TENTH AUSTRALASIAN FLUID MECHANICS
CONFERENCE - UNIVERSITY OF MELBOURNE
11-15 DECEMBER 1989

14A-2

ON THE STRUCTURE OF TURBULENT NONPREMIXED FLAMES NEAR EXTINCTION

A.R. MASRI[1], R.W. BILGER[1] and R.W. DIBBLE[2]

[1]Department of Mechanical Engineering
The University of Sydney, NSW 2006, AUSTRALIA

2Combustion Research Facility
Sandia National Laboratories, Livermore, CA, USA

Abstract

A regime diagram for turbulent nonpremixed combustion is developed in this paper. The relevant parameters are the mean scalar dissipation rate ratio, $\overline{\chi}/\chi_q$ and $\Delta\xi_R/\Sigma_\xi$. Here $\Delta\xi_R$ is the width of the laminar reaction zone in mixture fraction space and Σ_ξ is the scalar scale. Data reported for turbulent jet nonpremixed flames near extinction are plotted on this regime diagram. The fuels considered are CH_4, H_2, H_2/Ar and $CO/H_2/N_2$. It is found that the methane flame data lie close to the regime where laminar flamelets are expected. The $CO/H_2/N_2$ flames, as well as the H_2 and the H_2/Ar flames are well in the distributed reaction regimes. The bimodal-monomodal behaviour of these flames as they approach extinction is only slightly affected by Σ_ξ and is mainly dependent on $\Delta\xi_R$.

1 Introduction

Measurements of temperature and the concentrations of stable species, using the spontaneous Raman-Rayleigh scattering technique, have been reported for turbulent nonpremixed flames of CH_4 [1,2], $CO/H_2/N_2$ [3,4], H_2 [5], and H_2/Ar [6] fuels. The flames investigated range from ones with low mixing rates to flames close to blow off. In pilot-stabilised methane flames close to extinction [1,2], it is found that lean mixtures are either burnt or unburnt and the *pdf*'s of the reactive scalars are bimodal. The bimodal behaviour was observed for flames with a mean jet velocity, $\overline{u}_j \sim 60\%$ of the blow off value and the proportion of locally extinguished samples increases as the flame approaches blow off. For rich fluid mixtures, the *pdf*'s of the reactive scalars are monomodal and widely distributed between the limits of fully reacted and fully nonreacted, *i.e.* frozen. The centroid of these rich distributions gradually shifts towards the frozen limits as the flame approaches extinction. It should be noted that the bimodal and monomodal behaviour described here refer to flames which, although close to blow off, are aurally and visibly stable. It is evident that when the flames are unstable and blowing off intermittently, the *pdf*s of reactive scalars will also be bimodal. This is not however, the bimodality we refer to in this paper.

In pilot-stabilised flames of $CO/H_2/N_2$ fuels [3], localised extinction is not observed even for flames with mean jet velocity, $\overline{u}_j$ about 90% of the blow off velocity. The *pdf*'s of the reactive scalars show a monomodal distribution with the centroid gradually drifting from the fully burnt limits as the mixing rates increase. Unlike with methane fuels, $CO/H_2/N_2$ flames blow off abruptly and with a loud 'popping' noise. Measurements in unpiloted nonpremixed flames of H_2/Ar fuel near extinction [6] produce monomodal *pdf*'s of reactive scalars. Such flames blow off at the nozzle exit plane, intermittently and with a loud noise. Investigating flames of $CO/H_2/N_2$ fuels with slightly different composition, Stårner *et al.* [4] found that for flames with $\overline{u}_j \sim 95\%$ of the blow off value, the *pdf*'s are distributed between the fully burnt and the frozen limits. Whether these unburnt fluid samples are locally extinguished flamelets or simply mixed pockets of an otherwise broad reaction zone is yet to be determined. The narrow band over which the flame behaviour changes into the extinction mode is characteristic of the CO/H_2 fuel mixtures.

