Res. Rep. *Nagaoka National Coll. Tech. Vol.40,No.2* (2004)

Paper

Lift-off and Blow-off of Laminar Jet Premixed Flame of Flammable Mixture with Inert Gas

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Abstract

The effect of physico-chemical properties of an inert gas on the lift-off and blow-off of a laminar jet premixed flame from the burner exit was investigated experimentally. The inert gases; Helium, Argon, Carbon dioxide and Nitrogen, were premixed in the mixture of Methane-Oxygen of which the equivalence ratio is 2.1~2.4 and the exit flow velocity is 100~120 cm/s. Critical concentrations of the inert gases for the stable attachment of the flame base and for the blow-off of the lifted flame base were examined. It was shown that the properties of the inert gas; the density, the diffusion coefficient, the thermal diffusivity, and the shape of burner exit rim have a large influence on the stability of the base of the jet premixed flame.

Keywords: *Lift-off, Blow-off, Burning Velocity, Equivalence ratio, Recirculation zone*

1. Introduction

A safe operation in many combustors necessitates the stable attachment of the flame base at the burner exit rim. Prevention of the blow-off of the flame base from the burner exit is thereby a crucial factor for the safe operation in many combustors. For jet diffusion flames, many studies on the stability of the flame base; the mechanism of lift-off and blow-off, have thus been conducted for many years both experimentally and theoretically. For jet premixed flames, the stability of the flame base on the burner rim; the blow-off and the flash back has been discussed in many papers from the point of view of the concepts of *the critical boundary velocity gradient* [1), 2), 4)] and *the flame stretch factor* [3)].

For the effect of an inert gas on the stability of the premixed flame, there exist some studies on the effect of inhibition by halides [5), 6)]. We can not see, however, many studies on the effect of the property of an inert gas in the flammable mixture on the stability and blow-off of the laminar jet premixed flame. The present study aims to explore the effects of the property of an inert gas on the stability and blow-off of the laminar jet premixed flame.

2. Apparatus and Procedure

Figure 1 shows the slender tubular brass burners used in this experiment. The flammable gas mixture; methane, oxygen and inert gases, the volume flow rates of which are controlled independently by the float-type flow meter, is introduced to the slender tubular brass burner (Length; 200 mm, Inner diameter; 10 mm, Outer diameter; 16 mm).

The flow of gas mixture from the burner exit is laminated satisfactorily through the glass beads and metal net in the burner tube. The shapes of the exit rim of the burner are two types; tapered (the vertical angle; 30 deg) and non-tapered as shown. The average exit velocities of the mixture from the burner exit were set between 100 and 120 cm/sec. The equivalence ratios of the mixture were set as 2.1~2.4 in the experiment. The flow field around the burner exit rim was examined by the visualization technique using particle tracer and laser sheet (He-Ne). The temperature distribution of the burner exit rim was measured by the image of infrared thermography. The lift-off distance of the flame base was measured by the image of digital still camera.

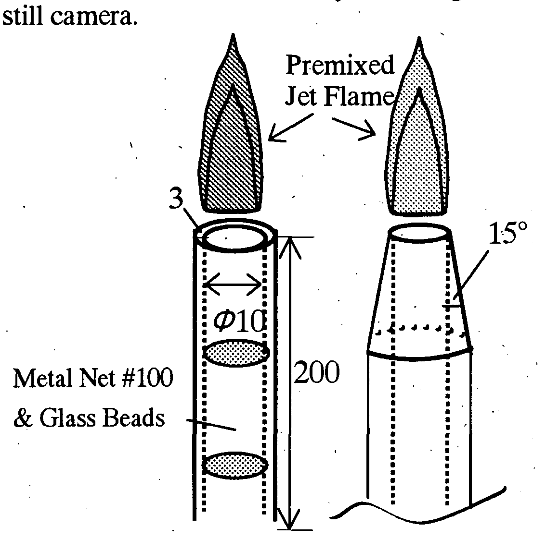


Figure 1: Slender Tubular Burners

3. Results and Discussion

The laminar jet premixed flames with no inert gas in the present condition show neither flash back nor blow-off. Some properties of the inert gases are shown in **Table 1**. As shown in this table, Helium has the largest thermal diffusivity and the lowest density. Carbon dioxide has the smallest thermal diffusivity and the highest density.

