Experimental Study on Flame Structure in Methane-air Diffusion Flames

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1 Introduction

Edge flame intrinsically has dynamic properties and is well understood even with a one-dimensional approach in the middle branch of S-curve flame response [1]. That is, the flame surface forms a hole at the place where scalar dissipation rate exceeds some critical value in a turbulent jet diffusion flame. The scalar dissipation rate of the edge flame, formed at the edge of the flame hole, decreases as the flame hole evolves downstream. Then the edge flame, moved to the middle branch of S-curve, is finally forwarded to the upper-branch through a re-ignition process (advanced wave) or to the lower-branch through extinction process (extinction wave). Our research is motivated from the feature of two extinctions in the disk flame and the flame hole. That is, the extinction of high strain rate flame is caused by flame stretch, in that high strain flame extinguishes through a flame hole. However that of low strain rate flame is due to a limit defined by heat losses. The previous study also showed that low strain rate flame is caused by the shrinkage of the edge flame formed at the outer part of flame disk [2-3]. Is there any co-existent regime of flame-hole and shrinking flame-disk when counterflow diffusion flame extinguishes? What is the main mechanism of flame extinction and edge flame oscillation at shrinking flame-disk? Experiments are conducted to clarify the above-mentioned questions as varying velocity ratio, global strain rate, and nitrogen curtain flowrate.

2 Experimental Methods

The counterflow burner with the inner nozzle diameters of 18.0 *mm* is installed in a compartment in order to prevent external disturbance. Nitrogen curtain flow, supplied by the outer duct nozzle of the lower burner, is employed to prevent external flame disturbance and to remove the redundant outer flame held by a wake flow. The volume flowrate of nitrogen curtain flow varies from 4 to 12 *l/min* to change the local strain rate near the outer flame edge and clarify effects of curtain flowrate in flame extinction. Fuel is supplied from the upper duct nozzle to force the flame not to be positioned near the upper duct nozzle since the flame zone forms in the oxidizer side. The separation distance between reactant duct nozzles is fixed to 15.0 *mm*, in that the flame is more prone to heat loss to burner rim due to buoyancy effects. The global strain rate in the present experiments is from 10 s^{-1} to 110 s^{-1}. The dynamic behavior of oscillating flame is captured by a digital media camera and analyzed by a matlab-based program.

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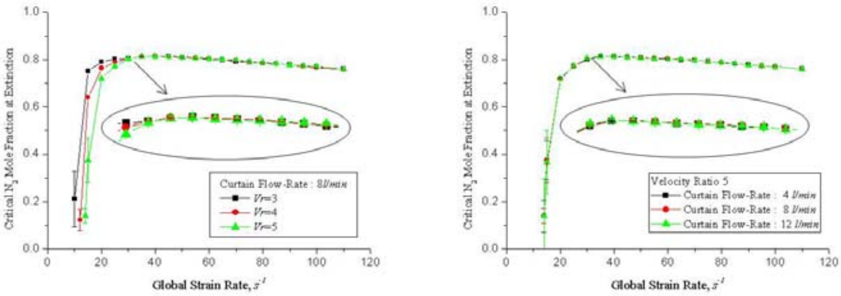
3 Results and Discussion

In Figure 1 flame extinction behavior are typically those of C-curve. That is, high strain rate flame extinction is responsible for flame stretch whereas low strain rate flame extinction is attributed by heat loss [1].



(a) (b)

Figure 1 shows variations of critical nitrogen mole fraction at flame extinction with global strain rate for (a) various velocity ratios at the nitrogen curtain flowrate of 8 *l/min* and (b) various nitrogen curtain flowrates at the velocity ratio of 5.

Table 1 The classification of flame extinction modes considering whether edge flame oscillates and at which condition flame hole forms.

