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Characteristics of Lifted Flame Resulting from Impulsive Change of Equivalence Ratio

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Abstract : This study investigated the characteristics of an unsteady lifted flame resulting from an instant change in the concentration difference through comparisons with those of a steady lifted flame to change from a premixed flame to a triple flame with a diffusion trailing flame identified in the middle. The instant change was done by an equivalence ratio conversion system using a solenoid valve and the flame photographs taken by an ICCD camera, were used for data extraction from the two lifted flames. The unsteady lifted flame stayed at for 1.6 seconds only and was classified into three regions, a premixed flame region, a critical flame region, and a triple flame region according to the gradients of the flames' curvature radius, width, lift-off height, and luminescence intensity as done in the steady lifted flame. The result was that the unsteady lifted flame made under a specific condition in this paper, showed a similar tendency in the gradients to the steady lifted flame. That is to say, the behavior of the unsteady lifted flame can be predicted based on the behavior of a steady lifted flame.

Key Words : Lifted Flame, Premixed Flame, Triple Flame, Unsteady Flame, Equivalence Ratio Conversion

1. Introduction

Research on laminar lifted flames is very important, as it can contribute to the modeling of more complicated flame phenomena, such as turbulent nonpremixed flames. As such, several diverse models have been proposed for the stabilization dynamics of a lifted flame. For example, Peters et al. [1] considered a turbulent flame as the general effect of a laminar flamelet and interpreted the lift-off height of a lifted flame in quantifiable terms using the scalar dissipation rate. Meanwhile, Schefer et al. [2] noted that the mean concentration and mean velocity of a turbulent lifted flame had a smooth, Gaussian shape, while an instantaneous fuel concentration had a very sharp boundary surface, and thereby demonstrated the existence of a concentration gradient of a mixture. There is also extensively theoretical and experimental evidence that the leading edge of a lifted flame stabilizes into a triple flame [3-5, 12-17]. For example, Kioni et al. [3,4] created a stable triple flame by manufacturing a slot burner, and studied information on radical and velocity fields through PLIF and PIV. Meanwhile, Azzoni et al. [5] studied the lifted state and attached state of a triple flame. Furthermore, based on the assumption that a triple flame would emerge from a turbulent diffusion flame as a laminar flamelet, Dold [6] studied the relationship between changes in the mixture fraction and the propagation speed of a triple flame in quantifiable terms. Plus, Jang et al. [7] and Kim et al. [8] suggested that a combustion model that describes the leading edge of a lifted flame in a slot burner must be able to describe both a premixed flame and a triple flame. They also observed a flame shape where a premixed flame transformed into a triple flame based on arranging the concentration difference in the premixture, then studied the unique features of each area by measuring the local concentration field and velocity field. Finally, when fixing the total velocity of the flow supply, the lift-off height was shown to change according to the concentration difference.

In the actual combustion field, an unsteady state, which changes with time when the condition of a constant equivalence ratio is not maintained, occurs frequently. While extensive research has already focused on observing and interpreting the structure of a lifted flame in a steady state, when the permanent equivalence ratio is maintained with the change of time, there has hardly been any research on identifying the behavior characteristics in an unsteady state.

In the studies of Jang et al. [7] and Kim et al. [8], experiments were conducted to investigate whether a premixed flame and triple flame could arise from a lifted flame under the conditions of

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maintaining a constant equivalence ratio. However, similar studies based on a wider range of circumstances, where the equivalence ratio changes with time, should be helpful for a lifted flame stabilization model. As, in the current lifted flame stabilization model based on a steady state, where the concentration difference is constant, it is questionable whether the leading edge of the lifted flame will appear as a premixed flame, critical flame, or triple flame in an unsteady state. Accordingly, this study investigated the characteristics of an unsteady lifted flame resulting from an instant change in the concentration difference through comparisons with those of a steady lifted flame to change from a premixed flame to a triple flame with a diffusion trailing flame identified in the middle. Plus, an equivalence ratio conversion system that can instantly alter the equivalence ratio, was developed to investigate the behavioral characteristics of an unsteady-state lifted flame.

