Velocity Statistics in Premixed Turbulent Flames

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Laser Doppler velocimetry was used to measure velocity statistics in six unconfined v-shaped premixed ethylene/air turbulent flames with incident turbulence generated by grid or perforated plate. Also obtained were high speed schlieren movies of the turbulent flames. The results discussed include two components of mean and rms velocities, probability density functions, macroscales, and Reynolds stress. In most cases, turbulent intensities increase within the flame zone. This increase is attributed to the intermittent measurement of the flow velocities in the burned and unburned states as the thin flame sheet fluctuates about the stationary measurement point. Reynolds stress also increases in the flame zone, but its sign suggests removal of turbulent kinetic energy. Therefore, conventional gradient transport modeling would break down for these flames. The sign of the Reynolds stress is in qualitative agreement with contributions due to intermittent measurement of the turbulent components in the burned and unburned states. These results show that the intermittency effect is a major influence on turbulent statistics in premixed flames and should require careful consideration in numerical models.

I. INTRODUCTION

Although considerable progress has been made in experimental and theoretical studies of premixed turbulent flame propagation [1-7], many aspects of the mutual interaction between fluid mechanical turbulence and combustion heat release are still not fully understood. Therefore, to gain better physical understanding of these stochastic processes, and to provide relevant data for comparing with theoretical predictions, more detailed and extensive statistical measurements of velocity and scalar properties in turbulent flames are required. With the development of laser-based diagnostic techniques, current emphasis in experimental studies is directed toward measuring statistical cross-correlations. The Reynolds stress (\(-\bar{u}\bar{v}\)), relevant to the turbulent kinetic energy production, and the cross-correlation of velocity and density (\(\bar{\rho}\bar{u}\)), relevant to the turbulent flux of scalar properties, are two such parameters which currently receive much attention. Such results would be useful for developing numerical models to close the time-averaged conservation equations for premixed turbulent combustion flows.

In a series of papers Bray and his collaborators developed a numerical model for premixed turbulent flames which achieved a considerable degree of success. In their first model, Bray and Libby [1] employed conventional mean gradient transport for the turbulent flux of scalar properties. However, experimental data to verify this turbulent flux model only became available recently. Using a technique combining particle light-scattering intensity measurement with laser Doppler velocimetry (LDV), Moss [5] measured the cross-correlation \(\bar{v}\bar{c}\) between the Favre-averaged turbulent velocity component \(\bar{v}\) and a characteristic reaction progress variable \(\bar{c}\). The sign of this cross-correlation was found to be positive within the flame region. Since the gradient \(\delta\bar{c}/\delta x\) was also positive, mean gradient transport formulation suggested countergradient diffusion. Yangi and Mimura [6] measured cross-correlations of both the axial and radial velocities with temperature using a combined compensated thermocouple...
and LDV. They reported that the radial velocity-temperature correlation was positive in the flame region, which also suggested countergradient diffusion. These experimental results demonstrated that the turbulent flux of scalar properties in premixed turbulent flames is not amenable to conventional mean gradient transport modeling. More recently, Libby and Bray [2] proposed nongradient transport modeling for scalar properties.

The interaction between turbulence and combustion is often expressed by the balance between the sink and source of the turbulent kinetic energy. In the first Bray and Libby [1] model for premixed flames, the Reynolds shear stress was modeled in terms of the inclination angle between the flame and the incident flow. The production terms due to buoyancy and pressure fluctuations were neglected. The simplified turbulent kinetic energy conservation equation then implied a balance between the Reynolds stress source term and the dilatation sink term. This model predicted that in normal flames or open oblique flames, turbulent kinetic energy was reduced by dilatation because turbulent kinetic energy production by Reynolds stress was insignificant, whereas in the case of an enclosed oblique flame, owing largely to the undeflected streamlines assumption, the Reynolds stress overcame dilatation and increased the turbulent kinetic energy substantially. Because these predictions do not generally agree with presently available data, recent studies (Bray et al. [3] and Strahle and Chandran [4]) have examined the contribution to the production of turbulent kinetic energy by the mean pressure gradient and pressure fluctuations within the flame zone.

Although there are numerous papers on experimental measurements of turbulence intensities in premixed turbulent flames of various enclosed or open configurations, [5-17], there are far fewer reports on the measurement of Reynolds stress. The first report we have found of Reynolds stress measurement in unconfined premixed turbulent flames using the laser Doppler velocimetry technique is by Durst and Kleine [7]. They observed an increase in both radial and axial turbulence intensities but did not attribute the turbulence to Reynolds stress production. Later, Moreau and Boutier [8] reported measurement of turbulence intensities and Reynolds stress in an enclosed planar flame in a high speed (20-100 m/s) combustion channel. They only observed an increase in axial velocity fluctuations and found that the effects of the flame on the cross-stream fluctuations and Reynolds stress to be insignificant. The probability density functions (pdf) associated with the streamwise fluctuations appeared in a subsequent paper by Moreau [9]. More recently, Yoshida [10] measured Reynolds stress and turbulence intensities in an open Bunsen-type flame with low incident turbulence. The structures of this flame were analyzed in an earlier paper [11] which characterized it as a wrinkled laminar flame. In contrast to the results of Durst and Kleine [7], Yoshida reported no increase in the axial velocity and radial velocity fluctuations. Also, the Reynolds stress were unaffected except in the region where the products mix with the surrounding air; in this region the cross-correlation $\langle \bar{u} \bar{v} \rangle$ becomes negative.

