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# Temperature and Velocity Measurements in Premixed Turbulent Flames

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**Turbulent flame-speed data for premixed flames of methane-air, propane-air, and ethylene-air mixtures stabilized in grid turbulence are reported and discussed. It is shown that turbulence effects on flame speed cannot be correlated fully by the turbulence length scale and rms velocity in the cold flow. Rather there appear to be significant flame-flow turbulence interactions affecting both turbulence level in the reaction zone and measured flame speeds. Results of detailed velocity measurements, including autocorrelations, by laser velocimetry are used to elucidate the nature of these interactions. It is concluded that flame-speed experiments must be designed and conducted to provide sufficient information (e.g., boundary conditions) to allow for reconstruction of the flowfield and these interactions by modelers if the data are to be of value in turbulent combustion model development and evaluation.**

## Nomenclature

$\ell$ = integral scale of turbulence
$P$ = pressure
$R_\ell$ = turbulence Reynolds number, $u\ell/\nu$
$R_\lambda$ = microscale turbulence Reynolds number, $u\lambda/\nu$
$S_L$ = laminar flame speed
$S_T$ = turbulent flame speed
$u$ = rms velocity, $=\sqrt{\overline{u'^2}}$
$u'$ = $U-\bar{U}$
$u''$ = $U-\tilde{U}$
$U$ = instantaneous velocity
$\tilde{U}$ = Favre average velocity
$\bar{U}$ = Reynolds average velocity
$\epsilon$ = Favre average energy dissipation rate
$\lambda$ = Taylor's microscale
$\rho$ = gas density
$\rho(\tau)$ = autocorrelation coefficient, $=\langle u'(t)u'(t+\tau)\rangle/u^2$
$\phi$ = equivalence ratio

*Subscripts*

$C$ = cold reactants
$H$ = hot products
$i$ = component along $x_i$

## Introduction

DESPITE a long history of research associated with turbulent combustion, the complex interactions of chemistry and fluid mechanics characterizing turbulent combustion are not well understood. These interactions have been discussed by many investigators, and different approaches have been suggested to describe turbulent combustion.[1,2] Assumptions made in theoretical models are sometimes hard to justify, and experimental data in the form of turbulent flame speeds for various combustible mixtures and flow conditions frequently are used in turbulent combustion model development and evaluation.

Libby et al.[3] have noted that there is a lack of sufficiently reliable experimental flame-speed data for the assessment of turbulent flame speed models. Scatter in the experimental data is large, and there are disagreements among workers over the best correlating parameters for flame-speed data. Bradley et al.[4] have suggested an empirical correlation in which the ratio $(S_T/S_L)$ depends only on the turbulence Reynolds number, $R_\lambda = u\lambda/\nu$. Ballal and Lefebvre[5] have related the ratio $(S_T/S_L)$ to a length scale of turbulence and to the ratio $(u/S_L)$. More recently, Abdel-Gayed and Bradley[6] have related the ratio $(S_T/S_L)$ to a function of turbulence Reynolds number $R_\ell = u\ell/\nu$, and to the ratio $(u/S_L)$.

Disagreement among the workers is due to several reasons. Some of the techniques do not make local measurements of the orientation of the flame front and of the magnitude and direction of the approach flow mean velocity in finding the flame speed. Smith and Gouldin[7] have shown the importance of such local measurements. Also, for unconfined oblique flames they have shown that, due to product gas expansion, there is appreciable deflection of streamlines approaching the flame and that one overestimates the flame speed if this deflection is not taken into account. This deflection is confirmed by Bill et al.[8] for unconfined flames, and for confined duct flames Howe et al.[9] have reported velocity measurements where deflection of cold flow streamlines is evident. Another possible problem with the published data, as noted by Libby et al.,[3] is that flame-speed data come from a variety of configurations—normal flames, unconfined oblique flames, and from flames in reaction vessels. Some of these configurations may be expected to lead to Reynolds shear stresses and, hence, to shear generated turbulence in the flame. Lastly, Hoult and Wong[10] have shown, using rapid distortion theory, that for flames in closed reaction vessels the rms velocity ahead of the flame front depends on the fraction of total mass burnt and on the density ratio for combustion. This effect may be significant in the experiments of Abdel-Gayed and Bradley[6] and in practical devices such as spark ignition engines. In addition to the aforementioned factors, the mean pressure field in the reaction zone is expected to influence turbulence levels in the flame and thereby flame speeds. The foregoing effects may account in part for the scatter and disparate trends observed in flame-speed data.

Some workers have observed increases in turbulence in the reaction zone of premixed turbulent flames, but whether or not the observed increase in turbulence affects the combustion process and flame speed is not clear. Durst and Kleine[11] have concluded that "...the observed turbulence in the reaction

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zone has a natural part of the measured velocity fluctuations as well as a temporal velocity difference resulting from convection of the flame structure across the measuring point which contributes to the overall effective value." Bill et al.[8] do not give any significance to increases in turbulence in the reaction zone that they observe and conclude that the lack of correlation in the reported flame-speed data is due to errors in the measurements. On the other hand, Yule et al.[12] have reported measurements on transition from laminar to turbulent flow in a round jet flame. Using the laser schlieren technique, they observe instabilities in the flame front at a series of discrete frequencies when the reaction zone is under mean flow shear. The observation leads one to expect that mean shear would, among other effects, cause a turbulent flame to wrinkle which, in turn, would increase the turbulent flame speed. Clearly, there is a need to investigate further the effect of shear generated turbulence on turbulent flame speed and to consider other mechanisms for turbulence generation in premixed flames.

The objective of this study is to obtain turbulent flame-speed data for premixed methane-air, propane-air, and ethylene-air flames using an apparatus and technique similar to those used by Smith and Gouldin.[7] Our measurements show higher rms velocities in the reaction zone which are found to affect flame speed, and therefore an effort is made to critically examine the universality of these and other flame-speed measurements. Also, detailed velocity measurements in and around the reaction zone, including autocorrelation measurements, are made in order to study flame-flow turbulence interactions and turbulence generation in the reaction zone.