2. Experimental Setup and Procedure

2.1. Experimental setup

The experimental device used in this study shown in Fig. 1 was similar to the one used in the preceding studies [7,8], except for the additional installation of an equivalence ratio conversion system. The fuel used was commercial LPG, while the oxidant was high-purity air (purity 99.99%) comprised of 79% nitrogen and 21% oxygen. To ensure the gases supplied at a constant pressure, each gas was passed through a regulator and the flow rate controlled by flow meters (Matheson 602, 604), adjusted to a precise flow rate using a bubble meter. After the flow meter, the gases were passed through a mixing chamber before being supplied to the slot burner. The mixing chamber was cylindrical in shape, 160 mm length, 314 ml volume, and inside diameter of 50 mm. As such, the fuel and oxidant, set at a certain equivalence ratio, flowed into the mixing chamber and became homogeneous as a result of the swirl flow inside.

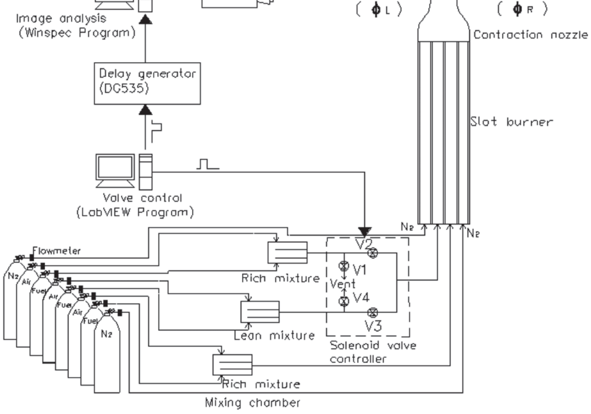


Fig.1　Schematic diagram of experimental setup.

The equivalence ratio conversion system was comprised of a solenoid valve, hardware (computer and PCI-MIO-16E1 board), and software (LabVIEW program) to allow the equivalence ratio of each slot in the slot burner to be altered from the condition for the generation of a premixed flame to the condition for the generation of a triple flame. Table 1 shows the solenoid valve state when supplying the premixture using the equivalence ratio conversion system. For the initial state, a rich equivalence ratio mixture (ϕ_R = 1.2) was supplied, whereas for the final state, a lean equivalence ratio mixture (ϕ_L = 0.4) was supplied. Hirota et al. [18] confirmed that the pressure variation was stabilized and the flow velocity turned to the initial setting one before the concentration change arrive at a burner, while a little pressure variation was caused by the operation of the solenoid valve.

The slot burner, designed to alter the gas concentration, included 4 slots, 10 mm width inside, 40 mm width, and 700 mm length, which were made of a 10 mm-thick acrylic plate and 0.5 mm-thick stainless steel plate combined with bolts. Inside the slot burner, a vinyl pipe (5 mm diameter and 200 mm length) and ceramic honeycomb (1.5 mm width, 1.5 mm length, and 250 mm height) were installed to ensure a uniform velocity for the flow field. The premixture was supplied to the two slots in the center in accordance with the experimental conditions, while ambient nitrogen was supplied at an ambient flow to the other two slots at the edge. The nitrogen acted to increase the exit velocity of the mixture, thereby preventing any inflow of an external oxidant as well as disruption from an outside flow.

After passing through the ceramic honeycomb, the premixture entered a contraction nozzle, and a flame was generated due to the concentration difference. The exit of the contraction nozzle was 21 mm width and 30 mm length, and made using a plaster mold patterned based on a 3rd order polynomial fitting of the inside shape used in the previous study conducted by Morel [11], and of rectangular shape so as to minimize the three dimensional influence on flame when taking pictures of the flames.

To qualitatively analyze the behavioral characteristics and forms of the flame in a steady and unsteady state, an ICCD camera (USA Princeton Instruments, PI-MAX) was used, where the

Table 1　Solenoid valve state for unsteady-state lifted flame.

	Initial state	Final state
Valve 1	closed	open(vent)
Valve 2	open	closed
Valve 3	closed	open
Valve 4	open(vent)	closed
ϕ_L	1.2	0.4

exposure time was set at 10 ms and the gain set at 10. The flame images were then used to measure the lift-off height, curvature radius of flame, and flame width at the leading edge, plus the video images generated by the ICCD camera were also expressed at a 16-bit arbitrary intensity using commercial software (Winspec program).

