Structures of Turbulent Bunsen Flames in the Corrugated-Flamelet Regime

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1 Summary of the Work

Structures of turbulent Bunsen flames in the corrugated-flamelet regime [1] were investigated by use of a three-color six-beam LDV system. Four different mixtures with identical laminar burning velocities (0.34 m/s) were selected, to facilitate comparisons – lean and rich methane, and lean and rich propane. A bimodal distribution, not previously reported in the literature, was observed in the radial component of gas velocity off-axis in the turbulent flame brush. Our previous measurements [2] enabled the low-velocity mode to be identified as velocity fluctuations of the fresh mixture and the high-velocity mode as fluctuations of the burnt-gas radial velocity. Favre-averaged and Reynolds-averaged reaction-progress variables were then calculated from these bimodal distributions, revealing an unexpected region near the flame tips, a kind of "bubble", where, at a fixed radius, the average progress variable decreased (rather than increasing) with increasing height over a short distance, at least for the lean propane flame, likely through enhanced flamelet flapping, which has not been predicted by modeling but which appears to occur quite generally for sufficiently tall turbulent Bunsen flames in the corrugated-flamelet regime. Conditioned and unconditioned Favre-average velocity components and intensities also were calculated from the data for future tests of modeling.

The distributions of the progress variables also clearly showed that the turbulent burning velocity of the rich propane flame was appreciably larger than that of any of the other three, as was its radial flame-brush thickness at any given height, and its high-radial-velocity mode had a higher average velocity magnitude than the others. Similarly, the turbulent burning velocity and flame-brush thickness appear to be smaller for the lean propane flame. These differences can be attributed to influences of preferential oxygen diffusion to turbulence-induced flamelet bulges, not included in existing modeling

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approaches, for the rich propane flames, and to a corresponding inhibition of fuel diffusion to the bulges in the lean flames. The former phenomenon is related to but different from the well-known cellular-flamelet instability, these effects occurring for flames that are stable to diffusive-thermal disturbances. It was concluded that a greater fraction of the total amount of heat release occurs in the upstream half of the turbulent flame brush in the rich propane flame, producing enhanced flow divergence in the upstream region, while the reduced ability of the slowly diffusing fuel to reach bulges in the lean flame generates the opposite effect. The results point to directions in which turbulent-combustion modeling needs to be improved, and an approach to modeling this type of preferential-diffusion effect is suggested.

2 Probability Distributions of Velocity Components

Representative probability distributions of the axial, tangential, and radial components of the gas velocity obtained in the present study are shown in Figure 1. The results of this radial traverse, at 50 mm above the burner exit of the lean propane-air flame, are qualitatively similar to the results of the traverses at the mid-turbulent-flame heights for all four flames. In the figures, N and N_s represent the number of samples in a bin of interval 0.04 m/s and the total number of samples, respectively. Mono-modal distributions are observed in the axial and tangential components of the gas velocity. The axial component is distributed approximately symmetrically between about 4.0 m/s and 6.5 m/s, with its peaks at 5.5 m/s in this case; such nearly symmetrical distributions of the axial component are characteristic of the results obtained at all heights in all of the flames. The tangential component is distributed symmetrically about 0 m/s, as it should be, according to the symmetry of the experiment; the slight departures from exact symmetry that are detectable here are typical of all of the data and reflect inaccuracies in alignment and insufficiencies in data rates, seen here to be very small. The range of fluctuations of the axial and tangential components increase with increasing radius at these mid-turbulent-flame-brush locations in all of the flames, until the radial position begins to emerge from the flame brush, at which point the range begins to decrease.

Contrary to the axial and tangential components, the radial component of the gas velocity is characterized by a bi-modal distribution in the interior of the flame brush. In this example, when the radial position r is less than 7 mm, a mono-modal distribution, which is composed almost completely of the velocity fluctuations of the unburnt mixture, is observed in the radial component. When the radial position r is between 7 mm and 12 mm, a bimodal distribution, composed of a low-velocity mode and a high-velocity mode, is observed in the radial component. As the radial position r increases, the number of samples in the low-velocity mode decreases, and the number of samples in the high velocity mode increases. The zone in which the bimodal distribution is observed can be interpreted as the turbulent flame brush, with the low-velocity data coming primarily from measurements made when the fresh mixture is present and the high-velocity data corresponding mainly to the presence of the burnt gas. When the radial position r is larger than 12 mm in this case, a mono-modal distribution again develops in this radial component, which now is dominated by the velocity fluctuations of the burnt gas. This type of development of bi-modality in LDV data does not appear to have been observed previously.

