Flame-Flow Interaction in Turbulent Premixed Bunsen Flames

Junichi Furukawa*

Department of Mechanical Engineering
Tokyo Metropolitan College of Technology

Forman A. Williams

Department of Mechanical and Aerospace Engineering
University of California, San Diego

An attempt has been made to examine the flame-flow interaction in turbulent premixed flames in a reaction-sheet regime. Vectors of the flame-front movement and gas velocity have been measured simultaneously by use of a two-color, four-beam LDV system and a three-element electrostatic probe at two positions in a turbulent flame brush, i.e., on the centerline and off axis. On the centerline, velocity vectors of the flame-front movement are distributed symmetrically with respect to the burner axis, independently of whether the flame front passes the measuring position in the burnt-to-unburnt or unburnt-to-burnt direction. Off axis, velocity vectors of the flame-front movement are directed mainly toward the burner axis when the flame front passes the measuring position in the unburnt-to-burnt direction but away from the burner axis when the flame front passes the measuring position in the burnt-to-unburnt direction. When the flame front passes the measuring position in the burnt-to-unburnt direction, the axial component of the gas velocity is smaller in the unburnt mixture. When the flame front passes the measuring position in the unburnt-to-burnt direction, on the other hand, the axial component of the gas velocity is smaller in the burnt gas

INTRODUCTION

Thermal expansion of gases caused by heat release in a flame, readily observable in laminar premixed flames(1), is also thought to be the cause of flame-generated turbulence in turbulent premixed flames(2), at least in flamelet regimes, because the rapidly fluctuating fronts of flamelets thereby induce velocity fluctuations. It is, however, difficult to substantiates this belief experimentally because of the complexities involved in detailed measurement of flamelet motions and gas velocities in a turbulent flame brush. We have been using electrostatic probes and laser-doppler velocimetry for such measurements(3). Here we report more detailed information than has been available previously on such flame-flow interactions, obtained by these experimental methods.

Although the previous work produced a great deal of information, most of it pertained to average statistical properties, such as distributions of flamelet orientations, turbulence intensities conditioned on unburnt or burnt gas and correspondingly conditioned spectra(3). The more detailed information that was developed concerned differences in gas velocities upstream and downstream of flamelets but did not track velocity evolution in the unburnt or burnt gas. In addition, little attention was paid to differences associated with flamelets passing the probe volume from the unburnt-to-burnt or burnt-to-unburnt directions, most of the information being obtained for burnt-to-unburnt passage(3). The present work augments previous results by identifying specific differences associated with the direction of passage and by reporting representative evolution histories. Paying attention to these details reveals previously unknown aspects of burner-stabilized turbulent flames.

EXPERIMENTAL

The burner used in the present study is the same cylindrical burner of 26 mm in diameter.(3,4). A uniform propane-air mixture is supplied at an average velocity of 4.0 m/s. Equivalence ratios studied were 0.80, 1.10 and 1.40.

Figure 1 illustrates the arrangement of the LDV and the electrostatic probe. This arrangement is identical to that employed previously(3, 4), as is the instrumentation itself. Since all of the experimental aspects are fully documented elsewhere(3), there is no need for repetition here. Suffice it to say that two gas velocity components in a vertical plane passing through the burner axis are measured, as are the same two velocity components of the line of intersection of the surface of the presumed locally planar flamelets with the same vertical plane. Since the flamelets in general are not perpendicular to the measurement plane and possess a nonzero component of velocity normal to that plane, the measured velocity of flamelet motion can exceed or be less than the velocity at which the flamelet moves normal to itself. Although in principle a four- element electrostatic probe with three-component LDV would provide complete information for planar flamelets(5, 6), the associated experimental complexity motivates extracting information form the present, less complete arrangement(3).

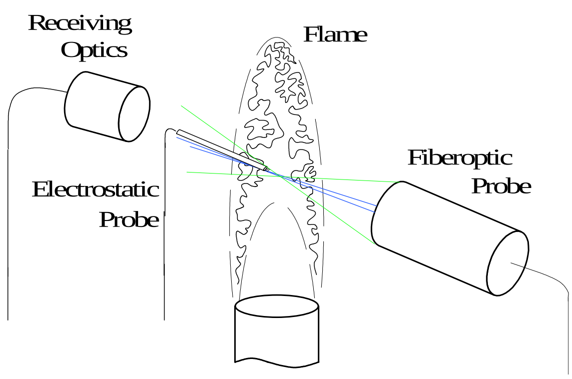

Fig. 1 Schematic illustration of the experimental arrangement

Measurements are reported for centerline and off-axis positions. The centerline position is the position of maximum average ion current on the centerline. The off-axis position, assigned a vertical height, *z*, half that of the centerline position, is located at the radial, *r*, position where the average ion current is maximum, subject to that constraint. These heights and radii differ for flames of different equivalence ratios.