2.2. Experimental procedure

In this study, the mixture and ambient flow supplied at a flow velocity of 1.1m/s, made a lifted flame without blowing out or flashing back to the exit of the burner. The premixture was initially supplied at an equal equivalence ratio of ϕ = 1.1 to the two slots in the center of the slot burner, and the equivalence ratio at the slot on the left side was eventually reduced. The slot on the right side was then supplied with a rich equivalence ratio, while the left side was supplied with a lean equivalence ratio. Depending on the equivalence ratio condition, the flame lifted, flashed back, blew out, or was quenched.

Figure 2 shows the region where the conditions produced a stable lifted flame, meaning that the conditions outside this region were unable to produce a stable lifted flame. As such, the lifted flame stabilization region, producing a stable lifted flame, without any flash-back, blow-out, or quenching, was ϕ_L = 1.1∼0.7 at ϕ_R = 1.1, ϕ_L = 1.2∼0.4 at ϕ_R = 1.2, ϕ_L = 1.2∼0.3 at ϕ_R = 1.3, ϕ_L = 1.1∼0.3 at ϕ_R = 1.4, ϕ_L = 0.7∼0.3 at ϕ_R = 1.5 and ϕ_R = 1.6, ϕ_L = 0.6∼0.3 at ϕ_R = 1.7, ϕ_L = 0.5∼0.3 at ϕ_R = 1.8, and ϕ_L = 0.3 at ϕ_R = 1.9. When changing the lean equivalence ratio on the left side of the slot burner, ϕ_R = 1.2 was identified as the region with the most stable lifted flame. Thus, when supplying at a constant value from ϕ_L = 1.2 to ϕ_L = 0.4, the state of the flame was defined as a steady-state lifted flame. A steady-state lifted flame was observed when maintaining a constant concentration difference for the mixture and the suggested data for that flame are expressed according to the concentration difference. Meanwhile, an unsteady-state lifted flame was created when fixing the rich equivalence ratio at ϕ_R = 1.2 and instantly changing the lean equivalence ratio from ϕ_L = 1.2 to ϕ_L = 0.4. The unsteady state lifted flame stayed at for a short period from 1.2 seconds to 2.8 ones after activation of the solenoid valves, and then turned to a steady state lifted flame. Therefore, the suggested data are made out on the basis of time.

3. Results and Discussion

Figure 3 represents the flame shapes in a steady state and unsteady state at the slot burner. The steady-state lifted flames in Fig. 3(a) represent the flame shapes with a rich equivalence ratio of ϕ_R = 1.2 on the right side and lean equivalence ratio of ϕ_L = 1.2, 1.0, 0.8, 0.7, 0.5, and 0.4, respectively, on the left side. The white lines with an arrow mark at the bottom of the photos show the flame was steadily lifted at the exit of the nozzle of the slot burner. The top left picture represents the flame premixed with an equal equivalence ratio on both sides of ϕ_R = 1.2 and ϕ_L = 1.2, where the shape of the flame is symmetrical with a light blue color, and the leading edge of the flame is hemispherical in shape due to the equal mixture ratios supplied to the right and left sides. As the concentration difference becomes larger with equivalence ratios of ϕ_R = 1.2 and ϕ_L = 1.0, the central area of the flame becomes brighter as shown in Fig. 4. Under even larger concentration difference with equivalence ratios of ϕ_R = 1.2 and ϕ_L = 0.7∼0.4, the center of the leading edge has a streamline shape that is more acute than the premixed flame, in addition a diffusion trailing flame appears in the middle of flame. The generation of such a diffusion trailing flame is a feature of a triple flame, and consistent with the results of preceding studies [3,7]. The diffusion trailing flame was formed when the rich premixed flame was mixed with the lean premixed flame: i.e. the residual fuel from the rich premixed flame was diffused with the oxidant from the lean premixed flame, resulting in a diffusion flame with a stoichiometry equivalence ratio at the center.