## Experimental Apparatus

Unconfined "V" shaped flames are stabilized in grid turbulence on a rod stabilizer (1.25-mm diameter) mounted across the exit plane of a cylindrical laboratory burner (50-mm diameter) similar to one used by Smith and Gouldin.[7] Turbulence is generated by interchangeable wire-mesh grids mounted in the central air-fuel jet 3 cm from its exit. The central air-fuel jet is surrounded by an annular air jet (76-mm diameter) as shown in Fig. 1. Velocities are measured by hot-film anemometry in the cold, approach flow and by laser velocimetry (LV) in the vicinity of the reaction zone and in the hot, combustion product gases. The LV apparatus consists of an argon-ion laser (Lexel), commercial optics with Bragg cell frequency shifter and a burst type signal processor (Thermo-Systems, Inc.). A dual beam, real fringe optical configuration is employed. The plane containing the two laser beams is aligned to be parallel to the flame stabilizer rod so that the major axis of the ellipsoidal fringe volume lies parallel to the plane of the time mean position of the flame front since the large mean velocity gradients are perpendicular to the time mean flame front.

The central fuel-air flow is seeded with aluminum oxide particles of 1-$\mu$m nominal diameter. Scattered radiation from the particles is collected at a 90-deg angle with the incident radiation, which reduces the effective length of the measuring volume to about 0.2 mm. Small dimensions for the measuring volume are desired for autocorrelation measurements of velocity fluctuations. Seed levels are low, and the data rate is approximately 400 Hz in the cold flow at all points of measurement. Output of the LV signal processor is stored for analysis on a DEC PDP11 computer.

All gases are supplied from high-pressure storage tanks. Flows are metered by needle valves, and flow rates are monitored by rotameters. For details of construction consult Ref. 13.

## Measurement Technique

The technique used for flame-speed measurements is similar to one developed by Smith and Gouldin.[7] They take the time-mean isothermal surface corresponding to twice

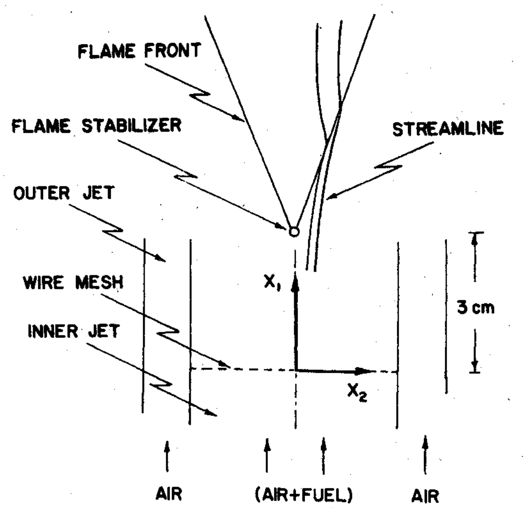


**Fig. 1 Schematic of apparatus of turbulent flame study (note coordinate system).**

room temperature as the flame surface and define the flame speed to be the mean velocity component of the approach flow perpendicular to this surface. In the present study, the isothermal surface corresponding to a mean temperature 10 K above room temperature is taken to be the flame surface. As noted in Ref. 7, isotherms in our flame configuration are not parallel, but at the same time the choice of flame surface is not entirely arbitrary. A similar problem is faced in laminar flame-speed measurements using stationary flame methods. After critically examining the various methods of measuring laminar flame speed, Andrews and Bradley[14] conclude that for stationary flames the best procedure is to identify the cold gas front of the flame as the flame surface and to measure the magnitude and direction of gas velocity at the flame surface by means of particle tracking. In this study, the velocity components of scattering particles are measured at the same point where the flame surface, as defined earlier, is determined. The orientation of the time-mean isotherm corresponding to the flame surface is measured using 0.125-mm (5-mil), silicon-coated, Pt/Pt-10% Rh thermocouples. This technique is considered to be consistent with the cited recommendations of Andrews and Bradley.[14] Another reason for choosing the above definition of the flame surface is that our velocity data show that horizontal and vertical mean velocity components are nearly constant in the neighborhood of the flame surface, making accurate measurements of velocity components less difficult.

Horizontal and vertical components of mean and rms velocity are measured using a counter or burst type signal processor, and therefore velocity bias corrections are required. Reference 15 indicates that for turbulent intensities less than 15% the one-dimensional correction method suggested by McLaughlin and Tiederman[16] is adequate. Such corrections are made for the vertical velocity component. However, for the horizontal velocity component, bias correction is not applied. The error involved is expected to be small for low turbulence intensity.[15] For measurements in the reaction zone, velocity bias due to nonuniform particle concentrations may also be important, but there are no convenient methods to make corrections for this biasing. Therefore, the data presented are corrected for velocity bias only. 2000 samples are used to calculate mean and rms velocities.

The method of "discretized lag products," is used to form autocorrelation estimates. Mayo[17] shows that by this method alias free spectral estimates may be obtained, in principle, with any mean sample rate however slow. The length of each time block is 1 s, and 200 such blocks are used. Comparisons

