대향류 슬롯 버너에서 이중 예혼합 선단화염의 전파특성

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Edge Flame propagation for Twin Premixed Counterflow Slot Burner

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ABSTRACT

Propagation rates (U_{edge}) of various premixed, twin edge-flames were measured as a function of global strain rate (σ), mixture strength, and Lewis number (Le). Using a counterflow slot-jet burner with electrical heaters at each end, both advancing (positive U_{edge}) and retreating (negative U_{edge}) edge-flames can be studied as they propagate along the long dimension of the burner. Experimental results are presented for premixed methane/air twin flames in terms of the effects of σ on U_{edge}. Both low-σ and high-σ extinction limits were discovered for all mixtures tested. As a result, the domain of edge-flame stability was obtained in terms of heat loss factor and normalized flame thickness, and comparison with the numerical result of other researchers was also made. For low ($CH_4/O_2/CO_2$) and high (C_3H_8/air) Lewis number cases, propagation rates clearly show a strong dependence on Le.

Key Words : edge flames, twin premixed flame, advancing, retreating, extinction limit, short-length flame.

기 호 설 명

d: gap spacing between burners, cm.
U_{edge}: propagation speed of edge, cm/s.
σ: global strain rate, 1/s.
S_L: 1-D laminar flame speed, cm/s.
Le: Lewis number
ρ_u: gas density of unburned mixture
ρ_b: gas density of burned mixture.
ε: normalized flame thickness.
κ: normalized heat loss factor

1. Introduction

For the past decade, the transition from burning to non-burning states, such as a hole created in a turbulent field, has been studied via the use of a simplified model known as an edge-flame. Edge-flames are idealized two-dimensional representations of more complex combustion phenomena that provide the insights and universal character necessary to understand flames with edges (Buckmaster, 2002). In order to better understand turbulent flow field phenomena, many situations arise in combustion where edge-flames are important. As pointed out by Buckmaster (2002), a flame spreading over a fuel bed, a candle flame in micro-gravity, and a lean methane/air flame in a tube are all cases which may exhibit a flame with an edge for which the propagation and/or

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extinguishment of the flame is directly related to the edge characteristics.

Many theoretical studies of both premixed (Vedarajan and Buckmaster, 1998 Vedarajan *et al.*, 1998; Daou and Liñan, 1999) and non-premixed (Daou and Liñan, 1998; Daou *et al.*, 2002, Daou *et al.*, 2004) edge-flames have been conducted in the past. As discussed by Cha and Ronney (2006), these theoretical studies show that edge-flames will typically propagate parallel to the flame sheet with positive, negative, or zero edge speeds (U_{edge}) depending on factors such as the global strain rate (σ), heat losses, and Lewis number (Le). The theoretical models specifically indicate that U_{edge} will be positive for moderate and negative for high , while significantly higher , that near the extinction strain (σ_{ext}), leads to a condition where U_{edge} approaches -∞. In the range between moderate and σ_{ext}, a continuous flame sheet is predicted which could last indefinitely unless a turbulent flow field, or some other locally high strain phenomena, were to create a hole. With the exception of the work by Cha and Ronney (2006) and Clayton *et al.* (2006), there are no experimental results in the literature which confirm or refute the predicted values of U_{edge}, or the effect of σ on such values. This work considers twin, premixed edge-flames and the role of global strain rate, mixture strength, and Lewis number on propagation speeds.

2. Experiment

One of the most common flow configurations in the study of edge-flames is the counterflow round-jet apparatus. However, round-jets are unsuitable here due to the fact that extensional strain occurs in both coordinate directions parallel to the plane of the flame. A counterflow slot-jet, or rectangular-jet, overcomes this problem by only creating extensional strain in the direction orthogonal to the slots themselves with only a very small extensional strain along the length of the slots (the long dimension), or direction of edge propagation (Kaiser et al., 2000).

The counterflow slot-jet burner employed (Fig. 1) for the experiments consists of two 0.5 cm 13 cm central rectangular which results in nearly plane strain in the plane orthogonal to the edge propagation (Cha and Ronney, 2006). A very small flow does occur in the direction orthogonal to the jets, or in the direction of edge-flame propagation, so small ceramic spacers were placed at both ends between the upper and lower jets to help minimize any unwanted extensional strain in this direction.

