Effects of high shear on the structure and thickness of turbulent premixed methane/air flames stabilized on a bluff body burner

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The effects of preferential transport and strain on the scalar structure (profiles of major species, elemental ratios, and equivalence ratio) of turbulent premixed bluff-body stabilized flames are examined using line-imaged Raman/Rayleigh/CO-LIF diagnostics combined with crossed-planar Rayleigh imaging to determine the 3D flame orientation. Comparison of the experimental measurements with laminar flow calculations shows strong effects of preferential diffusion on the flame structure and the product state in lean and rich flames. Measurements of the flame orientation show a strong correlation between the flame-front normal angle and the strength of the preferential transport effects. As the flame-front angle decreases (that is increasing the reactant velocity, or decreasing the distance from the surface), the coupling between the preferential diffusion through the flame brush and the recirculation region is increased, enhancing the preferential transport effects. Flame thickness measurements show good agreement (within 3%) with the laminar calculation for fuel lean flames, and ‘slow’ (2.0 m/s reactant velocity) fuel rich flames. The measured thickness for the ‘fast’ (9.4 m/s reactant velocity) fuel rich case is 2.4 times larger than the predicted value at 10 mm from the surface and shows a strong dependence on the flame normal angle.

1. Introduction

In practical premixed combustors the turbulent flame brush is often stabilized in a region of high shear by contact with recirculating combustion products, so there is motivation to better understand the effects of high shear on flame structure. Bluff-body burners allow reproducing some of the effects of high shear encountered in such combustors, but the simpler geometry makes acquisition and interpretation of experimental results easier. Recent experimental studies on bluff-body-stabilized premixed methane/air flames [1, 2] have shown that the scalar structure (profiles of major species, elemental ratios, and equivalence ratio) is strongly affected by preferential transport, when the flame brush is located in the high shear region adjacent to the bluff body recirculation zone. Comparison with laminar calculations using Chemkin with GRI Mech 3.0 and multicomponent transport showed significant increases in the C/H and C/O atom ratios across the flame brush. The authors concluded that the effect observed in the bluff-body burner were caused by preferential diffusion of H₂ and H₂O through the preheat zone, ahead of CO₂ and O₂ followed by convective transport downstream and away from the flame brush.

Numerical simulations on a similar bluff-body burner performed by Katta [3] showed that preferential transport effects are stronger at axial locations closer to the bluff-body. A similar trend was observed by Dunn [2] increasing the ratio of the bulk velocity to the laminar speed. The proposed explanation was that at low velocity the flame has a wide angle and there is a separation
between the flame brush and the recirculation region. As the velocity is increased the angle is reduced, the flame is pressed against the recirculation zone, and the coupling between the preferential diffusion effects and the recirculation region is enhanced. No measurements, other than visual observation of the flame chemi-luminescence, were available to support this explanation.

It was also reported as an initial observation that for fuel-rich flames some species profiles, plotted vs. temperature, had trajectories similar to those in strained laminar opposed-flow flame calculations, while instantaneous radial profiles of measured scalars were significantly thicker than for strained or unstrained calculations [2]. These profiles were measured in the direction normal to the mean flame. However, the experiments utilized only line-imaged Raman/Rayleigh/CO-LIF diagnostics, so the effect of instantaneous flame orientation on apparent flame thickness could not be evaluated.

The present study examines in more details the effects of high shear and the preferential transport phenomenon, by using the same simple annular bluff-body burner of [1, 2] and combining the Raman/Rayleigh/CO-LIF multiscalar diagnostic system used in those previous works with Cross-Planar Rayleigh Imaging (CPRI) for instantaneous measurements of the flame-front orientation. Measurements have been obtained in fuel-lean and fuel-rich flames, at three reactant velocities, and 6 axial locations. Experimental results are compared with freely propagating and strained laminar flame calculations. The objectives of this study are to:

1) Validate the proposed correlation between the flame orientation and the strength of the preferential transport effects.
2) Observe experimentally the relation between the preferential transport effects and the distance from the bluff-body found in Katta’s [3] numerical simulations.
3) Investigate the flame thickness dependence on the equivalence ratio, reactant bulk velocity, and distance from the bluff body.