Table 1: Some Properties of Gases

Gas	Spec. Heat: C [J/g·K]	Density: ρ [×10-3g/cm3]	Therm.Cond.: λ [J/(s·cm·K)]	Therm. Diff.: α $\lambda/(c \cdot \rho)$ [cm2/s]	Viscosity: P [×10-6Pa·s]	Diff.Coef: D [cm2/s]
He	5.23	0.18	14.22	15226.00	19.60	0.75
CH4	2.21	0.72	3.02	1906.00	11.00	0.24
O2	0.92	1.43	2.45	1860.00	20.40	0.23
N2	1.03	1.25	2.40	1857.00	17.60	0.21
Air	1.01	1.29	2.41	1853.00	18.20	
Ar	0.52	1.78	1.63	1747.00	22.30	0.18
CO2	0.84	1.98	1.45	876.00	14.70	0.11

The clear difference in the property of inert gas has a large influence, as discussed later, on the stability and blow-off of the laminar jet premixed flame. **Figure 2** shows the schematic illustration of the lifted jet flame above the burner exit rim. The shape of the lifted laminar jet premixed flame in this study resembles slender tubular cone.

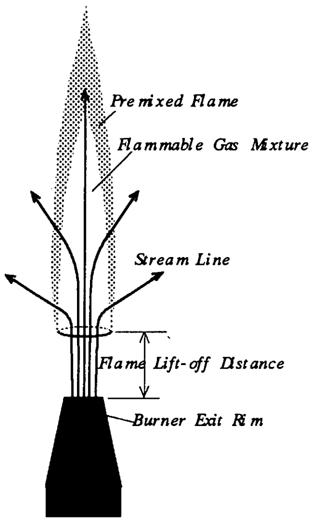


Figure 2: Schematic Illustration of Lifted Laminar Jet Premixed Flame and Streamline

Under the parameters of the equivalence ratio (ϕ) of the flammable mixture and the shape of the burner exit rim, the effect of the concentration of the inert gas on the flame lift-off distance is shown in **Figures 3 (a)** and **(b)**. As shown in the figures, for the mixtures including CO_2, N_2 and Ar with their high concentrations, the attached base of the jet premixed flame is able to be lifted-off above the tapered burner rim before the blow-off, although it can hardly be observed above the non-tapered burner rim. This will be attributable to the difference in the scale of the stable recirculation zone established around the burner exit rim, which has a large contribution to the stabilization of the flame base. The results show also that the change in the equivalence ratio; 2.1~2.4, has little effect on the lift-off distance of the flame.

For the mixture with Helium, the attached fame base is very easy to be lifted-off, but the lifted flame base is very stable even at the height of 60~80 mm above the burner exit. This is probably attributed to the increased lift force to the flame base, namely the increased buoyancy of the flammable mixture with low-density inert gas; Helium. The jet of fuel-rich mixture with a low-density inert gas will be easily mixed with the surrounding air, and thereby the concentration of mixture will enter appropriate flammable region. In addition, there is no heat loss from the lifted flame base to the burner rim. The base of the lifted flame will thus be stabilized.

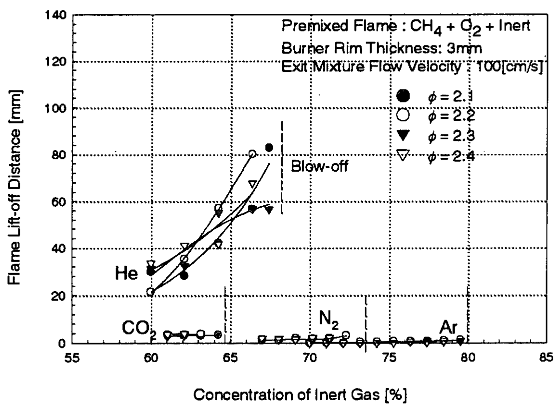


Figure 3 (a): Concentration of Inert Gas vs. Flame Lift-off Distance (Non-tapered Exit Rim)

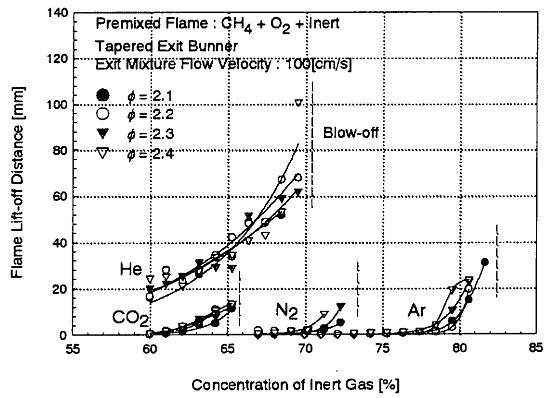


Figure 3 (b): Concentration of Inert Gas vs. Flame Lift-off Distance (Tapered Exit Rim)