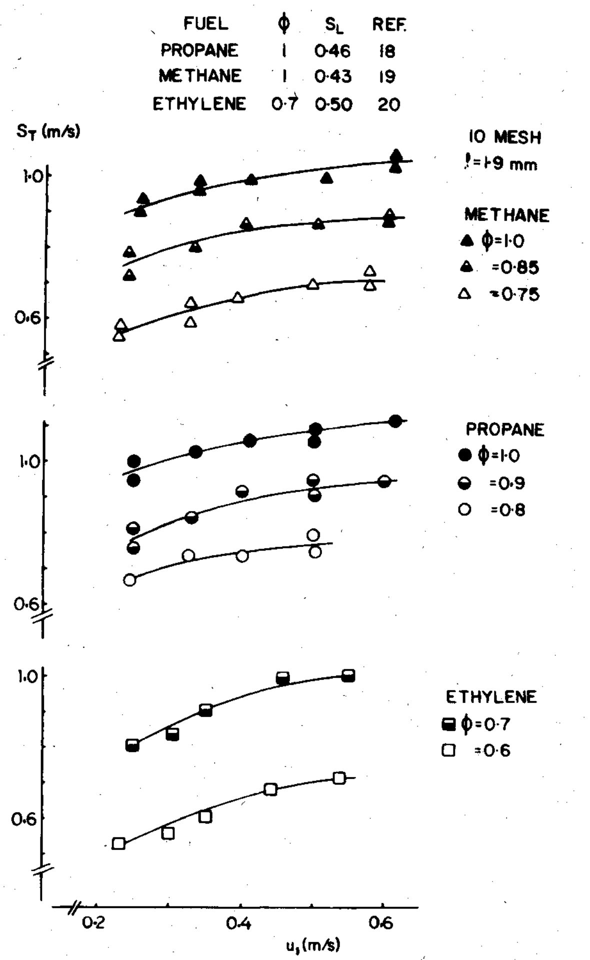


**Fig. 2 Turbulent flame speeds vs rms velocity in the cold approach flow for various fuel-air mixtures.**

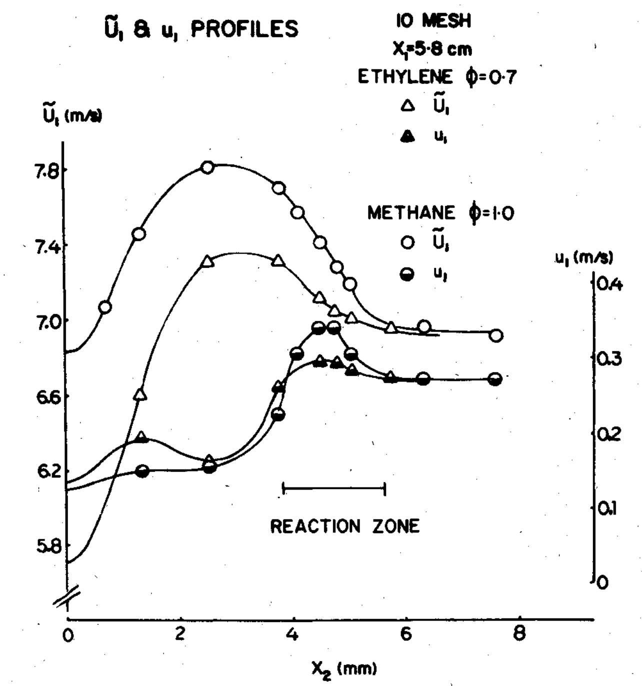


**Fig. 3 Comparison of vertical mean ($\tilde{U}_1$) and rms ($u_1$) velocities in ethylene ($\phi = 0.7$) and methane ($\phi = 1.0$) flames.**

between the measurements of autocorrelation coefficient in grid turbulence using laser velocimetry and hot-wire anemometry show reasonable agreement. These measurements are reported in Ref. 13.

## Results and Discussion

Turbulent flame-speed measurements were conducted using the same turbulence generators as in Ref. 7. Here measurements are reported only for the case when a wire (0.711-mm diameter) woven mesh No. 10 turbulence generator is used; other measurements are reported elsewhere.[13] Figure 2 shows the dependence of turbulent flame speed for various fuel-air mixtures on equivalence ratio and rms velocity in the approach flow. Flame-speed measurements are performed 5.8 cm downstream of the turbulence generator. The integral length scale of the approach flow turbulence is 1.9 mm at that downstream distance. $\ell$ is the same for all the cases shown in Fig. 2. The turbulent flame speed appears to be a strong function of laminar flame speed but only a weak function of rms velocity. The data are only in qualitative agreement with the data in the literature[5-7] and consistently show lower values of flame speed than the data of Smith and Gouldin,[7] primarily because they measured the cold flow deflection 5 mm away from the flame front. Later in this paper data are presented which show that such a procedure would underestimate the deflection of the cold flow streamlines, thereby overestimating the flame speed.

There is disagreement among workers about the way turbulent flame-speed data correlate with laminar flame speed. However, most agree that for identical approach flow turbulence, the turbulent flame speed increases with the laminar flame speed. From Fig. 2, comparison of flame speeds for methane and propane flames at unit equivalence ratio and ethylene-air flames at an equivalence ratio of 0.7 shows that the ethylene-air mixture consistently gives the lowest turbulent flame speed even though it has the highest laminar flame speed. The values for laminar flame speeds are taken from Refs. 18, 19, and 20 recommended by Andrews and Bradley.[14]

Figure 3 shows mean and rms vertical velocities as a function of distance $x_2$ for methane-air ($\phi = 1$) and ethylene-air ($\phi = 0.7$) flames subjected to identical grid turbulence. Outside the flame zone ($x_2 > 6.0$ mm) the mean and the rms velocities are uniform. In the reaction zone gases expand and, as the data indicate, their velocity increases. This increase is larger for methane than for ethylene flames. One reason for this difference is that during adiabatic combustion, the volume of cold mixture expands by a factor of only 7.2 in the case of the ethylene mixture as compared to 8.4 for the methane mixture. Thus, different flowfields are encountered in the two cases which give rise to different levels of turbulence production in the reaction zone as shown in Fig. 3. The reaction zone is defined here as bounded by mean isotherms corresponding to 10 K above room temperature and to 95% of the total increase above the room temperature due to chemical reactions. Furthermore, the data suggest that the higher rms velocity in the reaction zone of methane may be responsible for the higher methane turbulent flame speed.

One reason for higher rms velocity in the reaction zone than in the approach flow may be the mean shear as pointed out by Bray and Libby.[21] Another mechanism by which turbulence is generated in the reaction zone is pressure-velocity interactions. As indicated by streamline curvature in the flowfield on either side of the flame front (defined earlier) the mean pressure has a local maximum on this surface. In a study of normal turbulent flames, Libby and Bray[22] show that interaction between turbulence and the mean pressure gradient generates turbulence in the reaction zone. It is significant that their theory predicts larger increases in rms velocity in the reaction zone by this mechanism for larger density ratios between reactants and products which is in agreement with the data in Fig. 3.