2. Experimental Methods

The bluff-body premixed burner (Figure 1) used for this study is the same used in the previous studies discussed above [1, 2]. It consists of a 12.7 mm center-body surrounded by a premixed flow passing through a 5.0 mm annular gap. A perforated plate placed in the annular gap, 35 mm upstream of the exit, acts as turbulence generator. A N₂ co-flow isolates the premixed flow from the room air. Experimental data have been collected at two equivalence ratios (Φ=0.75 and 1.23), and with varying reactant bulk velocities. Table 1 shows for the six test cases, the equivalence ratios, the

Table 1: Bulk velocity $U_b$, ratio of reactant bulk velocity to laminar speed $U_b/S_L$, and Reynolds number based on the hydraulic diameter $Re_{Dh}$ for the test cases examined.

<table>
<thead>
<tr>
<th>$\Phi$=0.75</th>
<th>$\Phi$=1.23</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U_b$ (m/s)</td>
<td>$U_b/S_L$</td>
</tr>
<tr>
<td>1.3</td>
<td>5.2</td>
</tr>
<tr>
<td>7.7</td>
<td>31</td>
</tr>
<tr>
<td>12.9</td>
<td>52</td>
</tr>
</tbody>
</table>

Figure 1: Annular bluff-body burner
Reynolds number based on the hydraulic diameter $Re_{Dh}$, the bulk velocity $U_b$ and the ratio of the bulk velocity to the laminar flame speed $U_b/S_l$ (as computed in [4]). Flow rates were controlled through mass flow controllers calibrated against laminar flow elements, with 1% accuracy. The burner is mounted on a three-axis translation stage, and experimental data have been collected along radial directions (coincident with the laser probe) at 6 axial locations 5, 7.5, 10, 12.5, 15 and 20 mm from the bluff-body surface.

An updated version of the multi-scalar measurements diagnostic system described in [1] is used for the measurements here described. The system combines Rayleigh and Raman scattering and two photons CO-LIF for single-shot acquisition of temperature and major species concentration (N$_2$, O$_2$, CO, CO$_2$, CH$_4$, H$_2$, H$_2$O) along a 6 mm probe line. The Raman-Rayleigh imaging probe is provided by four frequency doubled Nd:YAG lasers, opportunistically delayed in time, overlapped and sent through 3 optical delay lines, to generate a 1.4 J/pulse laser beam, temporally stretched over 400 ns to prevent optical breakdown. An UV laser beam at 230.1 nm, overlapped to the Nd:Yag laser beams, is used for the CO-LIF (two photon) process.

A pair of 150 mm achromatic lenses (Linos Photonics f/2 and f/4) focuses the Raman-Rayleigh-COLIF signal onto the detection system. The main internal components include two custom-built motor-driven chopper wheels, six commercial camera lenses, a custom transmission grating (1200 lines/mm Kaiser Optical) and mirrors and filter to separate the signal from Raman scattering (~550-700 nm), Rayleigh scattering (532 nm) and CO fluorescence (~480-488nm). A non-intensified, low-noise, cryogenically cooled CCD camera (Princeton Instruments VersArray 1300B with CryoTiger cooling unit, -110°C operating temperature) is used for Raman detection. Gating for the Raman camera is 4.9 µs. A Princeton Instruments 1340/400 EMB CCD camera is used for the Rayleigh signal, and an intensified CCD camera (Andor DH-734-18F-03) for the CO-LIF signal.

Crossed-planar Rayleigh imaging (CRPI) from two 355 nm, crossed, laser sheets that intersected along the multiscalar probe line is used to determine the instantaneous 3D flame orientation. The two laser sheets are at 34 degrees with respect to the vertical direction. Two Andor (Istar DH-312T-18F-E3) intensified CCD cameras image the laser sheets through two CVI UV aplanar lens systems (double APMQ, 60 mm clear aperture, ~300 mm working distance) for 1:1 imaging. Both the camera and the lenses are oriented with their axis orthogonal to the laser sheets to minimize distortions.