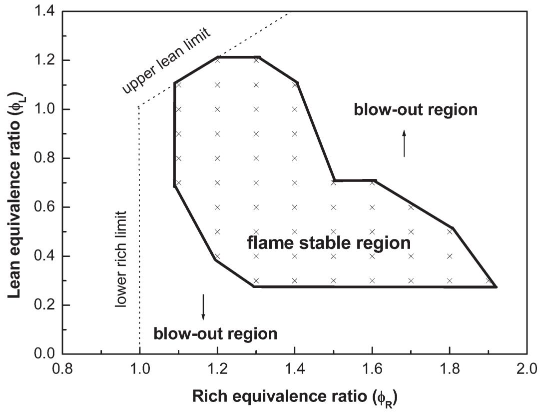
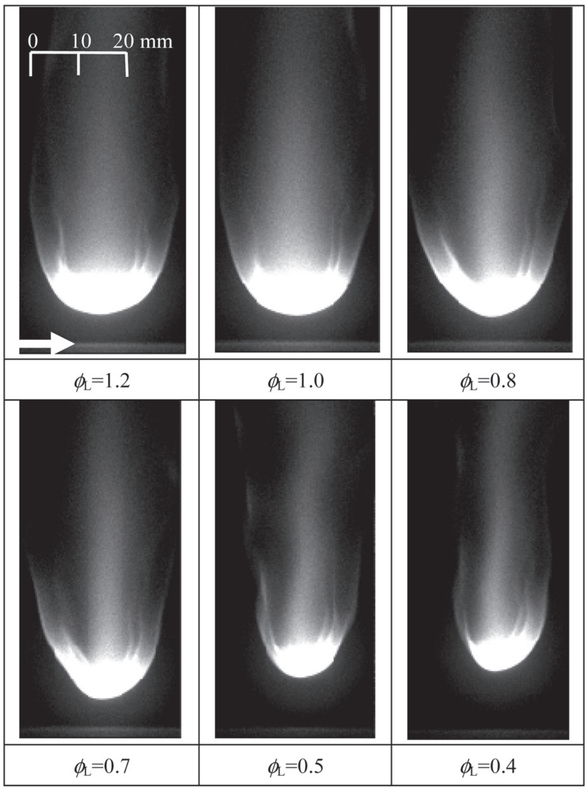


Fig.2 Stability curve according to equivalence ratios.

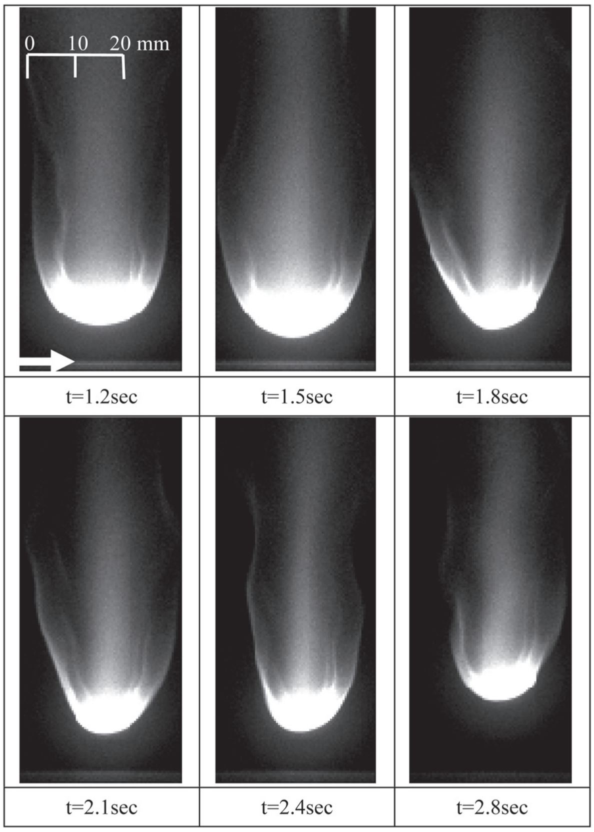
For this reason, a diffusion trailing flame is a feature of a triple flame. Previous experiments conducted by Jang et al. [7] have demonstrated that as the concentration difference becomes greater, a steady-state lifted flame changes from a premixed flame region to a critical flame region, then to a triple flame region.

