Flame Generated Turbulence in Turbulent Premixed Flames

Junichi Furukawa

Department of Mechanical Engineering
Tokyo Metropolitan College of Technology

Yoshiki Noguchi

Department of Mechanical Engineering
Ryukoku University

Toshisuke Hirano

National Institute of Fire and Disaster

Forman A. Williams

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

The present study addresses statistically stationary turbulent combustion in the flame-sheet regime, in which the laminar-flame thickness is less than the Kolmogorov scale, for flames stabilized on a vertically oriented cylindrical burner. The present work measures velocity changes and changes in turbulence across flamelets at different positions in the turbulent flame brush, for comparison with theory. The measurements employ a three-element electrostatic probe and a two-component LDV. The LDV measures axial and radial components of the local gas velocity, while the electrostatic probe measures arrival times of flamelets. From the arrival times, the projection of flamelet orientation and velocity on the plane are obtained. Theory predicts that the component of velocity tangent to the surface of a flamelet remains constant in passing through the flamelet. The data are consistent with this prediction, within the accuracy of the measurement. The data also indicate that the component of velocity normal to the flamelet, measured with respect to the flamelet, tends to increase in passing through the flamelet, as expected. The flamelets thereby can generate anisotropy in initially isotropic turbulence. They also produce differences in turbulent spectra conditioned on unburnt or burnt gas.

INTRODUCTION

Flames modify turbulence in many ways. The large temperature increase at nearly constant pressure increases the kinematic viscosity by more than an order of magnitude, thereby decreasing turbulence Reynolds numbers often substantially, tending to accelerate relaminarization. An additional general influence, associated with the density decreases produced by the temperature increase, is that turbulence scales are anticipated to tend to be larger in the burnt gas as a consequence of the expansion of the volume per unit mass. In the flame-sheet regimes of the present experiments, the density decrease across the sheet mechanistically modifies turbulence locally as well. Karlovitz[1, 2] was the first to popularize "flame-generated turbulence" by observing that since the accepted jump conditions require continuity of velocity components tangential to a sheet and an increase in the velocity component normal to a sheet in a frame of reference moving locally with the sheet, turbulent velocity fluctuations with respect to the sheets are augmented by the flamelets. The specific manner in which these jump conditions modify turbulence depends on the configuration and is not fully understood in every case, notably in the multiple-sheet regime. Clavin and Williams[3] concluded that for large-scale, low intensity turbulence the enhancement in turbulent kinetic energy initially occurs in velocity components transverse to the flame, but Aldredge and Williams[4] found that at low turbulence intensities in planar, one-dimensional, flat-flame configurations, there is a downstream region of hydrodynamic adjustment with thickness on the order of the integral scale, across which the transverse fluctuations are transformed into mainly longitudinal fluctuations, so that the enhancement ultimately appears preferentially in the normal direction. An objective of the present study is to investigate how flamelets modify turbulence in nonplanar burner-stabilized flames having turbulence intensities too large for reliable application of perturbation analyses like those employed in these last studies.

EXPERIMENTAL

The turbulent-flame burner used in the present study is a cylindrical burner of 26 mm in diameter[5]. A uniform propane-air mixture is supplied through the burner at an average velocity of 4.0 m/s. The equivalence ratios of the mixture are 0.80, 1.10 and 1.40.

Fig. 1 is a schematic illustration of the experimental arrangement. A LDV system, composed of a 1.0 W Argon ion laser operating with multiple lines, a two-color four-beam forward scattering optical arrangement and a Doppler signal analyzer, has been adopted for the measurement of the instantaneous axial and radial components of the local gas velocity.

The electrostatic probe adopted for the measurement of local movement of the flame front had three identical sensors, about 1 mm apart, in an equilateral triangular array [7]. Each sensor was constructed from a platinum wire 0.1 mm in diameter with a 0.5 mm long exposed tip, projecting from a finely drawn, electrically insulating quartz tube. All sensors had parallel leads, fitted for cooling purpose into common water-cooled brass tube and inserted into the flame coaxially with the LDV optical axis. The centers of the exposed probe tips were placed coplanar with the center of the vertical measurement plane of the LDV, and the electrostatic probe was slightly above the LDV optical axis, with its two highest sensors each at the same elevation and its lowest sensor 0.5 mm above the center of LDV measuring volume. The probe potential of each sensors was maintained at -12V with respect to the burner port.

