

# Nonpremixed Edge Flames in Spatially Varying Straining Flows

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Nonpremixed flames subject to steady but spatially varying straining flows were studied to examine one aspect of nonpremixed flames in strongly turbulent flows or near quenching conditions (e.g., near a burner rim), where strain-rate gradients are present and local strain rates may be high enough to cause local flame-front extinguishment. The spatially varying straining flow were created using an opposed slot-jet burner with slightly nonparallel jet exits. The most significant observation was that steady flame "edges" could be created where the flame would exist in the low-strain region but would be extinguished in the high-strain region. The local strain at the location of the stationary flame edge was almost always lower than the strain required to extinguish flames in the same mixture subject to a spatially uniform strain. The strain rate at the edge-flame location was independent of the strain-rate gradient and gradual transitions from edge-flame behavior to uniformly strained flame behavior were not observed, indicating that conventional nonpremixed flames and edge flames are quite distinct structures yet each has well-defined properties. At the flame edge, interferometer images indicate a region of locally intense burning and an abrupt transition to nonburning conditions away from the edge. These observations were found to be qualitatively consistent with recent theoretical models of flame edges. These results indicate that "laminar flamelet" models of nonpremixed turbulent combustion may require reevaluation at conditions approaching those where local flame quenching occurs. It is proposed that these models could be improved by adding edge-flame libraries to existing laminar flamelet libraries. © 1998 by The Combustion Institute

## INTRODUCTION

Flames subject to uniform hydrodynamic strain are frequently used as a model of the local interaction of flame fronts with a turbulent flow field [1-3]. This "laminar flamelet" concept treats each surface element of the flame front as though it were a steady isolated front subject to temporally and spatially uniform strain. On the other hand, it is well known [4] that the unsteadiness and nonuniformity of turbulent strain is an important factor whenever the effect of strain is important because the mean strain rate in Kolmogorov turbulence is on the order of  $(u'/L_I)Re_L^{1/2}$ , where  $u'$  is the turbulence intensity,  $L_I$  is the integral scale of turbulence,  $Re_L \equiv u'L/\nu$  is the turbulent Reynolds number, and  $\nu$  is the kinematic viscosity, and this strain occurs primarily at the

Kolmogorov length scale  $L_k \sim L_I Re_L^{-3/4}$ , where viscous effects dissipate the velocity fluctuations at a rate  $\nu/L_k^2 \sim \nu L_I^{-2} Re_L^{3/2} \sim (u'/L_I)Re_L^{1/2}$ . Thus the rate at which the strain changes is comparable to the strain rate itself, which is a natural consequence of the fact that only one time or length scale can be constructed from the energy dissipation rate and viscosity. Similarly, changes in the local flame-front curvature and strain rate occur over the spatial scale  $L_k$ , and thus the scale over which flame-front curvature and strain changes is the same as the curvature scale itself.

As a step toward more realistic quantification of this well-recognized limitation of quasi-steady quasi-uniform laminar flamelet models, *spatially uniform* flames subject to a *temporally varying strain rate* have recently been studied computationally [5] and experimentally [6]. In this work, we consider the opposite case of *steady* strained flames subject to a *strain-rate gradient*. In particular, it is of interest to determine how the extinction conditions compare with flames in uniformly strained flows, i.e.,

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will extinguishment in the highly strained region inevitably spread to other regions or can a steady flame "edge" be maintained? If a steady flame edge is exhibited, will its location be at a region of higher or lower strain than that of the uniformly strained flame? Similarly, Williams ([2], p. 409) has noted the importance of the formation of "holes" in flame sheets to understanding of nonpremixed combustion in highly turbulent flows. Buckmaster [7] notes other conditions where edge flames may appear, e.g., candle flames at microgravity and flame spread over a flammable liquid. Moreover, the study of flame "edges" is relevant to flame holding behind a burner rim; a theoretical study of this subject was recently presented by Buckmaster and Weber [8].