		4 *l/min*	8 *l/min*	12 *l/min*
		a_g, s^{-1}	a_g, s^{-1}	a_g, s^{-1}
Vr=3	Regime I	≤20	≤20	≤20
	Regime II	25	25	25
	Regime III	30-40	30-40	30-40
	Regime IV	45≤	45≤	45≤
	Turning point	40	40	40
Vr=4	Regime I	≤20	≤20	≤20
	Regime II	25-30	25-30	25-30
	Regime III	35-50	35-50	35-50
	Regime IV	55≤	55≤	55≤
	Turning point	40	40	40
Vr=5	Regime I	≤25	≤25	≤25
	Regime II	30	30	30
	Regime III	35-70	35-70	35-70
	Regime IV	75≤	75≤	75≤
	Turning point	35-40	35-40	35-40

Regime □ : Flame extinction through a shrinking flame-disk with edge flame oscillation and without a flame-hole

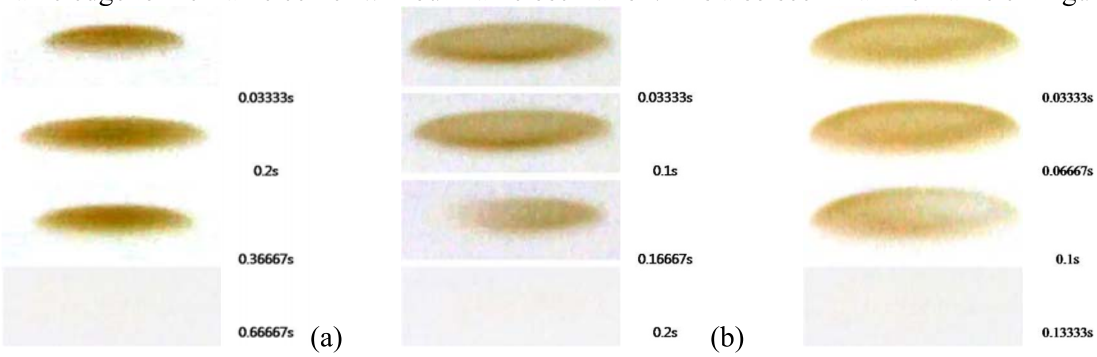
Regime □ : Flame extinction through a shrinking flame-disk with edge flame oscillation and a flame hole.

Regime □ : Flame extinction through a shrinking flame-disk without edge flame oscillation and a flame hole.

Regime □ : Flame extinction through a flame hole.

Critical mole fraction at flame extinction decreases in increase of velocity ratio at low strain rate flames in Figure 1a. This tendency is consistent with that of the previous study with the nozzle diameter of 26.0 mm, and these extinction behaviors were shown to be mainly caused by radial conduction heat loss [2-3], rather than radiative heat loss [4]. Meanwhile varying curtain flowrate may have two contrary effects at low strain rate flames. The increase of curtain flowrate at low strain rate flames increases the local strain rate particularly at the outer flame edge. On the contrary the increase of curtain flowrate at low strain rate flames may reduce the population of reactive species near the flame edge.

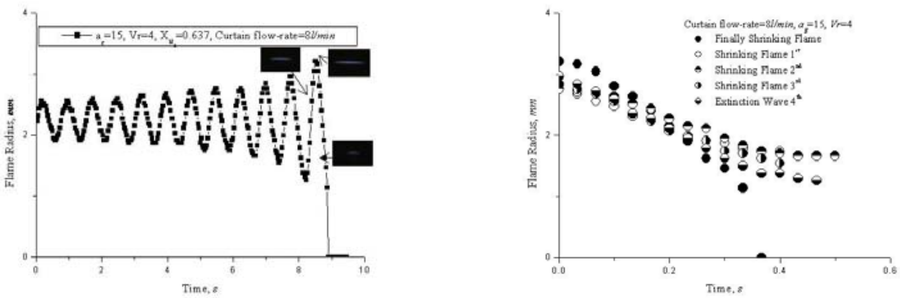
As shown in Figure 2a the flame extinction begins from the outer flame edge and is forwarded to the flame center while the flame oscillates. In Figure 2b there is a dark region with the lowest flame intensity at a finite distance from the flame center whereas the flame extinction is still progressed from the flame edge to the flame center without flame oscillation. It is also seen that the flame extinguishes



(a) (b) (c)

Figure 2. The representative photos of temporal evolution of flame extinction correspondent to the individual regime at the global strain rates of (a) 15 s-1, (b) 35 s-1, and (c) 55 s-1 for the velocity ratio of 4 and the curtain flowrate of 8 l/min.

through a flame hole on the flame surface without flame oscillation. Particularly Figure 2b is relevant to the transition from a shrinking flame-disk to a flame-hole in flame extinction. We can classify the flame extinction modes based on the displayed features. As shown in Table 1 varying curtain flowrate affects the classified regimes little.