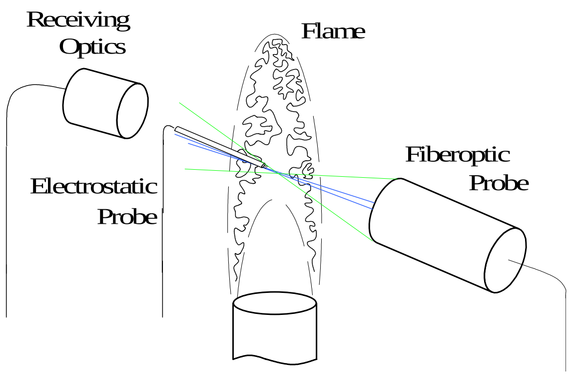

Fig. 1 Schematic illustration of the experimental arrangement

From simultaneous measurements by these two instruments at the same point, the axial and radial components of the local gas velocity across the flame front and local movement of the flame front in the same vertical plane above the burner can be measured[7].

In the present study, the measurements are reported for the centerline and off-axis positions. The centerline is a point of maximum average ion current along on the center line. The off-axis measurement point lies on the contour of maximum ion current at a height half that of the corresponding centerline point. The characteristics of turbulence in the non-reacting flow were examined by using a hot-wire velocimeter at these positions. The turbulence intensities for the centerline and off-axis positions were found to be 0.2 and 0.7 m/s, respectively.

RESULTS and DISCUSSIONS

The turbulent flame for which the jump conditions were tested most thoroughly was a slightly fuel-rich propane-air flame of equivalence ratio 1.10.

Since the different behaviors of the transverse and normal velocity components in crossing flamelets suggest generation of anisotropy, it is of interest to measure conditioned velocity spectra, to ascertain consequent differences in statistics in burnt and unburnt gases. Results are shown in figures 3 and 4. Also shown in these figures for use in comparisons is the probability-density function for the flamelet crossing frequency recorded by the electrostatic probe. The principal general observations that can be made from figures 3 and 4 is that the flamelets enhance the turbulence at low frequencies and reduce it at high frequencies, increasing the value of the cut-off length. Since the average turbulent kinetic energy per unit mass is obtained from the areas under the curves, it is clear that in all cases the flamelets cause this quantity to increase, that is, to be larger in the burnt gas. In this sense, these flames exhibit flame-generated turbulence of Karlovitz[1, 2]. Since the gas density is lower in the burnt gas, it is not clear whether the total kinetic energy per unit volume (the product of the density with kinetic energy per unit mass) is increased. Use of the theoretical thermodynamic density ratio suggests little change in this quantity. In this respect, it is of interest to recall that for reasonable density ratios Clavin and Williams[3] predict this quantity to increase in crossing a flamelet, while Aldredge and Williams[4] show that during further traverse of the downstream hydrodynamic zone, it decreases, achieving a value typically

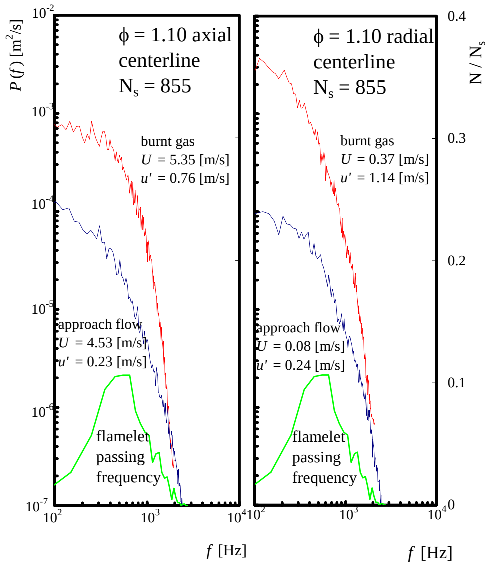

Fig. 2 Change of the power spectrum density function across the flame front for an equivalence ratio of 1.10 (Centerline)