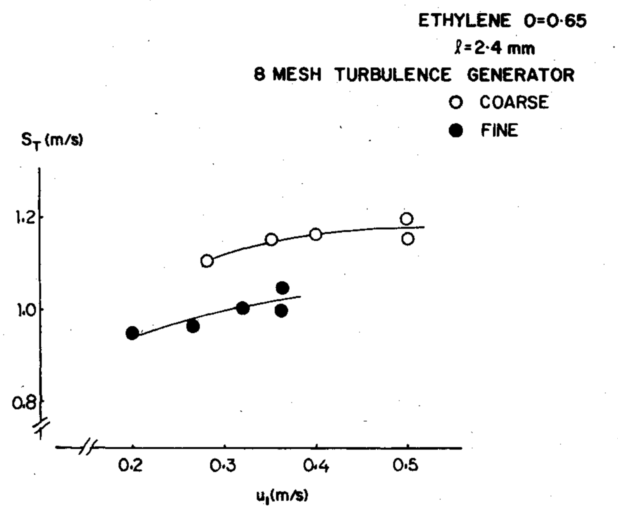


Fig. 4 Turbulent flame speed data obtained with coarse and fine 8 mesh turbulence generators.

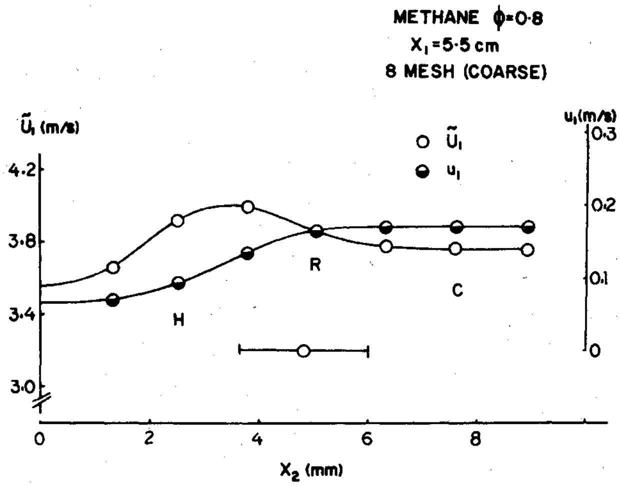


Fig. 6 $\tilde{U}_1$ and $u_1$ profiles in methane ($\phi = 0.8$) flame.

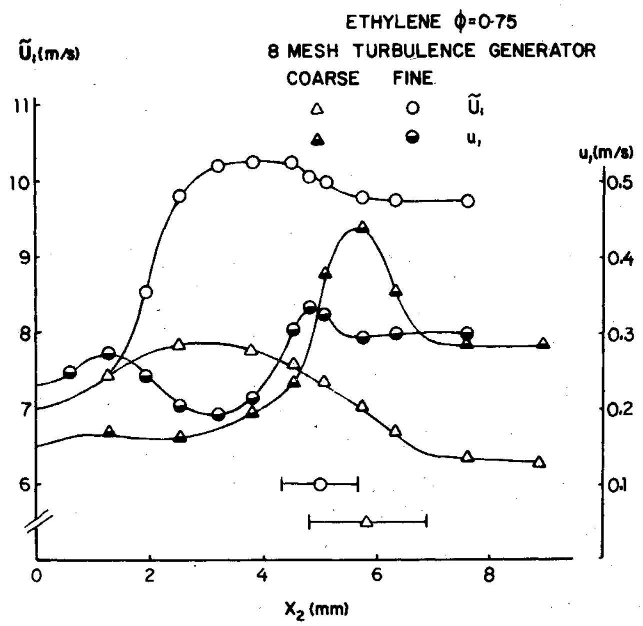


Fig. 5 Comparison of vertical mean ($\tilde{U}_1$) and rms ($u_1$) velocities in ethylene flames for coarse and fine 8 mesh turbulence generators.

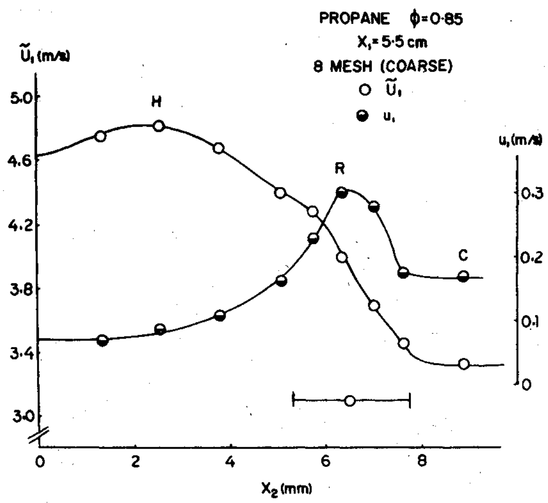


Fig. 7 $\tilde{U}_1$ and $u_1$ profiles in propane ($\phi = 0.85$) flame.

Frequently, it is assumed that flame structure and flame speed depend only on the mixture composition and approach flow turbulence; the influence of approach flow mean velocity magnitude and direction are ignored. To check the validity of these assumptions, two different turbulence generators of woven wire (mesh No. 8) are constructed to create grid turbulence of identical length and velocity scales at different mean velocities. Wires of 0.508-mm and 0.813-mm diam are used to construct the turbulence generators, referred to as fine and coarse, respectively. Using hot-film anemometry, the variations of length and velocity scales downstream of the turbulence generators are characterized with techniques described by Smith and Gouldin.[7] Measurement results, which are reported in Ref. 13, show that grid turbulence of the same length scale ($\ell = 2.4$ mm) using coarse and fine turbulence generators can be obtained, respectively, at 5 cm and 6 cm downstream of these generators. For these two turbulence generators, flame-speed data are obtained with ethylene-air flames ($\phi = 0.65$); see Fig. 4. The fine turbulence generator gives a lower flame speed even though the cold flow rms and integral length scale are the same for the two generators. Note, though, that the mean velocities of the approach flow are different because the turbulent intensities for the two generators are different (2.6% and 3.8% for fine and coarse turbulence generators, respectively).

