대향류 슬롯 버너에서 예혼합 선단화염의 전파특성

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Characteristics of Edge Flames for Premixed Flames in a Counterflow Slot Burner

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ABSTRACT

The propagation rates (U_{edge}) of various premixed 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}) edges can be studied as they propagate along the long dimension of the burner. Preliminary results are presented for single and twin premixed hydrocarbon edge-flames in terms of the effects on U_{edge}. A low-σ extinction limit has been discovered for all mixtures tested but further analysis is necessary for full characterization since sufficiently high-σ leads to an apparent stability limit. Propagation rates clearly show a strong dependence on Le. Future work will focus on completing the premixed hydrocarbon edge-flame analysis and include investigations into non-premixed edge-flames and edge-flames composed of fuels such as hydrogen (H_2) with significantly lower Le.

Key Words : edge flames, single (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 extinguishment of the

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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 $-\infty$. 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), there are no experimental results in the literature which confirm or refute the predicted values of U_{edge}, or the effect has on such values. This work considers premixed edge-flames for both single and twin cases, and the role mixture strength, Lewis number (Le), and heat loss play in the resulting 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.

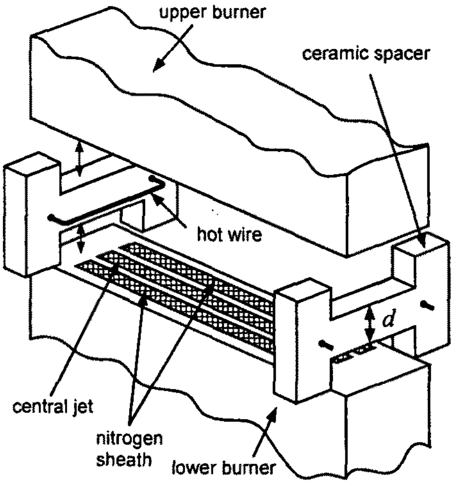

Fig. 1: Close-up view of counterflow slot-jet burner showing central jet, sheath flow jets, and ceramic burner spacers with electrically heated wire

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-flames propagation rates greater than 200 cm/s

3. Results and Discussion

Table 1 shows mixtures and flame properties for three single premixed CH_4/air flames. 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), κ_0 is a linear volumetric heat loss coefficient (units s^{-1}). Results are non-dimensionalized accordingly to compare with previous computational work.

Edge-flame propagation speeds, U_{edge}, for the three CH_4/air mixtures (shown in Table 1) are plotted in Fig. 2 as a function of global strain rate, σ, showing low-extinction limits. Each of the three mixtures has a low-extinction limit at $= 10 \pm 3$ s^{-1} where advancing "short-length" flames form. "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. "Short-length" flames are only observed near the low- extinction limit. The high-extinction limit varies considerably for each mixture but is only shown for 7.75% CH_4. The maximum value of U_{edge} occurs at $\sigma \approx 40$ s^{-1} for all three mixtures.

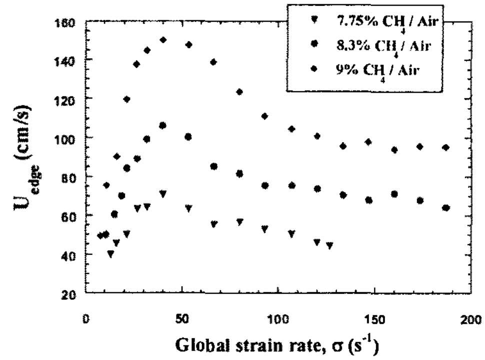

Fig. 2: Effect of dimensional strain rate (σ) on dimensional edge speed (U_{edge}) for various CH_4/air mixtures. Associated properties located in Table 1.

Figure 3 shows the same information as Fig. 2 in non-dimensional form. U_{edge} is scaled by $S_L(\rho_u/\rho_b)^{1/2}$ and is plotted against the dimensionless flame thickness, ε, proposed by Daou *et al.* (2003). It can be argued that the scaling factor of $S_L(\rho_u/\rho_b)^{1/2}$ may not be the most accurate option for single premixed flames but the resulting scale on the order of 1, which is the same in non-premixed edge flames, may prove acceptable for these preliminary discussions. Note that all three mixture strengths collapse along a similar curve at large values of .