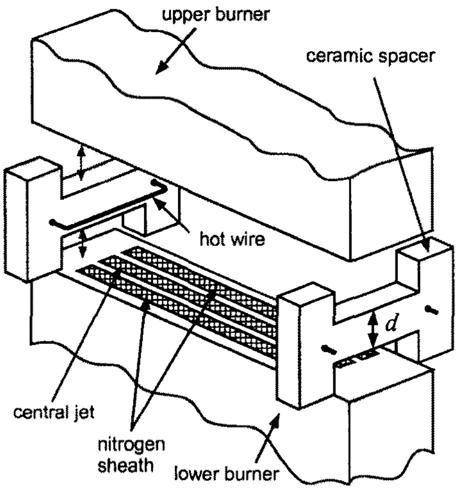


Fig. 1: Close-up view of counterflow slot-jet burner showing central jet, sheath flow jets, and ceramic burner spacers with electrically heated wire.

Equal values of velocity, U_{jet}, were employed for the upper and lower central jet streams. On both sides of these jets, additional 0.5 cm 13 cm slot jets provided N_2 sheath flow to suppress the shear layer between the flame jets and the ambient atmosphere. All six jets were filled with steel wool and the jet exits were fitted with stainless steel honeycomb (0.7 mm channel width) to ensure uniformity of the exit flow. The jets (and thus the gases at the jet exits) were maintained at room temperature by water cooling. Commercial mass flow controllers with accuracy 1% of full scale controlled the gas flows. The sheath flow velocities, U_{sheath}, were set to match the central jets, U_{jet}, to avoid shear-layer instabilities between the reactive flow and sheath flows.

Advancing edge-flames ($U_{edge} > 0$) are produced by establishing a uniform flame between the counterflow slot-jets, extinguishing or "erasing" part of the flame by sweeping a small round jet of N_2 across the length of the slot, leaving only a small burning region at one end, then suddenly removing the N_2 jet. This procedure results in an edge-flame that propagates across the length of the slot, thereby reestablishing the uniform flame. The conditions for retreating edge-flames ($U_{edge} < 0$) are not directly accessible in a slot-jet apparatus with "bare" slot ends. To overcome this limitation, electrical wire resistance heaters were added to the ceramic spacers (Fig. 1) at both ends of the slots which act as anchors. Retreating edge-flames can then be triggered with a jet of N_2 that extinguishes the flame in a region adjacent to the heated.

A Photron FASTCAM ultima 1024 high-speed camera is used to directly record edge-flame propagation or in conjunction with a Schlieren imaging system. With a framing rate as high as 500 Hz and a shutter speed as low as 0.125 ms the camera/Schlieren system is capable of capturing edge-flame propagation rates greater than 200 cm/s.

3. Results and Discussion

3.1 Effect of Mixture Strength

For premixed flames, Daou *et al.* (2003) expressed the combined effects of stain and heat losses in terms of a dimensionless flame thickness $\varepsilon \equiv (\sigma\alpha\ /(2S_L^2))^{1/2}$, where α is the gas thermal diffusivity and S_L is the laminar burning velocity of a stoichiometric mixture of the fuel and oxidizer streams, and a dimensionless heat loss $\kappa \equiv \beta(\alpha/S_L^2)\kappa_0$, where β is the non-dimensional activation energy (Zeldovich number) and κ_0 is a linear volumetric heat loss coefficient (units s^{-1}). Results are non-dimensionalized accordingly to compare with previous computational predictions.

Edge-flame propagation speeds, U_{edge}, for CH_4/air mixtures are plotted in Fig. 2 as a function of global strain rate, σ ($= 2U_{jet}/d$), indicating both low-σ and high-σ extinction limits. As with single premixed edge-flames, U_{edge} is lower for weaker mixtures for all values of σ. Strong mixtures, thus smaller κ and smaller impact of heat loss, exhibit "short-length" flames near the low-σ limit whereas weaker mixtures exhibit retreating edge-flames. "Short-length" flames are single or multiple flames on the order of 1 cm in length, with both a leading edge and trailing tail, advancing from one side of the burner to the other. The three strongest mixtures exhibit advancing "short-length" flames at a low-σ limit near $\sigma \approx 12 \pm 1\ s^{-1}$. "Short-length" flames are only observed near the low-σ extinction limit. For all conditions where the high-σ limit was reached, retreating edge-flames were observed. The high-σ extinction limit varies considerably for each mixture, but was not reached for the two strongest mixtures, 6.5% and 6% CH_4, due to burner flow limitations.