Velocity measurements in and around the reaction zone of an ethylene-air flame ($\phi = 0.65$) show that, for grid turbulence of constant velocity and length scales, $u_1$ and also $u_2$ in the reaction zone increase with decreasing axial mean velocity in the approach flow. For an equivalence ratio of 0.75, the effect of the mean velocity is even more apparent. In Fig. 5, mean and rms vertical velocities are presented as a function of horizontal distance $x_2$. The wake of the flame holder can be seen to have significant effect on the flow behind the flame as observed by Bill et al.[8] Furthermore, the reaction zone appears to be located in a shear layer between the fast moving, hot combustion gases and the slow moving cold reactant mixture.

Increases in rms velocity in the reaction zone have been observed in the past, but their significance is in dispute. Durst and Kleine[11] and more recently Bill et al.[8] have speculated that the increase in rms velocity in the reaction zone is due to slow drifting of the reaction zone back and forth across the measurement volume and therefore does not affect the combustion process.

The present results show that larger increases in rms velocity in the reaction zone are consistently associated with higher flame speeds. To investigate the contribution of drift and low-frequency oscillations of the reaction zone to

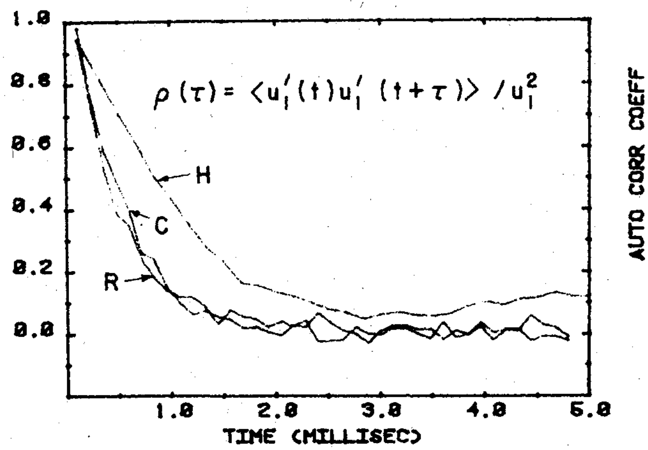


Fig. 8 Autocorrelation data for methane flame, see Fig. 6.

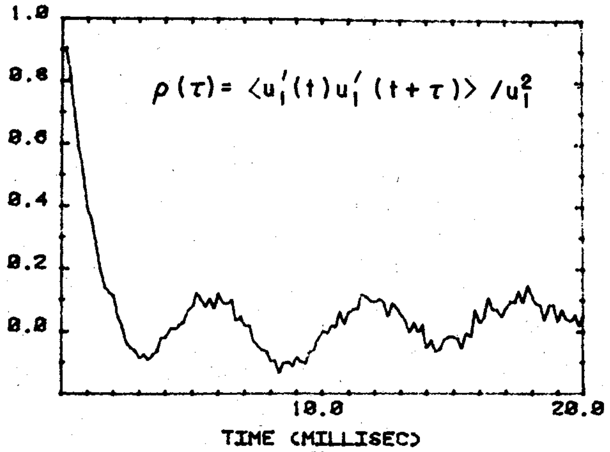


Fig. 10 Autocorrelation in propane flame at location H, see Fig. 7.

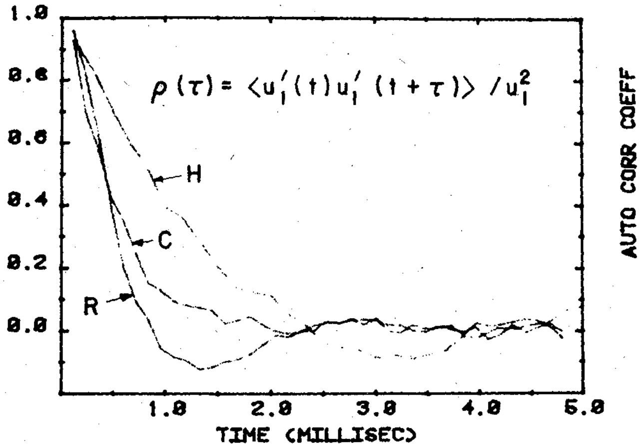


Fig. 9 Autocorrelation data for propane flame, see Fig. 7.

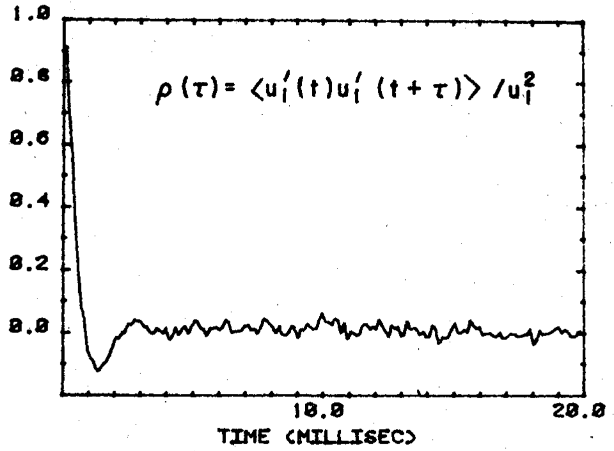


Fig. 11 Autocorrelation in propane flame at location R, see Fig. 7.