More recent measurements of velocity, temperature, and density fluctuations in premixed turbulent flames include the works of Kilham and Kirman [12], Susuki et al. [13], Yoshida and Tsuji [14], Yoshida and Gunther [15], Dandekar and Gouldin [16], and Bill et al. [17]. In most configurations, temperature and density fluctuations in the flame region were found to be quite substantial, increasing to a relative intensity approaching 30%. The bimodal distribution shown on the probability density functions suggested a thin flopping flame phenomenon. However, the velocity statistics were not as consistent. Both increases and decreases of turbulence intensities in the flame region were reported. In some cases, the peak turbulence intensity within the flame region was several times the incident turbulence level. Also, the flame configuration, flow velocity, incident turbulence level, and mixture composition were found to influence turbulence intensities. In general, turbulence intensities would increase to some degree in the flame, and, downstream from the flame region, turbulence would either increase above or decrease below the incident turbulence level.

Since the increase in turbulence intensities is not universal and the role of Reynolds stress is still inconclusive, these data are insufficient for
comprehensive analysis of the turbulent kinetic energy budget in the flame zone. Furthermore, experimental techniques for measuring most of the other production mechanisms due to combustion are still under development. Therefore, qualitative features of the flame shown by flow visualization would be most useful to complement the detailed statistical data. The significance of flow visualization has been demonstrated in recent studies of large scale turbulence structures in nonreacting flows such as boundary layers, shear layers, and jets [18-20]. In turbulent combustion studies, flow visualization records obtained by various techniques [21] were used mainly to infer the overall shape and size of the flame brush or to deduce a mean flame surface for determining the turbulent burning velocity. This information has not been used extensively to explore the possible interrelationship between the flame structures and the observed behavior of the turbulence statistics and correlations. This comparison, although qualitative in nature, is invaluable to the understanding of turbulence-combustion interaction.

The objective of the present study is to carry out a systematic investigation of the turbulence statistics in premixed turbulent flames using laser Doppler velocimetry (LDV) and schlieren cinematography. The configuration chosen is an open, rod-stabilized, v-shaped flame propagating in low intensity turbulence generated by a grid or perforated plate. This simple configuration is well suited to basic studies of turbulence-combustion interaction because the flame is free of geometric constraints of the burner, and is devoid of a flame tip as in Bunsen-type turbulent flames. Moreover, incident turbulence is uniform across the flow and the planar turbulent flame sheet can be approximated as two dimensional.

In our earlier paper [17], experimental results of mean and root mean square (rms) density measured by Rayleigh scattering and mean \( \langle U \rangle \) and rms \( \langle U' \rangle \) streamwise velocity measured by LDV are reported for four conditions, all with isotropic grid-generated incident turbulence. In a subsequent series of experiments, the mean and rms of both the streamwise and cross-stream velocity and the Reynolds stress were obtained. Preliminary analysis of these data to show the overall features of the streamline deflection and also the influence of the flames on the free stream turbulence have been presented [22]. In this paper, further statistical analysis of these data and the results from two additional conditions with nonisotropic higher intensity turbulence generated by perforated plates are described. To accompany the six sets of velocity statistical data, high speed schlieren movies have been made to show the development of the flame convolutions.

Presented in Section 3.2 is a comparison of the overall features of the flames in two-dimensional velocity vector plots. In the same section, some description of the turbulent flame structures show on the schlieren movies are included. In Section 3.3, the characteristic features of the turbulence intensities, pdfs, and Reynolds stress are discussed.

### 2. EXPERIMENTAL ARRANGEMENT

Figure 1 is a schematic of the experimental setup. Also shown are the orientation of the coordinate system and the orientation of the velocity components measured by LDV. The turbulent flame is stabilized by a 1.0-mm-diameter rod placed at the exit of the flow nozzle which provides a circular coaxial jet with an inner core of ethylene/air mixture 5.0 cm in diameter surrounded by an annular air jet of 10.0 cm o.d. The turbulence generator is placed 50 mm upstream of the exit. The center of the turbulence generator is chosen to be the origin of the coordinate system, with the flame stabilizer and optical axis parallel to the \( z \) axis. The turbulence generators consist of a biplane grid with mesh size \( M \) of 5.0 mm with 1.0 mm elements, and two perforated plates—\#1 with 3.2 mm circular holes 1.6 mm apart, and \#2 with 4.76 mm circular holes 1.8 mm apart. Listed in Table 1 are the experimental conditions of the six flames, and they are labeled accordingly flames \#1-6.

