STABILIZATION MECHANISMS OF INVERTED FLAMES ESTABLISHED IN A ROTATING FLOW

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INTRODUCTION

The flame speed in the vortex core of a flammable mixture approaches about 15 m/s [1]. If the characteristics of rapid flame propagation in the vortex core can be used, the flame may become stable even in the case in which unstable flames due to the lean combustion are established. As the flame speed increases with an increase in the rotating velocity of the mixture [1], the effects of rapid flame propagation become more powerful for stabilizing very lean and unstable flames. Thus, very lean combustion and high intensity of combustion can be realized using the characteristics of rapid flame propagation in the rotating flow.

In this study, the inverted flames established in the rotating flow have become of interest for developing the compact combustors, which have ultra low emission of NOx and high intensity of combustion. The characteristics of combustion of the inverted flames established in the rotating flow were examined and the stabilization mechanisms of the flame were discussed.

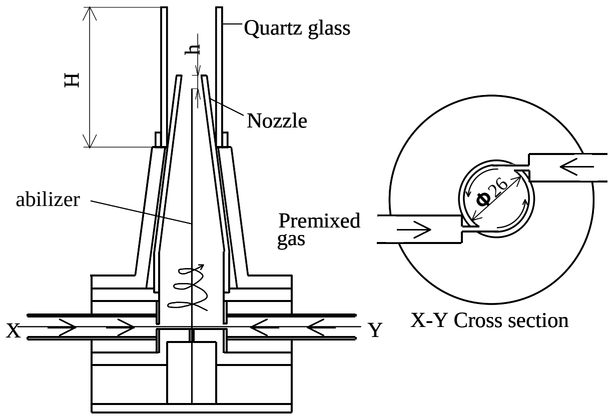
EXPERIMENTAL APPARATUS

The experiments were performed using a compact burner consisted of the nozzle, the stabilizer and the cylinder as shown in Fig.1. The premixed gas is tangentially supplied through the two holes of 2 mm diameter, which are taken at the lowest part of the nozzle. The rotating flow field is established at the low part of the nozzle and the downstream of the nozzle exit. The flame is anchored at the stabilizer witch is set along the central axis of the nozzle.

EXPERIMENTAL RESULTS AND DISCUSSION

The flame appearances established in a rotating flow are shown in Fig. 2. The flame base is anchored at the top of the stabilizer and the blue flame is stabilized. The flame shape is similar to that of the inverted flame established in a non-rotating flow. As the rotating velocity $V_{\theta 0}$ of the mixture is increased, the flame length is increased and the flame becomes slender and the heated part of the tip of the stabilizer becomes large. This means that the flame base moves upstream along the stabilizer as the rotating velocity is increased.

The stability limit is shown in Fig. 3. The region of stabilization of the inverted flame in the rotating flow is very extensive compared with that of the inverted flame in the



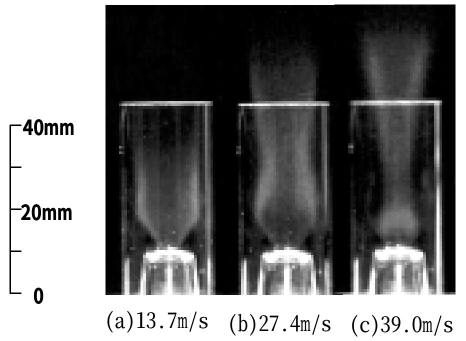
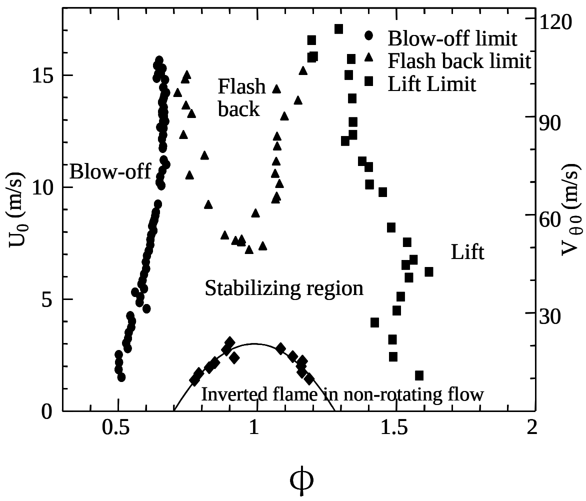