No experimental studies of flames in spatially varying strain or edge flames have been conducted to date. The only relevant theoretical studies are those by Buckmaster and collaborators [7-9]. In their initial study [7], which is the one most relevant to the experiments performed here, the configuration chosen is a mixing layer of fixed half-thickness ( $L$ ) with a fixed concentration of fuel supplied on one side and a fixed concentration of oxidant supplied on the other side. The half-thickness  $L$  is a prescribed parameter which in practice would depend on the local flow conditions, geometry, mixture properties, etc. For example, in a region of uniform strain, e.g., in an opposed-jet configuration,  $L$  would be proportional to  $(\alpha/s)^{1/2}$ , where  $\alpha$  is the mixture thermal diffusivity and  $s$  is the strain rate. In [7],  $L$  is assumed to be constant, thus spatially varying strain is not considered, but the model does allow for variations in properties in the transverse coordinate and thus allows for the possibility of edge flames. The Lewis number (ratio of mixture thermal diffusivity to reactant mass diffusivity) of oxygen was assumed to be unity, but the fuel Lewis number ( $Le_{\text{fuel}}$ ) was allowed to vary such that  $\beta(Le_{\text{fuel}} - 1)$  is a quantity of order unity in the limit  $\beta \rightarrow \infty$ , where  $\beta \equiv E/RT^*$  is the nondimensional activation energy,  $E$  is the activation energy,  $R$  is the gas constant, and  $T^*$  is the flame-front temperature for an adiabatic uniform nonpremixed flame with complete reaction, which in general is a function of the Lewis numbers of fuel and

oxidant [10] as well as the thermodynamic properties of the reactants. The model incorporates finite-rate chemistry effects through a Damköhler number ( $Da$ ) defined as  $\omega L^2/\alpha$ , where  $\omega$  is a characteristic chemical reaction rate. For a region of uniform strain,  $Da$  would then be  $\omega/s$ . Buckmaster's analyses allow for and predict flames with advancing, retreating, or stationary edges depending on  $Da$ .

The key prediction of Buckmaster's models that might be compared to experiments is the relative resistance of uniform flames and flame edges to extinction. For stationary edge flames, Buckmaster predicted that the ratio of  $Da$  at the flame edge to the extinction  $Da$  for a uniformly strained flame given by  $\beta(1 - \varepsilon)/e^2$ , where  $e = 2.718 \dots$ ,  $\varepsilon \equiv T_0/T^*$ , and  $T_0$  is the ambient temperature, thus the ratio of the strain rate at the steady flame edge,  $s_{\text{edge}}$ , to the extinction strain rate of a uniformly strained flame,  $s_{\text{uniform}}$ , is

$$\frac{s_{\text{edge}}}{s_{\text{uniform}}} = \frac{e^2}{\beta(1 - \varepsilon)}. \quad (1)$$

In the asymptotic limit  $\beta \rightarrow \infty$ ,  $s_{\text{edge}}/s_{\text{uniform}} \rightarrow 0$ , and thus edge flames are much weaker than uniformly strained flames. One physical explanation of this prediction is that the additional heat losses that occur from the flame edge to the unburned gases in the direction parallel to the flame sheet inevitably outweighs the benefits of premixing and more intense burning that occurs in the vicinity of the flame edge. Since practical values of  $\beta$  and  $\varepsilon$  are typically 10-20 and 0.15-0.2, respectively,  $s_{\text{edge}}/s_{\text{uniform}}$  is typically only slightly less than unity and thus edge flames are expected to be only moderately weaker than the uniformly strained flames.

Another prediction from [7] is that in the vicinity of the flame edge, the rate of heat release per unit area is larger than that of the nonpremixed flame sheet far behind the leading edge by a factor of  $\beta$  and that on the nonburning side of the flame edge, in the direction parallel to the flame sheet, there is an exponential temperature decay to ambient reminiscent of premixed flame fronts. The thickness of this zone scales with  $KL$ , such that the temperature profile  $T(x) = T_0 + (T_a -$

$T_0)e^{-x/KL}$ , where  $K$  is a constant that depends on the edge speed and is unity for stationary edges. This edge and preheat zone structure is clearly a result of the fact that the edge is adjacent to a nonburning region and thus is subject to a higher heat flux away from the reaction zone and a higher reactant flux to the reactant zone than the burning region behind the flame edge.

