Scalar structure of turbulent stratified swirl flames conditioned on local equivalence ratio

M. Mustafa Kamal [a],*, Robert S. Barlow [b], Simone Hochgreb [a]

[a] Department of Engineering, University of Cambridge, CB2 1PZ Cambridge, United Kingdom
[b] Sandia National Laboratories, California, United States of America

ABSTRACT

In a recent paper (Kamal, et al., 2015), we reanalyzed single shot species and temperature measurements from non-swirling flames stabilized on the Cambridge/Sandia stratified burner by conditioning measurements on the local equivalence ratio, and found that the state space structure of the flames was closely approximated by that of a laminar flame at the given equivalence ratio. In the present communication, we show that the same state space relationships remain robust for species CH_4, O_2, H_2O, and CO_2 in pre-mixed and stratified flames under high swirl. Conditioned mass fractions of CO and H_2 in the stratified swirl flame show a greater effect of stratification than was observed in the non-swirling cases, and this is attributed to larger gradients in equivalence ratio that occur with the addition of swirl. Aside from this modest effect of stratification, major species mass fractions in the swirling flame are also closely approximated by laminar flame results at the local equivalence ratio.

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1. Introduction

In a recent paper [1], the structure of premixed and stratified turbulent flames was analyzed based on the species and temperature database generated from the Cambridge/Sandia burner [2,3]. A major conclusion of [1] was that the relationship between major species mass fractions and temperature is primarily a function of the local equivalence ratio, with only secondary effects attributed to stratification and differential diffusion. The study also concluded that the mean scalar dissipation rate is lower than the nominal value for a laminar flame, owing to turbulent mixing.

The present study extends the conditional analysis to premixed and stratified flames in the same dataset, but which include swirl. These flames burn in the thin flame zone of the Borghi diagram (See Fig. 14 in [4]), where we expect that the reaction zone is not disrupted by turbulence, but the thermal zone is. Swirl leads to the following additional effects on the flames [4]: (a) higher levels of turbulence, with Karlovitz numbers up to 20 in the flame zone (as opposed to 6 in the non-swirling flames), and a ratio of turbulence intensity to laminar flame speed, u'/S_L, up to 14 (compared to 7 in the non-swirling flame); (b) significant three-dimensional effects owing to the tangential component of velocity, and significant changes in flame shape and velocity profiles, with strong entrainment of air from outside into the product recirculation zone;

and (c) larger gradients of equivalence ratio across the flame [2,3]. In this short communication, the same analysis techniques used in [1] are applied to premixed and stratified swirl flames to determine how swirl affects the relationships between species and temperature.

2. Experimental details

2.1. Burner and operating conditions

The burner has been described in the previous studies [2–5], and the reader is referred to the prior publications for details. The burner consists of two co-annular channels, with the flame stabilized by a central bluff body. Both inner and outer annuli are fed with specified premixed streams of methane and air. The main difference in the present study is that the outer annular flow is split between axial and tangential flow at the bottom of the mixture inlet, generating swirl and increased turbulence.

Only three flames are considered in this communication, but all of the swirl cases from [3] yielded results consistent with those presented here. Operating conditions are listed in Table 1. SwB1, which is uniformly premixed and without swirl, serves as a baseline. SwB3 adds strong swirl, and SwB11 combines strong swirl and high stratification. For all cases the bulk axial velocities in the inner and outer annuli were $U_i = 8.3$ m/s and $U_o = 18.7$ m/s, respectively, with laminar co-flow air at $U_{co} = 0.4$ m/s. In the stratified swirl flame, SwB11, the turbulent flame brush crosses the

Table 1

Operating conditions for the selected flames. Equivalence ratios ϕ_i and ϕ_o correspond to the inner and outer annular flows, respectively. The swirl number, S, is defined as the ratio of the tangential to the axial momentum flow at the exit of the burner. The maximum value of U'/S_L from three component velocity measurements [4] is listed.

Case	ϕ_i	ϕ_o	S	U'/S_L at $z = 30$ mm
SwB1	0.75	0.75	0.03	10.0
SwB3	0.75	0.75	0.54	17.9
SwB11	1.125	0.375	0.53	17.9

centre of the mixing layer between inner and outer annular flows ($\phi \approx 0.75$) at a distance $z = 30$ mm above the burner exit plane. Accordingly, we focus on results from this downstream location to compare scalar structure in the three flames.

2.2. Diagnostics

As described in [1,2], experiments were conducted at Sandia National Laboratories. The diagnostic setup allows for the line measurement of temperature and major species (CH_4, CO_2, CO, H_2, H_2O and O_2), with simultaneous cross-planar OH-LIF imaging to determine the instantaneous flame orientation relative to the measurement line. The species and temperature profiles were obtained by translating the 6.18 mm probe volume through each flame in overlapping steps, with 500 shots acquired at each step. The focus had a diameter of approximately 0.22 mm ($1/e^2$). The projected binned-pixel spacing for the combined Raman/Rayleigh/CO-LIF data was 103 μm. Measurement uncertainties are discussed in detail in [2], but are under 5% of the conditional mean for most species mass fractions, except CO and H_2 (10%), and around 2% for temperature. Turbulent velocity measurements acquired with laser Doppler anemometry (LDA) and particle image velocimetry (PIV) by Zhou et al. [4] place the Kolmogorov length scale around 30 μm in the middle of the shear layer between inner and outer annular flows (non-reacting) at a downstream distance of $z = 30$ mm.