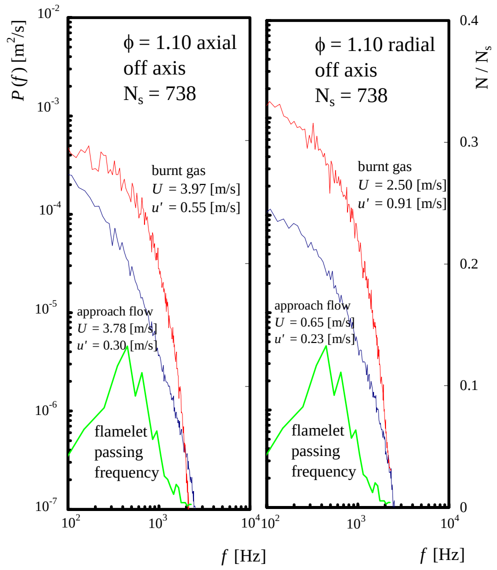

Fig. 3 Change of the power spectrum density function across the flame front for an equivalence ratio of 1.10 (Off-axis)

not very different from the initial value but often somewhat lower. Comparison of the changes in the total turbulent kinetic energy per unit mass previously measured for this and other configurations, as summarized conveniently by Videto and Santavicca(8), reveals qualitative agreement with many (but not all) earlier measurements on similar burners, although generally exhibiting a larger increase than previously observed, and there is surprisingly close agreement with the results of Videto and Santavicca(8) themselves, obtained in a very different configuration. On the other hand, the change is the opposite of that measured by Gokalp, et al.,(9) for V-flames, well ahead of and well behind the average flame position. Experimental differences in general are attributable not so much to different measurement techniques as to measurement locations; for example, although experimentally in cold flow the decay of turbulence is negligible over the measurement distances, because of the much higher viscosity in the burnt gas, farther downstream turbulence will have decayed, contributing to the results obtained by Gokalp, et al.,(9).

The reason for the observed increase in the cut-off length seems not likely to be rapid decay of the turbulence of the smallest scales. While it is true that the large viscosity increase across flamelets increases the rate of decay, estimates of the time available for decay to have occurred at the measurement position suggest only a small influence of decay on the results. For example, from average crossing frequencies and velocities it appears that fluid elements detected in the burnt gas are on the average perhaps 5 mm from a flamelet and have been burnt for a time of about 2 ms, while a time on the order of 10 ms is needed for significant decay at an eddy scale on the order of 1 mm. A more likely explanation appears to be the effect of the dilatation experienced by fluid elements in crossing flamelets. The density decrease can increase length scales and correspondingly reduce maximum fluctuation frequencies. Although the Kolmogorov scale is larger in the burnt gas because of the higher viscosity, there is likely to have been insufficient time for equilibrium turbulence to have developed, as can be inferred from the first curve in figure 3, for example. The change in cut-off cannot be compared with earlier results

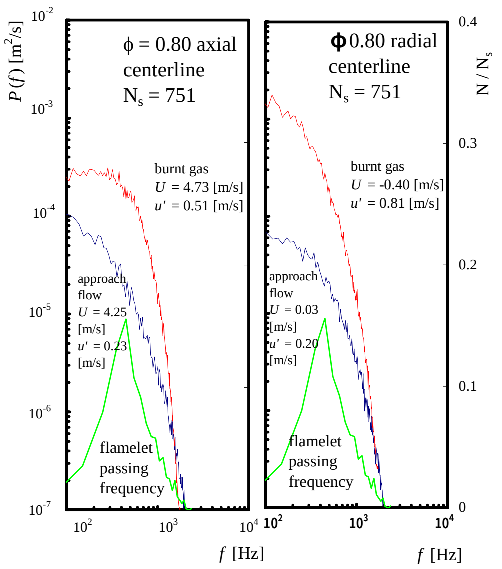

Fig. 4 Change of the power spectrum density function across the flame front for an equivalence ratio of 0.80 (Centerline)