Binning of the cameras is performed to improve the signal-to-noise ratio, and the resulting super-pixels are 0.103, 0.020, 0.101 and 0.05 mm along the laser axis, for the Raman, Rayleigh, CO-LIF and CRPI cameras, respectively. The optical resolution of the system is limited to 0.05-0.06 mm by the achromatic lenses chosen. Effective spatial resolution is limited by the beam diameter, the angle between the flame and the beam, and by the blurring effect caused by the flame itself. Focusing and alignment of all five cameras was accomplished by placing a target at the object plane and back illuminating the target through a diffuser with light of appropriate wavelength.

The Raman/Rayleigh/CO-LIF data analysis was performed using a hybrid method that integrates theoretically calculated Raman spectral libraries to determine the temperature dependence of each molecule, excluding methane [5]. Measurements in cold flows are used to obtain normalization curves for the camera response. An optimization algorithm calibrates several Raman gains and crosstalk terms to minimize the difference between experimental measurements in a set of premixed CH$_4$-air flat flames and corresponding chemical equilibrium calculations.

The CRPI is used to determine the instantaneous 3D flame orientation along the line imaging probe volume. Rayleigh images are background subtracted using the mean “dark” image obtained with the laser off. Images taken in ambient air are used to correct non-uniformities in the camera
response, and the time-averaged laser sheet profile. The Rayleigh images are smoothed using a Gaussian filter with standard deviation proportional to the measured temperature similar to what was done by Frank in [6]. The results from the Raman-Rayleigh-CO measurements are fed in input to the CRPI data analysis to determine the local Rayleigh cross section. Since only 1D profiles are available, the values of the cross section are then propagated in the direction orthogonal to the laser beam. This is a reasonable approximation in the neighborhood of the 1d probe line, but it gets increasingly worse moving away from it, and as the flame angle increases. The progress variable \( c \) is computed along the 1D probe volume

\[
c = \frac{(T - T_u)}{(T_{ad} - T_u)}
\]

with \( T \), \( T_{ad} \) and \( T_u \) the measured, the adiabatic and the reactant temperature respectively.

The flame front geometry is approximated to the contour of the Rayleigh temperature field at the location where the progress variable \( c \) is equal to 0.5. The isocontours are computed using a marching-square algorithm. The procedure to extract the flame normal from the two flame-front contours is the same detailed in [7]. The isocontour coordinates are indexed along the flame front \( s \). A 10-point cubic spline is fitted through the isocontour in the neighborhood of the 1D probe line. The polynomials are differentiated to determine the tangent to the flame front at the intersection with the 1D probe line. Knowing the angle between the two crossed planar images is possible to determine the flame front tangents \((t_1, t_2)\) in the laboratory reference frame, and obtain the instantaneous 3D normal as cross products of the two tangents

\[
n = t_1 \times t_2 = (\hat{x}_1 i + \hat{y}_1 sin\Omega j + \hat{y}_1 cos\Omega k) \times (\hat{x}_2 i - \hat{y}_2 sin\Omega j + \hat{y}_2 cos\Omega k)
\]

with \( i, j, k \) the unit vectors in the laboratory reference frame, \( \Omega \) the angle between the laser sheets and the vertical direction (\( k \)). The angle \( \theta \) between the flame normal and the 1D line measurements axis \( x \) is obtained as:

\[
\theta = arccos \left( \frac{n \cdot i}{|n|} \right)
\]

The procedure described above is repeated at 6 locations surrounding the location of \( c=0.5 \), and the flame angle \( \theta \) is defined as the mean of the measured angle over these 7 locations.

