Experimental Studies on Flame Stabilization and NO_x/Noise Reduction in Lifted Hydrogen-Jet Flames

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Introduction

Many combustion systems that use hydrogen as the fuel are assumed to be the most environment-friendly type of combustion. Hydrogen is considered to be the fuel of the 21st century, but still requires more research and development. In this research, turbulent diffusion hydrogen-air flame is studied.

Turbulent non-premixed flame is considered to be safe because there is no spread of the flame and the high combustion efficiency is obtained. For that reasons this type of flame is used practically and widely. For the practical applications, such as in the gas burners or gas turbines, the research on combustion and its basic properties, such as the flame structure and behavior are very important. Moreover, in certain cases there are additional effects to evaluate stability, flame lift-off, extinguishing or blow-off mechanisms.

The burning of high-speed hydrogen jets leads to highly turbulent flames. Especially, when the fuel is dispersed at high speeds, unburned area can be formed from the burner edge to the point where the flame is formed. This leads to the flame lifting. A number of experiments and the numerical analyses have been performed concerning a low-speed combustion of the hydrogen jet diffusion flames. However, for high-speed conditions the scale of the device and the accuracy of the measurement apparatus is a problem in the experiments. As the result the combustion in such situations (lifted flame) is not very well understood.

In this research the whole image and the feature of high-speed hydrogen jet flames are studied using a Schlieren laser systems, a microphone and a NO_x detector.

Experimental conditions

- **Fuel** **:** Hydrogen (300 K, atmospheric pressure at the nozzle exit)
- **Oxidizer** **:** Air (room temperature about 300K)
- **Velocity** **:** 0 ～ 1300m/s
- **Nozzle diameter** **:** ϕ1mm & ϕ2mm
- **Reynolds number** **:** ϕ1mm 0〜12000、ϕ2mm: 0〜24000

Hydrogen jet flame

Figure 1 shows the comparison of flames for various hydrogen velocities for the nozzle diameter of 2mm. Depending on the hydrogen velocity the flame has four modes of combustion: (a) a laminar flame, (b) a turbulent flame with laminar part just behind the nozzle, (c) a low-lifted turbulent flame, and (d) a high-lifted turbulent flame. The laminar flame (a) can be observed for the velocities up to about 100m/s, while the mixed laminar–turbulent flame (b) can be found from 100 m/s to about 600m/s. The laminar part disappears when passing ~600m/s and the combustion mode changes to a low-lifted turbulent flame (c). The flame lift height is equal to about 2-3mm and is almost constant to about 750m/s. For the velocities in the range of 750-800m/s the flame lift grows rapidly reaching 10-15mm at about 800m/s. For higher velocities the flame lifting increase rate is much smaller (see the slope in Fig. 2) and is accompanied by the oscillations of the lift-off height.

For the laminar flames and mixed laminar-turbulent flames the position of the transition point from laminar to turbulent flow/flame is quite steady (circles in Fig. 2), while for the high-speed flows (>800m/s in Fig.2) it becomes very oscillatory (triangles and squares in Fig. 2). This is obviously an effect of high turbulence in such flows.

Noise levels for hydrogen jet flame

The noise level accompanying the high-speed flow is shown in Fig. 3. The noise level is increasing steadily with the increase of the flow speed. The only one small non-monotonic change is observed at ~800m/s and is connected to the rapid increase of the lift-off height in Fig. 2.

NO_x production in lifted hydrogen jet flame

Figure 4 shows the NO_x concentration as a function of hydrogen velocity. The measurements have been taken at the points where the molecular oxygen (O_2) is not present. The results show that the NO_x concentration decreases with the increase of the gas velocity.

Since at present conditions the fuel is pure hydrogen then the NO_x production can only occur through the thermal mechanism [1]. The thermal NO_x is generated at high temperatures where the air is the source of nitrogen. The reduction of NO_x with increasing hydrogen velocity suggests that due to increased turbulence the mixing of the combustion products with fresh air is also enhanced. This mixing reduces the flame temperature and/or the high temperature zone, and there is not enough time to produce large amount of NO_x. This has to be confirmed in the future research by direct measurement of the temperature distribution.

Evaluation of flame stability, NOx concentration, and noise

Table 1 presents simple comparison of the combustion mode features: the flame stability, the NO_x production, and the noise level. It has been found that for high velocities the flame is very oscillatory that leads to very poor flame stability. In the range from the laminar flame to a low-lifted flame the stabilization is much better. The increase of hydrogen velocity also leads to the increase of noise. The noise already exceeds 100dB even for laminar flames but becomes unbearable for high-speed flows. The only one advantage of increased fuel velocity is reduced production of NO_x.

Based on this comparison it can be found that a low lifted flame is the best-balanced flame in results.