The unsteady-state lifted flames in Fig. 3(b) represent the flame shapes obtained over time when instantly changing the lean equivalence ratio from ϕ_L = 1.2 to ϕ_L = 0.4 using the equivalence ratio conversion system, while ϕ_R was fixed at 1.2. After changing the solenoid valve state, the flame changes began after t = 1.2 sec and ended after approximately t = 2.8 sec.

The pictures show that with the passage of time, the shapes of the unsteady-state lifted flame were similar to the flame shapes caused by a concentration difference with a steady-state lifted flame. The leading edge of the flame changed from a hemisphere



(a) steady lifted flames(ϕ_R = 1.2)



(b) unsteady lifted flames

Fig.3 Flame images.

to a more acute shape, and at t = 1.8 sec after the activation of the solenoid valve, a diffusion trailing flame appeared in the center of the flame, which is a feature of a triple flame. In other words, the flame changed based on the instant equivalence ratio. Until t = 1.2 sec after the activation of the solenoid valve, the flame remained the same as the steady-state lifted flame at ϕ_R = 1.2 and ϕ_L = 1.2. Then, after t = 2.8 sec, the flame became the same as the steady-state lifted flame at ϕ_R = 1.2 and ϕ_L = 0.4. At t = 1.8〜2.1 sec, the flame shape was very similar to the shape of the steady-state lifted flame at ϕ_R = 1.2 and ϕ_L = 0.7.

Figures 4 and 5 represent the luminescence intensity at the height of 19.7 mm and 28.9 mm from the leading edge of the lifted flame in an effort to clearly differentiate between the shapes of the steady-state lifted flame and unsteady-state lifted flame through direct photograph. When a triple flame was generated, a diffusion trailing flame of fuel and air appeared near the center, resulting in a stronger luminescence intensity at the center and allowing the region where a premixed flame and triple flame appeared to be mapped. Based on the central area of the picture (x = 0, flame center), the right area (x > 0) is the region where a rich equivalence ratio (ϕ_R) flame appeared, while the left area (x < 0) is the region where a lean equivalence ratio (ϕ_L) flame appeared. For the steady-state lifted flame in Fig. 4, the intensity in the central area sharply changed depending on the concentration difference. As such, the luminescence intensity was generally classified into three groups: ϕ_L = 1.2〜1.0, ϕ_L = 1.0〜0.8, and ϕ_L = 0.7〜0.4, where ϕ_L = 1.2〜1.0 represents the premixed flame region when the luminescence intensity was symmetrical on the right and left, ϕ_L = 0.7〜0.4 represents a triple flame when the intensity at the center sharply increased due to a diffusion flame at the center of the flame, and ϕ_L = 1.0〜0.8 represents the critical flame region, as defined by Jang, et al. [7], where the transition from a premixed flame to a triple flame took place.

The unsteady-state lifted flame in Fig. 5 changed in a manner very similar to Fig. 4, which describes the luminescence intensity of the steady-state lifted flame based on the equivalence ratio. While the equivalence ratio of the unsteady-state lifted flame changed rapidly from ϕ_L = 1.2 to ϕ_L = 0.4, the flame itself appeared to follow the same course of change into a triple flame as the steady-state lifted flame. The unsteady-state lifted flame at t = 1.2 sec was similar to the steady-state lifted flame at ϕ_L = 1.2, and the unsteady-state lifted flame at t = 2.8 sec similar to the steady-state lifted flame at ϕ_L = 0.4. Furthermore, the change between t = 1.8 sec and t = 2.8 sec was similar to that between ϕ_L = 0.7 and ϕ_L = 0.4, the region where the steady-state lifted flame formed a triple flame.