To assess the performance of the diagnostic system, measurements in a ‘vertical’, nearly planar, unstrained premixed flame described in [1] are compared with laminar premixed calculation performed with Chemkin PRO for an unstrained premixed CH\(_4\)/air flame using GRI Mech 3.0 and multi-component transport with the Soret effect included. Figure 2 shows spatial profiles of the mass fraction of major species, the C/H atom ratio, and the temperature. The equivalence ratio is computed from the fuel/oxygen atom balance:

\[
\Phi = \frac{[(x_{H_2O} + x_{H_2})/2] + x_{CO_2} + x_{CO} + 2x_{CH_4}}{x_{O_2} + x_{CO_2} + [(x_{H_2O} + x_{CO})/2]}
\]

The scalar profiles are projected onto the direction \( x' \) normal to the flame-front, to remove errors due to the flame orientation (such as flame thickening, gradient smoothing). The mean value of the measured flame angle \( \theta \) is 5.9 with a 4.7 degrees standard deviation. The standard deviation does not indicate the precision of the flame orientation measurements, but rather fluctuations of flame itself as shown later in this paper (Figure 6) for a fuel-lean low-speed bluff-body flame. To facilitate visual comparison the spatial profiles are shifted so that the progress variable \( c=0.5 \) is at the origin. The plots show excellent agreement between the experimental measurements and the predicted values, with differences within 1\% in the reactants and the products. The measurements show a thicker flame than in the calculation, and a discrepancy in the slope near the reactants. This may reflect differences in the boundary conditions from the ideal freely propagating flame. These validation tests were repeated once for each test day, and results presented here are typical.
Figure 2: Five single-shot profiles (blue) and average profile (black) of scalar quantities along the flame-front normal direction $x'$, in the vertical flame with $\Phi=0.7$ each shifted to place the origin at $c=0.5$, compared with unstrained laminar calculations (red dashed line).

3. Results and Discussion

Figure 3 shows conditional mean mass fractions, equivalence ratio (as defined in Eq. 4), and selected atom ratios, measured in the bluff body flame with nominal $\Phi=0.75$, 10 mm from the surface, and with a ratio of bulk velocity to laminar flame speed of 5.2 (magenta) and 52 (black). Statistics are based on 900 instantaneous 6 mm profiles (each containing 60 samples), with a minimum of 50 samples for each conditional temperature. Inaccuracies in the flowmeters produced an equivalence ratio $\Phi=0.73$ for the high speed case. The measurements are compared to a laminar unstrained premixed flame calculation at $\Phi=0.75$ (red dashed line) and $\Phi=0.73$ (black dash-dot line), obtained from Chemkin using the GRI Mech 3.0, including the Soret effect, and multi-component transport.

The discrepancies in the scalar structures between the measurements and the calculation are consequence of preferential transport, as discussed in details in [2]. When the flame brush is located in the high shear region adjacent to the bluff body recirculation zone, $H_2$ and $H_2O$ diffuse ahead of $CO$ and $CO_2$ in the reaction zone, and then are transported downstream and away from the flame brush. Since the gas in the recirculation region has a longer residence time, the effect is integrated over time, causing a significant increase in the $C/H$ and $C/O$ atom ratios. As the reactant velocity is increased the effects of the preferential transport are enhanced: $C/H$ and $C/O$ atom ratios, the equivalence ratio and the $CO_2$ mass fraction increase, where the mass fraction of $CO$, $H_2$ decrease.
At the lowest speed (bulk velocity equal to 5.2 times the laminar speed) the angle between the normal to the flame-front and the radial direction (from now on referred to as the flame-front angle) is large, causing a separation between the recirculation region and the flame brush. As the bulk velocity is increased the flame shape becomes more vertical and the preferential transport effects are amplified by a strong coupling with the recirculation zone. This explanation, first proposed in [1], is now confirmed by the flame front orientation measurements provided by CRPI. In fact the measured mean flame-front angle for the low speed case is 31.6 degrees, and 26.1 degrees for the high speed case.