Buckmaster's edge-flame model predicts that stationary flame edges may be obtained without a gradient in  $Da$  along the flame front, but the edge is stationary only for one specific value of  $Da$  and not over a range of  $Da$ . Consequently, in an experiment one would not expect to be able to maintain a steady flame edge without closed-loop control. According to the model, however, edges could be stable if a gradient in  $Da$  were present. To see this, we note that Buckmaster's results can be manipulated to show that the nondimensional edge velocity ( $U$ ) is given by

$$U = \frac{\Delta - 1}{\sqrt{\Delta}}, \quad (2)$$

where  $\Delta \equiv Da/Da_0$  and  $Da_0$  is the value of  $Da$  for which  $U = 0$ . Equation 2 indicates that  $U > 0$  (corresponding to advancing edges) for  $\Delta < 1$  and  $U < 0$  (corresponding to retreating edges) for  $\Delta > 1$ . As noted by Buckmaster, this relationship is very similar to one proposed heuristically by Müller et al. [11] in a study of partially premixed turbulent flames. Thus, when a gradient in  $Da$  is present, a flame in the high- $Da$  region with an edge located at  $Da = Da_0$  will be stable, because if the burning region retreats (advances) toward higher (lower)  $Da$ ,  $U$  will be greater than (less than) zero and the edge will advance (retreat) toward the location where  $Da = Da_0$  and thus  $U = 0$ . Furthermore, the edge location should be independent of the gradient, at least for gradients that are sufficiently small that Eq. 2 would apply, i.e., when  $ds/dx \ll s/L$ .

In the mixing-layer configuration, Buckmaster [7] also predicted that oscillations would occur for stationary flame edges when

$$Le_{\text{fuel}} > 1 + \frac{8}{\beta(1 - \varepsilon)}; \quad \varepsilon \equiv \frac{T_0}{T^*}. \quad (3)$$

The mechanism of these oscillations is analogous to the diffusive-thermal mechanism of premixed flames, for which oscillations in burning velocity are predicted [12] for sufficiently high  $Le_{\text{fuel}}$  and have recently been observed experimentally [13, 14]. For sufficiently low  $Le_{\text{fuel}}$ , cellular flames are predicted by the diffusive-thermal mechanism and have been observed for both premixed [15] and nonpremixed [16] flames. Cellular flame edges are predicted by Buckmaster's model for advancing edges at sufficiently low  $Le_{\text{fuel}}$ , but are not predicted for stationary edges regardless of  $Le_{\text{fuel}}$ . Furthermore, for  $|Le - 1|$  an  $O(1)$  quantity, it is predicted [7] that for a certain range of  $Da$ , at sufficiently high  $Le$ , there may be inherently unsteady edges with no stationary (constant  $U$ ) structure.

In this study simple experiments were performed to address some of the questions raised in the preceding text in relation to flames in spatially varying strain and to compare the results to Buckmaster's models of flame edges. The proposed stability of flame edges in strain-rate gradients was exploited in the design of the apparatus. While in principle, either premixed or nonpremixed flames could be studied with the apparatus we employed, in the current study only nonpremixed flames were examined because only for the nonpremixed case is a theoretical model available and because of the possible complications associated with the twin-flame structure of premixed flames in a counterflow experiment.

## EXPERIMENTAL APPARATUS AND PROCEDURES

The most common apparatus for studying strained *spatially uniform* flames is a pair of opposed counterflowing round jets [17], which provides an axisymmetric flame and straining flow field. A similar but less frequently employed apparatus is a pair of opposed counterflowing slot jets, which ideally provides a nearly plane strain flow. In either case, the imposed strain rate ( $s$ ) is proportional to  $V/d$ , where  $V$  is the jet exit velocity and  $d$  is the spacing between the jet exits. For ideal potential plane strain flow,  $s = 2V/d$ . In this work, the opposed slot-jet configuration is employed with

one important difference: the jet exits are intentionally misaligned slightly to produce a gradient in strain rate along the length of the slot. When the angle of divergence is sufficiently small, i.e., only a few degrees, it is expected that at each location ( $x$ ) along the slot length, the local strain rate  $s(x)$  can be estimated as  $2V/d(x)$ . The exit velocity  $V$  can be made constant in  $x$  through the use of flow-straightening elements at the jet exits.

The experimental apparatus we employed is shown schematically in Fig. 1. It consists of a counterflow burner configured as two opposed  $7.6 \text{ cm} \times 1.0 \text{ cm}$  rectangular nozzles. The internal construction of the burners consisted of steel wool and aluminum honeycomb to ensure uniformity of the exit flow. Steel mesh screens were placed above and below the flame location to minimize external disturbances and buoyancy effects. Commercial mass flow controllers were employed to deliver the gases to the burner and were commanded using a PC-based digital-to-analog converter board and custom software.

