Simultaneous Measurements of Velocity and Density in a Turbulent Nonpremixed Flame

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Simultaneous velocity and density measurements have been obtained throughout a turbulent nonpremixed flame under high Reynolds number conditions. The objective of the measurements was to obtain a better understanding of the structure of turbulent nonpremixed flames and the interaction between turbulence and combustion chemistry. The measurements were made with an apparatus which utilized both laser velocimetry and laser Rayleigh scattering. From these measurements it was shown previously that while the gradient diffusion submodel for the velocity-density correlations agreed with the radial correlation data, it was seldom consistent with the axial data. In the present paper the analysis of these data is extended to include information on flame intermittency, conditionally sampled results, and joint probability distributions of velocity and density. Comparisons made with results in nonreacting and analogous nonpremixed reacting jets show that both mean and fluctuating quantities and conditionally sampled results are dependent on flow conditions and the presence of combustion.

Introduction

THE development of models for turbulent reacting flows has proven difficult due to a limited understanding of the effects of turbulence on the combustion process. Recent evidence indicates that the use of submodels based on isothermal or nonreacting turbulent flows may not be valid in reacting flows.[1-3] Newly developed laser-based diagnostic techniques for the in situ measurement of velocity,[1-3] temperature and density,[3-5] and species concentrations[6,7] show considerable promise for providing the data needed in the validation of current turbulent combustion models and for the development of new modeling approaches.

In a previous study reported by Driscoll et al.[3] results were presented in which a combined laser velocimetry-laser Rayleigh scattering technique was used for the simultaneous measurement of gas densities and velocities in a high Reynolds number turbulent nonpremixed flame. The measurements were compared with a gradient diffusion submodel for the velocity-density correlation based on isothermal and nonisothermal turbulent flows.[8] It was concluded that, while the gradient diffusion submodel agreed with the radial correlation data, it was seldom consistent with the axial data. In the present paper the data have been analyzed to obtain intermittency profiles, conditionally sampled quantities, and the joint probability density distributions of velocity and density. Comparisons are made with results in nonreacting jets and analogous nonpremixed reacting jets to show the effects of combustion on turbulence and the mixing process.

The importance of intermittency in free turbulent shear flows has long been recognized and has led to numerous studies on intermittency in a variety of flows.[9-11] Intermittency is defined as the probability that a given flow is turbulent at a given point and time. Experimental techniques for conditional sampling have been developed to better understand the nature of intermittency through characterization of the turbulent and nonturbulent fluid states.[11,12] These studies, however, have largely been carried out in nonreacting flows and there is a need for such data in reacting flows.

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The joint probability density distribution of flow variables contains information on the mixing and combustion processes. Moss[2] has measured the joint probability density of velocity and concentration in premixed flames and found that the distribution is well modeled by a mixture of burned and unburned gas with very little contribution from the partially reacted gases. The measurement of both the joint probability density and conditionally sampled variables takes on added importance with the recent modeling approach of Pope[13] in which conditional modeling of the transport equation for the joint probability density of the velocity field and a scalar is used to predict the flow properties of a nonreacting turbulent jet.

In the remainder of this paper the combined laser velocimetry-Rayleigh scattering technique will be described and experimental results will be presented. Conventionally averaged mean and fluctuating velocities and densities will be discussed first. Intermittency data will then be presented and compared with results of other investigators. Next, conditionally sampled velocities, densities, and probability distributions of the length scales will be described and, finally, the joint probability density distributions of axial velocity and gas density will be presented.

Experimental

All measurements were performed in the Sandia Turbulent Diffusion Flame Facility.[14] This is an induced-draft horizontal wind tunnel with an axisymmetric fuel jet located at the upstream end of the test section (Fig. 1). The fully windowed test section has a 30 cm square cross section and is 200 cm long. The fuel nozzle inside diameter d is 0.53 cm and the bulk velocity of the fuel mixture u_j is 154 m/s with a resulting jet Reynolds number of 24,000. This Reynolds number is high enough so that differential diffusion and molecular transport effects can be neglected. The coflowing airstream velocity u_0 is 8.5 m/s.

