Burning Intensity of Laminar Premixed Flame with Continuous Changing Stretch Rate along the Flame Surface

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Introduction

The structure of turbulent premixed flames is an important issue problem in the performance of practical combustion devices. Experimental evidence shows that the wrinkled laminar flame is formed in most practical devices, and it takes place in so called laminar flamelet regime[1,2]. So, many researchers investigated about the flame structure in such regime by means of modeling in the laminar flow, and they indicate that the burning intensity is changed by the effect of flame stretch and preferential diffusion of heat and mass[3-7].

In such investigation, however, the influence of flame stretch and preferential diffusion were discussed in the only case of the local flame structure, although the wrinkled laminar flame has continuous some convex and concave curvatures so that the effect of flame stretch and preferential diffusion is changed continuously along the flame surface. So, in such flame, it is expected that an interaction may exist along the flame surface in which the burning intensity is changed continuously by flame stretch and preferential diffusion, so that the change of the burning intensity cannot be predicted accurately by the local flame stretch theory in the past investigation.The objective of this study is to investigate the influence of the continuous change of flame stretch and preferential diffusion along the flame surface, for the burning intensity. In this study, Two types of premixed flames, one is the flame with continuous convex and concave curvature and the other is the flame with a single convex curvature, were stabilized in a laminar flow on a multiple slit burner, and we discussed about the measured flame temperature and the flame stretch rate of those flames.

Experimental Setup and Measurement Techniques

The essential feature of the burner and the orientation of the coordinate system are shown schematically in Fig.1. In this burner, three thin plates (thickness is 0.3 mm) divided a rectangular channel into four equal slits which had 4.0×35.0 mm cross-section. Those plates had a sharp trailing edge and were stuck 2.0 mm out of the burner exit. Each slit were long enough (400 mm) to ensure a fully developed laminar flow with a parabolic velocity distribution at the burner exit. Then, two types of flames were stabilized on this burner. One was the flame with continuous convex and concave curvatures like (a) in Fig.1, and the other type was the flame with a single convex toward the fresh mixture like (b). The former is called 3V-type and the latter is called V-type in a following discussion. Used mixture was the lean Propane-Air, whose equivalence ratio ϕ was 0.72 and Lewis number Le was 1.82.

The shape of the flame front and the flow velocity distribution were measured in order to estimate the flame stretch rate along the flame surface. The shape of the flame front was measured by the laser tomographic visualization, and the flow velocity distribution was measured by particle image velocimetry (PIV). In both techniques, we seeded the unburned mixture with particles of silicone oil (about 2μm), and the particle illumination source consisted of a double-pulsed Nd:YAG laser. The PIV measurement window size was maintained at 8.6 × 6.5 mm, which corresponded to 640 × 480 pixels , taken by CCD camera. The size of interrogation subregion was 0.2 × 0.2 mm, the time between laser pulses was maintained at 300 μs. Moreover, 50% multiple overlap between subregions was used for the measurements reported herein, in order to increase the vector density.

The flame temperature was measured by the Pt/20%Rh-Pt/40%Rh thermocouple in order to discuss about the change of burning intensity along the flame surface. The wire of the thermocouple had 100 μm diameter, and coated by the silica. No correction was made for radiative losses, because not absolute values but relative values are important in this study.

Result and Discussion

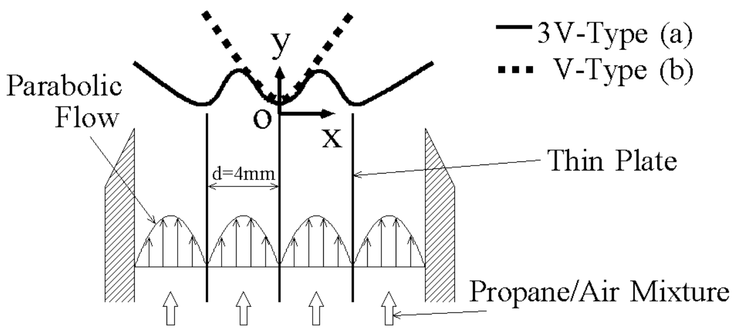
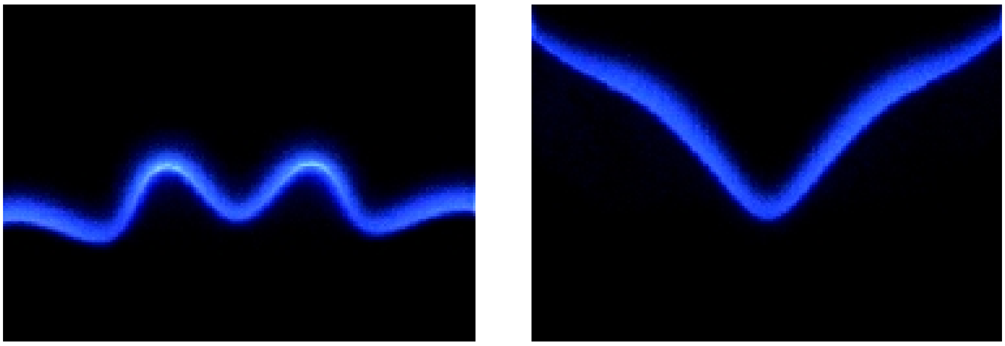