measured rms velocity, autocorrelation measurements are made in and around the reaction zone. Figures 6 and 7 present mean and rms velocity data for two flame conditions and indicate positions at which autocorrelation measurements are made. The locations marked H, R, and C denote hot zone, reaction zone, and cold zone, respectively. Figures 8 and 9 show the autocorrelation coefficient $\rho(\tau)$ as a function of the time lag $\tau$. Figure 8 corresponds to a flow condition where there is no increase in rms velocity in the reaction zone (Fig. 6). One notes that the shapes of $\rho(\tau)$ in the cold zone and the reaction zone are almost the same, while in the hot zone where the mean velocity is higher, the decay of $\rho(\tau)$ with $\tau$ is more gradual than in the other two zones, which indicates that the average eddy size is larger in the hot zone than in the cold zone. Dilatation is expected to increase the integral scale, and an order of magnitude increase in kinematic viscosity increases significantly the damping of small scale motions, thus increasing the average eddy size. Figure 9 presents $\rho(\tau)$ data for a propane flame for which a large increase in rms velocity is observed in the reaction zone as shown in Fig. 7. It is seen that in the hot zone $\rho(\tau)$ has a "ring," which is made clear by plotting $\rho(\tau)$ on a longer time scale (Fig. 10). Similar oscillations have been observed by Bill et al.[8] in their velocity data. In the reaction zone and in the cold zone, the measured autocorrelation coefficients are markedly different from each other (Fig. 9). If large-scale motion of the flame front were contributing significantly to the observed increase in turbulence in the reaction zone, a more gradual decay of $\rho(\tau)$ in the reaction zone than is seen in Fig. 9 or in Fig. 11 is expected. Furthermore, the data of Fig. 11 clearly show that the

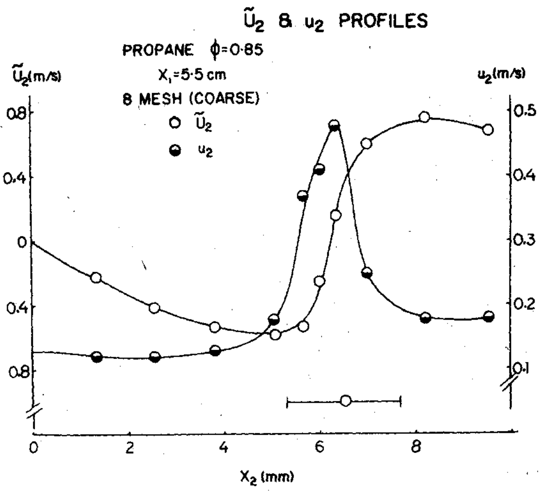


Fig. 12 $\tilde{U}_2$ and $u_2$ profiles for propane flame at the same flow conditions as Fig. 7.

reaction zone is not subject to periodic motions as observed in the hot zone or to marked long time scale drifting of the flame position.

Figure 12 shows horizontal mean and rms velocity for the same flame as in Fig. 7. The rms velocity is uniform in the cold zone, but the corresponding mean velocity decreases with distance away from the reaction zone. Therefore, the deflection of the cold flow streamlines is underestimated if the velocity measurements are done away from the flame front.

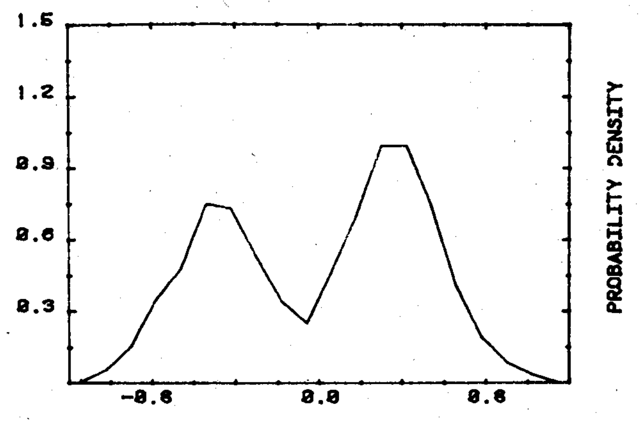


Fig. 13 pdf for $u_2'$ at the location of highest $u_2$ in Fig. 12.

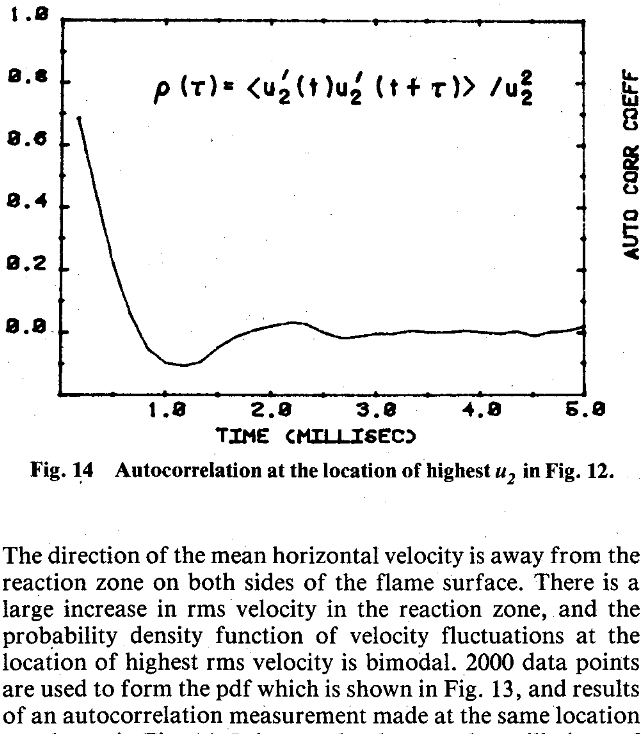


Fig. 14 Autocorrelation at the location of highest $u_2$ in Fig. 12.

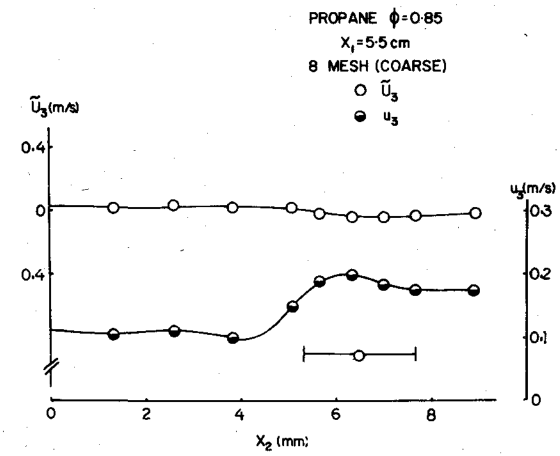


Fig. 15 $\tilde{U}_3$ and $u_3$ profiles at the same flow conditions as Fig. 7.