These findings raise questions regarding the spatial structure of the flames near extinction and the applicability of the various theoretical models which account for finite rate chemistry effects. Flamelet theories have been relatively successful in modeling the mean structure of turbulent jet nonpremixed flames of hydrocarbons [7]. This success, however, does not necessarily mean that the flamelet model is valid. Bilger [8] has shown that at the high Damköhler number limit, reaction zones in turbulent jet diffusion flames are broad and distributed except near the nozzle. At low Damköhler numbers where the flames are close to blow off, questions of flame structure become even more significant and relevant to models of practical combustors. Are the reaction zones thin and laminar or are they broad with turbulence within them? Is the difference in behaviour between the $CO/H_2/N_2$ and methane flames due to differences in the reaction zone structure or differences in the chemical kinetics or both? What is the mechanism of extinction in these flames? These questions are currently the subject of intense research. This paper addresses the above questions in light of the most recent data reported for piloted jet diffusion flames. Although direct evidence from multidimensional imaging is becoming available, useful inferences are made here from single point measurements.

2 Data Sources

Table 1 gives some relevant information regarding the flames addressed in this paper. The quenching value of the scalar dissipation rate, χ_q, the value of the stretch parameter at extinction, a_{ext} and the width of the reaction zone in mixture fraction space at stoichiometric, $\Delta\xi_R$ are determined for the CH_4, $CO/H_2/N_2$, and H_2/Ar fuels from calculations in laminar counterflow diffusion flames. The corresponding values in the H_2 flame are estimated. The jet Reynolds number, Re and the stoichiometric mixture fraction, ξ_s are also tabulated. The tables indicate by 'est' quantities which are only estimated because measurements are not available.

Table 1: Characteristics of various turbulent jet nonpremixed flames

	Drake *et al* [5]	Dibble *et al* [6]	Masri&Dibble [3]	Masri *et al* [1,2]
	nonpiloted	nonpiloted	piloted	piloted
fuel	100% H_2	$H_2/Ar =$ 78%/22% (by vol.)	$CO/H_2/N_2 =$ 45%/15%/40% (by vol.)	100%CH_4
D_j (mm)	3.2	5.2	7.2	7.2
$\overline{u}_j$ m/s	285	75, 150	41, 123	36, 41, 55
Re	8500	9000, 18000	18300, 55000	18000, 20500, 27000
ξ_s	.0284	.166	.370	.055
$\Delta\xi_R$	.1 (est)	.2	.45	.059
a_{ext} (s^{-1})	13000 (est)	10000 (est)	1950	360
χ_q (s^{-1})	430 (est)	330 (est)	65	12

3 Discussion

For pilot stabilised turbulent nonpremixed flames close to extinction, the most appropriate parameters characterising combustion are $\overline{\chi}/\chi_q$ and $\Delta\xi_R/\Sigma_\xi$. Here $\overline{\chi}$ is the mean scalar dissipation rate, χ_q is its quenching value and $\Delta\xi_R$ is the width of the reaction zone in mixture fraction space. The scalar scale, Σ_ξ is a measure of turbulence scales in scalar space equivalent to the Kolmogorov scale and

$$\Sigma_\xi \simeq \sqrt{2}\,\frac{\xi''}{Re_t^{1/4}}, \tag{1}$$

where Re_t is the turbulent Reynolds number given by

$$Re_t = \frac{u'\,L_u}{\nu}. \tag{2}$$

Here u' and ξ'' are the rms of velocity and mixture fraction respectively, L_u is the half-width of the velocity profile and ν is the kinematic viscosity. These parameters are used to construct a regime diagram for nonpremixed combustion as shown on Fig. 1. For $\overline{\chi}/\chi_q < 1$, reaction zones are expected to be broad and to have turbulence