To obtain a variety of Lewis numbers, two fuels with different diffusivities were employed: methane and propane. For both fuels the oxidizer stream was  $\text{O}_2$ . Various ratios of fuel mole fraction in the fuel stream to oxygen mole fraction in the oxidizer stream were employed. In order to maximize the range of Lewis numbers, for the  $\text{CH}_4\text{-O}_2$  flames each stream was diluted with  $\text{CO}_2$  and for the  $\text{C}_3\text{H}_8\text{-O}_2$  flames each stream was diluted with  $\text{N}_2$  or He. The estimated Lewis numbers at ambient temperature are as follows:  $\text{CH}_4$  in  $\text{CO}_2 \approx 0.70$ ;  $\text{O}_2$  in  $\text{CO}_2 \approx 0.84$ ;  $\text{C}_3\text{H}_8$  in  $\text{N}_2 \approx 1.74$ ;  $\text{O}_2$  in  $\text{N}_2 \approx 1.02$ ;  $\text{C}_3\text{H}_8$  in He  $\approx 3.55$ ;  $\text{O}_2$  in He  $\approx 1.69$ . For all experiments  $V$  was set to a fixed value in each jet and the fuel and

oxygen concentrations were varied, keeping the ratio of fuel to oxygen fixed, to obtain local or global extinction. Through the use of our computerized flow system, it was possible to control all gas flows simultaneously in order to accomplish this adjustment scheme. The most desirable flow configuration is matched jet exit velocities because this simplifies modeling. Because of buoyancy effects, it was found that in many cases a more uniform flame could be maintained and edge flames could be obtained over a wider range of conditions when the exit velocity for the upper jet ( $V_{\text{upper}}$ ) was larger than the exit velocity of the lower jet ( $V_{\text{lower}}$ ). Both matched and unmatched jet exit velocities were employed in this study; in the latter case the reported strain rate is the value averaged across the jet gap, i.e.,  $s(x) = (V_{\text{upper}} + V_{\text{lower}})/d(x)$ . Of course for all real flows, especially those with the thermal expansion induced by heat release,  $s$  is not constant across the gap; however, the average  $s$  employed here is useful for the primary objective of comparing flames in uniform and nonuniform strain.

## RESULTS AND DISCUSSION

### Visual Observations

It was found that it was indeed possible to obtain conditions where a flame "edge" was stabilized within the region between the two slot jets. The flame would exist where  $d(x)$  was larger and thus  $s(x)$  was smaller than a critical value. Direct photographs of typical edge flames are shown in Figs. 2a, 3a, 4a, and 5a. These figures show that the transition from burning to nonburning conditions at the flame edge is quite sharp; no region of gradually decreasing flame luminosity is evident.

The location of the flame edge could be varied by adjusting the fuel and oxidant mole fractions: increasing (decreasing) the fuel and oxidant mole fractions moved the flame edge toward smaller (larger)  $d(x)$  and thus larger (smaller)  $s(x)$  and smaller (larger) Da. No hysteresis was observed in this process. No oscillating flame edges were observed even when the edges were recorded using a video camera with a 0.001 s shutter speed. Also, there was no evidence of cellular flame structures at low

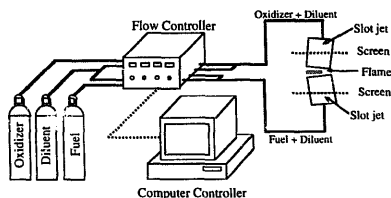
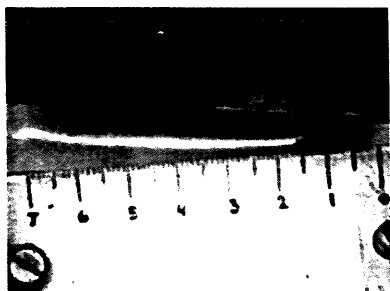


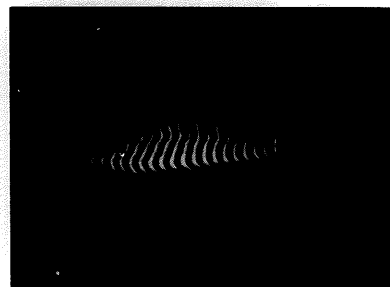
Fig. 1. Experimental apparatus block diagram.