The direction of the mean horizontal velocity is away from the reaction zone on both sides of the flame surface. There is a large increase in rms velocity in the reaction zone, and the probability density function of velocity fluctuations at the location of highest rms velocity is bimodal. 2000 data points are used to form the pdf which is shown in Fig. 13, and results of an autocorrelation measurement made at the same location are shown in Fig. 14. It is seen that large-scale oscillations of the flame front do not make a significant contribution to the observed rms velocity in the reaction zone even though the velocity pdf is bimodal.

Our flame speed data and autocorrelation measurements suggest that the observed increase in rms velocity in the reaction zone is significant to the combustion process. To isolate different mechanisms which affect turbulent kinetic energy in flow with nonuniform density, consider the high Reynolds number approximation of the equation for $\widetilde{\langle u_i'' u_i'' \rangle}$.[23]

$$\bar{\rho}\frac{\partial}{\partial t}\widetilde{\langle u_i'' u_i'' \rangle} + \bar{\rho}\tilde{U}_j \frac{\partial}{\partial x_j}\widetilde{\langle u_i'' u_i'' \rangle} = -2\bar{\rho}\widetilde{\langle u_i'' u_j'' \rangle}\frac{\partial \tilde{U}_i}{\partial x_j}$$
$$-\left[\frac{\partial}{\partial x_j}\langle \rho u_i'' u_i'' u_j'' \rangle + 2\frac{\partial}{\partial x_i}\langle p' u_i'' \rangle\right] - 2\epsilon\bar{\rho}$$
$$-2\overline{u_i''}\frac{\partial \bar{P}}{\partial x_i} + 2\left\langle p' \frac{\partial u_i''}{\partial x_i}\right\rangle \tag{1}$$

The first three terms on the right-hand side of Eq. (1) are production, transport, and dissipation terms. The last term is considered to be primarily acoustic in origin, and its importance is not yet established[1]; it is not considered further in this study.

Before comparing our data with Eq. (1), the limitations of these data should be noted. Due to gas density fluctuations, the number density of scattering particles is not uniform. According to Asalor and Whitelaw,[24] the number density of scattering particles may be assumed to be proportional to local gas density. Thus, for low turbulence intensity using one-dimensional velocity bias correction one can obtain Favre-averaged velocities from our data. However, rms velocities in the reaction zone can be in error due to biasing effects of nonuniform particle concentration in the reaction zone. In the hot and cold zones, where density fluctuations are negligible, the measurements are free of this bias problem.

Figures 7, 12, and 15 show mean and rms velocity components as a function of distance $x_2$. It is clear that the $\langle u_i' u_i' \rangle$ are almost constant in the hot and cold zones. The data of Bill et al.[8] exhibit similar properties. In constant density, turbulent flows, terms such as $\langle u_i' u_i' u_j' \rangle$ and $\langle p' u_i' \rangle$ are considered to be fluxes of turbulent kinetic energy, $\langle u_i' u_i' \rangle$. Under the gradient transport assumption the terms $\langle u_i' u_i' u_j' \rangle$ and $\langle p' u_i' \rangle$ are negligible in these two zones. Therefore, these transport terms are not expected to make a net contribution to changes in the turbulence kinetic energy as the fluid passes from the cold zone to the hot zone. On the other hand, these transport terms are probably significant within the reaction zone, but in this region our measurements are subject to biasing errors which makes the study of the transport terms difficult.

An equation for $\widetilde{\langle u_3'' u_3'' \rangle}$ can be written similar to Eq. (1).

$$\bar{\rho}\frac{\partial}{\partial t}\widetilde{\langle u_3'' u_3'' \rangle} + \bar{\rho}\tilde{U}_j \frac{\partial}{\partial x_j}\widetilde{\langle u_3'' u_3'' \rangle} = -2\bar{\rho}\widetilde{\langle u_3'' u_3'' \rangle}\frac{\partial \tilde{U}_3}{\partial x_3}$$
$$-\frac{2}{3}\bar{\rho}\epsilon + \text{transport} \tag{2}$$

Here the dissipative correlation is assumed to be isotropic,[23] and by symmetry terms such as $\partial\tilde{U}_3/\partial x_1$ and $\partial\tilde{U}_3/\partial x_2$ are taken to be zero. Also $\overline{u_3''}$ is zero on the plane of symmetry defined by $x_3 = 0$. The first term on the right-hand side of Eq. (2) is the removal of turbulent kinetic energy due to dilatation, and the second term is dissipation due to viscosity. Both terms are loss terms and cause a net reduction in $\widetilde{\langle u_3'' u_3'' \rangle}$ as fluid passes through the reaction zone along a typical streamline. Though Fig. 15 does not show measurements along a streamline, the observed changes are consistent with expected changes in $\widetilde{\langle u_3'' u_3'' \rangle}$ across the reaction zone.

The equation for $\widetilde{\langle u_1'' u_1'' \rangle}$ shows two important mechanisms by which turbulent kinetic energy is generated in the reaction zone.