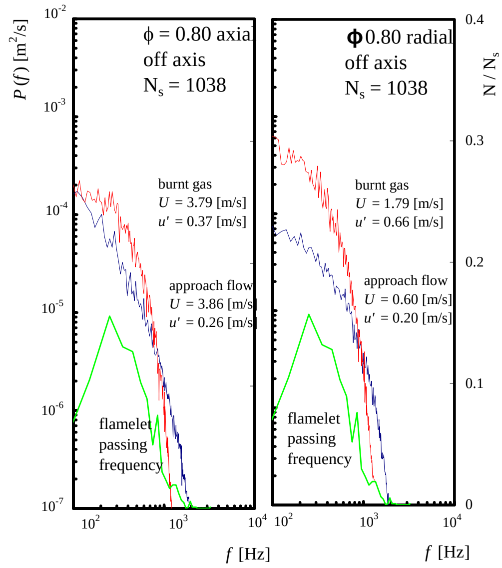

Fig. 4 Change of the power spectrum density function across the flame front for an equivalence ratio of 0.80 (Off-axis)

of other groups because of insufficient resolution, although there is some indication of an increase in cut-off length in the data of Gokalp, et al.,(9). On the other hand, the increased integral scales in the burnt gas, implied by figures 3 and 4, are entirely consistent with earlier experimental results.

Recalling that at centerline position the flamelets are predominantly horizontally oriented while at off-axis position they are more nearly vertically oriented, we may explain the differences between the axial and radial burnt-gas spectra in figures 3 and 4. The approach-flow spectra in these figures are approximately consistent with isotropy, that is, there is little difference between the axial and radial spectra. There are, however, substantial differences in the burnt-gas spectra, demonstrating production of anisotropy by the flamelets. The burnt-gas kinetic energy is larger in the radial component. This observation is consistent with the prediction of Aldredge and Williams(4) of the situation downstream in the zone of hydrodynamic adjustment and suggests that conditions right at flamelets are not being measured on the average but rather conditions somewhat downstream after hydrodynamics has been operative. It is noteworthy that, even in a propagating flat-flame configuration, Videto and Santavicca(8) observed a similar preferential increase in the component of turbulence intensity in the normal direction. This suggest that the result is of fairly broad applicability and not restricted to specific configurations.

A further qualitative difference between axial and radial spectra in figures 3 and 4 is the tendency for a peak to develop in the vicinity of the maximum crossing frequency for the axial component but not so much for the radial component. This is especially evident in the first of figure 3 but also is seen in the first of figure 4. This aspect evidently depends more on the mean flow and not on the direction with respect to the flame normal. The source of this phenomenon requires further investigation. In any event, it appears to be specific to the flow configuration and probably not generally applicable to the other configurations.

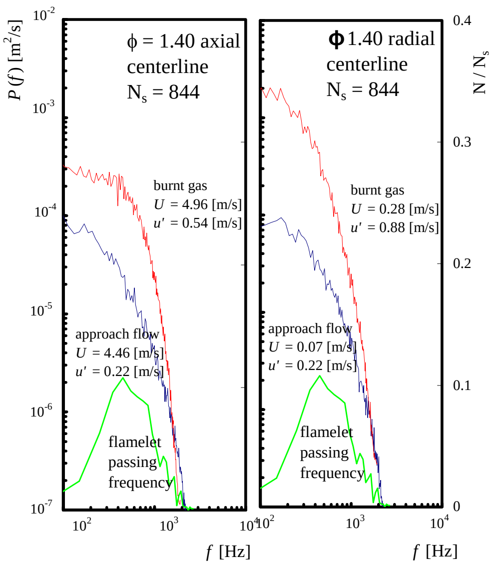

Fig. 6 Change of the power spectrum density function across the flame front for an equivalence ratio of 1.40 (Centerline)