Figure 4 shows the evolution of the scalar structure for the high speed case, as the distance from the surface increases from 5 mm to 20 mm. The preferential transport effects are strongest near the surface and decrease monotonically as the distance increases, a behavior that resembles the one observed decreasing the bulk velocity. This trend is qualitatively consistent with results of numerical calculations by Katta [3]. CRPI measurements of the flame-front orientation show that the flame angle grows monotonically with the distance, from 26.1 degrees at 10 mm to 30.4 degrees at 15 mm from the surface. In addition the recirculation zone bends inward, further away from the flame brush, as the distance from the surface increases. The combined effect is a reduction in the coupling between the preferential transport and the recirculation region with increasing distance from the surface. Dunn [2] observed a self-limiting behavior, with no noticeable changes in the profile when the bulk velocity was increased past 10.3 m/s. A plausible explanation is that the flame-front angle does not change significantly past this limiting speed, therefore no enhancement of the coupling between the recirculation zone and the preferential diffusion effects occurs. Interestingly, the self-limiting behavior is not observed when reducing the distance from the surface,
with profiles taken at 5 mm showing the strongest preferential transport effects. Unfortunately, excess scattering prohibited CRPI measurements below 10 mm, and it was not possible to determine if the flame angle is further reduced near the surface.

Figure 4: Measured conditional mean scalars in the bluff body flame series with $\Phi=0.75$ and $U_b/S_L=52$, for distances from the surface between 5 mm and 20 mm. Chemkin laminar unstrained flame results (red dashed line) are included.

Figure 5: Measured conditional mean scalars in the bluff body flame series with $\Phi=1.23$ and $U_b/S_L=26$, for distances from the surface between 5 mm and 20 mm. Chemkin laminar unstrained flame results (red dashed line) and opposed flow calculations (dash-dot red line) for a strain rate of 3370 s$^{-1}$ are included.
Figure 5 shows the conditional mean mass fractions, equivalence ratio, and selected atom ratios, measured in the bluff body flame for $\phi=1.23$, for a ratio of bulk velocity to laminar flame speed ($U_b/S_L$) of 42 at distances from the surface between 5 and 50 mm. As in the fuel-lean case, increasing the distance from the surface, diminishes the effects of preferential transport. Changes with the distance appear much larger in the fuel rich case than in the fuel-lean. The peak C/H atom ratio varies of 12 % in the fuel lean case, 25 % in the fuel rich case. Consistently, the measured flame angles vary from 16.2 degrees 10 mm from the base, to 29.3 at 20 mm, a variation almost 3 times larger than was observed in the fuel-lean case, further validating the proposed enhancing mechanism for the preferential transport effects.

Near the surface the CO$_2$ and H$_2$ profiles follow a nearly linear trend, suggesting an influence of strain in combination with the preferential transport effects [2]. Figure 5 compares the experimental measurements to Chemkin calculations for an unstrained flame (dashed line) and an opposed flow calculation at moderately high (3370 s$^{-1}$) strain rates. Qualitatively, increasing the strain rate in the simulation has an effect similar to increasing the bulk velocity of the reactants or to moving closer to the surface; the CO$_2$ and H$_2$ profiles straighten up, the mass fractions of O$_2$ and H$_2$ decrease, the CO$_2$ mass fraction increases, and the C/O and C/H atom ratios increase. In [2] a discrepancy was observed in the CO mass fraction, increasing, rather than decreasing, at higher speed. This is not observed for this data set. A quantitative comparison with the unstrained calculation does not provide further insight, because the opposed flow calculations were neglecting the dependence of the product state on the flowrate and the distance from the surface observed in the experiment. Future works will compare the measurements to opposed flow calculations including this dependence for a comparison with the measurements that is also quantitative.