(a)

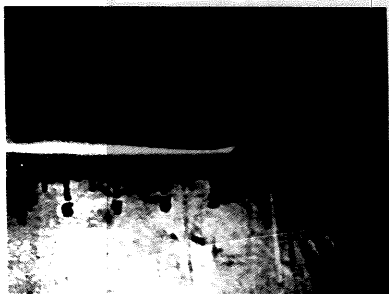


(b)



(c)

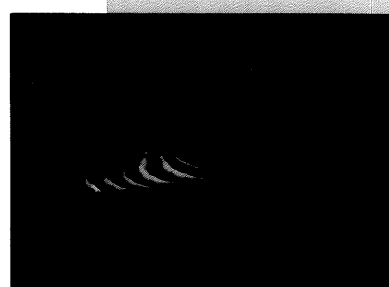
Fig. 2. Images of an edge flame. Arrows in (b) and (c) denote the location of the visible flame edge. The scale in (a) is cm. Upper stream: 37.8%  $O_2$  in  $CO_2$ ,  $V_{upper} = 14.3$  cm/s; lower stream: 18.9%  $CH_4$  in  $CO_2$ ,  $V_{lower} = 3.9$  cm/s. Slot angle  $3.69^\circ$ . (a) Visible flame. (b) Interferometer image, horizontal fringes. (c) Interferometer image, vertical fringes.



(a)

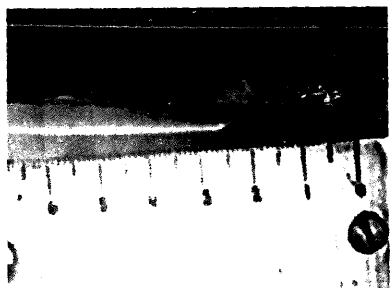


(b)

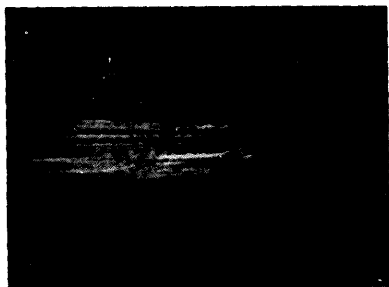


(c)

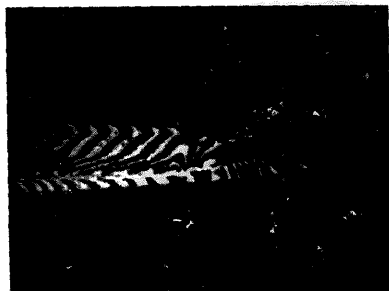
Fig. 3. Images of an edge flame. Arrows in (b) and (c) denote the location of the visible flame edge. The scale in (a) is cm. Upper stream: 70.6%  $O_2$  in  $CO_2$ ,  $V_{upper} = 9.0$  cm/s; lower stream: 10.6%  $CH_4$  in  $CO_2$ ,  $V_{lower} = 9.0$  cm/s. Slot angle  $3.69^\circ$ . (a) Visible flame. (b) Interferometer image, horizontal fringes. (c) Interferometer image, vertical fringes.



(a)



(b)

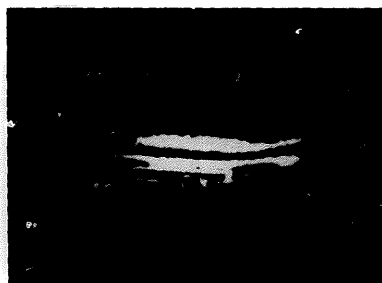


(c)

Fig. 4. Images of an edge flame. Arrows in (b) and (c) denote the location of the visible flame edge. The scale in (a) is cm. Upper stream: 27.1%  $O_2$  in  $N_2$ ,  $V_{upper} = 14.8$  cm/s; lower stream: 5.4%  $C_3H_8$  in  $N_2$ ,  $V_{lower} = 3.6$ . Slot angle  $4.10^\circ$ . (a) Visible flame. (b) Interferometer image, horizontal fringes. (c) Interferometer image, vertical fringes.



(a)



(b)



(c)

Fig. 5. Images of an edge flame. Arrows in (b) and (c) denote the location of the visible flame edge. The scale in (a) is cm. Upper stream: 41.0%  $O_2$  in He,  $V_{upper} = 10.0$  cm/s; lower stream: 4.1%  $C_3H_8$  in He,  $V_{lower} = 9.0$  cm/s. Slot angle  $4.51^\circ$ . (a) Visible flame. (b) Interferometer image, horizontal fringes. (c) Interferometer image, vertical fringes.

$Le_{\text{fuel}}$ . Moreover, no behavior reminiscent of tribrachial flame structures, which sometimes appear under conditions of uniform strain but spatially varying composition spanning stoichiometry [18], were observed.