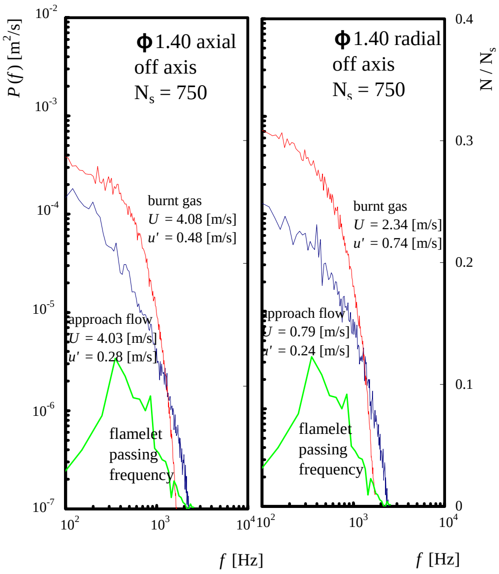

Fig. 7 Change of the power spectrum density function across the flame front for an equivalence ratio of 1.40 (Off-axis)

It is of interest to compare the burnt-gas spectra for different equivalence ratios. Differences in approach-flow spectra and intensities are consistent with different measurement points and show no clear influence of the flame on the upstream turbulence; it is of greater interest therefore to focus attention on the burnt gas. The burnt-gas intensities are larger for an equivalences ratio of 1.10 (figures 3 and 4) than for equivalence ratios of 0.80 or 1.40 (figures 5 through 8); this may be expected because of the greater amount of gas expansion through the flame at the near-stoichiometric equivalence ratio. It is noteworthy that the spectra for equivalence ratios of 0.80 (figures 5 and 6) and 1.40 (figures 7 and 8) are practically identical; these two mixtures have the same expansion ratio and laminar burning velocity and therefore produce the same effects on the turbulence. There are small difference for these two mixtures off axis, where the intensities are a little less in the lean mixture, as might be expected from the greater degree of instability of the rich mixture, which exhibits cellular flames. The principal conclusion, however, to be drawn form the comparisons for different equivalence ratios is that the main influences of equivalence ratio arise through its effect on burning velocity and gas expansion.

CONCLUSIONS

This work, focused on structures of premixed turbulent flames in flame-sheet regimes, has confirmed that, within experimental accuracy, the steady, laminar-flame jump conditions, namely, continuity of tangential velocity components and increase in normal velocity components of a fluid in crossing a flame sheet, apply locally to individual flamelets. The increase is much less than calculated for steady, planar, one-dimensional laminar flames because of effects of local gas expansion in the three-dimensional, turbulent field. These changes have been found to produce anisotropy of the turbulent velocity field in the burnt gas, as demonstrated by measurements of power spectra in the turbulent flame, conditioned on the presence of either a fresh or burnt mixture. In particular, there is a significant enhancement of the turbulent kinetic energy per unit mass by the flame, a kind of flame-generated turbulence, which is observed mainly in velocity components normal to the flame.

Financial support of this work was provided by Grant-in-Aid for Scientific Research from the Ministry of Education, Science and Culture in the Japan and Japan Society for Promotion of Science The participation of F. A. Williams was supported by the National Science Foundation through grant NSF INT9815204.

REFERENCES

1) Karlovitz, B. Proc. Combust. Inst. 4: 60-67 (1953)
2) Karlovitz, B., et al., Proc. Combust. Inst. 4: 613-620 (1953)
3) Clavin, P. and Williams, F.A. J. Fluid Mech. 116: 251-282 (1982)
4) Aldredge R.C. and Williams, F.A. J. Fluid Mech. 228: 487-511 (1991)
5) Furukawa J., et al., Combust. Science Technol. 154: 163-178 (2000)
6) Furukawa, J., et al., Proc. Combust. Inst. 26: 405-412 (1996)
7) Furukawa, J., et al., Combust. Flame 113: 487-491 (1998)
8) Videto, B. D. and Santavicca, D. A. Combust. Science Technol. 70: 47-73 (1990)
9) Gökalp I., et al., Combust. Flame 71: 313-323 (1988)