A Spectra Physics 4 W argon ion laser supplies the light source for schlieren cinematography and LDV. The schlieren optics consist of a pair of 75-mm-diameter, 1000-mm-focal-length lenses and a polarizing prism used as the schlieren stop. The high speed movies are taken with a Fastax camera operated at a maximum framing rate of 4 kHz.

The LDV system is a dual-beam, fixed separa-
Fig. 1. Schematics of the experimental setup.

Operation design similar to commercially available systems. The beams are separated by 5.0 cm and are focused by a 250-mm-focal-length lens to form the scattering volume. Aluminum oxide particles of 0.3 μm are introduced by a cyclone canister dispenser. The collection optics consists of a lens, filter, and photomultiplier assembly which is placed so as to measure the direct forward-scattered light. The Doppler signals are processed with a TSI counter which is interfaced with a computer-controlled data acquisition system based on a PDP 11/10 computer. The computer is also interfaced with the stepping motor-controlled three-axis traverse table to enable rapid scanning of the flame flow field by the stationary LDV probe [17].

<table>
<thead>
<tr>
<th>Flame number</th>
<th>( U_{in} ) (m/s)</th>
<th>( \phi )</th>
<th>Turbulence generator</th>
<th>Free-stream turbulence at ( x = 60 \text{ mm} )</th>
<th>( u'/U_{in} ) (%)</th>
<th>( u'/U_{in} ) (%)</th>
<th>( l_x ) (mm)</th>
</tr>
</thead>
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<tr>
<td>1</td>
<td>7.0</td>
<td>0.75</td>
<td>Grid</td>
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<td></td>
</tr>
<tr>
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<td>5.0</td>
<td>0.8</td>
<td>Grid</td>
<td>6.0</td>
<td>6.0</td>
<td>4.5</td>
<td></td>
</tr>
<tr>
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<td>5.0</td>
<td>0.7</td>
<td>Grid</td>
<td>4.5</td>
<td>4.5</td>
<td>5.0</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>7.0</td>
<td>0.66</td>
<td>Grid</td>
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<td>5.0</td>
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<td>7.0</td>
<td>0.75</td>
<td>Plate #1</td>
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<tr>
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<td>Plate #2</td>
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The procedure to measure two velocity components, \( U \) and \( V \), their rms fluctuations \( u' \) and \( v' \), and the Reynolds stress \(-\overline{uv}\) using a single-component LDV system is described in many LDV references, e.g., [23]. It involves measuring the mean and variances of three velocity components. For this study, the three components, \( U \), \( U_1 \), and \( U_2 \), are oriented at \( 0^\circ \) and \( \pm 30^\circ \) with respect to the \( x \) axis (Fig. 1). Typical data ready data rates for all three velocity components are about 10 kHz in the freestream region, dropping to about 3.5 kHz in the hot region. Due to the fairly high data rate, it can be assumed that the counter output is essentially continuous. At each measurement position, the computer data acquisition system is programmed to digitize and to record a velocity time series consisting of 8192 samples of the LDV counter output at a fixed rate of 2.5 kHz.

The technique of sampling the LDV counter output at a fixed frequency sufficiently lower than the data rate is now generally accepted as one of the more convenient means to circumvent the complex procedures to correct for the velocity and LDV biasings [24]. This technique yields a good approximation of the time-mean velocity data. The procedure to deduce \( V \), \( v' \) and \(-\overline{uv}\) involves solving a set of algebraic equations using the data of the three velocity components. The error in \( V \) is estimated to be about 0.1 m/s. This is based on comparing \( U \) with the value deduced from \( U_1 \) and \( U_2 \) [i.e., \( U = (U_1 + U_2)/2 \cos \theta \)]. Since several independently measured velocity variances are needed to evaluate \( v' \) and \(-\overline{uv}\), the uncertainty associated with each variance will be compounded in the final results. The percentage uncertainty could be fairly large if the actual values of \( v' \) and \(-\overline{uv}\) are small. Sources of uncertainty and error in the measurements are electronic noises, finite resolutions of the measuring instruments, biasing errors associated with LDV, and uncertainty in the LDV fringe orientation. It is difficult to quantify the uncertainty and error individually in order to estimate their compounded effect on \( v' \) and \(-\overline{uv}\). The error bar shown in the Figures represents scatter of the values of \( u' \) and \(-\overline{uv}\) obtained from several sets of ensemble measurements. This LDV technique has been used in our previous study of a strongly heated turbulent boundary layer [25]. The results were found to compare quite satisfactorily with classical boundary layer profiles.

