Experimental Study on Near Extinction Behavior of Microflame in Preheated Air

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1 Introduction

Small-scale combustion is one of hot topic in “new concept” combustion in these days since it has abnormal as well as unfamiliar characters. According to the most recent review brought by Maruta [1], these features could contribute to the discovery of unknown flame nature, although many of them have not been fully understood yet. In addition to provide such academic impact, small-flame has a potential to be unique energy source from the view of combustion technology. These facts bring a strong motivation for us to investigate the fundamental character of small-scale flames and the present study is also performed due to this purpose.

Once the small amount of fuel is issued through a fine needle burner, a millimeter-size of diffusion flame is formed over the burner; this is what we call “microflame” [2]. Since the flame size is much smaller as compared to the conventional diffusion flames, the buoyancy effect on the flame shape is minimized, resulting that it becomes nearly spherical. This feature can be utilized in various ways, for example the spot heater for welding purpose [3]; the micro-burner could be inserted into the point where the localized heating is required from any angle without considering of the deformation of the flame shape due to the buoyancy. Although the miniaturizing of flame provides such advantage, there exists apparent disadvantage as well; such as the less-stability. Once the flame size gets smaller, the flame size becomes comparable to the quenching distance; hence the structure of flame base, which is key factor to determine the flame stability, is affected and modified. In fact, the smaller flame is easily extinguished when a small disturbance is added. This fact implies that the structure of flame base in microflame would be different from that of stable flame and this difference could be the reason of less-stability. In this sense, it is our hope to have an effective technique increase the stability of such small-scale flames and establish the steady small heat source with high resistance from the disturbance. One idea to this happen is to apply the preheating. According our past numerical works, it is revealed that the stability could be greatly improved when the preheated air is adopted [e.g., 4]. Main reasons could be addressed to following two-fold; enhancement of chemical reaction at the flame base and the reduction of the heat loss to the burner to avoid the thermal quench (namely, the improvement of the stability could be made through the modification of chemical and thermal structure of flame base induced by high-temperature air condition). However, one-step chemistry model was used in our past works and no detail analysis was made for near-quenching behavior with high-temperature air condition. Therefore, there is still a need of work to convince and understand more detail about key factors to improve the stability experimentally (without any modeling). In this work, we develop the corresponding experimental apparatus to investigate the effect of surrounding air temperature on the stability of micro-jet flames. Since the current experiment is specially designed to examine the near-extinction condition with high precision; this work is believed to deliver the fundamental knowledge of an achievable smallest flame scale as well. The obtained results are compared with the existing lower-limit flame theory developed by Kuwana et al. [5], as well as the numerically-predicted near-quenching behavior with various wall conditions [6-7] done by authors.

2 Experimental method

The burner system used in the present study is schematically shown in Figs. 1 and 2. The thermal insulator was surrounded to the main combustion chamber made by quartz glass to minimize the heat loss to the ambient. Preheated air brought by the electric heater flows through the section of the bed filled with ceramic ball (dai. of 2.0 mm) to eliminate large eddies to achieve the spatially uniform velocity field, then it flows into the main chamber. Volumetric flow rate of co-flow air was set to be a constant value (1 mL/min at standard state; corresponding air velocity is 1.0 cm/s) throughout the study. Temperature of the preheated air was measured by using thermocouple (K-type, wire diameter: 0.3 mm, junction diameter: 0.7 mm) inserted from the top. Note that the radiation correction is not made. Once the temperature of preheated air reached to the target value and the temperature field becomes steady state, the thermocouple was removed and the micro burner (inner diameter: 0.8 mm, outer diameter: 1.2 mm) with small methane flame was inserted from the bottom, then the fuel flow rate was adjusted accordingly. The fuel flow rate (V_f) is controlled by fine needle valve and measured by soap bubble meter (measurement error is less than 1.0 %). In this study, air temperature, T_{air} (up to 770 K), and fuel flow rate, V_f, are considered as experimental parameters. Air temperature is varied from 293 K to 770 K. A flame height, L_f, and a quenching distance, L_q, were measured from the image taken by digital camera (camera: Sony HDR-XR500V, Shutter speed and exposure the camera are set to 1/250 s and full open, respectively.) as shown in Fig. 3. Because L_q is defined as a vertical separation distance between the flame base and the burner tip (see in Fig.3), it becomes “zero” when the flame base located lower than burner surface.

