Dynamic Behaviour of Oscillating Edge Flame in Low Strain Rate Non-premixed Methane Flames

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1 Preliminary consideration

It has been well known that one-dimensional premixed flames oscillate for sufficiently large Lewis numbers and the oscillations are augmented by the presence of heat losses. The large Lewis number instabilities are indeed a consequence of non-similar thermal and reactant fields, of which non-unity Lewis numbers are one cause. Flame oscillation also occurs even in one-dimensional diffusion flames. The theoretical study by Kirkby and Schmitz showed that oscillatory instabilities were relevant to near-extinction conditions, large Lewis numbers and heat losses[1]. It was also clarified that appreciable volumetric heat losses reduce the critical Lewis number for the oscillatory instabilities[2]. Partially premixed edge flame is an intermediate regime between the limiting cases of premixed and nonpremixed combustion. This has recently attracted research interest because of its unique propagation behavior in mixing layers. These have been found in flame holes, and, lifted flames. They could act as local ignition fronts or failure waves. As in the case of one-dimensional flames, it was possible that appropriate heat losses may result in edge flame oscillation even for unit Lewis number[3]. Onset conditions of edge flame oscillation were verified that these could be influenced by differential diffusion, mixture strength, flow rate, and radiative heat losses. There have been several studies on edge flame behaviors conducted in counterflow diffusion flame configurations. Santoro et al. decribed the entire process of flame holes(creation, growth, recovery)[4]. A stable negative edge flame was formed using a coannular nozzle where outer nitrogen-guard flow velocity was so high that the outer flame could be extinguished[6]. However, these studies were on the edge flame behaviors near stretch-induced flame extinction. The previous study[6] investigated the extinction behaviors of counterflow diffusion flames through experiments and 2DNS. The numerical simulations also illustrated that low strain flame extinction is attributed not only to radiative heat loss but also to lateral conductive heat loss. It was implied that the flame length in low strain rate flame could be an indicator of lateral conductive heat loss. As shown in Fig. 1 the configuration of concentration field formed near the edge of the outer flame in a low strain rate is that of a partially premixed flame. In this paper, we report the onset conditions of edge flame oscillation and their oscillation modes near extinction in low strain rate flames. Special concern is also given to effects of heat losses on edge flame instabilities.

2 Experimental setup

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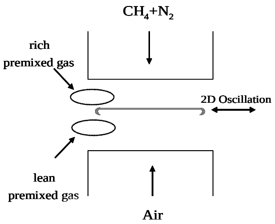

Fig. 1 Schematic diagram of low strain rate counterflow diffusion flame configuration.

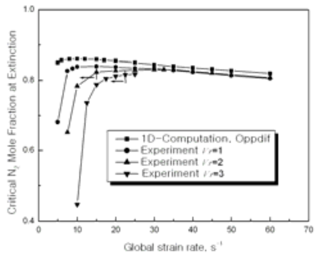

Fig. 2 Measured and computed critical nitrogen mole fractions of the fuel stream at extinction with global strain rate for various velocity ratios.

The inner diameters of the reactant duct nozzles are 26.0 *mm* and the separation distance between the reactant duct nozzles is set to be 15.0 *mm*. The water jacket of the upper nozzle is used to cool down the burner surface. Exhaust gases, sucked through a couple of pipes by a vacuum pump, pass through the water jacket. 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. Fuel is supplied from the upper duct nozzle to force the flame not to be positioned near the upper duct nozzle. Fuel used is a high grade of methane with a purity of 99.95% and that of nitrogen is also 99.95%. The global strain is defined as follows:

$$a_g = \frac{2V_a}{L}\left(1 + Vr\frac{\sqrt{\rho_f}}{\sqrt{\rho_a}}\right) \qquad (1)$$

Where V_r is defined as $V_r = V_f / V_a$ which is the velocity ratio between the exit velocities of the upper and lower duct nozzles. The parameters, V and ρ, denote the velocity and density of the reactant stream at the duct boundary, respectively, L is the duct separation distance, and the subscripts, α and f, represent the air and fuel streams, respectively. The key contribution to low strain rate flame extinction was not only radiative heat loss[7] but also lateral conduction heat loss[6]. The Oppdif code[8], based on a similarity concept, is used to compare numerical prediction with experimental observations though the one-dimensional calculation does not consider multi-dimensional effects such as a lateral conductive heat loss.

3 Results and discussion

Fig. 2 depicts the critical nitrogen mole fraction at extinction with varying global strain rates through the experiments and the numerical predictions. 1D calculation does not consider finite burner diameter, while both effects appear in all experiments. In Fig. 2, the numerically obtained critical nitrogen mole fractions at extinction indicate a maximum at 8 s^{-1}**.** Flame extinctions at global strain rates less than 8 s^{-1} were known to be responsible for flame radiation and those larger than 8 s^{-1} were attributed to flame stretch[7]. The experimentally obtained critical nitrogen mole fractions at extinction shows a maximum between 10 and 15 s^{-1} for $V_r = 1$, and those shift to higher strain rates with the velocity ratio increase. The experimentally attained critical mole fractions at extinction are almost the same at high strain rate flames irrespective of velocity ratio, while those at low strain rate flames decrease as velocity ratio increases. The large differences between these curves may be due to laterally conductive heat loss in addition to radiative heat loss as was shown in the previous study[6]. This is because flame length, which is an inverse indicator of laterally conductive heat loss, decreases with decreasing global strain rate and increasing velocity ratio as can be seen in the following equation:

$$q_r = k\frac{\partial T}{\partial r} \sim \frac{1}{l_f} \qquad (2)$$

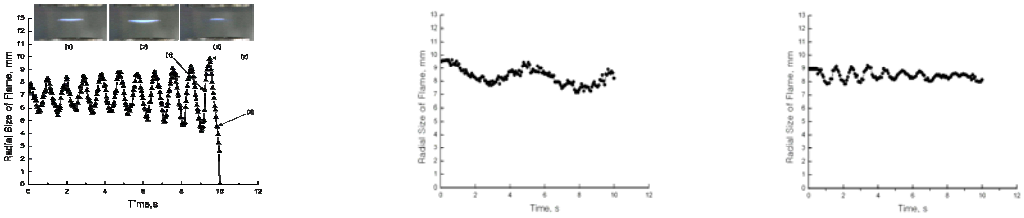

Fig. 3 Representative flame oscillation modes: (a) a glow oscillation mode, a_g =10 s^{-1}, X_{N2}=0.448, V_r =3, (b) a harmonic oscillation mode, a_g =10 s^{-1}, X_{N2}=0.407, V_r =3, and (c) a decaying oscillation mode, a_g =12.5 s^{-1}, X_{N2}=0.712, V_r =3.

where l_f is a flame length. The differences among these curves become small with the increase of global strain rate since radiative heat loss deceases due to the reduction of flame thickness, and flame length increases with increasing global strain rate. In Fig. 2, the vertical solid lines mean the limit of flame oscillation. That is, at the extinction conditions of $V_r = 1$, edge flame oscillation does not appear in all global strain rates. The limit global strain rate of edge flame oscillation is extended to a higher strain rate as velocity ratio increases. This is so because flame length decreases as velocity ratio increases, and thus lateral conductive heat loss increases as can be known in the equation (2). As was explained in Fig. 2, edge flame oscillation occurred at some ranges of global strain rate for the extinction conditions. It might be necessary to elucidate the onset conditions of flame oscillation and flame stability maps for various parameters. Figure 4 displays representative flame oscillation modes. In Fig. 4 the dynamic flame behaviors for about 10 s were taken by a digital media camera. The edge flame oscillations are categorized into three: a decaying-, a harmonic-, and a growing-oscillation mode. In the growing oscillation mode, flame oscillates periodically and the amplitude increases gradually prior to flame extinction. The frequency is near about 1.0 Hz. The growing modes appear only at the individual flame extinction conditions of low strain rate flames. In the harmonic oscillation mode of Fig. 4(b), the flame oscillates without the change of oscillation amplitude and the frequency varies between 0.2 and 1.0 Hz. In the decaying oscillation mode in Fig. 3(c), the flame oscillates periodically for some time, but the amplitude decreases gradually and its periodicity disappears finally. Figure 4 displays flame stability map and their flame oscillation modes with the variation of global strain rate. In Fig. 6 the circle symbol means that flame does not oscillate and extinguishes abruptly. The inverse triangle symbol implies the boundary between decaying- and harmonic-oscillation modes. The triangle symbol indicates the onset conditions of flame oscillation. Decaying oscillation mode appears at the nitrogen mole fractions between 0.192 and 0.448 for a_g =10 s^{-1}. At the nitrogen mole fraction of 0.192, there co-exists a decaying- and harmonic-oscillation mode. Flame oscillation disappears at the global strain rates larger than 22 s^{-1} since lateral heat loss decreases due to the increase of flame length. In the present study, the fuel Lewis number is 0.7912 at the onset condition of flame oscillation for a_g =10 s^{-1}, and it should be noted that the lowest critical fuel Lewis number, experimented in the present study, is much lower than those in the previous studies[3]. It should be also kept in mind that the previous studies were on the edge flame oscillations near stretched flame extinction. Meanwhile, the edge flame oscillations occurred even at the fuel Lewis numbers much less than unity at low strain rate flames in the present study because of excessive lateral heat loss in addition to radiative loss. It is, consequently, clarified that flame extinction conditions and oscillatory edge flame instabilities in low strain rate counterflow diffusion flames are relevant not only to fuel Lewis number but also heat losses.

4 Conclusion

Experimental studies in CH_4/N_2-Air counterflow diffusion flames have been implemented to clarify the edge flame dynamics near flame extinction with the variations of global strain rate, fuel Lewis number, and velocity ratio. Flame length is closely relevant to lateral heat loss, and this affects flame extinction and flame oscillation instabilities directly. That is, the critical nitrogen mole fraction at flame extinction decreases as velocity ratio increases at low strain rate flames. This is because lateral heat loss increases with the increase of velocity ratio as can be confirmed by the reduction of flame length and also the equation (2), and that in addition to radiative loss

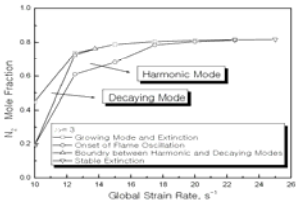

Fig. 4 Flame stability map and their flame oscillation modes with global strain rate; V_r =3.

makes flame strength become weak. The edge flame oscillation instabilities in low strain rate counterflow diffusion flames are categorized into three: a growing-, a decaying-, and a harmonic-oscillation mode. Growing oscillation mode appears only at the flame extinction conditions of low strain rate flames,The growing oscillation also disappears at the global strain rates larger than a critical value which corresponds to a_g =22 s^{-1} with the inner burner diameter of 26.0 *mm* in the present study. The regime of the oscillation modes at low strain rate flames is also definitely provided. It is also found that lateral heat loss in addition to radiative loss can be the key to adjust the individual flame oscillation modes. Flame extinction conditions and oscillatory edge flame instabilities in low strain rate counterflow diffusion flames are relevant not only to fuel Lewis number but also heat losses. It is consequently seen that lateral heat loss in addition to radiative loss contributes to flame extinction and edge flame oscillation importantly.

5 Acknowledgement

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