Figure 6 represents the lift-off heights of the steady-state lifted flame and unsteady-state lifted flame from the slot burner. The steady-state lifted flame is expressed at the upper end of the

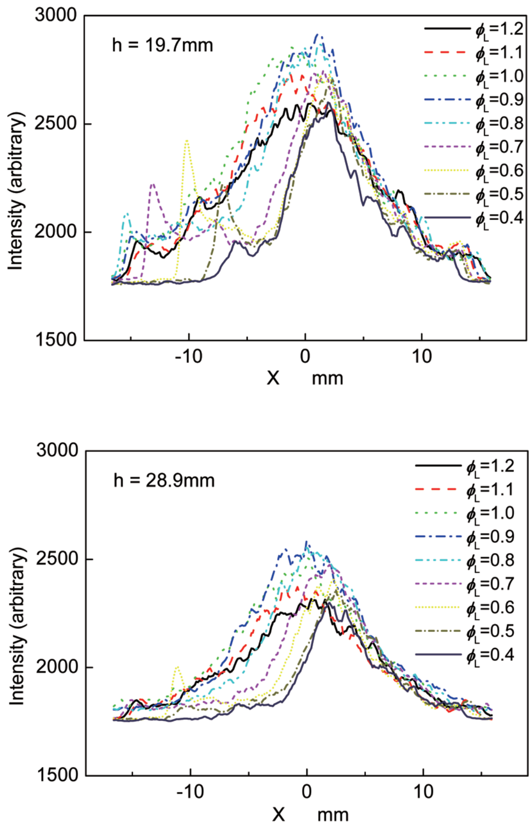


Fig.4 Intensity of steady-state lifted flame.

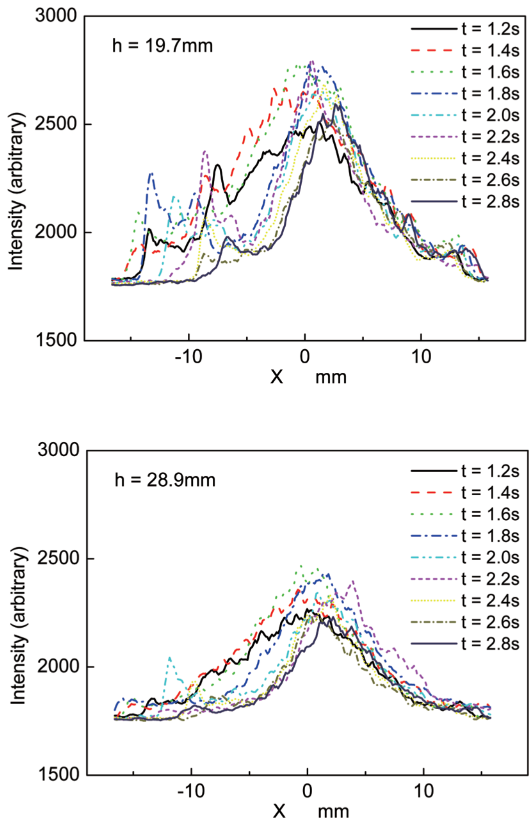


Fig.5 Intensity of unsteady-state lifted flame.

horizontal axis based on the changes in the lean equivalence ratio, while the unsteady-state lifted flame is expressed at the lower end of the horizontal axis based on time. For the steady-state lifted flame, the lift-off height changed with the concentration difference of the mixtures supplied to the right and left slots. The lift-off height of a propane triple flame at a jet nozzle, as reported by Chung et al. [10], changes due to the exit velocity, nozzle diameter, and ambient flow velocity. Meanwhile, Jang et al. [7] reported that changes in the lift-off height of a flame with a fixed exit-flow velocity are due to changes in the flame propagation speed resulting from a concentration difference.

Jang et al. [7] also showed that the transition from a premixed flame to a triple flame takes place near the lowest lift-off height, and defined this area as the critical flame region.

This study also reconfirmed the change in the lift-off height caused by a concentration difference with a fixed exit-flow velocity. The lift-off height decreased in the premixed flame region of ϕ_L = 1.2～1.0, reached the lowest point near ϕ_L = 1.0～0.8, then increased when approaching the triple flame region of ϕ_L = 0.7～0.4. In the case of the unsteady-state lifted flame, the lift-off height initially remained constant with passage of time, declined from point t = 1.2 sec when a change occurred in the shape of the flame, reaching the lowest value at approximately t = 1.5～1.6 sec, then increased. When compared to the shape of the flame, t = 1.2 sec definitely represented a premixed flame, t = 2.8 sec represented a triple flame, and t = 1.5～1.8 sec represented the transition from a premixed flame to a triple flame. By demonstrating that even with an unsteady-state lifted flame the lift-off height of the flame changed due to a concentration difference, this confirms that the lift-off height is clearly affected by the concentration difference of the mixture. Therefore, further studies on the effect of the concentration difference on the lift-off height are necessary.