3 Effects of Differential Diffusion

It is of interest to compare the shapes of the distributions of the radial velocity components for the flames of the four different mixtures, in the center of the flame brush, where the bimodal peaks are of approximately equal areas. This position occurs where the root-mean square tangential velocity component is a maximum and is found at slightly different locations in each flame. Figure 2 shows such a comparison. It can be seen from this figure that the distributions are quite similar for both the lean and rich methane flames but differ appreciably for the lean and rich propane flames. The distributions for the lean propane flame in fact resemble those of the methane flames more than they resemble that of the rich propane flame, although its high-velocity portion clearly has a narrower distribution than that of the methane flames. The low-velocity mode for the rich propane flame is similar to the other peaks, but its high-velocity mode is much broader, opposite to that of the lean flame, and it extends to higher velocities. This is consistent with the turbulence preferentially enhancing individual flamelet propagation in rich propane flames and impeding it in lean flames. The effect is perhaps seen most clearly in the averages for the radial component shown in Figure 3.

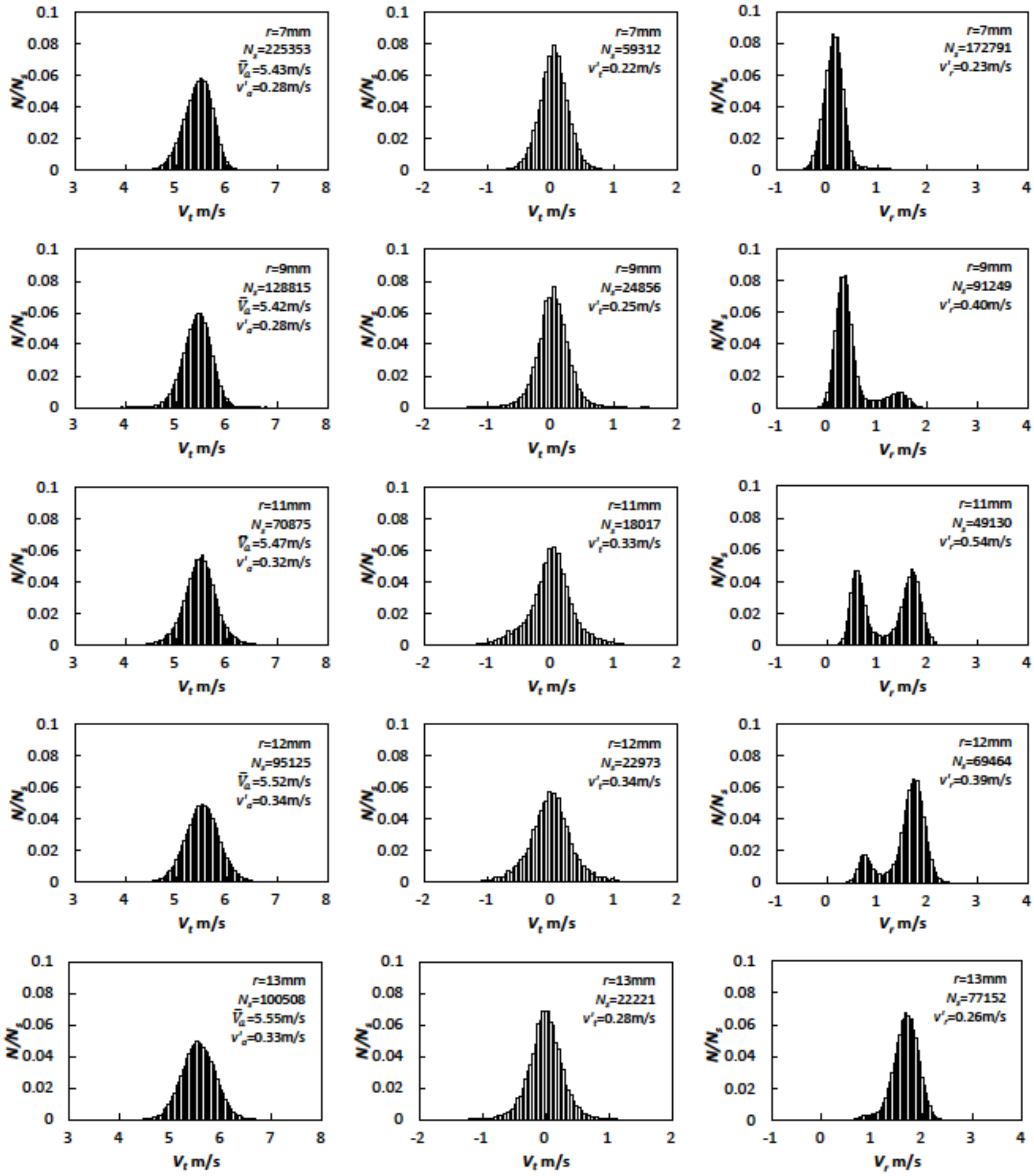

Figure 1. Change in the probability distributions of the axial (left), tangential (center) and radial (right) components of the gas velocity at 50 mm height in propane-air flames with an equivalence ratio of 0.85.

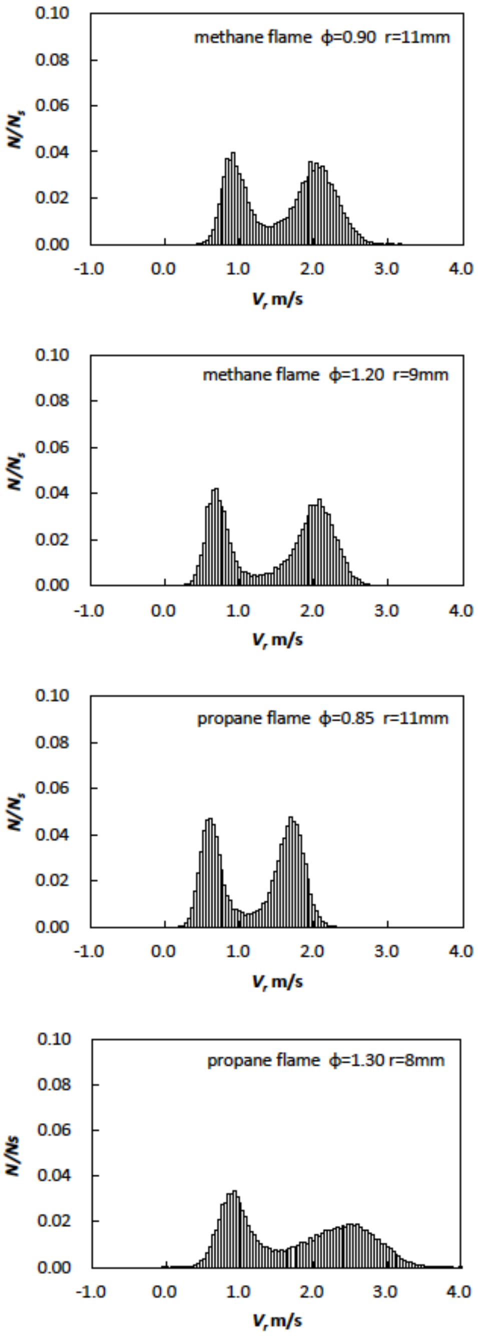

Figure 2. Radial component distributions at 50 mm.

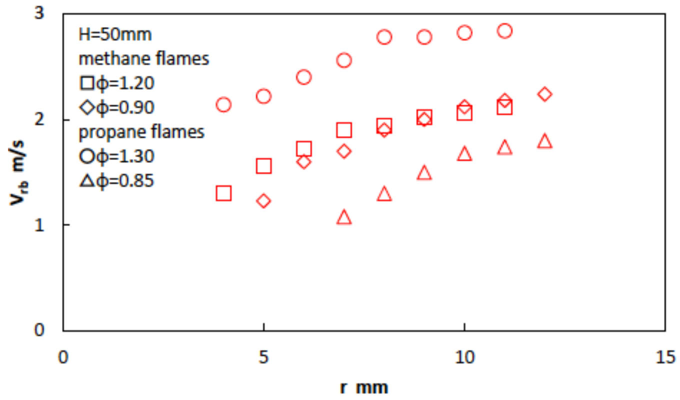

Figure 3. Radial distribution burnt-gas averages.