A mixture of 22 mole percent argon in hydrogen is used as the fuel. Since the Rayleigh scattering intensity is dependent on gas composition (due to variations in the scattering cross section with gas species), Rayleigh scattering cannot, in general, provide an unambiguous measurement of gas density in reacting systems with varying gas composition. As discussed in Ref. 3, however, a fuel mixture can be selected so that the Rayleigh scattering signal provides a direct measurement of either density or temperature. In the present case, the above fuel mixture results in a Rayleigh scattering signal proportional to gas density to within 2.9% and alleviates the need for corrections due to gas composition changes irrespective of whether air, fuel mixture, or combustion products are present.

The combined laser velocimeter-laser Rayleigh scattering apparatus, shown in Fig. 2, is described in greater detail elsewhere.[3] Briefly, the laser velocimeter (LV) is a commercially available forward-scattering system in which the velocimeter laser beams (488 nm, 1 W) are focused to overlap a separate laser beam (514.5 nm, 5 W) used for the Rayleigh measurements. The resulting measurement volume has a 0.5 mm diameter and a length of 2.0 mm. Rayleigh scattered light is collected by a 20-cm-diam collection lens (f/1.5) and sent to an integrator with a sample-and-hold circuit which averages the signal over an integration time of 60 μs. Since 60 μs is the effective response time of the Rayleigh system, frequency components up to approximately 8 kHz contribute to the mean and rms measurements. The Rayleigh signal is updated continuously in the sample-and-hold circuit during the measurements until a velocity validation pulse from the LV counter signals the computer to transfer the Rayleigh signal corresponding to the validated velocity measurement from the sample-and-hold circuit.

The concentration of LV seed particles is an important consideration since contamination of the Rayleigh signal by Mie scattering from the LV particles at high seed rates was found to occur. Both the fuel and air flows were sparsely seeded with 0.3-μm-diam alumina particles using commercial seeders to obtain up to 10 valid LV bursts per second. Approximately 3 min were needed at each spatial location to record 1000 velocity-density pairs. At spatial locations where more statistical information and temporal resolution were desired, additional Rayleigh scattering measurements were made with no seed particles in the flow. In this case, the maximum data rate was limited by the transfer rate of the Rayleigh data to the computer which was approximately 180 μs. Typically 14,000 measurements were made at these locations.

Results

Conventionally Averaged Velocities and Densities

The centerline variation in mean and fluctuating axial velocity is shown in Fig. 3 for nonreacting and reacting jets. In both cases the jet composition and the flow conditions were identical. Axial distance x is normalized by the jet exit diameter d. The mean velocity results are presented in the

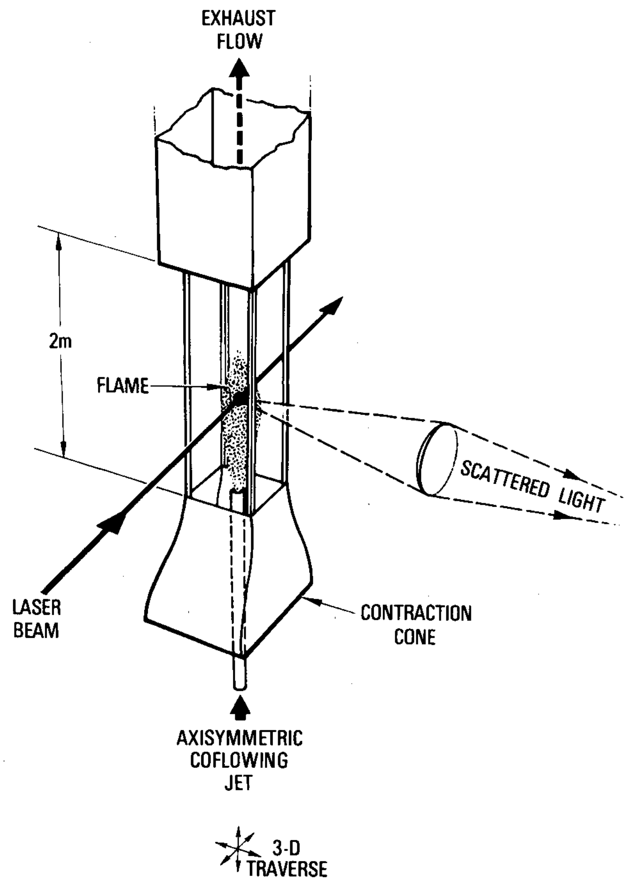

Fig. 1 Experimental test facility.