The characteristics of turbulence in the non-reacting flow were examined by a hot-wire velocimeter in cold flow. The average velocity at the centerline and off-axis positions were 4.5 and 3.9 m/s, respectively, the corresponding turbulence intensities (root-mean-square velocity fluctuations), being 0.22 and 0.38 m/s, the integral scales being 10.9 and 12.9 mm, the Taylor scales being 3.5 and 2.3 mm, the Kolmogorov scales being 260 and 160 microns, and the Reynolds numbers based on the integral scale being 154 and 314, respectively [(3)].

RESULTS and DISCUSSIONS

Velocity vectors $\mathbf{V}_f$ of the flame-front movement at the centerline position and off axis are shown in Figs. 2 and 3, respectively, as vector-distribution maps, where each point represents the tip of a vector from the origin. Vectors for which the flame front passes the measuring position in the burnt-to-unburnt direction are shown in the upper plot, and passage in the unburnt-to-burnt direction in the lower plot. The analysis for extracting velocities and orientations of the flame-front movement from the three ion currents is detailed elsewhere [(5)]. Although measurements were made at the three different values of ϕ indicated previously, results are shown only for ϕ=1.1 because they are essentially the same for all ϕ.

On the centerline, the velocity vectors of the flame-front movement are distributed symmetrically around the burner axis, independently of whether the flame front passes the measuring position in the burnt-to-unburnt or unburnt-to-burnt direction. On the other hand, off axis there is an influence of the direction of flame-front passage. The burner axis is at the left-hand side of Fig. 3. When the flame front passes the measuring position in the burnt-to-unburnt direction, the velocity vectors of the flame-front movement are distributed away from the burner axis, but when the flame front passes in the unburnt-to-burnt direction, the velocity vectors of the flame-front movement are distributed toward the burner axis. Because of the overall symmetry of the distributions, in the absence of considerations of directions of passage it was previously assumed that the flame-front movement is always symmetrical in the radial direction even at the off-axis position. The present work shows, for the first time, that there is a difference in the flame-front movement depending on whether it passes the measuring position in the burnt-to-unburnt or unburnt-to-burnt direction. Explanations involve considerations of change in gas velocities.

Changes of gas-velocity vectors across the flame front on the centerline are shown in Fig. 4, where again each point is the tip of a velocity vector from the origin. In the figure, triangles represent velocity vectors behind the flame front ($\mathbf{V}_{gb}$) and circles ahead ($\mathbf{V}_{ga}$). Again, results of measurements for other equivalence ratios were quite similar to those shown here for ϕ =1.1.

These centerline gas-velocity vectors are distributed symmetrically around the burner axis. When the flame front passes the measuring position in the burnt-to-unburnt direction, the axial components of the gas-velocity vectors behind the flame front are larger than those ahead of the flame front. The radial components behind also are larger than those ahead. When the flame front passes the measuring position in the unburnt-to-burnt direction, on the other hand, the axial component