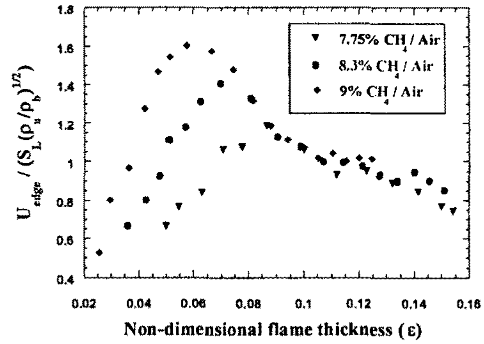

Fig. 3: Scaled U_{edge} vs. non-dimensional flame thickness

Table 1: Experimental conditions for CH4/air single premixed edge-flames and corresponding flame properties.

Mixture	Mixture volume ratio	S_L (cm/s)	d (cm)	T_{ad} (K)	$(\rho_u/\rho_b)^{1/2}$	α (cm^2/s)	β	κ
CH_4/Air	1/11.9	23.1	0.75	1996	2.58	0.2	9.10	0.00914
CH_4/Air	1/11.1	28.6	0.75	2085.3	2.64	0.2	8.78	0.00575
CH_4/Air	1/10.1	34.7	0.75	2181.4	2.70	0.2	7.66	0.00341

for various CH_4/air mixtures. Associated properties located in Table 1.

Table 2: Experimental conditions for single premixed edge-flames and corresponding flame properties

Mixture & Lewis numbers	Mixture volume ratio	S_L (cm/s)	d (cm)	T_{ad} (K)	$(\rho_u/\rho_b)^{1/2}$	α (cm^2/s)	β	κ
CH_4/Air $Le_{fuel} = 0.96$ $Le_{O2} = 1.10$	1/11.1	28.6	0.75	2085.3	2.64	0.200	8.78	0.00575
$CH_4/O_2/CO_2$ $Le_{fuel} = 0.74$ $Le_{O2} = 0.86$	1/2/3.69	28.6	0.5	2304.8	2.81	0.134	13.5	0.00402
C_3H_8/Air $Le_{fuel} = 1.86$ $Le_{O2} = 1.05$	1/30.3	28.6	0.7	2022.8	2.64	0.187	6.26	0.00359

Table 2 shows mixtures and flame properties for three single premixed edge-flames with varying Le. While Le is different for each of the three mixtures, the laminar burning velocity is kept constant. Figure 4 shows the scaled propagation rates for the three mixtures plotted against the non-dimensional flame thickness. Like the CH_4/air cases, these mixtures develop "short-length" flames at the low-σ extinction limit.

Observations indicate that the lowest Le mixture, $CH_4/O_2/CO_2$, has the highest value of maximum scaled U_{edge} while the highest Le mixture, C_3H_8/air, has the lowest. This indicates that Le results in similar behavior as that described for non-premixed flames in Cha and Ronney (2006). Conversely, the highest Le mixture, C_3H_8/air, has the lowest maximum propagation rate and the highest low-σ extinction limit which indicates it acts weaker than the other two mixtures.

U_{edge} scaled by $S_L(\rho_u/\rho_b)$ plotted against the non-dimensional flame thickness for three twin premixed conditions (shown in Table 3) is shown in Fig. 5. Each of the three mixtures has a low- extinction limit at = 15 ± 3 s^{-1} where advancing "short-length" flames form as with single premixed edge-flames.

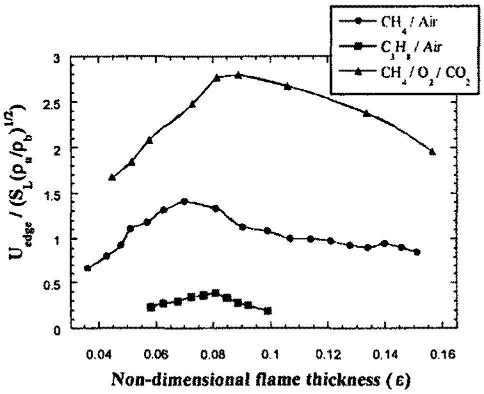

Fig. 4: Scaled U_{edge} vs. non-dimensional flame thickness for single premixed edge-flames of varying Le. Associated properties located in Table 2.

Initially all three mixtures were to have identical laminar burning velocities but the C_3H_8/Air mixture

Table 3: Experimental conditions for twin premixed edge-flames and corresponding flame properties.