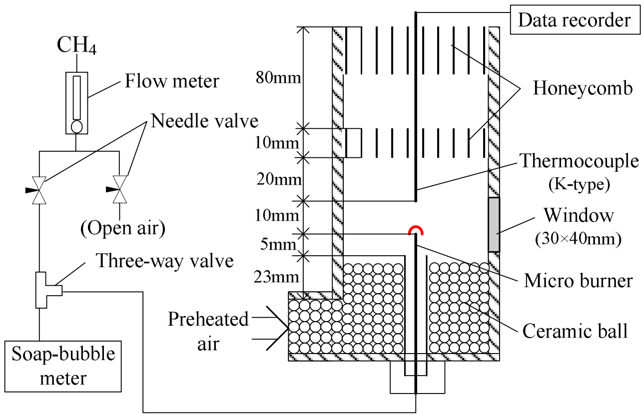

Fig. 1 Experimental apparatus (overview)

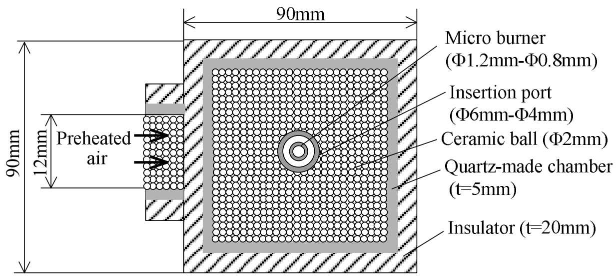

Fig. 2 Experimental appurtus (dimensions)

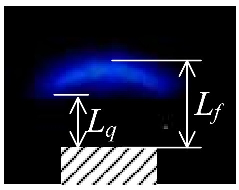

Fig. 3 Definitions of the quenching distace L_f and the flame hight L_q

3 Result and discussion

Direct photographs of the microflames in a various conditions are shown in Fig .4. It is found that the flame shape varies when the temperature of preheated air and fuel flow rate are varied. As air is preheated, the flame base closes to the burner wall and especially, at which the fuel flow rate is sufficiently stable condition [e.g., fuel flow rate is 6.5 mL/min in Fig. 4], the flame base is nearly attached to the burner wall, somehow similar to the one predicted with adiabatic wall condition [6-7]. Fig. 5 shows the relationship between the minimum fuel flow rate (V_{Lf}) and air temperature (T_{air}). This figure shows that the minimum fuel flow rate decreases as the air temperature increases. Best fit curve of Fig. 5 is given as follows,

$$V_{Lf} = 1.45 EXP \frac{355}{T_{air}} \qquad (1).$$

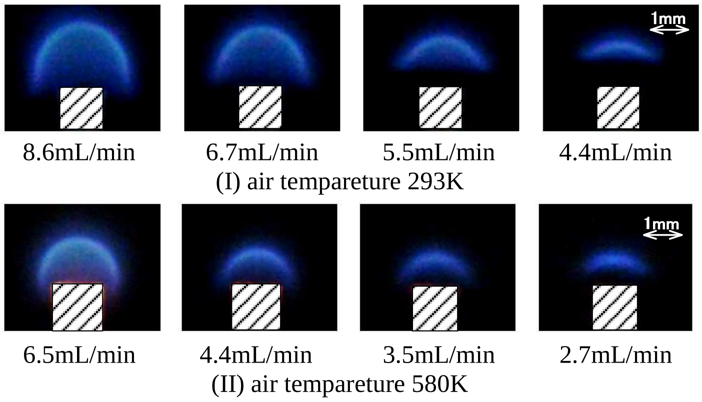

Fig. 4 Direct photograph of the microflames in each fuel flow rate and air temperature