The qualitative agreement of the measurements with the strained calculations does not hold in physical space, where increasing strain level produces a thinning of the calculated laminar flame. On the contrary Dunn [2] observed a thickening of the flame for the fuel rich case, although it could not be quantified because no information on the flame-front angle was available. CRPI measurements of the flame-front angle allow plotting scalar profiles along $x'$, the direction orthogonal to the instantaneous flame front (computed as $x'=xcos(\theta)$), removing the flame thickening produced by the relative orientation of the flame-front normal and the 1D probe direction. Figure 6 shows the scalar profiles along the 1D probe direction $x$ for the fuel-lean case ($\phi=0.75$) at the lowest speed ($U_b/S_L=5.2$). Figure 3 showed good agreement in temperature space with the unstrained calculations, and therefore it is reasonable to expect good agreement in physical space as well. The blue lines are instantaneous profiles shifted so that for $x=0$ the progress variable $c$ is equal to 0.5. The mean profile (black) is obtained by averaging 900 shifted instantaneous profiles. The agreement with the unstrained flame calculations is overall good (within 1%) outside of the reaction zone, except for a 4% difference in the C/H ratio in the products region. On the other hand the flame thickness, defined as the distance over which the progress variable $c$ goes from 0.05 to 0.95, appears 17% larger and fluctuating from shot-shot (the mean value of the flame thickness is 1.78 mm and the standard deviation is 0.4 mm).
Figure 6: Five single-shot profiles (blue) and average profile (black) of scalar quantities along the 1D probe direction $x$ in the bluff-body flame with $\phi=0.75$ and $U_b/S_L=5.2$ each shifted to place the origin at $c=0.5$, compared with unstrained laminar calculations (red dashed line).

Figure 7 shows the same measurements of Figure 6 projected onto the flame-front normal. The measured mean flame angle for this case is 31.6 degrees, with a standard deviation of 9.1 degrees. Measured flame angles for the profiles shown range from 18 to 51 degrees. The scalar profiles all collapse onto each other, proving that changes in the flame orientation were the main responsible for the fluctuations observed in Figure 6. The measured flame thickness is 1.47 mm, only 2.5% smaller than the value predicted from Chemkin. A small discrepancy in the slope of the experimental and the calculation is visible moving toward the reactants as already observed in the “vertical” flame. The flame angle correction assumes that the flame is planar, using a single value to correct for the flame orientation. This correction may be inadequate when approaching the reactants. The algorithm used to extract the flame orientation from the CRPI images produces accurate results only in presence of strong gradients, and it is inadequate to determine the flame orientation near the reactants.

Figure 8 shows the scalar profiles in the adjusted physical space for the fuel lean case, at the highest bulk velocity tested ($U_b/S_L=50$), at distance from the surface ranging from 10 to 15 mm. As already observed in the temperature space (Figure 4), increasing the distance from the surface the scalar structure tends toward the unstrained flame calculations. The temperature profile does not show any significant changes and the slope matches well the predicted one, except near the reactants as already observed for the low speed case. The flame thickness matches the predicted value, and does not change moving downstream.
Figure 7: Five single-shot profiles (blue) and average profile (black) of scalar quantities along the flame-front normal direction $x'$, in the bluff-body flame with $\Phi=0.75$ and $U_b/S_L=5.2$ each shifted to place the origin at $c=0.5$, compared with unstrained laminar calculations (red dashed line).

Figure 8: Average scalar profiles along the flame-front normal direction $x'$, in the bluff-body flame with $\Phi=0.75$ and $U_b=52$ for the indicated values of the distance from the surface compared with unstrained (red dashed line) laminar calculations. Similar results (Figure 9) have been obtained for the bluff-body flame at equivalence ratio $\Phi=1.23$, bulk velocity to laminar speed ratio $U_b/S_L=5.5$, 10 mm away from the surface. The scalar profiles have been corrected for the flame front angle (mean value 40.8 degrees with a standard deviation of
11.3 degrees). As already observed for the fuel lean case, the five single-shot profiles (blue lines) collapse onto each other and match reasonably well the unstrained Chemkin calculations. Small differences with respect to the laminar calculations are noticeable in the C/H ratio, the CO and CO₂ profiles and the equivalence ratio, as already discussed above and previously reported in [1]. The expected flame thickness based on Chemkin calculation is 1.34 mm. The measured mean flame thickness before the flame orientation correction is 1.86 mm, 38% larger than the theoretical value. After the correction for the flame-front angle, the measured mean flame thickness reduces to 1.35 mm, 0.9% larger than the expected value.

Figure 9 shows the scalar profiles projected onto the flame-front normal direction x', in the bluff-body flame with Φ=1.23 and U_b/S_L=5.5 each shifted to place the origin at c=0.5, compared with unstrained laminar calculations (red dashed line).