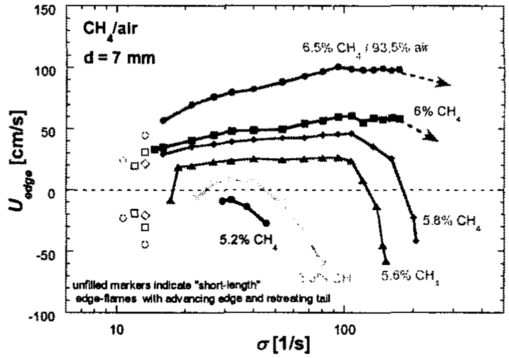


Fig. 2: Effect of dimensional strain rate (σ) on dimensional edge speed (U_{edge}) for various CH_4/air mixtures.

Figure 3 shows the same information as Fig. 2 in non-dimensional form. U_{edge} is scaled by $S_L(\rho_u/\rho_b)$ and is plotted against the dimensionless flame thickness, ε, proposed by Daou *et al.*(2003). It can be argued that the scaling factor of $S_L(\rho_u/\rho_b)$ may not be the most accurate option for twin premixed flames but results in scaled propagation speeds on the order of 1, similar to results of nonpremixed edge-flames, and may prove acceptable for these preliminary discussions (Cha and Ronney, 2006).

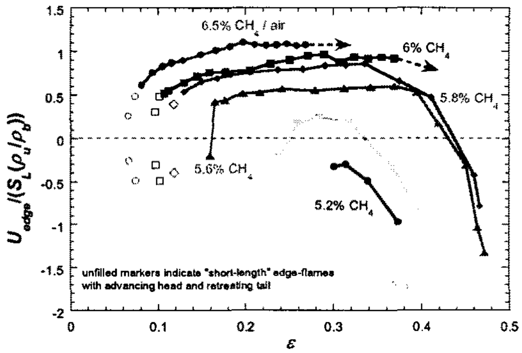
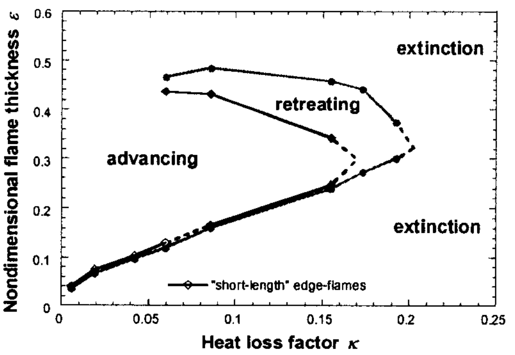


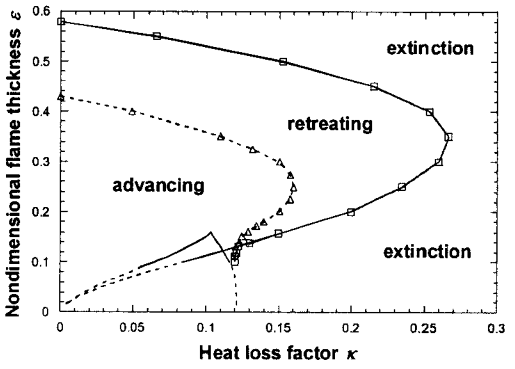
Fig. 3: Scaled U_{edge} vs. non-dimensional flame thickness ε for various CH_4/air mixtures.

To summarize the effect of mixture strength, a map of flame behavior in κ-ε space is shown in

Fig. 4a along with the corresponding predictions by Daou et al. (2003) in Fig. 4b. Similarities between the two plots include (1) the strain-induced extinction limit occurs near ε = 0.35, (2) the heat-loss-induced limit occurs along a limit line with roughly $\varepsilon \approx 1.5\kappa$, and (3) the ultimate extinction limit, where strain and heat loss limits converge, is near κ = 0.25 which is approximately ten times larger than single premixed flames indicating that twin flames are much stronger due to the back-to-back configuration.



(a)



(b)

Fig. 4: Map of propagation mode and extinction limits of edge-flames with heat loss factor κ and non-dimensional flame thickness ε. (a) Experimental results for CH_4/air mixtures. (b) Theoretical predictions from Daou et al. (2003).