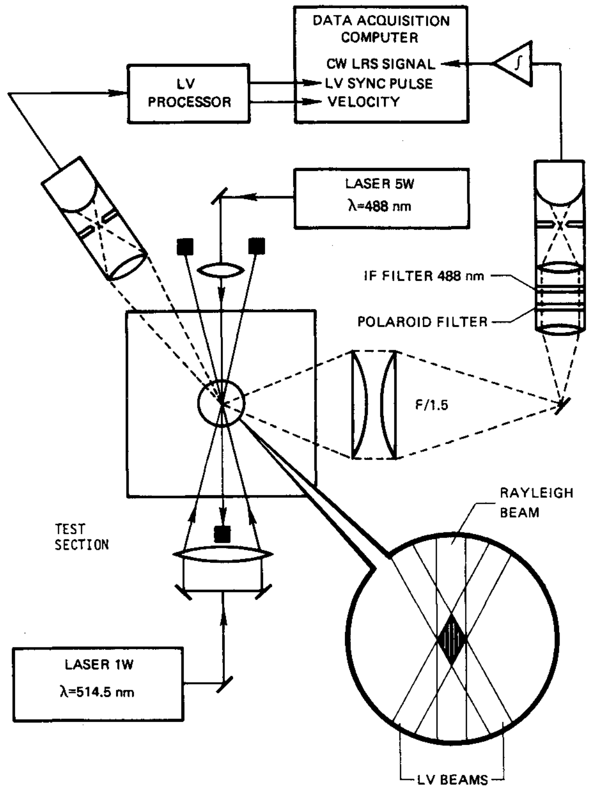

Fig. 2 Schematic of combined Rayleigh scattering-laser velocimeter apparatus.

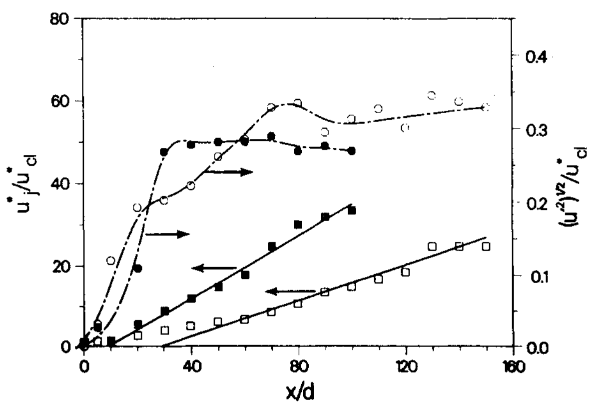

Fig. 3 Normalized mean excess axial velocity and axial velocity fluctuations measured along centerline. Solid symbols indicate measurements with no flame present; open symbols indicate measurements in a reacting jet.

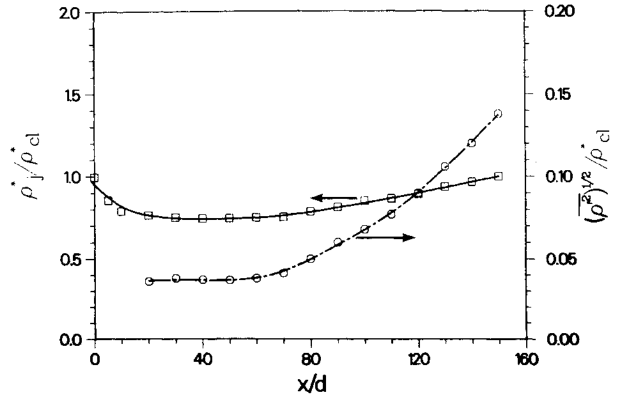

Fig. 4 Normalized mean excess density and density fluctuations measured along the centerline in a turbulent nonpremixed flame.