(a) (b)

Figure 3. (a) temporal variation of the flame-disk radius through edge flame oscillation, and (b) that during the shrinking period of edge flame oscillation at the global strain rate of 15 s^{-1}, the velocity ratio of 4, the critical nitrogen mole fraction of 0.637, and the curtain flowrate of 8 *l/min*.

In Figure 3 the oscillating flame is shown to be accelerated while the flame reaches the extinction. Furthermore the temporal variation of flame-disk radius for the last shrinking flame is quite different from those for the shrinking flames during the other periods. This means that the last shrinking flame can not be sustained anymore prior to the flame extinction.

If the flame is positioned at the stagnation plane, the edge flame propagation velocity is expressed as $V_f=dr_f/dt-ar_f$. Here a is the local strain rate at the outer flame edge of flame-disk and thus the last term becomes the gas flow velocity. However the actual edge flame propagation velocity is approximated to $V_f=dr_f/dt-Car_f$ since the flame is established in the oxidizer-side. Here C is dependent upon the flame location, the flame radius, the global strain rate, the velocity ratio, and the curtain flowrate. However C can be approximated to unity since the radial flow velocity at the flame edge is similar to that at on the same radial location on the stagnation plane. In our experimental ranges the orders of gas flow velocity are of O (10 *cm/s*) whereas all the edge travelling-velocities in Figure 4 are of O (10 *mm/s*). It is seen that the edge flame propagation velocities are always negative even during the expanding period at low strain rate oscillating flames. Figure 4 also demonstrates that the flame radius, which may be an indicator of flame stabilization, has to increase in order to have a zero edge travelling-velocity (a stationary flame). Meanwhile from the inspection of the flame radius in the regimes I and II from Table 1 in our experiment range it is found that the flame is stabilized for the flame radius more than 7.5 mm whereas the flame oscillates for that less than 7.5 *mm*. This implies

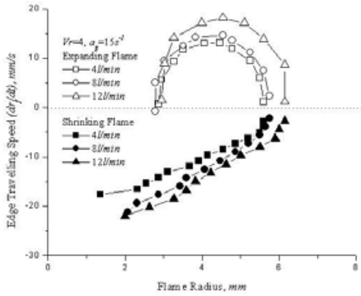


Figure 4 The travelling-velocities of expanding and shrinking edge flames at the last stage prior to the extinction according to curtain flowrate at the global strain rate of 15 s^{-1} and the velocity ratio of 4.

that there exists a critical flame radius for edge flame oscillation. In the foregoing statements we addressed that radial conduction heat loss is relevant to the inverse of flame radius and small flame radius accelerates edge travelling-velocity. Then we can explain the reason why curtain flowrate did not impact critical nitrogen mole fractions at low strain rate flames in Figure 1b. At low strain rate flame the increase of curtain flowrate causes the increase of the local strain rate, in that it contributes to flame stabilization. However as shown in Figure 4 the edge travelling-velocity also increases as curtain flowrate increases, and this plays a role of flame de-stabilization. It is therefore understood that the cancellation of these contrary effects did not impact the response of critical nitrogen mole fraction to curtain flowrate.

4 Conclusions

Experiments have been conducted to clarify impacts of curtain flow and velocity ratio on low strain rate flame extinction, and to further display transition of shrinking flame disk to flame-hole.

1) Flame extinction behavior with global strain rate shows the classification of flame extinction 4 modes whether edge flame oscillates and at which condition flame hole forms.
2) The temporal variation of flame-disk radius for the last shrinking flame is quite different from those for the shrinking flames during the other periods. This means that the last shrinking flame can not be sustained anymore prior to the flame extinction.
3) The edge flame propagation velocities are always negative even during the expanding period at low strain rate oscillating flames. It is understood that the cancellation of contrary effects, are the increase of the local strain rate and travelling-velocity as curtain flowrate increases, did not impact the response of critical nitrogen mole fraction to curtain flowrate.

References

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