The data acquisition system was programmed to scan the flame flow field in a measurement grid of 30 traverse (\( y \)) positions at 6 axial (\( x \)) locations. At least two to three sets of experimental data were obtained for each experimental condition. The results were found to be highly reproducible. The raw data were stored on 7-track magnetic tapes for postprocessing at the Lawrence Berkeley Laboratory CDC 7600 computer. Progress of the experiments was monitored by plotting the mean signal graphically on a video terminal.

In addition to mean, rms velocities and Reynolds stress, two other turbulent statistical quantities are also deduced. The probability density functions (pdf) are based on the histogram of the velocity time series consisting of 40 spectral windows. Using Taylor's hypothesis, the streamwise macroscale \( l_x \) is determined from the product of the local streamwise velocity and the integral time scales \( \tau_x \):

\[ l_x = U \cdot \tau_x. \]  

The integral time scale is obtained by numerical integration of the difference between the autocorrelation function \( f(t) \) and its asymptotic value \( f(a) \):

\[ \tau_x = \frac{1}{1 - f(a)} \int_0^\infty (f(t) - f(a)) \, dt. \]  

3. RESULTS AND DISCUSSION

3.1. Incident Turbulence

Turbulence intensities in the nonreacting jet are shown in Fig. 2 on the \((U^{**2}/u'^2)\)-versus-(\(x/M\)) plane. As discussed by Batchelor and Townsend [26], and also in our earlier paper [17], the decay of grid turbulence downstream of the generator is shown linearly on this plane. The grid data in Fig. 2 correspond to a slope of 68. The data for the two perforated plates also show a linear decay with \( x \), but with lower decay slope of 16 for plate \#1 and 22 for plate \#2. The streamwise
macroscale of the grid turbulence average approximately 5.0 mm; this is within the range $2.0 < l_x < 6.0$ mm predicted for this condition. In all cases, $l_x$ increases linearly with $x$ as turbulence intensities decay. As seen in Table 1, the grid turbulence is isotropic, but the turbulence produced by the perforated plates is nonisotropic, with $u'$ slightly higher than $v'$. Slight variations in the grid turbulence level is due to the influence of the flame on freestream turbulence, as discussed in our previous paper [22].

As proposed by Abdel-Gayed and Bradley, turbulent flames with upstream conditions of $s_u/u' > 1$, where $s_u$ is the laminar flame speed, fall into the wrinkled laminar flame regime. Our present initial conditions correspond to $s_u/u'$ ranging from 1.4 to 2.4 for the flames with grid-generated turbulence, and 0.9-1.1 for flames with perforated plate-generated turbulence. Therefore our experimental conditions seem to be mostly within the wrinkled laminar flame regime.

3.2. Mean Velocities and Flame Structures

Compared in Fig. 3 are some overall features of the flow fields of flames #1, #5, and #6, with identical initial conditions of $U_\infty = 7.0$ and $\phi$ of 0.75, but with different turbulence generators. The size of the turbulent flame brush is shown by the contour of the mean flame position and cold boundary of the flame region. These contours are deduced using the $V$ profiles because the changes in $V$ through the flame region are more pronounced than in $U$. The mean flame position is defined as the point of $(dV/dy)_{\text{max}}$, and the cold boundary is defined as the point of $(d^2V/dy^2)_{\text{max}}$ close to the reactants.

The most apparent effect of the more intense perforated plate-induced turbulence is the enlargement of the flame brush. However, the flame brush thickness does not seem to be directly proportional to incident turbulence intensity, since the flame thickness of flame #5 is generally larger than that of flame #6, although the incident turbulence intensity of flame #5 is lower. The local flame angles, defined as the inclinations of the mean flame position contours, are not significantly different. Since flow deflections in the free stream up to $x = 80$ mm are quite similar, this implies that the turbulent burning velocity defined with respect to the mean flame angle for the three cases would also be quite similar. This interesting aspect of the results will be discussed more fully in a subsequent paper [27], which focuses on the
Fig. 3. Two-dimensional velocity vector plots of three flames using (a) the grid (Flame #1), (b) plate #1 (Flame #5), and (c) plate #2 (Flame #6) to generate incident turbulence. --- mean flame position, --- cold boundary.
significance of this generally accepted definition of the turbulent burning velocity.

In Fig. 4, the effect of turbulence intensity on increasing the size of the flame brush is again shown on the schlieren records of flames #1 and #5. Since the optical axis is parallel to the plane of the turbulent flame brush, the schlieren image would be the compounded effects of all the flame fronts along the optical path; therefore details of the convoluted flame sheet are not clearly shown. To better illustrate these details, schlieren movies of blunt body-stabilized conical flames with the same initial conditions of flames #1 and #5 were made. The results are shown in Fig. 5.

For flame #1 (Fig. 5a), the flame sheet is relatively free of disturbances near the stabilizer. Further downstream, the flame sheet develops wrinkles which grow and amplify into the rounded flame convolutions as they move downstream along the flame plane. Throughout the growth of
the convolutions, the flame sheet appears to be continuous. The features of this flame essentially comply with the description of a wrinkled laminar flame. The schlieren movies of flame #3 show similar features. For flame #2, a condition of higher burning rate resulting in a larger mean flame angle, the flame sheet is highly convoluted. For flame #4, with lean fuel/air mixture and highly oblique flame angle, the flame sheet is relatively smooth, with only slight wrinkles near the top of the flame.