Table.1 Evaluation of flame stability, NOx density, and noise

	Laminar flame	Flame with the laminar flame	Low lifted flame	High lifted flame
Flame stability	◎	◎	◎	×
NO_x production	×	△	○	◎
Noise	◎	△	△	×

◎ : very good ○ : good △ : bad × : very bad

Conclusion

Depending on the flow velocity, the hydrogen jet flame has four modes of combustion: a laminar flame, a mixed laminar- turbulent flame, a low-lifted flame and a high-lifted flame. Their characteristics can be summarized as follows:

Noise level:

⇒ A noise level grows almost linearly and monotonically with the increase of the fuel velocity.

NO_x concentration:

⇒ NO_x concentration is the highest for the laminar flames, and is the lowest for high-lifted flames.

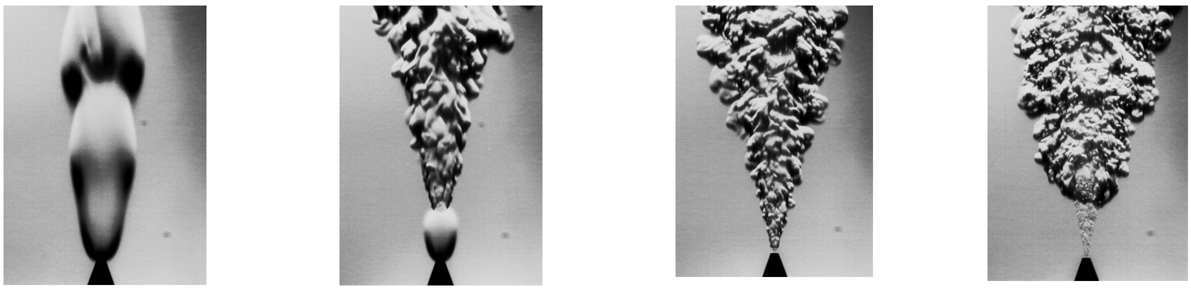
Flame stability:

⇒ The laminar and low-lifted flames are found to be the most stable because they do not oscillate.

According to these results, it can be said that a low-lifted flame has the most sufficient balance of advantages and disadvantages. As a future research subject, it will be necessary to perform additional experimental verifications. It is planned to use PLIF method for OH and NO_x measurements, and PIV for the detailed investigation of the flow inside the flame, and in the close vicinity of the nozzle. In addition, in order to raise the flame stability, the studies on the flame structure and control methods have to be considered.

References

[1] J.A.Miller and G.A.Fisk, C & E, American Chemical Society, August 31, 22(1987)



(a) Laminar flame 100m/s　(b) Flame with laminar part 300m/s　(c) Low-lifted flame 600m/s　(d) High-lifted flame 1300m/s

Fig. 1. Four types of hydrogen diffusion flames

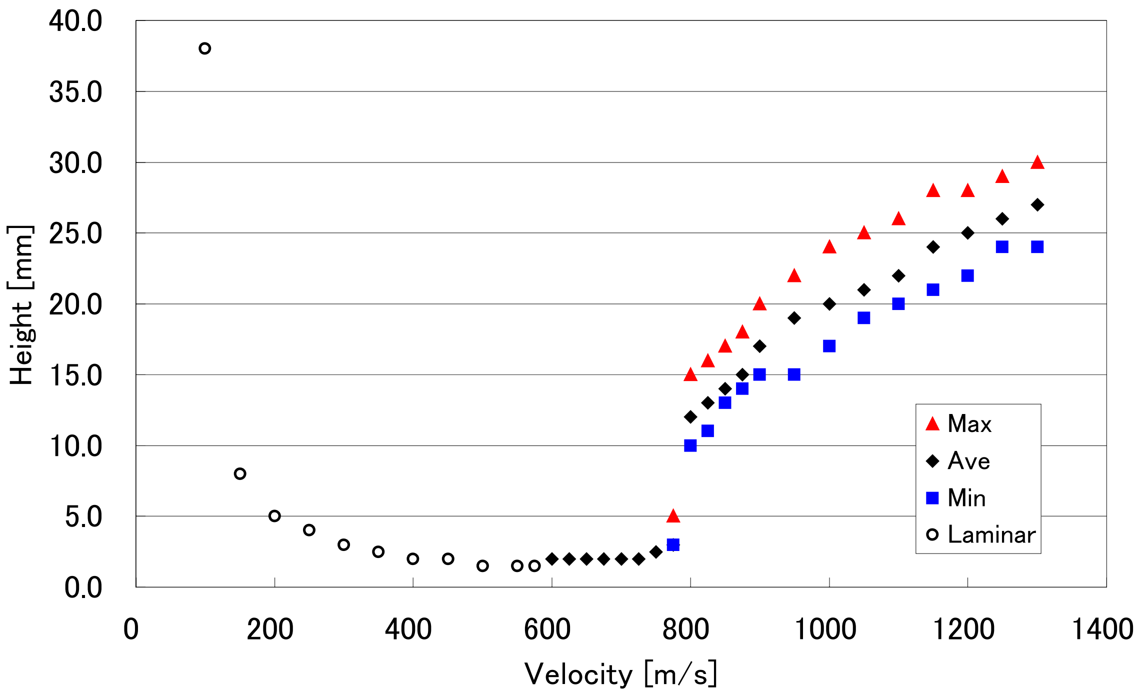


Fig.2. Lift-off height of hydrogen jet flame (ϕ2mm nozzle)