Figure 7 represents the radius of the curvature of the steady-state lifted flame and unsteady-state lifted flame from the slot burner. The radius of the curvature of a circle inscribed in the center of the flame's leading edge was observed using the photographs taken with the ICCD camera. For the unsteady-state lifted flame, the radius of the curvature decreased as ϕ_L decreased. In other words, it decreased as the concentration difference of the mixture increased. Ko et al. [9] already theoretically demonstrated that the fuel mass fraction gradient and curvature have a linearly proportional relationship. Jang, et al. [7] also reported that as the concentration difference increases, the radius of the flame curvature decreases.

For the unsteady-state lifted flame, the radius initially showed

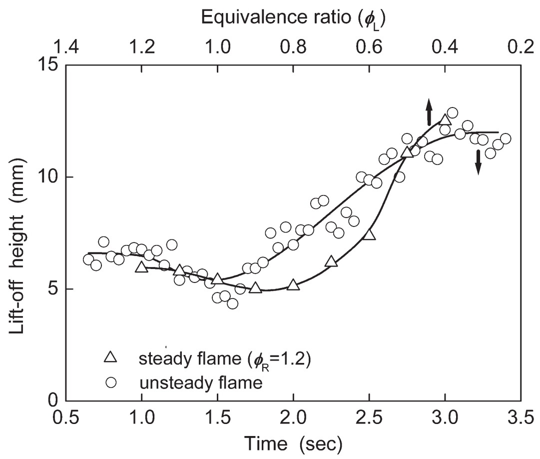


Fig.6 Lift-off height.

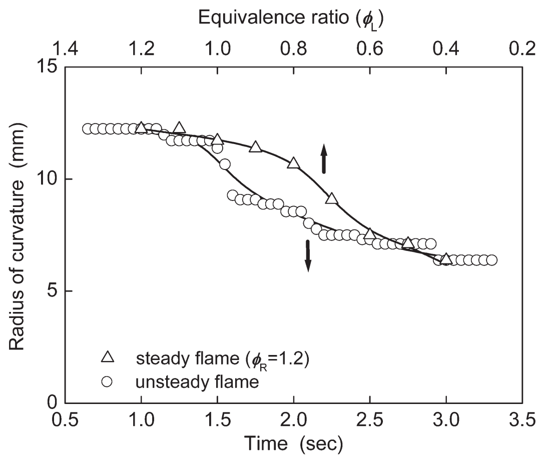


Fig.7 Radius of curvature.

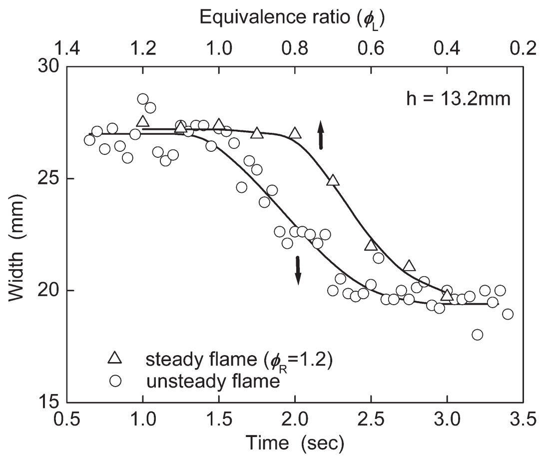


Fig.8 Flame width.