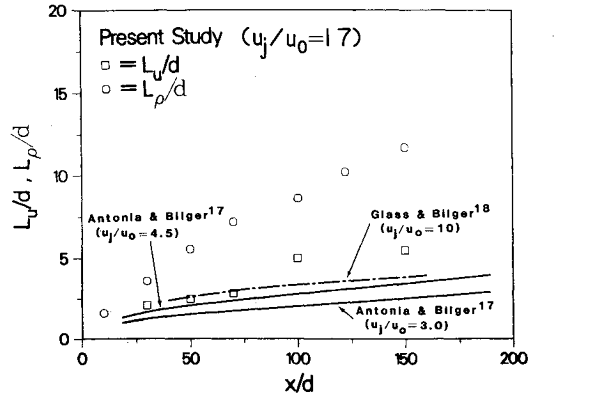

Fig. 5 Variation of velocity and density half-radius with axial distance.

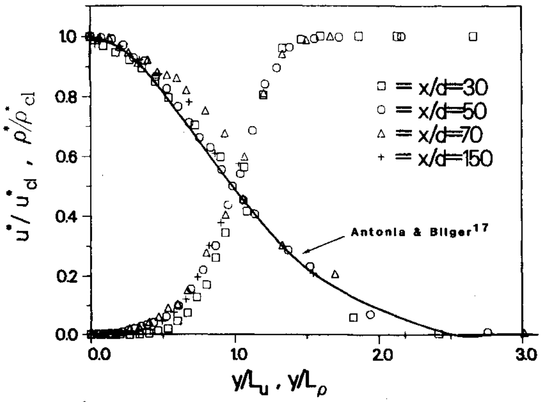

Fig. 6 Radial profiles of normalized mean axial excess velocity and excess density in a turbulent nonpremixed flame.

form u_j^*/u_{cl}^* where u_{cl}^* is the centerline excess velocity (excess velocity is defined as the difference between the local velocity and the coflowing air velocity) and u_j^* is the difference between the jet exit velocity and the coflowing air velocity. The present results for a nonreacting jet show that u_j^*/u_{cl}^* varies linearly with x/d for distances greater than 20 diameters from the nozzle exit. The axial velocity fluctuations increase rapidly downstream of the nozzle exit to a value of approximately 26%, and for x/d greater than 40 they remain nearly constant. In the reacting jet case, a linear dependence of u_j^*/u_{cl}^* on distance downstream is also observed but does not occur until approximately 60 diameters downstream. The corresponding shift in the hypothetical origin is from approximately 10 diameters downstream of the jet exit for the nonreacting jet to 30 diameters downstream for the reacting jet. The initial increase in velocity fluctuations downstream of the jet exit is suppressed in the region of the reaction zone (which extends approximately 50 diameters downstream of the jet exit), but the fluctuations increase to a higher value downstream of the reaction zone. Since the coflowing air velocity was maintained constant for both the nonreacting and reacting data, the observed shift in hypothetical origin and the suppression of velocity fluctuations in the reaction zone are attributable to the effects of combustion heat release. Direct comparisons with results in the literature are difficult due to the wide range of flow conditions studied. However, some general comparisons can be made. An x^{-1} dependence in centerline velocity decay has also been observed by Wygnanski and Fielder in a self-preserving jet into still air,[15] and by Antonia and Bilger in nonreacting isothermal jets[16] and heated jets[17] into coflowing air. The maximum axial velocity fluctuation level of 26% for the nonreacting jet is slightly less than the 28% value obtained in isothermal jets into still air[15] and the 30% value for a heated jet with coflowing air ($u_j/u_0 = 4.5$),[17] while the 34% value compares well with the value of 35% obtained by Glass and Bilger[18] in a turbulent hydrogen-air diffusion flame ($u_j/u_0 = 10$).