For  $T_0 = 300$  K, Eq. 3 predicts oscillations would occur for  $Le_{\text{fuel}} > 1.75$ , which is close to the value of 1.74 for the  $C_3H_8$  fuel in  $N_2$  (see preceding text). Note also that the Lewis number of  $O_2$  in  $N_2$  is about 1.02, which is close to the unit value assumed by Buckmaster. Thus, the experimental conditions for the  $C_3H_8$ - $N_2/O_2$ - $N_2$  flame are very close to the predicted conditions for marginal stability; however, no such instabilities were observed for this case or even the  $C_3H_8$ -He/ $O_2$ -He case, which has much higher  $Le_{\text{fuel}}$ . Whether this is due to differences between the model configuration (a stagnant mixing layer) and the experiment (a strained flame), an effect of the Da gradient (a factor not present in the model), or some other factor is not known. As discussed in the Introduction, cellular flame edges are not predicted for stationary edges and, as noted previously, cellular edges were not observed even for the  $CH_4$ - $CO_2/O_2$ - $CO_2$  flame which has  $Le_{\text{fuel}} < 1$ .

### Effect of Strain Rate and Strain-Rate Gradient

Examples of data on the strain rate at the edge location as a function of the fuel concentration in the fuel stream are shown in Fig. 6a-d. Also shown for these plots are the extinction strain rates for parallel slots with the same  $V_{\text{upper}}$  and  $V_{\text{lower}}$  as the nonuniformly strained flames, in which case extinction is obtained by varying the slot gap  $d$ . The following features may be noted:

- For a given composition the extinction strain for the uniform flame is larger than (or in a few cases equal to) the strain rate at the flame edge for the nonuniform flame. Also, the minimum fuel concentration at which a flame can be maintained is larger in the case of the spatially varying strain. Thus, edge flames are weaker than uniformly strained flames.
- The angle between the slot burners has practically no effect on the values of  $s$  at the

edge location. This indicates that under these conditions the strain-rate gradient used to stabilize the edge flames does not affect the edge-flame properties significantly. The angle independence of the results also suggests that any flow in the direction along the length of the slot (the  $x$ -direction) induced by angling the slots is insignificant; otherwise, the flame edge would have to move to different  $x$ -locations having different  $d$  and thus different Da in order to balance the edge velocity  $U$  with the local flow velocity in the  $x$ -direction.

- There is no gradual transition in behavior from edge-flame to uniform-strain behavior as the divergence angle was decreased and thus the strain-rate gradient decreased. Thus, edge flames are distinct from uniformly strained flames; each type of flame exhibits consistent but different response to strain.
- The extinction curves for uniformly strained flames are C-shaped, such that at very low flow velocities the fuel concentration at extinction increases with decreasing flow velocity. This is likely due to a transition from a strain-induced extinction to a heat-loss extinction mechanism. In this case, the heat loss is probably conductive loss to the burner rims. This dual-limit extinction behavior of nonpremixed flames has been demonstrated previously both theoretically [19] and experimentally [15, 20]. Since most of the data for the edge flames were obtained at higher strain rates than the strain rate at the turning points for the uniform flames, it is reasonable to conclude that the data for the edge flames are not strongly influenced by conductive heat losses.
- There is no qualitative difference in edge-flame behavior for different Lewis numbers.
- For flows in which the upper jet has a larger exit velocity, edge flames can be maintained over a larger range of fuel concentrations, probably due to partial suppression of buoyancy effects.

It was not possible to obtain edge flames at very low divergence angles. The minimum angle was about  $2.5^\circ$  and was nearly the same for all conditions tested. For smaller angles, the flame would either fill the entire slot width or