Figure 10 shows the scalar profiles projected onto the flame-front normal direction, for the fuel-rich case, at the highest speed (U_b/S_L=26), 10 mm from the surface. The measured mean flame-front angle is 16.8 degrees, with a standard deviation of 7.8 degrees. As already shown in the temperature space (Figure 5), the effects of preferential transport are enhanced, and the scalar profiles differ significantly from the predicted unstrained profiles. The highest speed, fuel-lean case showed comparable changes in the product states, but no noticeable change in the flame thickness. The mean flame thickness measured in the fuel rich flame is 3.2 mm, 2.4 times thicker than the predicted value. Changes in flame thickness of turbulent flame with respect to their laminar counterpart have already been observed in the past in both experimental [8-10] and numerical studies [11-13]. Both thickening and thinning of the flame has been observed, and it is not clear yet what the physical mechanism is behind or what are the parameters governing it. The fluctuations in the instantaneous profiles indicate that turbulence certainly plays a role in the flame thickening, but the fact that the thickening was not observed in the fuel-lean case suggests that the Reynolds number, by itself is not a critical parameter. Numerical simulations and PIV measurements of the velocity field may help in understanding the physical mechanism driving the flame thickening.
Moving away from the surface the flame thickness becomes smaller as illustrated in Figure 11. The mean flame thickness goes from 3.2 mm measured at 10 mm to 1.77 mm measured at 20 mm from the surface. The flame-front angle increases with the distance from the surface, reducing the coupling between the preferential transport effects and the recirculation region. There is a strong correlation between the flame thickness and the flame orientation, but at the moment there are not sufficient elements to identify the thickening governing mechanism. Data taken further increasing the bulk velocity may provide additional insight on this phenomenon. In temperature space a self-limiting behavior was identified when the velocity was increased, for given distance from the surface. If the flame thickness shows an analogous limiting behavior it would indicate that the changes in composition, rather than the shear are driving the thickening of the flame.

Figure 10: Five single-shot profiles (in blue) and average profile (black) of scalar quantities along the flame-front normal direction $x'$, in the bluff-body flame with $\Phi=1.23$ and $U_b/S_L=26$ each shifted to place the origin at $c=0.5$, compared with unstrained laminar calculations (red dashed line).
Figure 11: Mean scalar profiles along the flame-front normal direction $x'$, in the bluff-body flame with $\Phi=1.23$ and $U_b/S_f=26$ for the indicated values of the distance from the surface compared with unstrained (red dashed line) and moderately strained (3370 s$^{-1}$) laminar calculations.

4. Conclusions

A cross planar Rayleigh imaging (CRPI) system has been added to the multi-scalar Raman/Rayleigh/CO-LIF system, to provide instantaneous orientation of the flame front, in addition to temperature and major species concentration measurements. The combined instrument has been validated in a laminar “vertical” flame and used to obtain scalar structures profiles in a bluff-body flame when varying the equivalence ratio ($\Phi=0.75$ and 1.23), ratio of bulk velocity to laminar flame speed ($U_b/S_f=5$ to 50), and distances from the bluff-body (ranging from 5 to 20 mm). Scalar measurements revealed an increased importance of preferential transport effects as the bulk velocity increases or the distance from the bluff-body surface decreases. In a previous work this behavior was attributed to the closer coupling between the preferential diffusion within the reaction zone and the scalar conditions of the recirculation zone, as consequence of a reduced angle between the flame brush and the recirculation zone. Flame-front angle measurements from the CRPI showed a strong, negative correlation with the intensity of the preferential transport effect, validating this interpretation.

Knowledge of the flame front orientation also allows for accurate measurements of the instantaneous flame thickness. Predicted and measured flame thickness values agree within 3% for the fuel lean cases and the low-speed fuel-rich one, but the measured thickness is 2.4 times larger than the predicted value for the high-speed, fuel-rich case at 10 mm from the surface. Further increasing the distance from the body the flame thickness decreases toward the laminar unstrained value. Future work will focus on determining the parameters governing the flame thickening and understanding the physical mechanism driving it.
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