Fig.1 Schematic diagram of the burner



(a) 3V-type (b) V-type

Fig.2 Direct images of flames

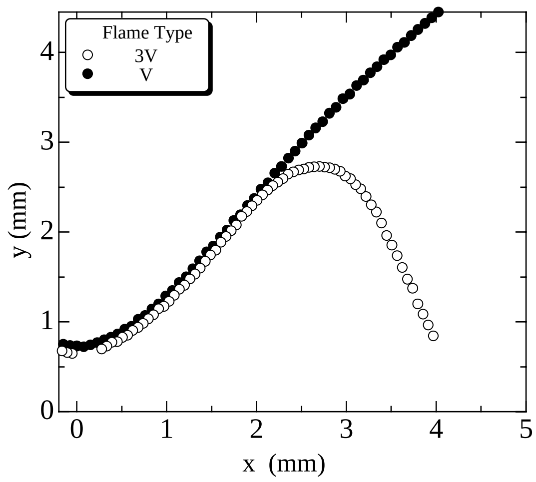


Fig.3 Shape of flame front

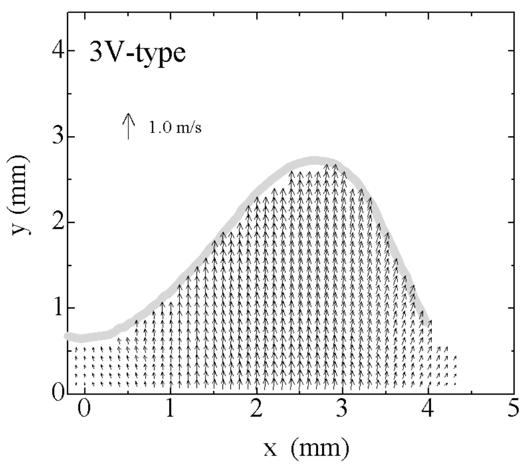
Fig.2 shows direct images of flames (3V-type (a) and V-type (b)). Here, we set mean velocities, in which curvatures of the convex are the same between 3V-type and V-type (3V-type ; $\overline{V}$ =0.32 m/s , V-type ; $\overline{V}$ =0.43m/s). Shapes of flame fronts measured by the laser tomographic visualization are shown in Fig.3. Seeing this figure, it is found that curvatures of convex are the same between 3V- and V-type. Moreover, shapes are also the same except the concave segment of 3V-type.

We consider about the effect and the flame stretch and preferential diffusion on the flame. This effect was discussed theoretically by Sun et al.[4], and they led for the stationary flame as a following equation.

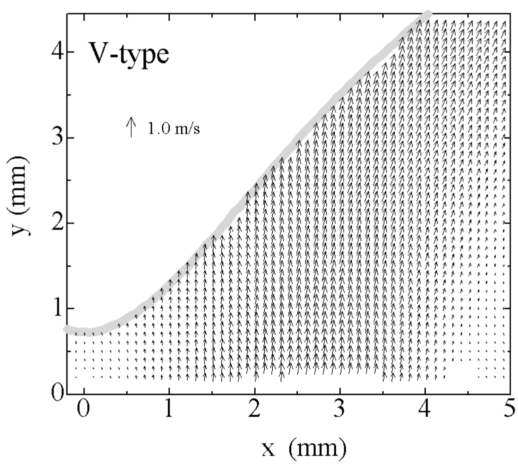
$$\frac{T_b - T_u}{T_{ad} - T_u} = 1 + \alpha^0 \, \tilde{\kappa} \left(\frac{1}{Le} - 1 \right) \qquad (1)$$