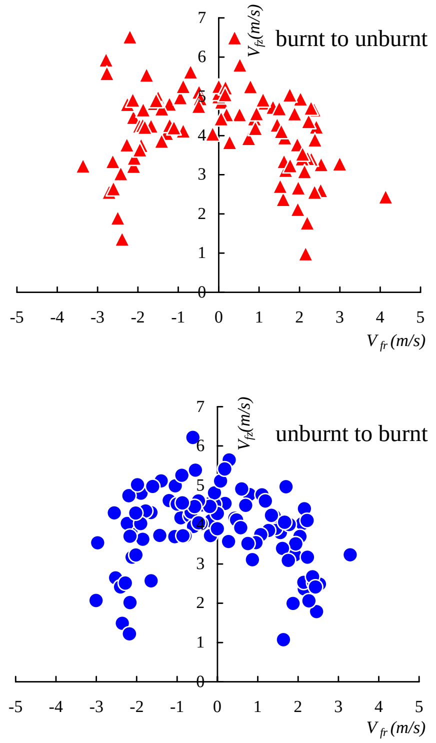

Fig. 2 Vector distribution map of the flame-front movement on the centerline

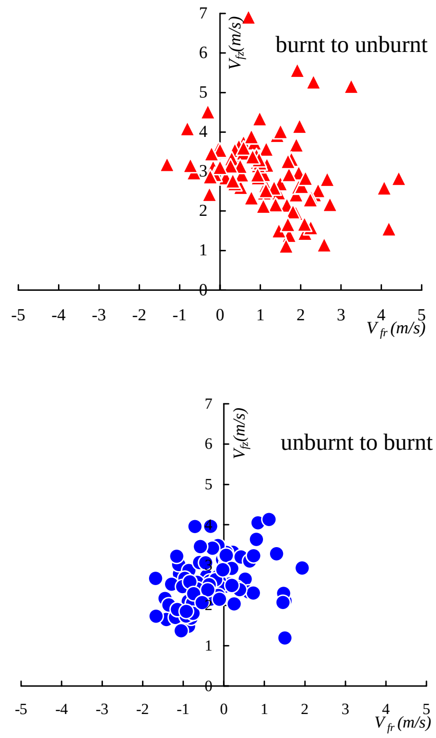

Fig. 3 Vector distribution map of the flame-front movement off axis

of the gas velocity vectors behind the flame front are smaller than those ahead, but the radial components behind still are the larger. These results might at first seem counterintuitive, but they are explicable as being due to the direction in which the gas expansion occurs.

Because of the high upward average gas velocity, the flame front is always moving upward when it passes the measuring position. Therefore, when it passes in the burnt-to-unburnt direction, the burnt mixture is above, but when it passes in the unburnt-to-burnt direction, the burnt mixture is below. The gas expansion takes place towards the burnt mixture. With this in mind, Figs. 5 and 6 have been prepared to illustrate the difference between burnt-to-unburnt (Fig. 5) and unburnt-to-burnt (Fig. 6) passage.

Figures 5 and 6 show that, for burnt-to-unburnt passage the gas expansion is upward, leading to a larger axial component of the gas-velocity vector behind the flame front, while for unburnt-to-burnt passage the gas expansion is downward, producing a smaller axial component of the gas-velocity vector behind. To obtain vertical components of gas velocities relative to the flame, it is necessary to consider flame-fixed coordinates that move upward at the velocity of the flame front. In these coordinates, the vertical components of gas velocity are much smaller than shown in Figs. 5 and 6, and the expansion is much larger in comparison with the gas velocities. For burnt-to-unburnt passage, the vertical component of $\mathbf{V}_{ga}$ must exceed the vertical component of the flame-front motion because the flame locally propagates into the unburnt mixture; in Fig. 5 this causes the vertical components in flame-fixed coordinates to be upward for both $\mathbf{V}_{ga}$ and $\mathbf{V}_{gb}$, with $\mathbf{V}_{gb}$ now large compared with $\mathbf{V}_{ga}$ because of the large expansion. For unburnt-to-burnt passage, however, the vertical component of $\mathbf{V}_{ga}$ must be less than the vertical component of the flame-front motion for the flame to locally propagate into the unburnt mixture; in Fig. 6, therefore, in flame-fixed coordinates the axial components of $\mathbf{V}_{ga}$ and $\mathbf{V}_{gb}$ must both be downward, again with $\mathbf{V}_{gb}$ large in magnitude because the large gas expansion. The resulting differences in velocity vectors ahead and behind, illustrated in Figs. 5 and 6, are thus entirely consistent with the differences in the axial components of velocity seen in Fig. 4.

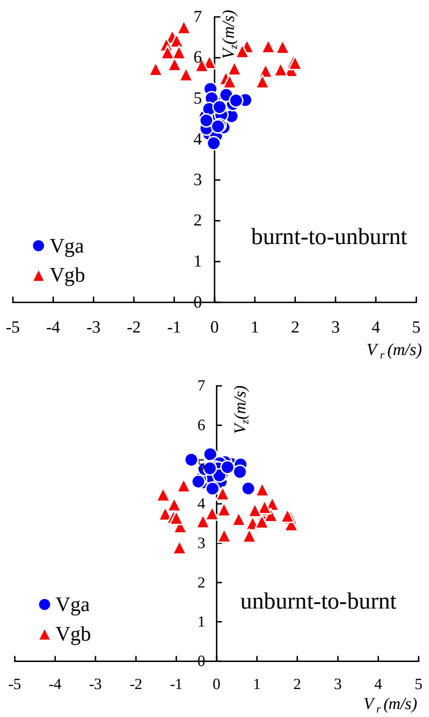

Fig. 4 Vector distribution map of the gas velocities at the flame front on the centerline