3.2 Effect of Lewis Number

The effects of the nondimensional flame thickness ε on the scaled edge-flame propagation speed for fuel Le larger than unity are shown in Fig. 5. Data for a CH_4/air mixture (Le $\approx$ 1) with a lower S_L than the weakest C_3H_8/air mixture tested are also shown for comparison purposes. Figure 5 shows that the values of U_{edge} are much lower for the Le > 1 cases even at higher S_L (thus lower heat loss parameter κ) and same ε. It should be noted that none of the C_3H_8/air mixtures tested exhibit "short-length" flames or retreating edge-flames.

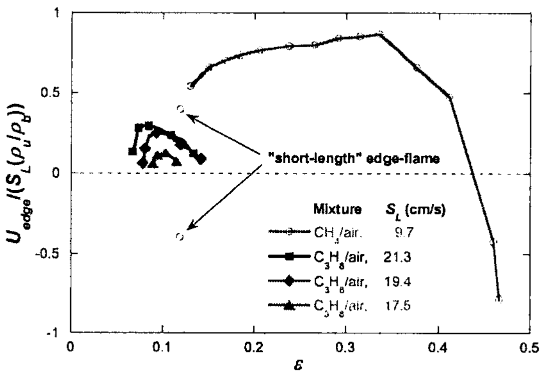


Fig. 5: Scaled U_{edge} vs. for C_3H_8/air mixtures (Le > 1) compared to CH_4/air (Le $\approx$ 1)

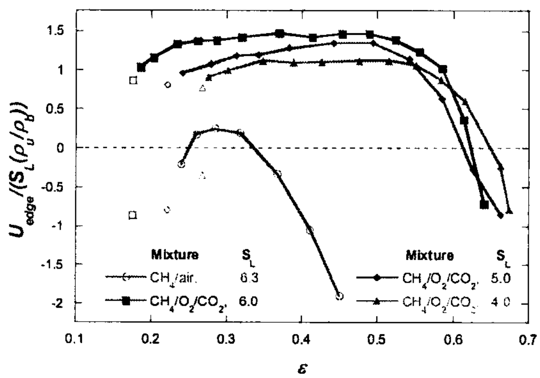


Fig. 6: Scaled U_{edge} vs. for $CH_4/O_2/CO_2$ mixtures (Le < 1) compared to CH_4/air (Le $\approx$ 1)

Edge-flame propagation speeds for Le < 1 mixtures are shown in Fig. 6. By using $CH_4/O_2/CO_2$ mixtures, the fuel and oxygen Lewis numbersare nearly equal and both are less than unity. Figure 6 shows that Le < 1 mixtures have much higher scaled values of U_{edge} than Le $\approx$1 mixtures having similar S_L (thus κ). The high-σ extinction limit occurs at ε = 0.66 0.02 for the mixtures shown in Fig. 6, which is higher than that for Le $\approx$ 1 mixtures (Fig. 3) or Le > 1 (Fig. 5), but for each mixture family having nearly the same Le, the extinction limits are nearly independent of S_L (thus κ).

4. Conclusions

Propagation rates of twin, premixed edge-flames in a slot-jet counterflow were measured as a function of strain rate for varying mixture strength and Lewis number. "Short-length" flames having concurrent propagating head and retreating tail were observed near the low-strain extinction limit for strong mixtures, while weaker mixtures exhibited retreating edges. High-strain conditions near extinction resulted in retreating edges for all Le $\leq$ 1 conditions in which the high-strain limit was reached. In addition, flame behavior as depicted in κ-ε space for CH_4/air mixtures compares favorably with predictions by Daou et al. (2003).

U_{edge} is well scaled with $S_L(\rho_u/\rho_b)$, since expanded burnt gas between the two premixed flame sheets pushes the flame edge and thus scales to the first order of the density ratio whereas single premixed edge-flames scale better to the one-half power.

Similar to nonpremixed edge-flames, high (low) Le mixtures behave like a weaker (stronger) mixtures compared to Le $\approx$ 1, and heat loss induced low-ε extinction limits were well correlated with heat loss factor for each tested mixture irrespective of Lewis numbers.

Future experiments will consist of nonpremixed fuel-air edge-flames and edge-flames with much lower Le, such as Hydrogen.

Acknowledgments

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