where T_b is the flame temperature affected by flame stretch and preferential diffusion, T_{ad} and T_u are the adiabatic flame temperature and the temperature of unburned gas respectively, Le is Lewis number, $\alpha^0 = 1 + \ln\{ \sigma^0 + (1-\sigma^0) e^{-1} \}$ is the factor accounting for the thermal expansion effect and $\sigma^0 = T_u / T_{ad}$, $\tilde{\kappa} = \kappa \delta_T^0 / S_u^0$ is the nondimensional flame stretch factor (δ_T^0; flame thickness, S_u^0; laminar flame speed), and flame stretch factor κ is estimated by a follow[8]:

$$\kappa = -\{\nabla \times (\mathbf{V}_f \times \mathbf{n})\} \cdot \mathbf{n} + (\mathbf{v} \cdot \mathbf{n})(\nabla \cdot \mathbf{n}) \qquad (2)$$



(a) 3V-type



(b) V-type

Fig.4 Velocity vector measured by PIV

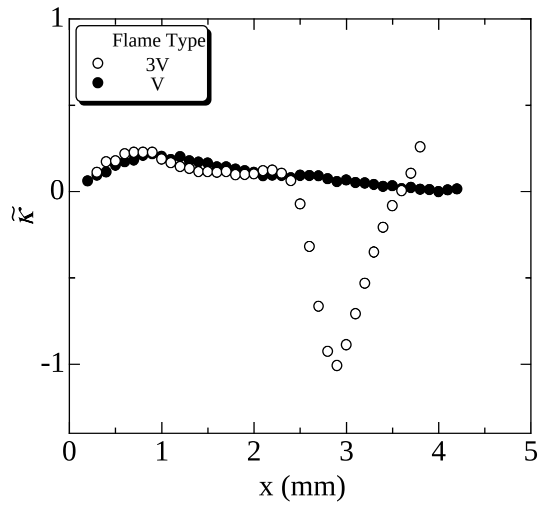


Fig.5 Nondimentional flame stretch rate along flame sureface

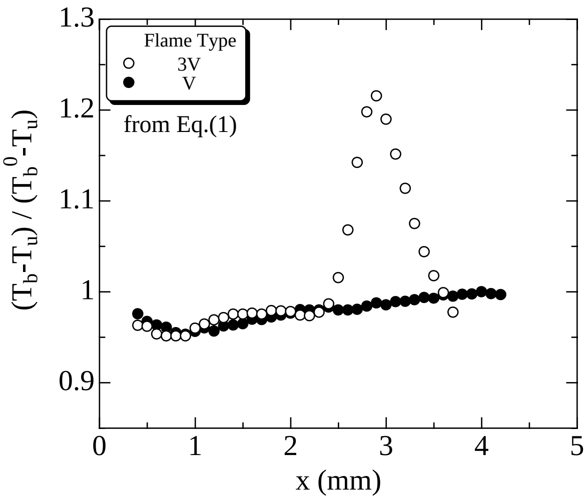


Fig.6 Nondimentional flame temperature estimated from Eq.(1) along flame surface

where $\mathbf{V}_f$ is the flow velocity vector on a flame front, **n** is the unit normal vector of the flame surface, **v** is the velocity of the flame surface and **v** = **0** because the flame surface is stationary in this study. So, we estimated the flame temperature T_b by using above equations. Here, the flame stretch factor was estimated by **n**, which is measured from the shapes of flame front in Fig.3, $\mathbf{V}_f$ which is the value measured by PIV (Fig.4) , and their gradients. Fig.5 and Fig.6 show $\tilde{\kappa}$ and T_b along the flame surface. Here, $\delta_T^0 = \lambda / \rho_u c_p S_u^0$, ρ_u = 1.20 kg/m^3, λ and c_p are respectively 0.0724 W/m·K and 1.27 kJ/kg·K at 1000K (near the ignition temperature), S_u^0 = 0.236 m/s[9], T_{ad}= 1914 K, we used. The horizontal axis in figures show the horizontal distance from the center plate. Seeing these figures, $\tilde{\kappa}$ is positive at the location near the convex so that T_b is lower than T_{ad} in both 3V and V-type. That is to say, the burning intensity is weakened by the flame stretch and preferential diffusion. $\tilde{\kappa}$ is negative at the location near the concave of 3V-type, while $\tilde{\kappa}$ is near zero in V-type. Consequently, T_b near the concave is higher than T_{ad} in 3V-type, and T_b in V-type is hardly changed from T_{ad}. In the location of x = 0.3～2.4mm, moreover, $\tilde{\kappa}$ are almost the same between 3V and V-type, although flow fields does not agree (mean velocities, and the diverge to outside in the case of V-type as seeing in Fig.4). So, it might be inferred that $\tilde{\kappa}$ is dominated by not the flow but the shape of the