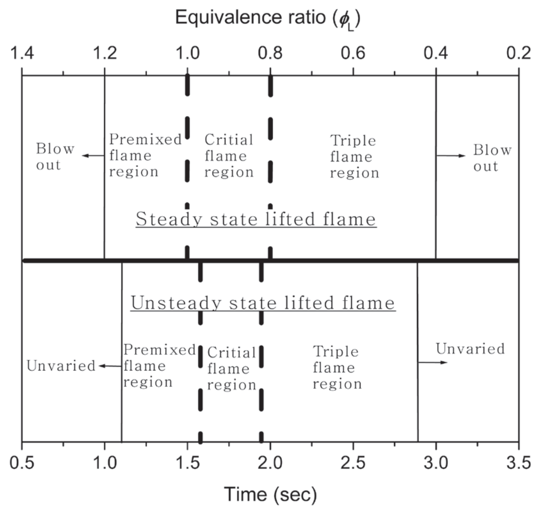


Fig.9 Flame classification.

a constant value with the passage of time, then from time, t = 1.2 sec when the shape of the flame changed, it gradually decreased, from approximately t = 1.5～1.8 sec it rapidly decreased, and thereafter gradually decreased.

Figure 8 represents the flame width of the steady-state lifted flame and unsteady-state lifted flame from the slot burner. The flame width was measured from the left to the right at a height of 13.2 mm from the leading edge of the lifted flame. For the steady-state lifted flame, the width decreased as ϕ_L decreased. Kioni et al. [3] previously experimentally observed the width of a triple flame in relation to the fuel mass fraction gradient and demonstrated that, as the fuel mass fraction gradient increases, the flame width decreases.

This is also consistent with results of the study by Jang et al. [7], which showed that, as the concentration difference increases, the flame width decreases. In the present study, the flame width of the unsteady-state lifted flame initially maintained a constant value with the passage of time, then decreased at t = 1.2 when the shape of flame changed, decreased sharply from t = 1.5, and continued to decrease until t = 2.8.

Figure 9 classifies the regions of the lifted flame in a steady state and unsteady state into the premixture flame region, critical flame region, and triple flame region based on the gradients of the flames' curvature radius, width, lift-off height, and luminescence intensity. For example, in case of the steady lifted flame, the gradient of the lift-off height at the lean equivalence ratio (ϕ_L) between 1.2 and 1.0 is gentle, that of the equivalence ratio (ϕ_L) between 1.0 and 0.8 is gentler and that of the equivalence ratio (ϕ_L) between 0.8 and 0.4 is steep. Depending on the change in the instantaneous equivalence ratio of the premixture supplied, the characteristics, including the lift-off height, flame width, curvature radius, and luminescence intensity, of the lift-off flame in an unsteady state tended to be similar to those of the lift-off flame in a steady state.

As presented in Figs. 2～9, the steady-state lifted flame changed, with changes in the concentration difference, from a premixed flame to a critical flame, then to a triple flame with a diffusion trailing flame in the middle. Furthermore, as the concentration difference increased, the lift-off height declined where the leading edge of the flame was located, then increased again near the triple flame, in addition the changes in the flame width, curvature radius, and luminescence intensity were all consistent with the results of previous studies by Jang, et al. [7]. Meanwhile, the lift-off height, flame width, radius of the curvature, and luminescence intensity for the unsteady-state lifted flame all showed a similar tendency to those for the steady-state lifted flame, depending on the instant equivalence ratio of the mixture supplied.

Therefore, it is concluded that the behavior of an unsteady-state lifted flame made under a specific condition in this paper, can be effectively forecast using the behavior of a steady-state lifted flame.

4. Conclusions

Characteristics of lifted flame resulting from an instant change of equivalence ratio were studied. Results show that the unsteady lifted flame made by an equivalence ratio conversion system for a given fuel, has a similar tendency in the gradients to the steady lifted flame when comparing with the characteristics of a steady lifted flame to change from a premixed flame to a critical flame, then to a triple flame with a diffusion flame positioned in the middle according to the concentration difference. The unsteady lifted flame is also classified into three regions, a premixed flame region, a critical flame region, and a triple flame region based on the gradients of the flames' curvature radius, width, lift-off height and luminescence intensity as done in the steady lifted flame, even though the unsteady lifted flame stay at for 1.6 seconds only.

The present study shows that the behavior of the unsteady lifted flame made under a specific condition in this paper, can be predicted based on the behavior of a steady lifted flame.

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