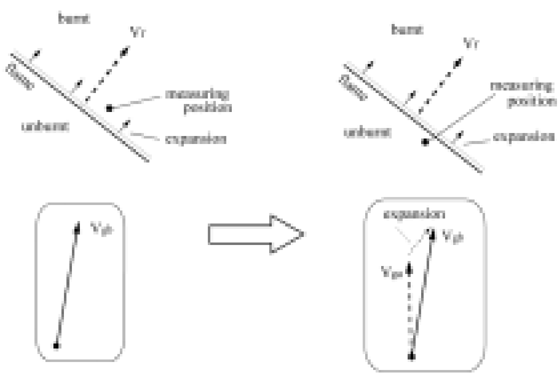

Fig. 5 Direction of gas expansion when the flame front passes the measuring position in the burnt-to-unburnt direction

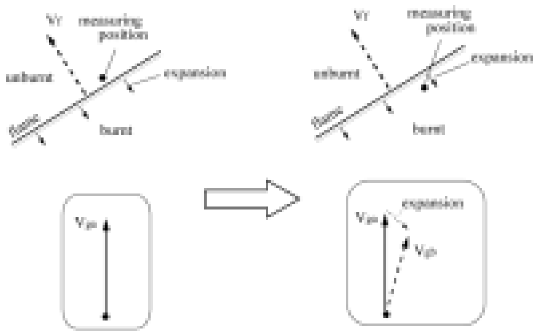

Fig. 6 Direction of gas expansion when the flame front passes the measuring position in the unburnt-to-burnt direction

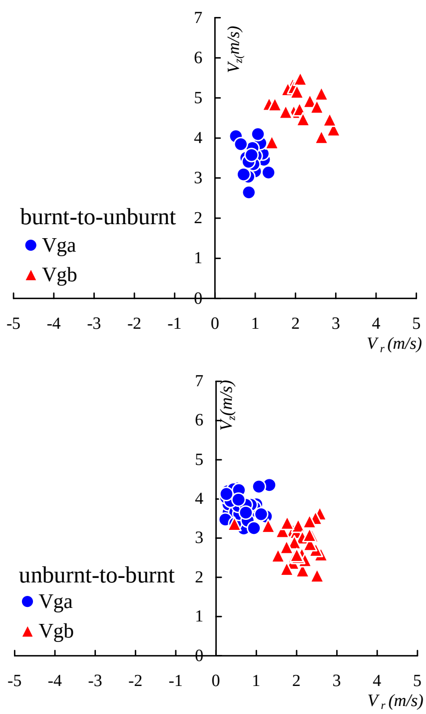

Fig. 7 Vector distribution map of the gas velocities at the flame front off axis

Since the flame fronts are tilted, there is a radial component of gas expansion as well as the axial component. The burnt gas therefore generally will have a larger radial component of gas velocity irrespective of the direction of flame-front passage, as seen in Fig. 4.

Fig. 7 shows changes of the gas-velocity vectors across the flame front at the off-axis position, in the same manner as in Fig. 4. The burner axis is at the left-hand side of the figure, as in Fig. 3, and therefore $\mathbf{V}_{gb}$ exceeds $\mathbf{V}_{ga}$ in the direction of gas expansion, usually away from the burner axis. Aside from this difference Figs. 7 and 4 are similar, and the preceding qualitative explanation of what is observed in Fig. 4 also applies to Fig. 7.

These effects explain the differences seen in Fig. 3 associated with the different directions of flame-front passage. First, comparison of the vectors of flame-front movement in Fig. 3 with vectors of gas velocities in Fig. 7 immediately shows that the former are much more scattered. This striking qualitative difference must be due to flame-front propagation with respect to the gas. These propagation velocities, however, are less than 0.5 m/s in the unburnt gas and less than 3.5 m/s in the burnt gas. Some of the velocity differences between Fig. 3 and Fig. 7 clearly exceed these values. This is because it is only the velocity of the line of intersection between the flame front and the measurement plane that is recorded in Figs. 2 and 3. If, for example, the flame front is tilted with respect to the measurement plane and moving toward it, then the velocity of the line of intersection can exceed the propagation velocity substantially. This effect can explain the wide range of values seen not only in Fig. 3 but also in Fig. 2.