Mixture & Lewis numbers	Mixture volume ratio	S_L (cm/s)	d (cm)	T_{ad}(K)	$(\rho_u/\rho_b)^{1/2}$	α (cm^2/s)	β	κ
CH_4/Air $Le_{fuel} = 0.96$ $Le_{O2} = 1.10$	1/16.2	10.7	0.75	1640.8	5.47	0.200	8.92	0.0418
$CH_4/O_2/CO_2$ $Le_{fuel} = 0.74$ $Le_{O2} = 0.86$	1/2/5.58	10.7	0.5	2032.1	6.83	0.126	15.16	0.0634
C_3H_8/Air $Le_{fuel} = 1.86$ $Le_{O2} = 1.05$	1/40.7	18.4	0.7	1674.1	5.71	0.190	8.55	0.0140

was too weak and needed an increased fuel concentration in order to establish stable flames. Even after increasing the fuel percent of propane, and thus S_L, the mixture shows the lowest peak U_{edge} and lowest high-σ extinction limit. In other words, as the only mixture with Le > 1, it acts as the weakest mixture even though it has the highest laminar burning velocity.

The scaling factor $S_L(\rho_u/\rho_b)$ used in Fig. 5 represents the gas expansion experienced by the burned product gases. A qualitative explanation can be posited by realizing that the burned reactant products reside between the two premixed flames. The trapped hot combustion products have a lower density, ρ_b, than the unburned reactant gas, ρ_u. Conservation of mass dictates that the propagating edge speed must increase in order to account for the expansion of burned products. It should be noted that U_{edge} is measured in the laboratory reference frame while the flame burning velocity, S_L, is computed relative to the unburned gas ahead of the propagating edge-flame. Figure 5 shows scaled U_{edge} on the order of 1 so for the purposes of exhibiting these preliminary results the scaling factor seems reasonable.

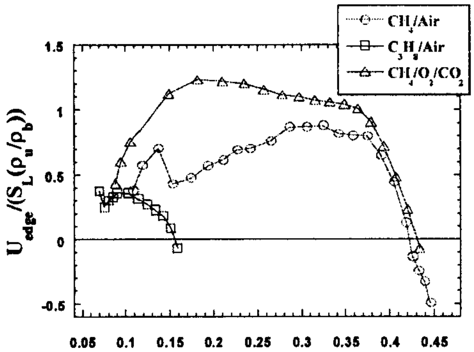

Fig. 5: Scaled U_{edge} vs. non-dimensional flame thickness for twin premixed edge-flames of varying Le. Associated properties located in Table 3.

All three mixtures in Fig. 5 show a steep decrease in scaled U_{edge} at the high-σ end with each exhibiting retreating edge-flames prior to extinction. Both the CH_4/air and $CH_4/O_2/CO_2$ mixtures have the same S_L (thus similar) and exhibit similar trends across the entire range of . CH_4/air must be double-checked to verify the values of edge speed for moderate values of (thus σ) are repeatable or an anomaly. The C_3H_8/air mixture has the highest S_L (thus lowest κ) but results in the lowest values of edge speed and high-σ extinction. Preliminary observations appear to indicate that high-Le mixtures, i.e. C_3H_8/air, act weaker than low and moderate-Le mixtures as in single premixed edge-flames.

The low-ε heat loss induced extinction limit occurs at nearly the same for the Le < 1 and Le ≈ 1 mixtures having nearly the same S_L (thus κ). This is further evidence that the low-ε heat loss induced extinction limit is practically unaffected by Le. To quantify this assertion further, Fig. 6 shows the correlation between at the low-σ extinction limit and the heat loss parameter for all low-σ limits measured in this study. The data covering a nearly 2-decade range of fit a simple power-law relation with exponent 0.59 reasonably well with no noticeable influence of Le. It should be noted that the definition of is slightly altered here to include a factor of β which is the definition used for non-premixed edge-flames (Daou *et al.*, 2004) and may not be entirely appropriate for premixed edge-flames regardless of the apparent correlation.

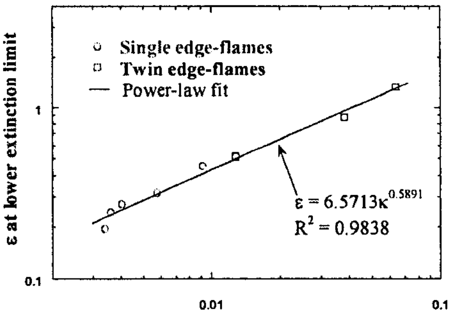

Fig. 6: Non-dimensional flame thickness () at low-strain (heat loss induced) extinction limit as a function of non-dimensional heat loss () for all conditions tested in this work.