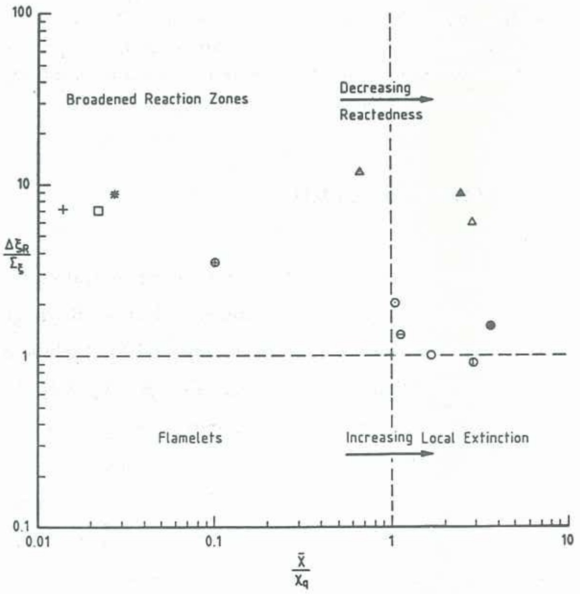

Figure 1: Regime diagram for turbulent nonpremixed combustion showing $\Delta\xi_R/\Sigma_\xi$ versus $\overline{\chi}/\chi_q$.
○: CH_4 flame, $\overline{u}_j$=36 m/s, x/D_j=20;
⊙: CH_4 flame, $\overline{u}_j$=41 m/s, x/D_j=20;
●: CH_4 flame, $\overline{u}_j$=41 m/s, x/D_j=30;
⦶: CH_4 flame, $\overline{u}_j$=55 m/s, x/D_j=20;
⊖: CH_4 flame, $\overline{u}_j$=55 m/s, x/D_j=30;
⊕: CH_4 flame, $\overline{u}_j$=55 m/s, x/D_j=50;
△: $CO/H_2/N_2$ flame, $\overline{u}_j$=41 m/s, x/D_j=10;
▲: $CO/H_2/N_2$ flame, $\overline{u}_j$=123 m/s, x/D_j=10;
◬: $CO/H_2/N_2$ flame, $\overline{u}_j$=123 m/s, x/D_j=30;
+: H_2/Ar flame, $\overline{u}_j$=75 m/s, x/D_j=50;
∗: H_2/Ar flame, $\overline{u}_j$=150 m/s, x/D_j=50;
□: H_2 flame $\overline{u}_j$=285 m/s, x/D_j=20.

within them when $\Delta\xi_R/\Sigma_\xi > 1$, while flamelets are more probable when $\Delta\xi_R/\Sigma_\xi < 1$. For $\overline{\chi}/\chi_q > 1$, local extinction occurs more frequently when $\Delta\xi_R/\Sigma_\xi < 1$, while a decreasing reactedness is expected when reaction zones are broad and $\Delta\xi_R/\Sigma_\xi > 1$. It should be noted that the cut-off between these regimes is not sharp considering that the statistical distribution, which may differ for each of the controlling parameters, is not accounted for.

The data shown for the methane and $CO/H_2/N_2$ flames correspond to various flames of different jet velocities and various axial locations. The values for $\overline{\chi}$ and Σ_ξ are derived from data reported for the flames [1-6]. It is seen that the methane flame data lie close to the regime where laminar flamelets are expected. The $CO/H_2/N_2$ flames, as well as the H_2 and the H_2/Ar flames are well in the distributed reaction regimes. It is surprising that for the H_2/Ar flames which are close to blow off, the values of $\overline{\chi}/\chi_q$ are much smaller than one. This is expected to be due to overestimating the value of χ_q.

Distributed reaction zones and a monomodal flame behaviour are favoured by a large reaction zone width and a small scalar scale. However, in the flame region where blow off occurs, Σ_ξ for the monomodal $CO/H_2/N_2$ flames are larger than those for the bimodal CH_4 flames. This implies that the bimodal-monomodal structure of turbulent nonpremixed flames close to extinction appears to be determined more by the chemical kinetics rather than by the flow condition. For hydrocarbon flames, $\Delta\xi_R$ is small and the bimodal behaviour is due to the depletion of radicals from the rich side of the reaction zones causing rich mixtures to be inert. Lean mixtures extinguish intermittently due to locally high values of scalar dissipation χ. For flames of H_2 and $CO/H_2/N_2$ fuels, reaction zones are broad and $\Delta\xi_R/\Sigma_\xi \gg 1$. The concentration of radicals remains high even for very fuel rich mixtures preventing the abrupt stoppage in chemical reaction which causes the bimodal behaviour.

The implications of these findings on the modeling of turbulent nonpremixed combustion with finite rate kinetic effects are significant. A successful model should be capable of not only predicting the mean flame structure and global blow off, but it should also be physically relevant to the combustion phenomenon it represents. The size of the turbulence scales with respect to the width of the reaction zones remains an issue concerning the physical relevance of flamelet modeling in such flames. It would quite a challenge for the existing models to predict the bimodal-monomodal approach to extinction and the variation of such approach with the fuel ($\Delta\xi_R$) and the flow condition (Σ_ξ).

ACKNOWLEDGEMENTS

This work has been supported by the U.S. Department of Energy, Office of Basic Energy Sciences, the Australian Research Grants Scheme and the Garrett Turbine Engine Company of Phoenix, Arizona, U S A. Dr Masri is supported by the Henry Bertie and Florence Mabel Gritton Postdoctoral Fellowship granted by the University of Sydney.

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