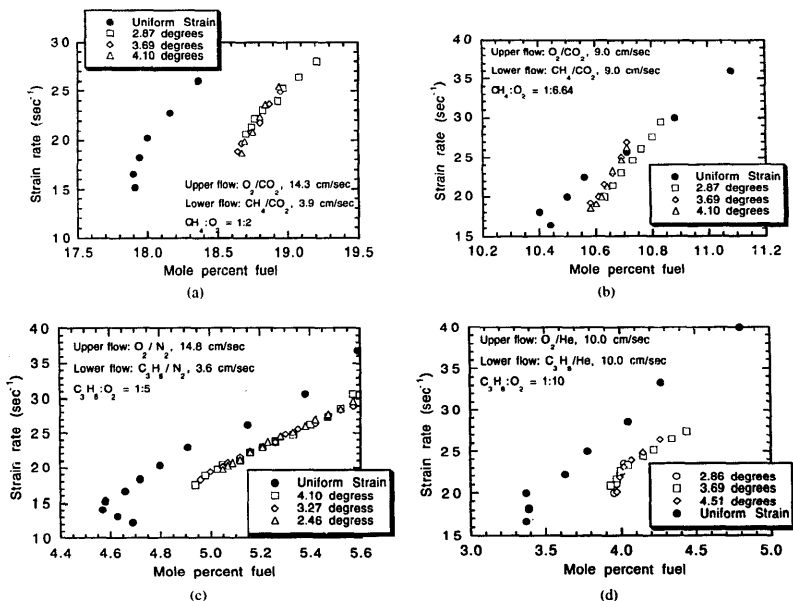


Fig. 6. Strain rates at the flame-edge location (for nonuniformly strained flames) and extinction strain rates (for uniformly strained flames) as a function of the fuel concentration in the fuel stream for varying angles of divergence of the slot jets. (a) Upper stream: O<sub>2</sub>/CO<sub>2</sub>; lower stream: CH<sub>4</sub>/CO<sub>2</sub>, unmatched exit velocities. (b) Upper stream: O<sub>2</sub>/CO<sub>2</sub>; lower stream: CH<sub>4</sub>/CO<sub>2</sub>, matched exit velocities. (c) Upper stream: O<sub>2</sub>/N<sub>2</sub>; lower stream: C<sub>3</sub>H<sub>8</sub>/N<sub>2</sub>, unmatched exit velocities. (d) Upper stream: O<sub>2</sub>/He; lower stream: C<sub>3</sub>H<sub>8</sub>/He, matched exit velocities.

extinguish completely, as if the flame were uniformly strained. Thus, the value of the strain-rate gradient does seem to play a role in determining whether edge flames can be stabilized or not. This may be due to the fact that as the gradient in  $Da$  decreases, the strength of the proposed stabilizing mechanism described in the Introduction will decrease, which may allow small flow disturbances, for example, due to buoyancy-induced fluctuations, to prevent stabilization. A rough estimate of the magnitude of these disturbances can be made as follows. The sloshing of an inviscid gravity wave of wavelength  $\lambda$  along the flame front would have a frequency of  $(g/\lambda)^{1/2}$ , which would result in a strain-rate gradient of  $(g/\lambda^3)^{1/2} =$

$[(980 \text{ cm/s}^2)/(7.6 \text{ cm})^3]^{1/2} \approx 1.5 \text{ s}^{-1}/\text{cm}$ . The typical minimum strain-rate gradient corresponds to an angle of  $2.5^\circ$ , such that  $d(x)$  increases from 0.5 to 1.16 cm. For a typical  $V_{\text{upper}} + V_{\text{lower}} = 18 \text{ cm/s}$ , this corresponds to a strain-rate gradient of  $(18 \text{ cm/s})[(0.5 \text{ cm})^{-1} - (1.16 \text{ cm})^{-1}]/(7.6 \text{ cm}) = 1.5 \text{ s}^{-1}/\text{cm}$ , which is on the same order of magnitude as the estimated buoyancy-flow driven value. Thus it is reasonable to propose that buoyancy-induced flow disturbances are responsible for our inability to sustain edge flames at very low divergence angles.

The ratio  $s_{\text{edge}}/s_{\text{uniform}}$  for the data shown in Fig. 6 away from the turning points, where heat loss (a factor not present in the model)



may be important, varies from about 0.65 to 1. This is in agreement with the theoretical prediction (see Introduction) that the nonuniformly strained flame is weaker than the uniformly strained flame. Quantitatively, the agreement between the model and experiment is fair; for typical hydrocarbons  $E \approx 40,000$  cal/mol and thermocouple measurements indicated typical near-extinction values of  $T^*$  were about 1700 K, thus according to Eq. 1 the predicted ratio  $s_{\text{edge}}/s_{\text{uniform}} \approx 0.75$ .

### Thermal Properties

To test some of the predictions concerning the structure of the edge flame, a shearing interferometer system [21] was employed. This simple system provides a qualitative, nonintrusive means of imaging the thermal field. The shearing interferometer causes a phase object to interfere with itself, offset by a distance called the shear distance, rather than with a reference phase object as in other types of interferometry. Thus, in the shearing interferometer, the displacement of the fringes from their location in a uniform density field is proportional to the index of refraction gradient, rather than to the difference in the index of refraction between the test and the reference object. In this sense, the shearing interferometer responds in a manner similar to a Schlieren system but with the fringe displacement rather than the gray level indicating the gradient.