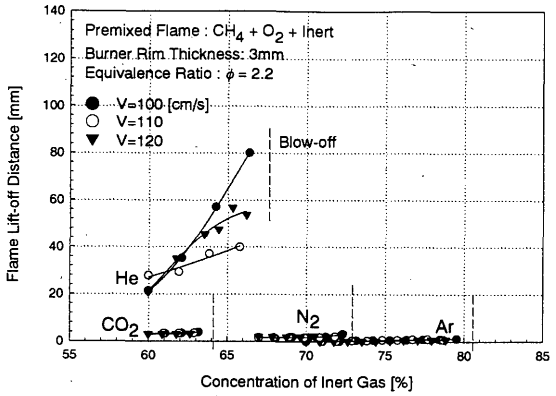


Figure 4 (a): Concentration of Inert Gas vs. Flame Lift-off Distance (Non-tapered Exit Rim)

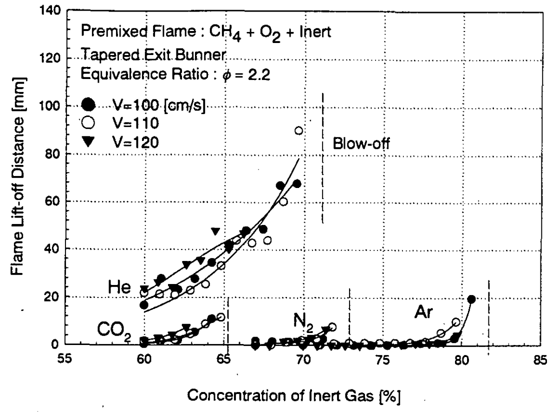


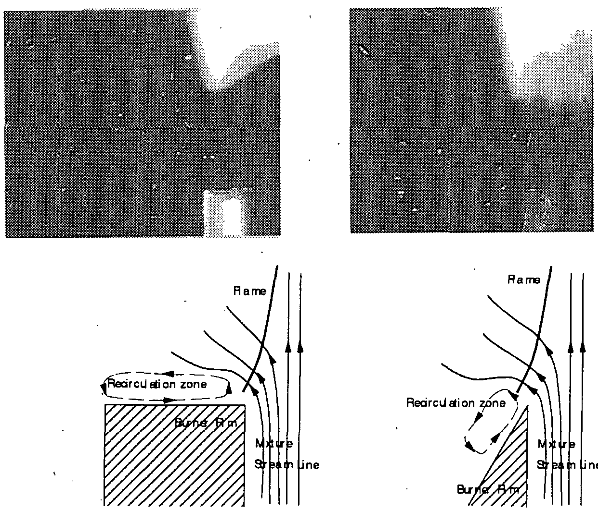
Figure 4 (b): Concentration of Inert Gas vs. Flame Lift-off Distance (Tapered Exit Rim)

On the other hand, for the mixtures with high-density inert gases; CO_2, N_2 and Ar, the attached flame base is very stable at the burner exit rim. Once the flame base is lifted, however, it is very unstable (easy to be blown-off). The unstable lifted flame is probably due to the large momentum of the flow of the mixture compared with that of the mixture with very low-density inert gas, He.

Under the parameters of the exit flow velocity of the flammable mixture and the shape of burner exit rim, **Figures 4(a)** and **(b)** show the effect of the concentration of inert gases on the lift-off distance of the flame. The exit flow velocity in the range; 100~120 cm/s, has little effect on the lift-off distance of the flame base, which is probably attributed to the little difference in the momentum of the flow of the mixture. For the mixtures including high-density inert gases with their high concentrations, the flame base is able to be lifted-off from the tapered exit rim before the blow-off, but is never lifted-off from the non-tapered rim before the blow-off.

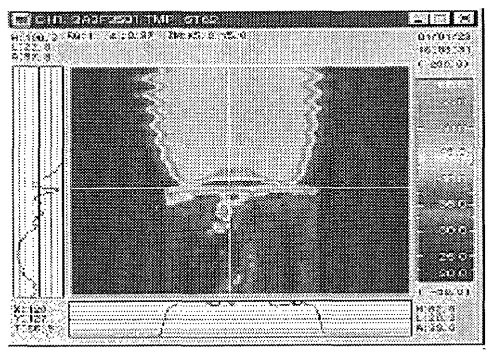
To examine the difference in the factors influencing the stabilization of the attached flame base between the taped and the non-taped burner exit rims, the flow field around the rim and the temperature distribution of the rim were examined.

Figure 5 shows the photograph and the schematic illustration of the recirculation zone near the burner rim beneath the flame base. Through the observation of the closed-up images we can confirm the recirculation zone near the non-tapered rim although it is very small near the tapered rim. Air entrainment near the tapered rim is observed clearly compared with that near the non-tapered rim. The differences in the scale of the recirculation zone and the air entrainment will lead to the difference in the heat transfer from the flame base to the exit rim.