When the upward-moving flame front passes in the burnt-to-unburnt direction, it is being transported past the measurement position by the burnt gas, which has comparatively large radial and axial components of velocity, but when it passes in the unburnt-to-burnt direction, it is being transported past the measurement position by the unburnt gas on the side of the flame front towards the centerline in Figs. 2 and 3, and it is also propagating into that unburnt gas. In this last situation, the flame propagation contributes to the measured negative radial component of flame-front movement by the mechanism discussed above, but the fluctuating radial gas velocity distributes the flame-movement velocity towards the positive radial direction, causing the overall distribution to be more symmetrical, but still with a bias towards negative radial components because of the flame-front propagation. In the former situation (burnt-to-unburnt passage), the larger outward fluctuating radial velocity causes the flame-movement velocity to be mainly outward and larger in magnitude, with only a few negative radial components associated with the flame-front propagation into the unburnt gas. In short, flame-front propagation is much more dominant for unburnt-to-burnt passage, but transport by gas velocity is relatively more dominant for burnt-to-unburnt passage because of the larger burnt-gas velocities.

In view of these explanations of the results shown in Fig. 3, questions arise as to why the distribution of points in Fig. 2 is independent of the direction of flame-front passage. The explanation lies in the gas-velocity plots of Fig. 4. For unburnt-to-burnt passage, flame-front propagation distributes the flame-movement velocity broadly and symmetrically in the radial direction about the common, narrowly distributed values of $\mathbf{V}_{ga}$, upward propagation into the unburnt mixture leading to a number of axial components in excess of those of $\mathbf{V}_{ga}$. For burnt-to-unburnt passage, however, downward flame-front propagation into the unburnt mixture leads to many axial components of flame-movement velocity less than axial components of $\mathbf{V}_{gb}$. The results is that the distributions of flame-movement velocities are quite similar for the two directions of flame-front passage, there being only a few burnt-to-unburnt points exhibiting the wider fluctuations seen in the burnt-gas vectors $\mathbf{V}_{gb}$.

CONCLUSIONS

The present work confirms that the steady, laminar-flame jump conditions, namely, continuity of tangential components and increase in normal components of gas velocity across the flame front. It has been confirmed from the observation of histories of gas-velocity vectors during the periods of flame-front passage that change of gas velocity across the flame front depends on whether the flame front passes in the burnt-to-unburnt or unburnt-to-burnt direction. In the burnt-to-unburnt passage, the normal component of gas velocity changes, while the tangential component is kept constant. Consequently, the axial component of gas velocity decreases across the flame front and the radial component of the gas velocity increases in the direction opposite to that of the flame motion. On the other hand, in the unburnt-to-burnt passage, the jump condition is conserved across the flame front. In the burnt gas behind the flame front, the gas flow is accelerated along the flame front because of the buoyancy effect. The gas velocity does not change in the normal direction to the flame front but changes in the tangential direction. It has been found that the buoyancy effects appear to play an important role in the burnt gas behind the flame front in the unburnt-to-burnt passage.

Acknowledgments

Financial support of this work was provided by Grant-in-Aid for Scientific Research from the Ministry of Education, Science and Culture in Japan and the Japan Society for Promotion of Science. The participation of F. A. Williams was supported by the National Science Foundation through grant NSF INT 9815204.

REFERENCES

1) Lewis B., and von Elbe G., "Combustion, Flames and Explosion of Gases", 3rd edition (1987) pp. 226-305, Academic Press
2) Karlovitz B., Denniston D. W., Knapschaefer D. H., and Wells F. E., Proc. Combust. Institute **4** (1953), 613-620
3) Furukawa J., Noguchi Y., Hirano T., and Williams F. A., J. Fluid Mech. **462** (2002), 209-243
4) Furukawa J., Noguchi Y., and Hirano T., Combust. Science Technol. **154** (2000), 163-178
5) Furukawa J., Hirano T., and Williams F. A., Combust. Flame **113** (1998), 487-491
6) Furukawa J., Suzuki T, Hirano T., and Williams F. A., Combust. Science Technol. **170** (2001), 151-168