Of course, like all deflectometry devices, the shearing interferometer integrates the phase difference along the ray paths and thus does not readily yield quantitative information at a point or in a plane in the manner of, for example, planar laser-induced fluorescence. Attempts to obtain point temperature measurements via thermocouples were unsuccessful; inevitably the presence of the thermocouple would cause the flame edge to move in unpredictable ways. (Thermocouples were useful, however, for determining  $T^*$  far behind the flame edge which was necessary for estimating a theoretical value of  $s_{\text{edge}}/s_{\text{uniform}}$  in the previous section.)

Interferometer images of edge flames showing transverse gradients (corresponding to displacements of horizontal fringes) are shown in

Figs. 2b, 3b, 4b, and 5b. Interferometer images showing streamwise gradients (displacements of vertical fringes) are shown in Figs. 2c, 3c, 4c, and 5c. The largest fringe displacements are seen in Fig. 2b and c simply because the  $\text{CO}_2$ -diluted mixtures have the largest densities and thus the largest index of refraction gradients. The smallest displacements are seen in the helium-diluted mixtures (Fig. 5b and c) because these mixtures have the smallest densities. All of these images show that a sharp change in density gradients occurs near the visible flame edge which implies a sharp change in temperature. The scale of this temperature change in the direction along the flame front is comparable to the scale of temperature change in the direction orthogonal to the flame front. Away from the edge, the scale is much larger in the direction along the front than in the direction orthogonal to it. This is consistent with the predictions of the edge-flame models discussed in the Introduction. Also, as expected, the fringe displacements are significantly larger on the burning side of the edge than on the nonburning side.

### SUMMARY AND CONCLUSIONS

A study of nonpremixed flames in nonuniformly strained flows indicates a substantial influence of strain-rate gradients on extinction conditions. In particular, it was found that flame "edges" were formed in the presence of such gradients. The strain rate at the flame edge is lower for a nonuniformly strained flame than the extinction strain rate for a uniformly strained flame having the same reactants. Also, the edge flames that appear in nonuniformly strained flames are distinct from uniformly strained flames in that gradual transitions from one to the other were not observed. These results are qualitatively consistent with the predictions of recently developed theoretical models.

The properties of these edges were practically independent of the strain-rate gradient; however, the strain-rate gradient did influence whether edge flames could be stabilized or not, probably because of the influences of buoyancy. In strongly turbulent flows, buoyancy would not be a factor but the strain-rate gradi-

ent (and the strain rate itself) would change sign and would be time-variant. These factors would need to be incorporated into more complete edge-flame models for turbulent combustion.

The results have implications concerning the applicability of the often invoked flamelet modeling assumption for nonpremixed flames, especially near extinction conditions. Since turbulent nonpremixed flames are frequently modeled using "laminar flamelet libraries," and since edge flames, like uniform flames, have well-defined responses to strain, it is proposed that the range of applicability of laminar flamelet models could be extended by adding "edge-flame libraries" to existing laminar flamelet libraries. This addition is facilitated by the apparent independence of edge-flame properties on strain-rate gradients, thus, at least at the first stage, the strain-rate gradient does not need to be a parameter in edge-flame libraries. Of course, rules for merging edge flames and locally uniform flames would need to be developed, since one would need to know if a particular strain-rate gradient (and perhaps strain-rate history) would cause the flame to exhibit uniform-flame or edge-flame characteristics.

In future work, laser Doppler velocimetry will be used to examine the estimation for the local strain rate  $s(x) = (V_{\text{upper}} + V_{\text{lower}})/d(x)$ . Also, the dynamical properties of edge flames, i.e., the rate of advancement or retreat of nonsteady edges, will be measured and compared to Eq. 2 or its successors. Nonintrusive point or plane measurements of temperature or species concentrations, e.g., via Raman scattering or laser-induced fluorescence, would be useful to obtain more quantitative information about the edge-flame structure. Finally, the limitations of laminar flamelet models discussed in the Introduction are equally applicable to premixed turbulent flames, thus premixed flames in spatially varying strain will also be examined.

*The authors thank Professor J. D. Buckmaster and Dr. J. S. Kim for helpful discussions, Professor J. B. Liu for his assistance in obtaining the*

*interferometer images, and Q. Blackburn for programming the flow control system. This work was supported by the NASA Lewis Research Center under grant NAG3-1611.*

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*Received 25 October 1996; accepted 21 February 1997*