Figure1 Burner

Figure 2 Flame appearances (Φ=0.6)



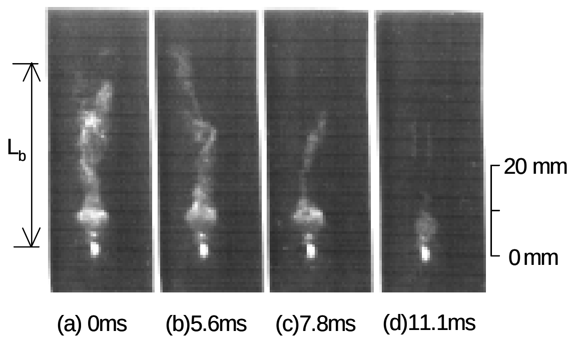


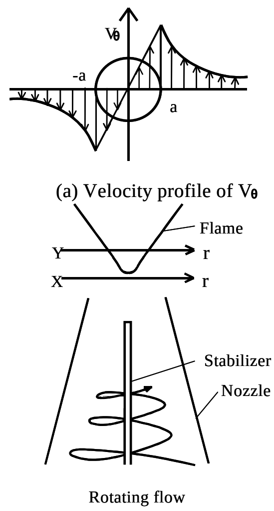
Figure 3 Stability limits

Figure 4 Flames at an instant of blow-off

non-rotating flow. The flame can be stabilized even at the equivalence ratio below ϕ= 0.64 below witch there is almost no production of thermal NOx because of the low temperature of the flame [2]. The maximum mean velocity of the nozzle exit at which the flame can be stabilized is about 16 m/s at the condition of ϕ= 0.7. Flash back occurs at the conditions of the equivalence ratios from 0.7 to 1.2. On the other hand, the mean velocity U_0 at the stability limit is decreased in the rich side over ϕ= 1.2 as the equivalence ratio is increased. But, the flame of ϕ= 1.4 can be stabilized even at the high velocity of about U_0 = 10 m/s.

Figure 4 shows the flames at an instant of blow-off. The flame is first extinguished at the downstream far from the top of the stabilizer as shown in Fig. 4-(a). Once the flame is extinguished, the flame is continuously extinguished towards the upstream direction and the flame anchored at the top of the stabilizer is finally extinguished as shown in Fig. 4-(b) ~ (d). The location of the flame that is first extinguished may be related to the length of recirculation zone, which is established in the rotating flow.

The rotating flow field in which the inverted flame is established is given schematically as shown in Fig. 5. It is assumed that the velocity distribution at the downstream of the nozzle