More importantly, Eq. (1) indicates that V_{Lf} converges to limit value, 1.45 mL/min, when T_{air} is set to infinitely large. It means that there is the minimum fuel flow rate to sustain the flame even if air temperature increases sufficiently. Fig. 6 shows the relationship between the quenching distance (L_q) and the fuel flow rate (V_f) on each air temperature. It is found that the quenching distance becomes larger with closing to extinction limit and smaller when air temperature increases. Then, the effect of heat loss to burner can not be negligible at the near extinction condition and also it is convinced that the applying high-temperature air could improve the flame stability experimentally, as predicted the numerical works with simple (one-step) kinetics model. In followings, let us investigate/analyze the data of the minimum fuel flow rate and the quenching distance under various preheated-air conditions to get fundamentals of near-quenching limit flame behavior and an achievable smallest flame scale as well.

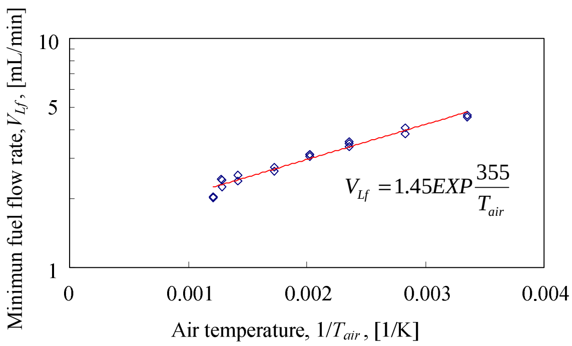

Fig. 5 Relationship between minimum fuel flow rate and air temperature

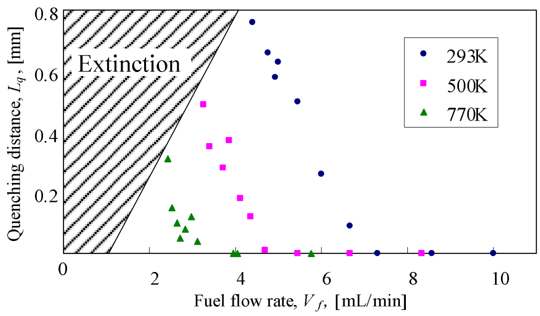

Fig. 6 Relationship between quenching distance and fuel flow rate

Quenching distance

Now, simplest thermal balance between the flame and the burner is considered to understand the behavior of L_q against V_f near quenching limit as seen in Fig. 6. The corresponding thermal balance model is shown in Fig. 7. The amount of heat generated by the flame, Q_{in}, and the heat loss to the burner, Q_{loss}, are roughly expressed as follows:

$$Q_{in} = \dot{m} c_p (T_f - T_u)$$

$$Q_{loss} = A_w \lambda (T_f - T_w) / L_q$$

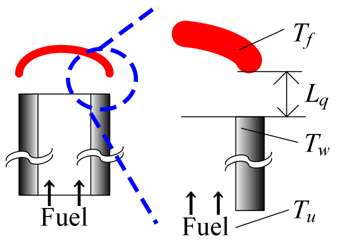

Fig. 7 Model of quenching distance

where T_u =293 K (< T_w), because burner wall is heated by the flame. Introduce α defined as the ratio of Q_{loss} to Q_{in} (αQ_{in} = Q_{loss}), let us assume that this is constant at present. Under this assumption, L_q can be rewritten as follows,

$$L_q = \frac{\lambda A_w}{\alpha c_p \dot{m}} \frac{T_f - T_w}{T_f - T_u} \qquad (2).$$

Let us assume that T_u is much higher than T_f (T_u/T_f << 1), Eq. (2) could be reform to

$$L_q \propto \frac{1}{\dot{m}} \frac{1 - T_w/T_f}{1 - T_u/T_f} \sim \frac{1}{\dot{m}} \left(1 - T_w/T_f\right) \qquad (3),$$

According to our previous numerical work [7], temperature of the flame (T_f) decreases when the flame height becomes shorter to reach lower extinction condition; thus T_f should have positive relation to $\dot{m}$, so as to V_f. Thus L_q behavior of near extinction is somewhat similar to $\dot{m}^{-n}$, where n>1, which is non-linear dependency as noted above. In addition, T_w becomes higher when the imposed air temperature increases, resulting that smaller L_q, which is also qualitatively agree with Fig. 6. Overall, although the estimation is quite rough, thermal balance between the flame and the burner could reveal the qualitative trend in near-extinction behavior of microflame.