In contrast to flame #1, the flame sheet of flame #5 (Fig. 5b) is much more convoluted, indicating a substantial increase in flame surface area. The convolutions occur much closer to the flame stabilizer and appear smaller. Also, the shape of the convolutions are somewhat different (as indicated by the arrows on the left side of both Figs. 4b and 5b). These convolutions sometimes coalesce and interact to create larger swells or flaring of flame pockets out into the freestream. An example of this feature is indicated by the arrow on the right side of Fig. 4b. This occasionally violent interaction of the flame convolutions may possibly cause a detachment of flame pocket from the continuous flame sheet. Therefore, this flame may not fully comply with the descriptions of wrinkled laminar flame.

This propagation and growth of flame disturbances or flame convolutions along the flame sheet as freestream turbulence decays has been reported in many earlier works. The propagation velocity is generally close to the tangential velocity component parallel to the flame sheet. Petersen and Emmons [28] reason that this growth is due to the excitation of amplifiable wavelength of the flame sheet. The response of flames #1, #2, and #4 to the grid turbulence therefore suggests that the amplification of these disturbances increases with increasing equivalence ratio. Moreover, the distance from the flame origin should represent a convection time after a flame segment leaves the attachment region. Comparing the development of the flame convolutions in flames #1 and #5, it is apparent that the flame sheet response more rapidly to the perforated plate induced turbulence. Also, as shown by the thicknesses of flames #5 and #6, the amplification of the flame convolutions may not be directly proportional to the incident turbulence intensities and scales. In the next section, the role of these flame convolutions in influencing turbulence statistics will be discussed.

3.3. Velocity Statistics

3.3.1. RMS Fluctuations

Shown in Fig. 6 are the streamwise and cross-stream rms velocity fluctuation profiles of flame #1 at x = 60, 80, and 100 mm. As discussed earlier, the freestream turbulence is isotropic with $u'$ and $v'$ both at 5%. At x = 60 mm, the turbulence intensities are not significantly affected by the flame, since they remain essentially unchanged through the mean flame position at $y = 2.5$ mm. At $y = 0$, the increase in $u'$ to about 8% is due to the flame stabilizer wake as mentioned earlier [17, 22]. At x = 80 and 100 mm, both $u'$ and $v'$ increase sharply within the flame region, with the maximum intensities becoming progressively larger at locations farther from the flame origin. The uncertainty bar shown for $u'$ represents the deviation of $u'$ obtained from several sets of data. Note that the flame turbulence is anisotropic, with $v'$ substantially higher than $u'$. Also, the positions of the fluctuation peaks are not coincidental; for example, at $x = 100$ mm, $u_{\text{max}}'$ of 9.8% is at $y = 12$ mm and $v_{\text{max}}'$ of 16% is at $y = 16$ mm. Therefore, the $v'$ peaks are nearer to the cold boundary and the $u'$ peaks are nearer to the hot boundary. In the hot region, the fluctuations fall back to levels slightly lower than the incident turbulence, indicating that the overall turbulent kinetic energy has not been increased by combustion. It is also interesting to note that a trace of the flame stabilizer wake remains near $y = 0$ up to $x = 80$ mm.

Similar features are shown on the profiles of flames #2 and #3 in that no increase in turbulence within the flame region is observed at locations close to the flame stabilizer, but a substantial increase is found farther downstream. Also, the $v'$ peaks are generally higher than the $u'$ peaks. The largest difference between $u_{\text{max}}'$ and $v_{\text{max}}'$ is found in flame #2 at $x = 100$ mm, where $u_{\text{max}}'$ reaches 20% with $u_{\text{max}}'$ at 10%. For flames #5
and #6 with perforated plate-induced turbulence, the peak intensities \( u_{\text{max}}' \) and \( u_{\text{max}}'' \) are about equal, as shown in Fig. 7. In contrast, for flame #4, no significant change in the turbulence intensity is observed in the flame region up to \( x = 100 \text{ mm} \).

In comparison, Yoshida [10] reported that the turbulence intensities were unaffected by wrinkled laminar flames. His measurements were made at axial locations close to the stabilization region of a conical bunsen flame where the flame angle was quite oblique to the incident flow. His estimation of the flow deflection through the flame was less than \( 2^\circ \). These conditions would be quite similar to the condition of flame #4. Indeed, in both situations the turbulence intensities did not increase. Dandekar and Gouldin [16] measured
turbulence intensities in premixed v-shaped methane, propane, and ethylene flames. Their measurements were made at one fixed location 2.5 cm downstream of the flame stabilizer. They reported increases in both streamwise and cross-stream turbulence intensities as in our ethylene flames. They observed that the increase in turbulence intensities within the flame region was approximately proportional to the temperature ratio across the flame.