None of the premixed edge-flames tested exhibit negative values of U_{edge} at the low-σ regions as predicted by Daou *et al.* (2003) for conditions where $\kappa < 0.1$. While twin premixed cases exhibit negative values of U_{edge} at the high-σ extinction limit as predicted, single premixed cases are hindered by a self-induced flame hole before reaching a true extinction limit. Though entire flame did not extinguished totally by this self-induced-hole, the behavior of the flame edge at this hole was not determinant. It demonstrated propagating or retreating behavior, unconditionally. For further increasing jet velocity, entire flame was extinguished by retreating edge of this hole, eventually.

4. Conclusions

The propagation rates of single and twin premixed edge flames in a slot-jet counterflow were measured as a function strain rate for varying mixture strength and Lewis numbers. For single premixed flames, representative negative edges were not observed. Short-length flames having propagating head and retreating tail at the same time were observed for low-strain rate region, and self-induced flame holes were observed for high-strain region. However, for twin premixed flames, flame edges having negative edge propagation speed could be observed near the high-strain extinction limits. Short-length flames were also observed for low-strain region.

For single premixed cases, U_{edge} is well scaled with $S_L(\rho_u/\rho_b)^{1/2}$ like non-premixed edge flames. On the contrary, for twin premixed cases, U_{edge} is well scaled with $S_L(\rho_u/\rho_b)$, since expanded burnt gas in between two premixed flame sheets pushes a flame edge accordingly.

Similar to non-premixed edge flames, high (low) Le mixture behaves like a weaker (stronger) mixture compare to Le $\approx$ 1 for both single and twin premixed flames, and heat loss induced low-ε extinction limits were well correlated with heat loss factor for each tested mixture irrespective of Lewis numbers.

Future work will consist of verifying the effect of the burner gap spacing, d, on U_{edge}, double-checking results for the twin CH_4/air mixture in the moderate-σ regime, and further analyzing the stability limit exhibited by single premixed edge-flames at high-σ. Future experiments to complement the edge-flame propagation rate study will center on pure diffusion edge-flames and edge-flames with much lower Le.

Acknowledgments

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References

[1] Buckmaster, J. D. "Edge-flames." *Prog. Energy Comb. Sci.* 28 (2002): 435-475.

[2] Daou, R., J. Daou and J. Dold. "Effect of volumetric heat loss on triple-flame propagation." *Proc. Combust. Inst.* 29 (2002): 1559-1564.

[3] Daou, R., J. Daou and J. Dold. "Effect of heat-loss on flame-edges in a premixed counterflow." *Combust. Theory Modelling* 7 (2003): 221-242.

[4] Daou, R., J. Daou and J. Dold. "The effect of heat loss on flame edges in a non-premixed counterflow within a thermo-diffusive model." *Combust. Theory Modelling* 8 (2004): 683-699.

[5] Daou, J. and A. Liñan. "The role of unequal diffusivities in ignition and extinction fronts in strained mixing layers." *Combust. Theory Modelling* 2 (1998): 449-477.

[6] Daou, J. and A. Liñan. "Ignition and extinction fronts in counterflowing premixed reactive gases." *Combust. Flame* 118 (1999): 479-488.

[7] Cha, M. S. and P. D. Ronney. "Propagation rates of nonpremixed edge-flames." *Combust. Flame* (2006): In press.

[8] Kaiser, C., J. B. Liu and P. D. Ronney (2000). "Diffusive-thermal instability of counterflow flames at low Lewis number." 38th Aerospace Sciences Meeting & Exhibit, American Institute of Aeronautics and Astronautics, Reno, NV, January 11-14, 2000.

[9] Verdarajan, T. G. and J. D. Buckmaster. "Edge-flames in homogeneous mixtures." *Combust. Flame* 114 (1998): 267-273.

[10] Vedarajan, T. G., J. D. Buckmaster and P. D. Ronney. "Two-dimensional Failure Waves and Ignition Fronts in Premixed Combustion." *Proc. Combust. Inst.* 27(1998): 537-544