Near-limiting flame behavior in high temperature air

Kuwana et al. [5] have proposed the theoretical description of lower-limit condition to sustain the microflame, as shown in Eq. (4), under the assumption of unity of Schmidt number (Sc = 1). Let us examine whether this can be used to predict the present microflame behavior established in the high-temperature air.

$$Da \cdot \mathrm{Re}^2 = const \qquad (4).$$

Express Re and Da to $Re = ud\nu^{-1}$ and $Da = \omega d^2 \nu^{-1}$, where ω is reaction rate which has Arrhenius-type temperature dependency and consider that the minimum fuel flow rate (V_{Lf}) is defined as $V_{Lf} \sim ud^2$. Now therefore, Eq. (4) is given as

$$V_{Lf} \sim \nu^{3/2} \exp\left(\frac{E}{2RT_{air}}\right) \qquad (5).$$

The dependency of air temperature on minimum fuel flow rate is same between Eq. (1) and Eq. (5). Thus the approximate expression is suitable and extinction limit of microflame is described as Damköhler-number. The relationship between the flame height and the quenching distance in each air temperature on the near extinction condition is shown in Fig. 8. It is found that the quenching distance is linearly proportional to the flame height and the value of difference between flame height and quenching distance is constant in each air temperature. According to this result, when the quenching distance becomes zero by preheated air, the flame height becomes about 0.39 mm. Interestingly, this value is similar to the ones of predicted in our previous numerical work (under the assumption of ideal adiabatic wall condition which the least heat loss is taken into account) [6].

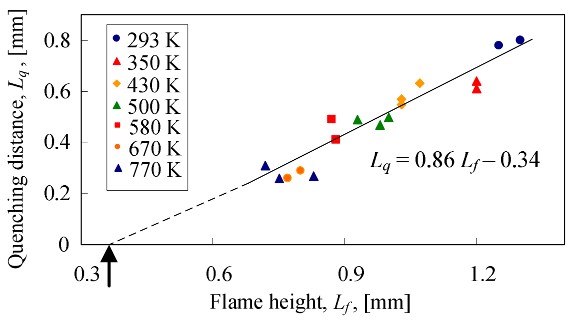

Fig. 8 Relationship between minimum flame height and quenching distance in each air temperature

The effect of burner material

It is now considered in order to further examine the above considerations; the material of the micro burner is changed. According to Eq. (3), near-extinction behavior of microflame is affected by burner wall temperature. Then its behavior is affected by heat flux which is dependent on thermal property of burner. Thermal conductivity on each burner material is shown in Tab. (1). Air temperature was set to be constant at 293K and the experimental conditions (apparatus dimensions of the micro burner and air flow rate) were same without burner material.

Tab. 1 thermal conductivity on each burner material

	mullite	alumina	stainless iron	Brass	Aluminum
thermal conductivity[W/mK]	2.5	7.2	16	122	225

Relationship between the minimum fuel flow rate and the thermal conductivity of each material is shown in Fig. 9. This figure shows that the minimum fuel flow rate rapidly decreases with thermal conductivity closing to zero. It means that the stability of microflame is improved dramatically when burner condition approaches adiabatic condition. The relationship between the flame height and the quenching distance at the near extinction condition in each burner material is shown in Fig. 10. It is found that the quenching distance is linearly proportional to the flame height and the flame height becomes about 0.24 mm when the quenching distance becomes zero. This trend and limiting value are the same as preheated air condition (shown in Fig. 8). Fig. 11 shows the relationship between the flame height and the quenching distance and in this figure, cross mark and open dot indicates respectively preheated air condition (shown in Fig. 8) and each burner material condition (shown in Fig. 10). This figure suggests that the flame height at the near extinction condition has unique relation to the quenching distance regardless of surrounding condition. As a result, our previous work [6] is valid and almost all the heat loss on small jet flames is heat loss to burner wall. Therefore, it is important to take care of the heat loss to solid surface to stabilized small flames.