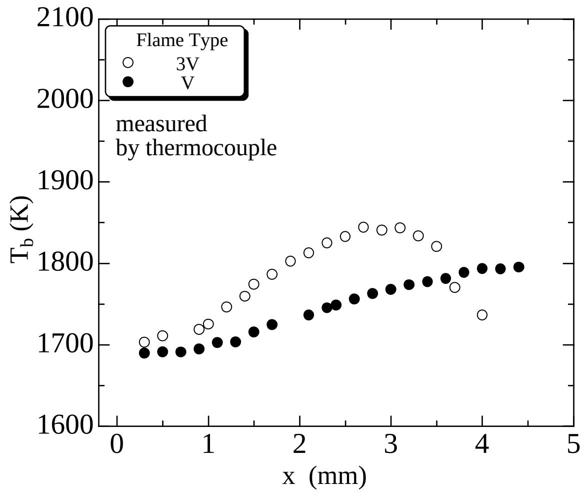


Fig.7 Flame temperature measured by the thermocouple

flame front.

Fig.7 shows T_b measured by the thermocouple along the flame surface. Here, T_b is determined as the maximum temperature on a given horizontal or vertical plane. Seeing Fig.7, the tendency, which is that T_b is lower at the convex and higher at the concave, agree qualitatively with theoretical data in Fig.6. The point of the notice is the difference of T_b between the 3V and V-type at the location of x = 0.3～2.4mm. In this region, $\tilde{\kappa}$ are the same between 3V and V-type, so it is expected theoretically that T_b are about the same (as seeing in Fig.6). However, the difference appears in measured T_b. Here, we would like to emphasize that 3V-type has the continuous adjacent concave segment, where the temperature is higher, in comparison with V-type. So I guess that the concave flame segment is performed as a heat source and the heat is transferred along the flame surface, so that the tendency of measured T_b does not agree with T_b estimated theoretically.

According to above results, it is concluded that the heat transfer is occurred along the flame surface in the case where the effect of flame stretch and preferential diffusion is changed continuously along the flame surface. In a such case, consequently, the change of the burning intensity cannot be predicted accurately by the theory of the local flame stretch and preferential diffusion as Eq.(1), and we suggest that the heat transfer along the flame surface should be considered in that theory.

References

1. Gouldin, F. C., Hilton, S. M., and Lamb, T., 22th Symp. (Int.) on Combust., The Combustion Institute, Pittsburgh, pp.541-550, 1988
2. North, G. L., and Santavicca, D. A., Combust. Sci. Tech., 72:215-232, 1991
3. Chung, S. H., and Law, C. K., Combust. and Flame, 72:325-336, 1988
4. Sun, C. J., Sung, C. J., He, L., and Law, C. K., Combust. and Flame, 118:108-128, 1999
5. Tsuji, H., and yamaoka, I., 19th symp. (Int.) on Combust., The Combustion Institute, Pittsburgh, p.1533-1540, 1982
6. Mizomoto, M., and Yoshida, H., Combust. and Flame, 70:47-60, 1987
7. Nye, D. A., Lee, J. G., Lee, T. –W., and Santavicca D. A., Combust. and Flame, 105:167-179, 1996
8. Chung, S. H., and Law, C. K., Combust. and Flame, 55:123-125, 1984
9. Vagelopoulos, C. M., Egolfopoulos, F. N., and Law, C. K., 25th symp. (Int.) on Combust., The Combustion Institute, pp.1341-1347, 1994