3. Results

3.1. Conditioned species state space maps

In the same way as was done for the non-swirling flames in [1], species mass fractions in the swirl flames were conditioned on the instantaneous local equivalence ratio. The equivalence ratio is reconstructed from the atomic balance of the measured species molar fractions, X_i:

$$\phi = \frac{X_{CO_2} + 2X_{CH_4} + X_{CO} + 0.5(X_{H_2O} + X_{H_2})}{X_{CO_2} + X_{O_2} + 0.5(X_{CO} + X_{H_2O})} \qquad (1)$$

Figure 1 shows CH_4, H_2O, O_2, CO_2, CO, and H_2 mass fractions as functions of temperature for narrow ranges in equivalence ratio. Results of unstrained and strained laminar flame calculations at the corresponding equivalence ratio are included for comparison. The selected strain rate of 1000 s^{-1} is representative of the radial gradient in mean axial velocity across the shear layer at $z = 30$ mm above the burner exit in the swirling flames.

In the case of CH_4, the good agreement shows that all swirling and non-swirling flames [1], fuel disappearance is only controlled by the local equivalence ratio and temperature according to the relationships in laminar flames, even at high equivalence ratios. The same is observed for H_2O and O_2. Note also that there is little effect of strain rate on the laminar results for mass fractions of CH_4, H_2O and O_2. (See also Fig. 7 in [1].)

The conditional mean CO_2 measurements for the zero swirl case SwB1 are between the strained and unstrained laminar curves,

whereas the values for the swirling premixed (SwB3) and stratified cases (SwB11) (except those for $\phi = 0.65$), agree well with the strained laminar flame. The influence of higher strain is apparent in both swirling cases (SwB3 and SwB11), as expected from the calculated higher sensitivity of CO_2 to strain, but there is no obvious additional influence of local gradients in equivalence ratio for the stratified case SwB11 compared to SwB3. Thus, as concluded in [1] for the non-swirl cases, Fig. 1 demonstrates that the state space behavior of CO_2 mass fraction in the stratified swirling flame is also primarily a function of local equivalence ratio.

In the case of CO, the peak in the conditional mean for the non-swirling premixed flame SwB1 is consistent with the *unstrained* laminar calculation, while that in the swirling premixed flame SwB3 is consistent with the lower CO levels found in the 1000 s^{-1} strained calculation. The flame brush in SwB3 at $z = 30$ mm occupies a narrow region between the conical recirculation zone and the outer mixing layer between reactants and coflow air. Inclusion of slightly diluted samples from these regions within the conditioning interval in equivalence ratio could reduce the mean CO levels. However, narrowing the conditioning interval to $\phi = 0.75 \pm 0.5\%$ caused no change in the conditional mean. Therefore, the lower CO levels in SwB3 compared to SwB1 can be attributed to increased strain associated with the addition of swirl. The two swirling cases, SwB3 and SwB11, have comparable levels of bulk strain and turbulence intensity, but the peak CO level in the stratified case, conditioned on $\phi = 0.75 \pm 2.5\%$, is higher than in the premixed case. For each of the four conditioning intervals in local equivalence ratio, the peaks in measured CO in SwB11 are approximately equal to those in the corresponding *unstrained* laminar flame. This suggests that the effect of stratification on CO in SwB11 roughly offsets the effect of increased turbulence.

The effect of stratification on CO levels in the swirling flames (comparing SwB3 and SwB11 at the $\phi = 0.75 \pm 2.5\%$ condition) is greater than in the corresponding non-swirling flames (as shown in [1] by comparing SwB1 and SwB9 at the $\phi = 0.75 \pm 2.5\%$ condition). This can be attributed to the fact that the increased levels of turbulence generated by adding swirl also produce larger gradients in equivalence ratio across the flame. Distributions of the instantaneous change in equivalence ratio across the thermal ramp in all of the premixed and stratified, swirling and nonswirling flames were reported by Sweeney et al. [2,3], and the reported mean values at $z = 30$ mm are $\overline{\Delta\phi} = 0.17$ in the non-swirling stratified flame, SwB9, and $\overline{\Delta\phi} = 0.28$ in the swirling stratified flame, SwB11. It is important to note that peak heat release in lean premixed methane flames occurs near the location of peak CO mass fraction. While results in Fig. 1 reveal a modest elevation in peak CO levels due to stratification, the conditional mean CO levels are still primarily a function of local equivalence ratio.

For the highly stratified case SwB11, at temperatures below the point of peak CO, the measured mean values are somewhat higher than the laminar calculations. This can be seen by comparing the SwB11 mean results conditioned on $\phi = 0.75$ with SwB1 and SwB3. This difference was also seen in [1] for the non-swirling stratified flames, and it may well be an effect of stratification, with elevated CO levels from the richer product zones diffusing toward the leaner preheat region of the flame.

Results for H_2 follow trends similar to those for CO. H_2 levels are slightly lower in SwB3 than in SwB1, due to increased turbulence in the swirling premixed case, and they are higher in SwB11, conditioned on the corresponding equivalence ratio, than in SwB3, due to stratification. For each of the four conditioning intervals the elevation of H_2 levels is greatest at low and intermediate temperature, rather than the region of maximum heat release. This is attributed to rapid diffusion of H_2 from richer regions of the stratified flame. At higher temperatures and especially at higher local equivalence ratios, the effects of stratification on H_2 are relatively