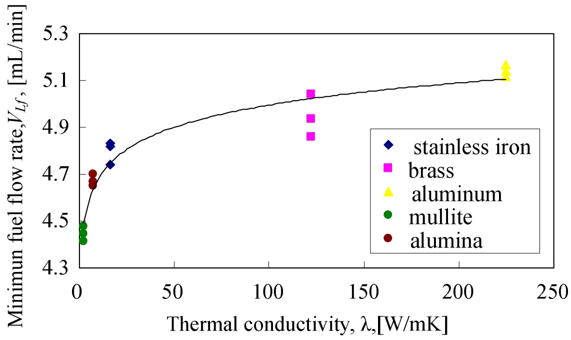

Fig. 9 Relationship between minimum fuel flow rate and thermal conductivity on each material

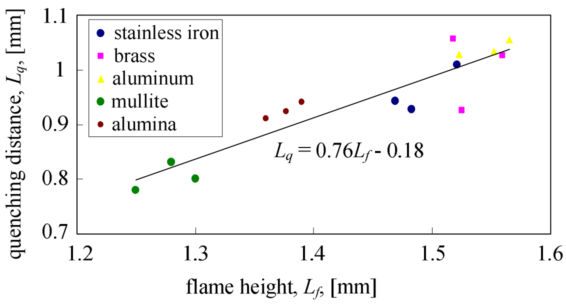

Fig. 10 Relationship between flame hight and quenching distance on each material

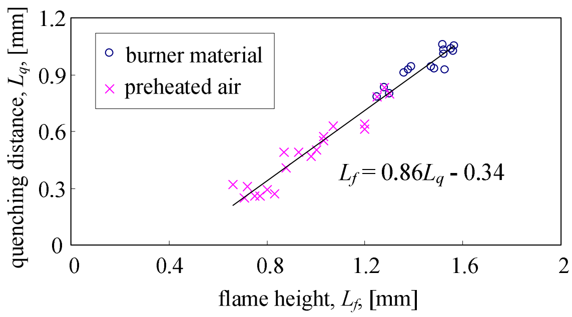

Fig. 11 Relationship between flame hight and quenching distance

4 Conclusion

In this study, we investigate the flame shape (quenching distance and flame height) and the minimum fuel flow rate on each air temperature and burner material. Also, we estimate the limiting flame behavior. The minimum fuel flow rare can be predicted by Kuwana's theory and the extinction limit (lower limit) is organized by the Damköhler-number. To consider the thermal balance between the flame and the burner, behavior of the quenching distance which is related to the stability of microflame is roughly predicted. The flame height and the quenching distance at the near extinction condition decrease by preheated air and have linearly proportion in each air temperature. When the air temperature increases sufficiently, the flame height becomes 0.39 mm and also we verify that this limiting value is same as ideal adiabatic wall condition numerically and experimentally. It is suggested that the flame height at the near extinction condition has unique relation to the quenching distance regardless of surrounding condition and it is confirmed that the imposing high temperature air is good way to examine the ideally limiting behavior of tiny flames.

Nomenclature

V_f	volumetric fuel flow rate [mL/min]	$\dot{m}$	mass fuel flow rate [kg/s]
T_{air}	temperature of ambient air [K]	L_f	flame height [mm]
L_q	quenching distance	ρ	density [kg/m^3]
c_p	heat capacity in constant pressure [J/kgK]	T_f	temperature of the flame [K]
T_u	temperature of the unburned gas [K]	T_w	temperature of the burner wall [K]
A_w	surface area of the burner port [m^2]	λ	thermal conductivity [W/mK]
ω	reaction rate [1/s]	Da	Damkhöler number [-]
Re	Reynolds number [-]	Sc	Schmidt number [-]
u	fuel jet velocity [m/s]	d	inner diameter of burner [m]
v	kinematic viscosity [m^2/s]	E	activation energy [J/mol]

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