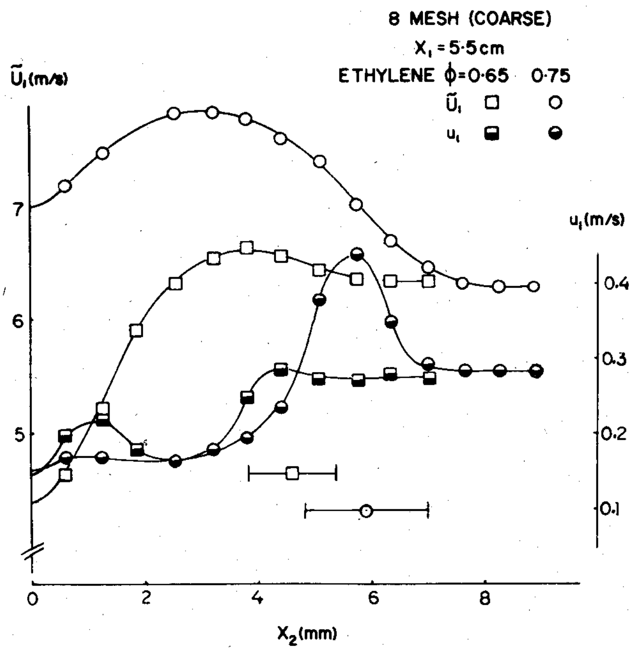


**Fig. 16 Comparison of $\tilde{U}_I$ and $u_I$ profiles in ethylene flames at $\phi = 0.65$ and $\phi = 0.75$.**

$$\bar{\rho}\frac{\partial}{\partial t}\widetilde{\langle u_I'' u_I'' \rangle} + \bar{\rho}\tilde{U}_j \frac{\partial}{\partial x_j}\widetilde{\langle u_I'' u_I'' \rangle} = -2\bar{\rho}\widetilde{\langle u_I'' u_I'' \rangle}\frac{\partial \tilde{U}_I}{\partial x_I}$$

$$-2\bar{\rho}\widetilde{\langle u_I'' u_2'' \rangle}\frac{\partial \tilde{U}_I}{\partial x_2} - 2\overline{u_I''}\frac{\partial \bar{P}}{\partial x_I} - \frac{2}{3}\bar{\rho}\epsilon + \text{transport} \qquad (3)$$

The first and the fourth terms on the right-hand side of Eq. (3) are the loss terms due to dilatation and viscous dissipation. The second term is the shear production term.[21] The third term is production due to interactions of density and velocity fluctuations with the mean pressure gradient; it is discussed by Libby and Bray.[22] In our experiment, the mean pressure has a local maximum on the flame surface, as explained before, and $\partial\bar{P}/\partial x_I$ is negative in the reaction zone. Since higher mean velocities are associated with the lower density combustion product gases (see Fig. 7), $\overline{u_I''}$ is expected to be positive in the reaction zone. Thus, this interaction increases $\widetilde{\langle u_I'' u_I'' \rangle}$ in the reaction zone which is consistent with the measurements shown in Fig. 7.

For all flow conditions, a net decrease in rms velocity is observed across the reaction zone. This drop is due in part to the dominance of dilatation as noted by Bill et al.[8] and others and in part to viscous dissipation. The turbulence Reynolds number is 30 in the cold zone but is estimated to be about 2 in the hot zone indicating the importance of viscous forces in the hot zone.

Bilger[25] has shown that $-\overline{u_i''}\,(\partial\bar{P}/\partial x_i)$ can be a source or sink of turbulent kinetic energy. In our configuration, as shown earlier, it is expected to be a source term in the reaction zone. The shear term is a source of turbulent kinetic energy with its magnitude depending on the flowfield. These facts suggest that disagreements among workers over the best correlating parameters for flame-speed data stem in part from the fact that these workers are investigating different flame configurations which give rise to different amounts of turbulence generation in the flame and, therefore, to different flame speeds. In other words, while studying the effect of a parameter, say, laminar flame speed, a change of the parameter alters the flowfield in a way which is characteristic of the experimental configuration used and in a way which influences the flame speed. Therefore, the effect of a parameter on turbulent flame speed can be expected to show different trends when studied in different flow configurations. For example, Fig. 16 shows a comparison of vertical mean and rms velocities for ethylene flames at equivalence ratios of 0.65 and 0.75. It is seen that, in our flow configuration, for the same approach flow conditions, the hotter flame is subjected to a higher level of turbulence.

There is a need to identify a flow configuration in which flame-flow interactions are minimal. Spherical flames in closed vessels have been studied by many workers, e.g., Sokolik et al.,[26] Andrews et al.,[27] and more recently by Abdel-Gayed and Bradley.[6] The flow configuration in these cases is attractive because of its simplicity and deserves consideration. Andrews et al.[27] have correlated the ratio $(S_T/S_L)$ with the microscale turbulence Reynolds number $Re_\lambda$ and they report that $(S_T/S_L)$ tends to be smaller at a given turbulence Reynolds number for mixtures with higher values of $S_L$. This secondary effect of laminar flame speed is also observed by Abdel-Gayed and Bradley[6] who hypothesize the existence of different flame structures depending on the value of the parameter $(S_L/u)$ to explain this influence of laminar flame speed.

On the other hand, this secondary influence of laminar flame speed may be the result of flame-flow turbulence interaction. Hoult and Wong[10] have used rapid distortion theory to calculate rms velocities ahead of flames in closed vessels of cylindrical geometry. Their findings indicate that higher density ratios of combustion $(\rho_C/\rho_H)$ cause larger increases in rms velocity ahead of the flame. For the same laminar flame speed, ethylene and hydrogen flames have lower density ratios $(\rho_C/\rho_H)$ than methane flames. Therefore, for the same $Re_\lambda$ ethylene and hydrogen flames can be expected to have lower $(S_T/S_L)$ values than methane flames as observed by Andrews et al.[27] and by Abdel-Gayed and Bradley.[6] The effect of the density ratio of combustion cannot be overemphasized. In this regard, it is interesting to note that the flame-speed data reported by Sokolik et al.[26] are correlated using rms velocity and adiabatic flame temperature as parameters.

## Summary

The flame-speed data in the literature are generally correlated with parameters such as velocity and length scales of turbulence and laminar flame speed which are found to be inadequate to account for the interactions between fluid mechanics and combustion. The density ratio of combustion appears to be an important parameter because it has an effect on the flowfield which is found to influence combustion processes and turbulent flame speed. Also, the magnitude and direction of the mean velocity of the cold reactants relative to the flame appears to be important.

The presence of flame-flow turbulence interactions and their effect on turbulent flame speed are demonstrated. Because of these interactions, flame-speed data available in the literature are dependent on the measurement technique and on the apparatus. Flame-speed data are of value for model development and evaluation only if the flowfield in which the flame is situated is known in sufficient detail to predict or model these interactions. The significance of these interactions even in the simplest possible flame configurations underscores the need for being able to model these effects. Turbulent combustion models are needed which can predict both the observed turbulence production in the reaction zone and the influence of this turbulence on combustion processes.

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