Centerline variations in the mean and fluctuating densities are shown in Fig. 4 for the reacting jet. The mean density results are presented as the inverse of the normalized excess centerline density where the excess centerline density ρ_{cl}^* is the difference between the coflowing air density ρ_0 and the local centerline density ρ_{cl}. This is normalized by the difference between the air density and the jet exit density ($\rho_j/\rho_0 = 0.36$). The effects of heat release due to combustion are shown by the decrease in density over the flame length which extends approximately 50 diameters downstream from the jet exit. For axial distances greater than 50 diameters the density increases due to mixing with surrounding air. The normalized density fluctuations remain at a relatively low value until approximately 50 diameters downstream before increasing due to mixing with surrounding air. Although no direct measurements of gas density in nonreacting heated jets are available in the literature, the x^{-1} dependence of excess centerline temperature measured in nonreacting heated jets would indicate a nearly linear increase in centerline excess density. Thus the initial decrease in excess density over the initial 50 diameters from the jet exit is due to the effects of reaction.

The variation in velocity half-radius L_u with axial distance is shown in Fig. 5. L_u is defined as the radial location at which the excess velocity is equal to one half of the centerline excess velocity. Shown for comparison are results for an isothermal jet with coflowing air ($u_j/u_0 = 3.0$ and 4.5),[17] and results for a hydrogen-air diffusion flame ($u_j/u_0 = 10$).[18] The trend of increasing half-radius with both downstream distance and increasing u_j/u_0 is consistent with the trends analytically predicted by Steward and Guruz[19] for nonreacting jets. The departure from a linear growth rate observed in isothermal jets into still air[15] is due to the effects of the coflowing airstream. Also shown in Fig. 5 is the density half-radius L_ρ. The density half-radius L_ρ increases linearly with axial distance for x/d greater than 50. The present results give a value of 0.49 for the ratio L_u/L_ρ. This compares with a value of 0.825 found by Steward and Guruz[19] for a nonreacting heated jet. The low values of L_u/L_ρ in reacting flows are consistent with radial expansion of low-density combustion gases due to heat release in the combustion region.

Radial variations in the mean axial velocity are shown in Fig. 6. The radial distance y from the centerline is normalized by the corresponding half-radius. The velocity results are presented as excess velocity u^* and are normalized by the

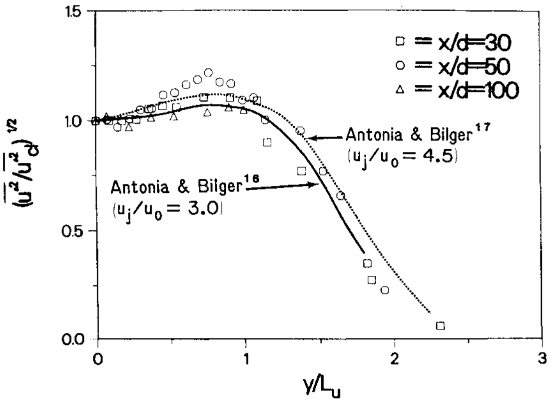

Fig. 7 Radial profiles of normalized axial turbulence intensity in a turbulent nonpremixed flame.

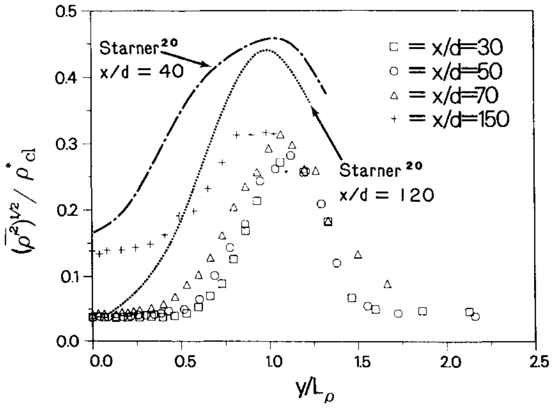

Fig. 8 Radial profiles of normalized gas density fluctuations in a turbulent nonpremixed flame.

centerline excess velocity u^*_{cl}. The velocity data show good agreement with results for a nonreacting heated jet in a coflowing airstream[17] (indicated by the solid line) and with results for a turbulent hydrogen-air diffusion flame[18] (not shown). Also shown in Fig. 6 is the excess density, defined as the difference between the coflowing air density ρ_0 and the local gas density $\bar{\rho}$, and normalized by the centerline excess density.