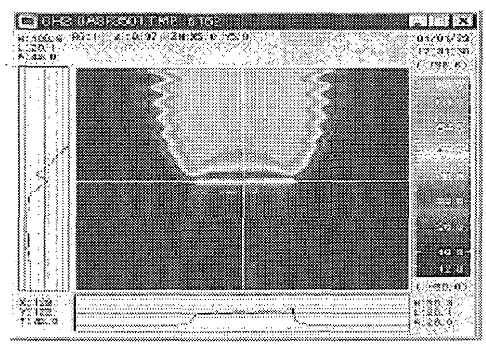


Non-tapered Rim Tapered Rim

Figure 5: Schematic Illustration of Recirculation Zone near the Burner Rim beneath Flame Base.



(a) Non-Tapered Rim



(b) Tapered Rim

Figure 6: Image of Temperature Distribution of Burner Rim by Infrared Thermography.

The temperature distribution of the heated exit rim beneath the flame base, shown in the **Figure 6** as the image by infrared thermography, shows clearly that the temperature of the non-tapered exit rim is very higher (shown as the red zone) than that of the tapered exit rim. The heated non-tapered exit rim will heat the flammable mixture, and thereby have a large contribution to the stabilization of the attached flame base. This will account for the difference in the results in **Figures 3 (a)** and **4(a)**; for the mixtures with CO_2, N_2 and Ar, there is no lift-off distance of the flame base before the blow-off above the non-tapered exit rim. The critical concentrations of CO_2 and He at the blow-off of the lifted flame above the non-tapered exit rim, shown in **Figures 4 (a)** and **(b),** are lower than those above the tapered exit rim. Namely the lifted flame above the non-tapered exit rim is unstable compared with that above the tapered exit rim.

It should be noted here that the large difference in the thermal diffusivity, the diffusion coefficient and the density of the flammable mixture would also account for the difference in the burning velocity. At the stable base of the lifted flame, the flow velocity of the flammable gas mixture must be equal to the burning velocity.

The burning velocity, S_u of the premixed laminar flame is expressed from the point of view of the diffusion theory as follows:

$$Su \propto \sqrt{D/\rho} \qquad (1)$$

From the point of view of the thermal theory, S_u is expressed also as;

$$Su \propto \sqrt{\alpha/\rho} \qquad (2)$$

where D : diffusion constant, α : thermal diffusivity, ρ : density of flammable gas mixture.

The burning velocity of the premixed laminar flame is, namely, proportional to the square root of diffusion constant or thermal diffusivity, and inversely proportional to the square root of the density of the flammable gas mixture. We see that for both values of the square roots of D/ρ and α/ρ, He $>>N_2 >$Ar $> CO_2$.

Helium gas has a large diffusion coefficient, a high thermal diffusivity and a very low density compared with those of N_2, Ar and CO_2. The flammable mixture with Helium will thereby have a larger burning velocity than that of the mixtures with N_2, Ar and CO_2, and will account for the very stable lifted flame above the burner exit rim.

For the reason why the attached flame base of the mixtures with CO_2, N_2 and Ar is stable at the burner exit but the lifted flame base is very unstable (easy to be blown off), clear interpretation can not be given in the present stage. Also the large difference in the critical concentrations at blow-off of the lifted flames of the mixtures with N_2, Ar and CO_2 can not be explained clearly in the present stage. However, the lowest values of the square roots of D/ρ and α/ρ for CO_2 will account for the lowest critical concentration at blow-off, compared with that of the mixtures with He, N_2 and Ar.

4. Concluding Remarks

Through the fundamental experiment on the lift-off and blow-off characteristics of the Bunsen type premixed laminar jet flame of the mixture with inert gases, the present study showed some interesting and important results as follows:

(1) For the flammable mixtures with high-density inert gases, the attached flame base at the non-tapered burner exit is stable owing to the heated exit rim beneath the flame base, and to the large recirculation zone near the exit rim.

(2) Once the flame base of the flammable mixtures with high-density inert gases is lifted, however, the lifted flame is very unstable (easy to be blown-off). The instability is probably due to the large momentum of the flow of the mixture.

(3) There is a large difference in the critical concentrations at the blow-off of the lifted flames of the mixtures with high-density inert gases; N_2, Ar and CO_2.

(4) For the flammable mixture with a very low-density inert gas such as Helium, the attached flame base is very easy to be lifted-off but the lifted flame base is very stable above the burner exit.

(5) The stable lifted flame of the flammable mixture with Helium is probably due to the increase in the burning velocity, because Helium has a large diffusion coefficient, a large thermal diffusivity and a very low-density.

Acknowledgments

The author expresses his sincere thanks to Messrs. Ishizawa, Tan, Tomita, Nakamura, Yokoyama and Ms. Watanabe for their great help in conducting the experiment.

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(Received July 23, 2004)