The increase in turbulence intensities tends to correspond to the growth of the flame convolutions. At locations where the flame sheet appears smooth and free of wrinkles, as near the flame stabilizer in flames #1, #2, and #3 and throughout flame #4, measured turbulence intensity is unchanged. Farther downstream from the stabilizer, as flame convolutions begin to develop, turbulence intensities begin to increase. As the flame sheet becomes more convoluted, the turbulence intensities become higher.

The influence of the flame convolutions on turbulence intensities can be explained by the passage of a thin flame sheet through the stationary LDV probe. Depicted in Fig. 8 is the encounter of the incident flow with a flame segment on the oblique flame sheet. As a result of this encounter, the velocity component tangential to the local flame orientation is conserved, while the normal component undergoes maximum acceleration. Therefore, the flow direction is deflected toward the flame center. This flow deflection has been observed by particle tracking [28, 29] in v-shaped flames and is shown in the velocity vector plots (Fig. 3).

The thin flame moving across the stationary LDV probe would cause intermittent measurement of slow outward-moving velocities in the reactant $U_{ir}$, and fast inward-moving velocities in the products $U_{ip}$. The difference in the magnitude and direction of the velocities in the two states would make a significant contribution to the overall turbulence intensities. In regions where the flame sheet is only slightly wrinkled, the intermittency effect would not be as significant and the rms fluctuations would not be strongly affected.

This contribution to flame turbulence has been considered in the joint pdf model of Libby and Bray [2]. In the model, the turbulence intensity is represented by three terms. The first is the direct contribution arising from the conditioned mean velocities in the reactant and product; the other
two terms represent genuine turbulence components in the reactant and product, i.e., $u'_x$, $u'_r$, $u'_p$, $v'_p$. Since the first term is caused by the flame sheet movement, it only appears in the Eulerian description of the turbulence field. Therefore, it is normally not regarded as true turbulence and can only be considered as apparent turbulence. The Lagrangian description of a fluid element going through the flame would only consider the true turbulence fluctuations in the reactant and products.

As our data indicated, the intermittency effect seems to be the most significant contribution to flame turbulence. Unfortunately, the present diagnostic technique would not enable us to assess the magnitude of this contribution. Further study would require conditional sampling techniques for differentiating between the statistics measured in the burned and unburned states.

It is interesting to note that the relative locations of $U_{\text{max}}'$ and $v_{\text{max}}'$ within the flame region may also be related to the flow deflection. Referring to Fig. 8, it can be seen that a flame front more oblique to the incident flow would primarily increase $v'$, whereas a flame front more perpendicular to the incident flow would increase $u'$. As shown on the schlieren records, the former situation would occur near the cold boundary where the flame front on the flame convolutions are more parallel to the $x$-axis; hence, $v'$ would reach its maximum there. On the other hand, the latter situation would take place in the flame cusps which are found closer to the hot boundary of the flame region; consequently this is where $u'$ reach its maximum. This argument also suggests that the relative magnitudes of $U_{\text{max}}'$ and $v_{\text{max}}'$ could be related to the relative probability of the orientations of the flame fronts on the convoluted flame sheet.

### 3.3.2 Probability Density Function (pdf) and Streamwise Macroscale

More features of the thin flame phenomenon are shown on the three sets of pdfs in Fig. 9. These pdfs for $U$, $U_1$, and $U_2$ are obtained at the position of $v_{\text{max}}'$. In Fig. 9a, for flame #2, the distribution for $U_2$ is highly bimodal. The distribution for $U$ is slightly bimodal, but for $U_1$ a single-peaked distribution is shown. These features
would be consistent with a thin flame sheet fluctuating across the measurement probe and inducing acceleration primarily in the direction normal to the mean flame angle. This could result in the $u_{max}'$ being substantially higher than the $u_{max}'$, as described in Section 3.3.1. Since $U_2$ is almost normal to the mean flame orientation, the effect is shown very plainly. The $U$ component is oblique to the flame and its distribution is less affected. The $U_1$ component is more parallel to the flame and therefore it is not very sensitive to the influence of the flame.
In Fig. 9b for flame #1, the $U_2$ distribution is less bimodal, the $U$ distribution shows a single-peaked distribution, and the $U_1$ distribution remains unaffected. These distributions seem to indicate that the flame fronts are more randomly oriented than those of the previous case and therefore the bimodal distribution is not as clearly shown on any of the pdfs. For flame #5 (Fig. 9c), the $U_2$ distribution is not bimodal but skewed toward the lower velocities. Note that the $U$ and $U_1$ distributions are almost identical. These distributions suggest that in this highly convoluted flame, the acceleration across the flame fronts would have no preferred direction and therefore a single-peaked distribution is shown for all three velocity components, so that as a result the $u_{max}$ and $v_{max}$' are about equal, as shown in Fig. 7.