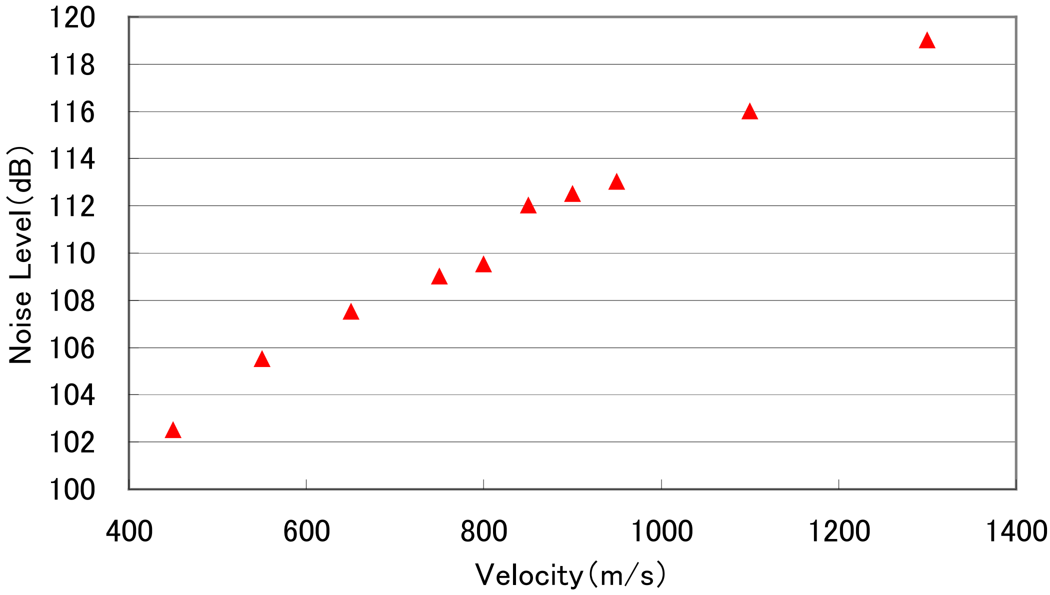


Fig.3. Noise level for ϕ 2mm nozzle

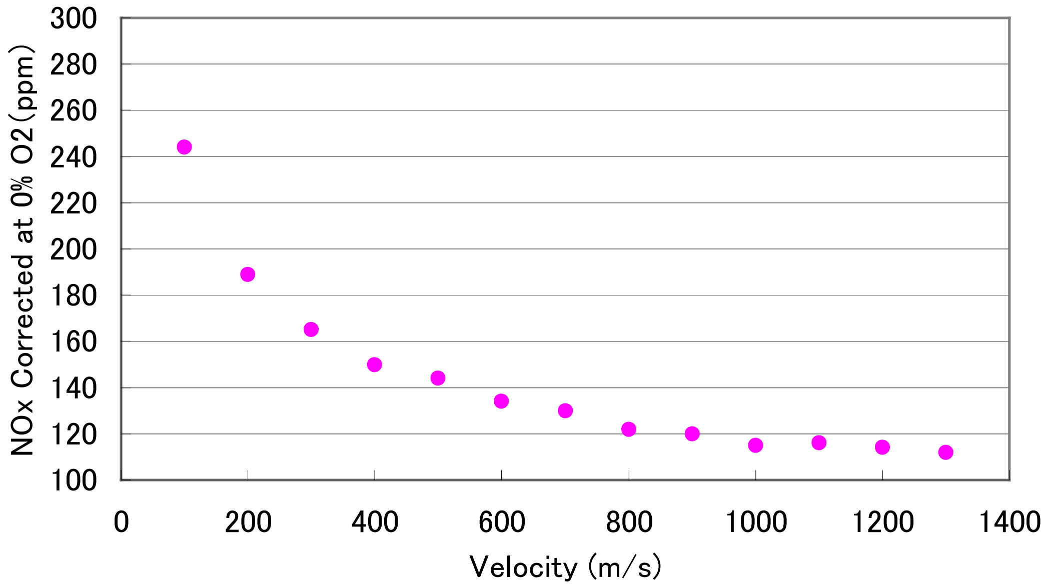


Fig.4. NO_x production for ϕ 2mm nozzle