The physical phenomenon and its consequences can be discussed in terms of turbulent burning velocities. The magnitude of the resulting fractional change in the turbulent burning velocity, compared with that of a stoichiometric mixture, may be expected to be proportional to a factor *f*, defined as the difference between the maximum laminar burning velocity and the laminar burning velocity of the fresh mixture, S_L, divided by S_L. Letting D denote the difference between the diffusion coefficient of the deficient reactant and an effective diffusivity of the mixture, the change in the turbulent burning velocity must also be proportional to D/l, where l is a representative radius of curvature of a wrinkled flamelet. The value of l should be on the order of the integral scale L of the turbulence in the approach flow, so long as S_L is small compared with the root-mean-square turbulent fluctuation velocity u' of the fresh mixture. Since laminar flame propagation through turbulent eddies reduces flamelet curvature, a final approximation to the fractional change of the turbulent burning velocity can be suggested to be $f(D/L)\exp(-S_L/u')$.

This result indicates that the differential diffusion phenomenon encountered here thus should scale with the fractional diference in laminar burning velocities, with the difference in the diffusion coefficient of the deficient component, and with the reciprocal of the integral scale of the turbulence, exhibiting an attenuation factor dependent on the ratio of the laminar burning velocity to the fluctuation velocity of the turbulence. The heat-release rates, wrinkling, and flamelet-surface-area increases are enhanced when the diffusion-coefficient difference is positive (the deficient reactant has the larger diffusion coefficient), and they are reduced when this difference is negative (the deficient reactant has the smaller diffusion coefficient). Small-scale, high-intensity turbulence, so long as it is still in the corrugated-flamelet regime, would favor this mechanism becoming important, according to the scaling formula proposed here.