A typical profile of streamwise macroscale $l_x$ is shown in Fig. 10. The flame region at this location extends from $y = 6.0$ to $15.0$ mm, with the mean flame position at $y = 9.0$ mm. As can be seen, the macroscale in the region close to the cold boundary is relatively unaffected by the flame except for a slight dip near the mean flame position. Toward the hot region, $l_x$ increases gradually to its maximum value of about $13$ mm at $y = 0$. The enlarged macroscale in the hot region suggests that the overall sizes of the turbulent eddies are increased by dilatation.

3.3.3. Reynolds Stress

The Reynolds stress profiles of flame #1 at $x = 60$, $80$, and $100$ mm are shown in Fig. 11. At $x = 60$ mm, the Reynolds stress in the freestream is almost zero, and remains essentially unchanged through the flame region. In the wake region, a slight increase is shown. The freestream data agree with isotropic turbulence assumptions that the velocity fluctuations are uncorrelated. At $x = 80$ and $100$ mm, the Reynolds stress increases within the flame region. The peak Reynolds stress,
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\((-\bar{u}\bar{v})_{\text{max}}\) also increases with distance downstream from the flame origin. In the hot region, the Reynolds stress falls back to approximately its freestream level. Note that at \(x = 100\) mm near \(y = 0\), where the slight dip in streamwise velocity is not apparent (Fig. 10), the Reynolds stress is not increased. This indicates that the flame stabilizer wake has been dissipated. The overall features shown in Fig. 12 are also shown on the Reynolds stress profiles of flames #2, #3, #5, and #6. In general, through the turbulent flame regions, an increase in Reynolds stress level is consistently accompanied by an increase in turbulence intensities. In flame #4, the overall Reynolds stress is not affected by the flame. Since the corresponding turbulence intensities are not increased through the flame region, our result is in agreement with the result of Yoshida [10].

The coefficient of correlation \((-\bar{u}\bar{v}/u'v')\) in flame #1 is shown in Fig. 12. The peak values of this coefficient in the flame region at \(x = 80\) and 100 mm are 0.55 and 0.75, respectively. The high value at \(y = 0\) for the \(x = 80\) mm profile is due to the wake. The peak values in the other flames vary from 0.7 to 0.9. These results indicate that turbulence in the flame region is highly correlated.

In the wake region the cross-correlation \(uv\) is negative and the local gradient \(dU/dy\) is positive. The Reynolds stress term in the turbulent kinetic energy equation \(-\bar{u}\bar{v}(dU/dy)\) is then positive and represents production of turbulent kinetic energy. This result is typical of conventional wake flow where turbulence obtains its energy from the mean motion. In the flame region, the cross-correlation \(uv\) is also negative. But the mean velocity gradients \(dU/dy\) and \(dV/dx\) are both negative because the flow is accelerated by combustion heat release. Therefore the terms \(-\bar{u}\bar{v}(dU/dy)\) and \(-\bar{u}\bar{v}(dU/dx)\) both become negative, which implies that the Reynolds stress reduces rather than produces turbulent kinetic energy and supplies energy to the mean motion. Since dilatation also removes turbulent kinetic energy, to balance the turbulent kinetic energy within the flame, these results imply that other production mechanisms would have to be quite significant in order to account for the increase in turbulent kinetic energy.

As discussed in the Section 3.3.1, the intermit-
tency effect is most certainly a major contribution to turbulence intensities. This effect should also influence the Reynolds stress. Therefore, it would be useful to explore the effect of flame movement on the $\overline{uv}$ correlation. Although quantitative analysis of the Reynolds stress would require instantaneous Reynolds stress data, a qualitative analysis can be carried out to explain the sign of the Reynolds stress.

The mean Reynolds stress is usually analyzed by comparing the contributions from four quadrants of the turbulent components $u$ and $v$. The four quadrants are (1) $u > 0$, $v > 0$, (2) $u < 0$, $v > 0$, (3) $u < 0$, $v < 0$, and (4) $u > 0$, $v < 0$, with positive contributions from quadrants (1) and (3) and negative contributions from quadrants (2) and (4) (Fig. 8). Inside the flame region the time-mean velocities $U_i$ would fall between the velocities of the slow reactants $U_{ir}$ and the velocities of the fast products $U_{ip}$. Therefore, the turbulence components $u_r$ and $v_r$ in the slow outward-moving reactant would be negative and positive, respectively, and would contribute negative $\overline{uv}$ correlation in quadrant (2). In the fast inward-moving products the signs of the turbulence components would be reversed with $u_p$ positive and $v_p$ negative, contributing negative $\overline{uv}$ correlation in quadrant (4). Since the major contributions from intermittent measurement in the reactant and product are both negative, the overall $\overline{uv}$ correlation would also be negative.