(a) Velocity profile of Vθ

(b) Flame and flow Field

Figure 5 Flame and flow field

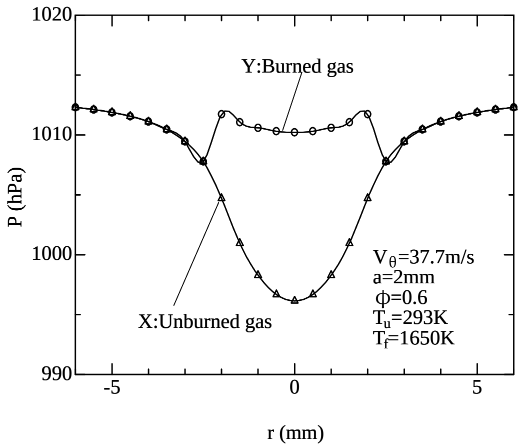


Figure 6 Pressure distributions of the unburned and burned gases

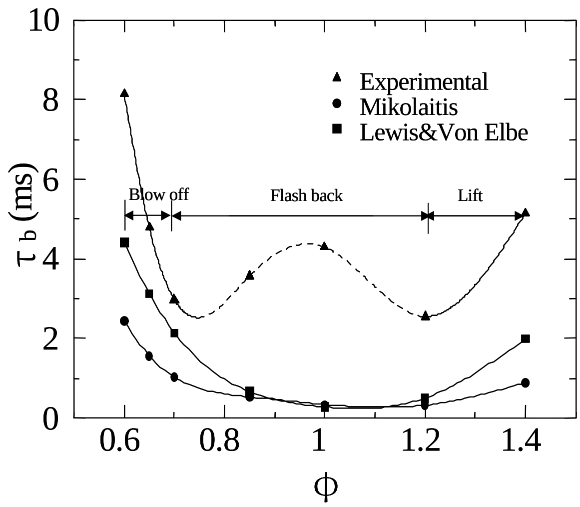


Figure 7 Characteristic ignition times at stability limits

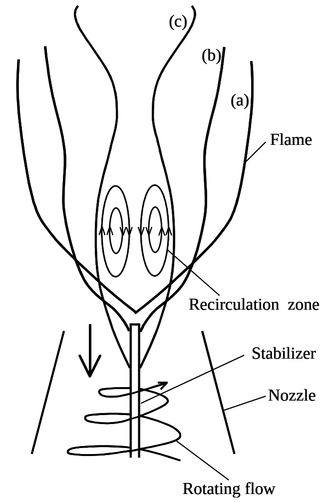


Figure 8 Stabilization mechanisms of the inverted flames established in the rotating flow

is characterized by that of Rankine's vortex as shown in Fig. 5-(a). The pressure distributions were calculated using the equation of motion in the rotating flow field shown in Fig. 5. A example of the calculated pressure distributions at the unburned and burned regions in the rotating flow are shown in Fig. 6. The pressure difference between the unburned and burned gases described in Fig. 6 is the driving force that the flame moves upstream along the stabilizer. As the pressure difference is increased with an increase in the rotating velocity V_θ and with a decrease in the density of the burned gas, the flame moves further upstream along the stabilizer and flash back occurs at a critical velocity. This is the mechanism of flash back, which occurs at the conditions of the equivalence ratios between 0.7 and 1.2.

Another mechanism of stabilization is related to the recirculation zone. Zukoski and Marble [3] found that the stability limit is determined by the time τ which a mass element takes to travel past the recirculation zone and that the critical time τ_b is independent on the stream variables and is only a function of the mixture variables. The critical time τ_b is given by L_b/U_{0b}. Here L_b and U_{0b} are the length of ricirculation zone and the mean velocity at the blow-off conditions. Figure 7 shows the characteristic ignition time τ_b in the rotating flow. The results obtained from the models of Lewis and Von Elbe [4], and of Mikolaitis [5] are also shown in Fig. 7. Experimental results are qualitatively agreement with the results obtained from the models of Lewis and Von Elbe, and Mikolaitis except the equivalence ratios between 0.7 and 1.2. This is the region in which flash back occurs. We can understand from these results that the blow-off and lift of the flame are significantly related to the extinction due to flame stretch at the downstream end of the recirculation zone.

Figure 8 schematically shows the stabilization mechanism of the inverted flames established in the rotating flow. As V_θ is increased, the flame at the downstream end of the recirculation zone is first extinguished at a critical velocity as shown in Fig. 4-(a). Once the flame is extinguished, the flame established around the recirculation zone is continuously extinguished towards the upstream direction as shown in Fig. 4-(b) ~ (d) because the unburned gas of low temperature flows into the recirculation zone. However, The flame base moves also upstream along the stabilizer with an increase in V_θ. The stability limits at the regions of ϕ= 0.5 ~ 0.7 and 1.2 ~ 1.5 are determined by the extinction due to flame stretch at the downstream end of the recirculation zone prior to the movement of the flame base upstream along the stabilizer with an increase in V_θ. On the other hand, the stability limit at the region of ϕ= 0.7 ~ 1.2 can be explained by the reverse of two effects mentioned above. Therefore, the stability limits of the inverted flames established in the rotating flow are determined by competition of the extinction due to flame stretch at the downstream end of the recirculation zone with the movement of the flame base upstream along the stabilizer due to the characteristics of rapid flame propagation that is produced in the rotating flow field.

CONCLUSIONS

(1) The region of stabilization of the inverted flame established in the rotating flow is very extensive in both the lean and rich sides of the mixture. Therefore, the combustion of ultra low emission of NOx and high intensity can be realized by using the inverted flames established in the rotating flow.

(2) The stability limits of the inverted flame established in the rotating flow are determined by competition of the extinction due to flame stretch at the downstream end of the recirculation zone with the movement of the flame base upstream along the stabilizer due to the characteristics of rapid flame propagation that is produced in the rotating flow field.

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