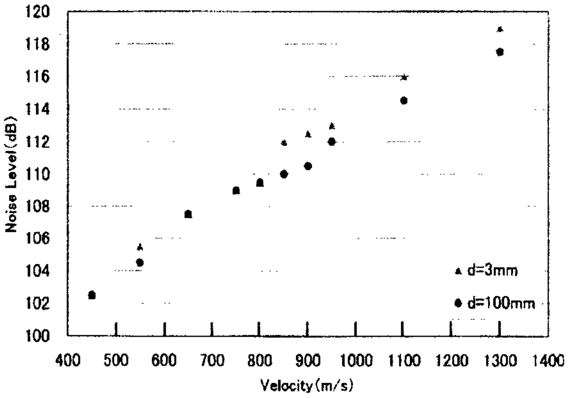


Figure 7. Noise level of hydrogen jet non-premixed flames under various fuel injection velocities.

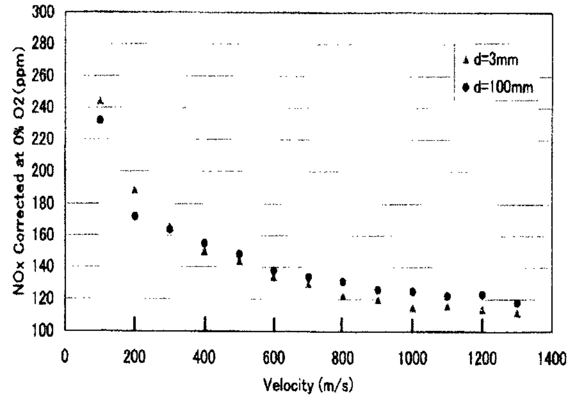
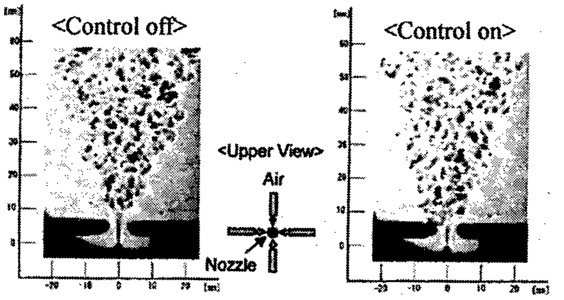


Figure 8. NOx emission level of hydrogen jet non-premixed flames under various fuel injection velocities.

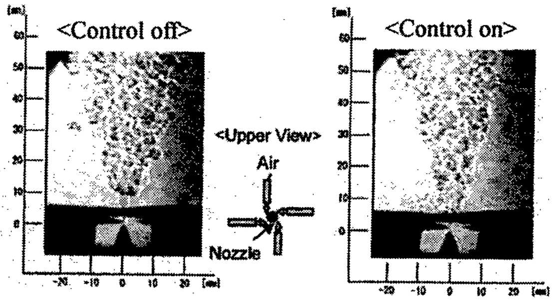
hydrogen jet to reduce slightly the lifted height, but not to anchor the flame at the nozzle rim. The burning position at the flame edge is moved to the upstream since the hydrogen jet is mixed with oxidant better. Furthermore, because of the interaction between fuel jet flow and injected airflow, combustion noise is generated.

Figure 9-b indicates the results of tangentially flow-in type. Comparing the image of control-off with that of control-on, the lift-off height is reduced larger than that of the perpendicularly flow-in type of Fig. 9-a. Furthermore, the combustion noise is disappeared in the tangentially air flow-in type of Fig. 9-b. As for the result of the tangentially flow-in type, the fuel-air mixing is accelerated due to the tangential flow formed by tangentially swirling entrainment. Although it is thought that the origin of the noise might be interaction between the fuel-jet flow and the air-injection, the tangential airflow is not injected to the fuel jet directly rather than the case of the perpendicularly flow-in type, resulting that the noise is disappeared.