In numerical models of reacting turbulent flows using Favre-averaged conservation equations, the Reynolds stress appears as $u''v''$, where $u''$ and $v''$
are the turbulence components with respect to the Favre-averaged or density-weighted velocities. Although the values of Favre- and conventionally averaged Reynolds stresses would be different, their signs should be identical, since the second term in the equality \( \overline{u'v'} = uv + (\overline{\rho u'/\rho})(\overline{\rho v'/\rho}) \) is also negative. This is because in the reactant \( \rho' > 0, v > 0 \) and \( u < 0 \), whereas in the product \( \rho' < 0, v < 0 \) and \( u > 0 \). Therefore, our discussion of the implication of the sign of the Reynolds stress should also be pertinent to the Favre-averaged energy equation.

A similar analysis was used by Yagni and Mimura [6] to explain the sign of the temperature and radial velocity correlation. Although it has been proposed that “the physical process accounting for this (counter gradient diffusion) effect may be envisaged as a buoyancy mechanism in which packets of low-density, burned gas are preferentially accelerated relative to packets of reactants in mean pressure gradient across the flame,” this analysis is also useful in explaining the positive \( c''v'' \) correlation measured by Moss [5]. Moss’s correlation was between the concentration parameter and the velocity component at 23° to the vertical axis in a conical Bunsen-Type flame. His experimental condition was consistent with \( s_u/u' \) of about 2.0. Therefore this flame could also be characterized as a wrinkled laminar flame, and the intermittency effect should be significant. In his case the four quadrants are (1) \( v'' > 0, c'' > 0 \), (2) \( v'' > 0, c'' < 0 \), (3) \( v'' < 0, c'' < 0 \), (4) \( v'' < 0, c'' > 0 \). It follows that in the reactants, \( v'' \) is negative and \( c'' \) is also negative, resulting in a positive \( c''v'' \) contribution in (3). In the product, both \( v'' \) and \( c'' \) are positive in (1) and therefore the overall correlation is positive. It should be noted that the concept of preferential acceleration of product relative to reactant stems from the model of a highly turbulent flame characterized by separate packets of burned and unburned gases in the flame region. For less turbulent flames such as the one studied by Moss, where the reactants and products are separated by a continuous convoluted flame sheet, the present explanation appears to be more appropriate.

Our results and qualitative analysis have demonstrated that the intermittent measurements caused by the thin flame movement is a major contribution to turbulent intensities and correlations. This may explain the large discrepancy among the results reported in the literature, for it would seem likely that the intermittency effect would be different in different flame configurations. Interpretation of our results leads to the surprising conclusion that Reynolds stress removes turbulent kinetic energy, while at the same time the turbulent kinetic energy is substantially increased. This means that the conventional gradient transport model of Reynolds stress would breakdown and another form of modeling may be required.

To model these contributions properly, quantitative measurement of the flame structure and determination of its contribution to turbulence intensity and other correlations would be most helpful. At present, several diagnostic techniques are available for this type of measurement. Quantitative features of the growth of the flame convolutions can be obtained by the use of the two-point Rayleigh scattering technique. This technique would provide temporal and spatial scales of the flame convolutions. The two-color (two-component) LDV technique would provide direct instantaneous Reynolds stress measurements which can be used to obtain conditional statistics for differentiating between Reynolds stress contributions from the burned and the unburned states. Conditional sampling of turbulence intensities within the flame region would remove the turbulence contribution from intermittency and would be useful in determining whether the genuine turbulence intrinsic to the burned and unburned states is affected by combustion heat release. These techniques will be used in our future studies of premixed turbulent flames.

4. SUMMARY AND CONCLUSIONS

The turbulence intensities within the v-shaped flames were found to increase with distance from the flame origin. In most cases, both streamwise and cross-stream turbulence intensities reach their maxima in the flame region. Maximum increase is about four times the incident turbulence level. Turbulence within the flame region is nonisotropic, with the cross-stream fluctuation generally more
intense than the streamwise fluctuations. For a lean flame, no increase in turbulence intensities is observed. Comparison with schlieren records shows the correspondence between turbulence intensities and flame convolutions growth. Intermittent measurement of the conditioned mean velocities of the reactant and product caused by the movement of the thin flame sheet is most likely a major contribution to the turbulence intensities. The increase in turbulence intensities appeared to be dependent on whether this effect is predominant.

An increase in Reynolds stress in the flame region is found to accompany the increase in turbulence intensities. However, the sign of the Reynolds stress ($-\bar{uv}$) is positive. Since the mean velocity gradients through the flame region are both negative, our results imply that this Reynolds stress removes rather than increases turbulent kinetic energy. Therefore, gradient transport modeling would break down for these flames. The sign of the Reynolds stress is in qualitative agreement with the intermittent measurement of the turbulent velocity components in the burned and unburned states. These results further demonstrated that the movement of the thin flame sheet has a profound influence on the turbulence statistics and correlations. This influence should require careful consideration in numerical models of premixed turbulent flames.

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