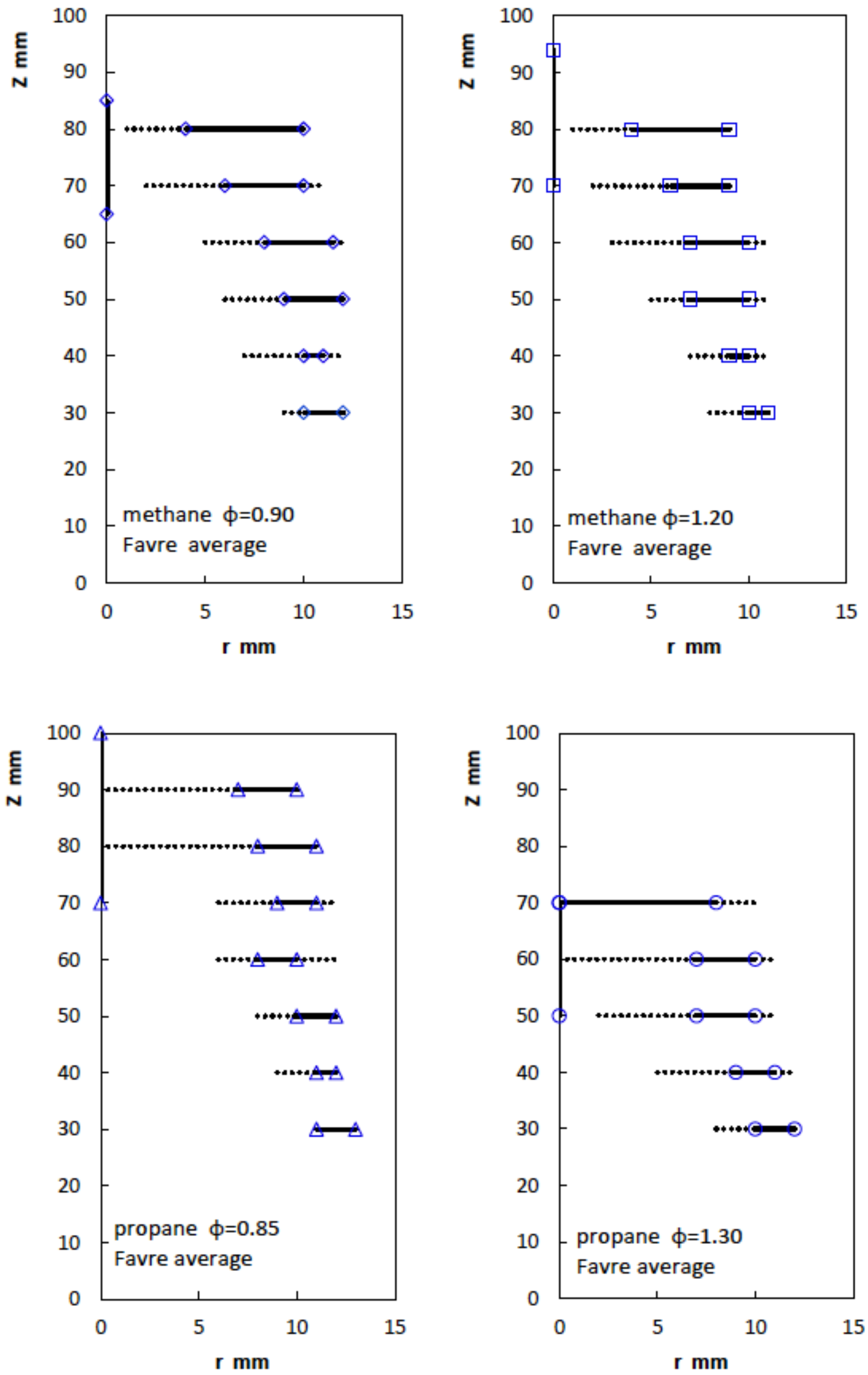

Figure 4. Distribution maps of the possible range of the progress variable *C=0.5*.

4 Fields of Progress Variables

The bi-modal LDV data for the radial component of velocity can be employed to obtain estimates of local average values of the progress variable *C*. The data produce Favre averages directly, but Reynolds averages also can be computed. Suitable assumptions are necessary to obtain both results, thereby introducing possible ranges of error. Figure 4 shows the final results for the Favre-averaged contours of 0.5. In the figure, the points bound the limits of that contour, and the dashed lined cover the full range over which bi-modal distributions were found. The outer radius of the bimodal region does not vary much with height, but the inner radius decrease rapidly with height, causing the turbulent-flame thickness to increase with height, nearly until the flame tip is reached. The more rapid increase for the rich propane flame is a further indication of the previously discussed preferential-diffusion effect. The lengths of the solid lines, representing the range of uncertainty of the contour, generally increase with height because the clarity with which the bi-modality can be identified decreases as the flame-brush tip is approached, associated with an increasing range of radius over which two weak peaks may exist. The bounds, notably for the lean propane flame in the lower left-hand plot, strongly suggest that the contour achieves a minimum radius, in that case at a height of 60 mm. Above that is a kind of fresh-mixture average "bubble", which closes rapidly at the top of the flame, just below 100 mm, in that case. The experimental methods of Kobayashi et al. [3] reveal what appear to be flapping near-vertical flamelets that could be responsible for the development of the "bubble" at the top of the turbulent flame brush in the progress-variable iso-contours of the Bunsen flame. This phenomenon has not been found in turbulent-flame modeling, and it would be of interest to investigate what types of modeling assumptions might lead to the prediction of such a phenomenon, along with predictions of the observed bi-modality.

5 Conclusions

It may be concluded from this study that LDV measurements are capable of revealing a number of aspects of the structures of turbulent Bunsen flames in the corrugated-flamelet regime. Through flapping motions of predominantly nearly vertical flamelet sheets in this regime, non-monotonic variations of mean reaction progress variables with increasing height at a fixed radius develop for sufficiently tall turbulent flames. Equidiffusional mixtures in this regime exhibit essentially identical turbulent flame structures for rich and lean flames having the same laminar burning velocity. The turbulent flame structures, however, are different for rich and lean mixtures having the same laminar burning velocity if the diffusion coefficient of the fuel is appreciably less than that of the oxygen and diluent. In that case, through preferential diffusion of oxygen to turbulence-induced flamelet bulges extending towards the fresh mixture, the rich mixture develops higher average flamelet propagation velocities and greater flamelet areas, which lead to greater turbulent burning velocities and turbulent flame-brush thicknesses than those of the corresponding lean mixture. In addition, for this lean mixture, the slower rate of fuel diffusion to such bulges reduces the average flamelet propagation velocities and flamelet areas, compared with those of the corresponding equidiffusional mixtures, thereby leading to smaller turbulent burning velocities and flame-brush thicknesses. Preferential diffusion, thus, in general, exerts measurable influences on turbulent flame structures in the corrugated flamelet regime.

References

[1] Peters N. (2000). Turbulent combustion. Cambridge University Press (ISBN 0-521-66082-3).

[2] Furukawa J, Noguchi Y, Hirano T, Williams FA. (2002). Anisotropic enhancement of turbulence in large-scale, low-intensity turbulent premixed propane-air flames. J. Fluid Mech. 462: 209.

[3] Kobayashi H, Nakashima T, Tamura T, Maruta K, and Niioka T. (1997). Combust. Flame 108:104.