To examine the mechanism of lift-off height inhibition, a numerical simulation is performed with the same conditions of experiments. In this numerical simulation, a verification of the experimental results obtained by the perpendicularly air flow-in type is performed since the simulation is two-dimensional. Figure 10 shows the results of temperature distribution and flow field vectors, where Fig.10-a is the case without air-injection and Fig.10-b is the case with air-injection. From the results of temperature distribution, the

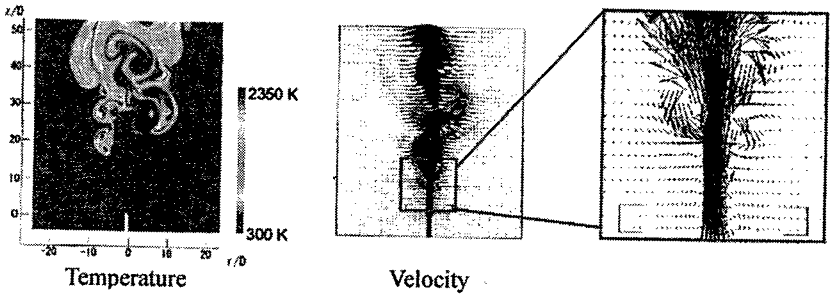


(a) Cross air flow-in type.

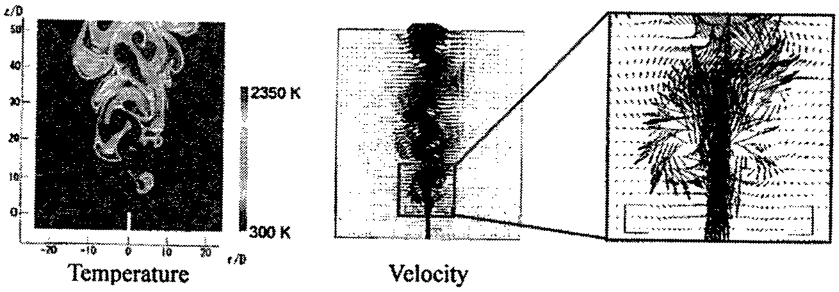


(b) Circular air flow-in type.

Figure 9. Control of lift-off height of the high-speed hydrogen jet flames; Air jet velocity Va =20m/s, Hydrogen jet velocity V_f = 900 m/s.



(a) Air jet velocity Va = 0 m/s.



(b) Air jet velocity Va = 20 m/s.

Figure 10. Temperature distribution and vectors of velocity in the case of circular air flow-in type; Hydrogen jet velocity V_f = 900 m/s.

lifted height is reduced due to the perpendicularly air flow-in and the lift-off phenomenon observed in the experiment is recreated well by the numerical simulation. As for the results of flow field, the large and strong scale of vortex is generated downstream near the position of air flow-in. As a conclusion, the effects of air-injection can be worked as the prompt fuel-air mixing, so that the air-injection into the lift-off position is effective to control the lift-off height of turbulent jet flames.

SUMMARY

For the lift-off phenomena of hydrogen jet diffusion flames, lift-off height, noise, and NOx emission levels are investigated to examine the control factors of lift-off phenomena with the view to the effects of fluid dynamic interaction. The following conclusions are obtained presently:

1. Combustion features of hydrogen jet diffusion flame are divided into three fundamental flame shapes such as laminar flame, transition flame without lifted position, and high lift-off flame.
2. Noise level becomes low as fuel jet velocity increases, and a shoulder on the burner exit is effective to reduce the lift-off height of the flames.
3. NOx level is reduced as fuel jet velocity increases. In the case of shoulder-equipped burner, NOx level becomes slightly high due to the production of thermal NOx.
4. Air-injection method to control the lift-off height of the flames is effective. Particularly, the circular air flow-in type, where the air is injected tangentially into the main lifted flame, performs well due to the influence of fluid interaction like as air entrainment.

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