The axial velocity fluctuations (Fig. 7) are normalized by the axial velocity fluctuations at the centerline. Also shown for comparison are the isothermal[16] and heated[17] jet data of Antonia and Bilger. The present results at both $x/d = 30$ and 100 fall within the range for the nonreacting jets, while results at $x/d = 50$ exhibit a somewhat higher peak which is shifted closer to the centerline. Similar results were obtained in a hydrogen-air diffusion flame by Glass and Bilger,[18] who noted a collapse of the axial velocity data into two distinct regions: a far upstream and far downstream region (corresponding to $x/d = 40$ and 160, respectively) where the data fell within the results for isothermal and heated jets, and a midrange region downstream of the flame tip ($x/d = 80$ and 120) where a higher peak intensity located closer to the centerline was observed.

Radial variations in the density fluctuations (normalized by the centerline excess density) are shown in Fig. 8. The maximum density fluctuations are found to occur in the mixing region between the airstream and the fuel jet and then decrease to relatively low values in both the airstream and near the centerline. At $x/d = 30$ and 50 the density fluctuations reach a maximum of approximately 0.27 at $y/L_\rho = 1.1$. At $x/d = 70$ some divergence of the profiles occurs although the centerline values compare well with the upstream results. At $x/d = 150$ the maximum fluctuation level has increased to 0.32 and the location of the peak has shifted toward the centerline. The data of Starner[20] (also shown) for a hydrogen-air diffusion flame were obtained using Mie scattering from the seeded jet fluid to determine the gas density. Starner's data indicate considerably higher maximum and centerline values than obtained in the present study. Our observations are consistent with those of Drake et al.,[21] who argue that the Mie scattering technique used by Starner overestimates the fluctuations in mixture fraction due to the low diffusivity of the Mie scattering seed particles introduced into the fuel stream.

Probability distributions for the axial velocity are shown in Fig. 9 for $x/d = 50$. The distributions are "Gaussian like" with some skewness apparent in regions of higher radial velocity gradients and near the centerline. The general behavior is that of a unimodal distribution shifting to a higher average velocity as the centerline is approached. These results are in contrast to the probability distributions for the normalized density presented in Ref. 3. In the outer airflow the density distribution was found to be characterized by a narrow spike centered at the freestream air density. Moving radially inward from the airstream toward the centerline, a continuous transition was observed from a mixture of high-density air and lower-density combustion products to a gradually narrowing peak with a maximum probability closely approaching the theoretical minimum density for an adiabatically reacted equilibrium stoichiometric mixture ($\bar{\rho}/\rho_0 = 0.138$). In the mixing region where fuel and product gases mix with entrained air, bimodal distributions characterized by the sum of an intermittency spike corresponding to coflowing air and a wider continuous distribution corresponding to reacted and partially reacted gases were found. Bimodal distributions have also been observed by Dibble and Hollenbach[5] for gas temperature and Drake et al.[21,22] for mixture fraction in analogous turbulent diffusion flames. The above results are consistent with a mixing process for nonpremixed turbulent flames in which the density of the entrained gas is preserved for a time longer than the velocity during large-scale vortex motion.

Intermittency

Intermittency is defined as the probability that a given flow is turbulent at a given point and time. The intermittency γ was obtained by considering only the gas density measurements. In the present study, γ is defined as the fraction of time that the gas density is less than the freestream air density. For densities above a certain threshold value γ is set equal to 0 (corresponding to unmixed air), and for densities less than the threshold value the fluid is considered as lower-density mixed fluid consisting of heated air, combustion products, and jet fluid ($\gamma = 1$). The method of Bilger et al.[23] was used to determine a threshold density corresponding to freestream air. In this approach, the finite width of the density distribution corresponding to freestream air (and due to electronic noise) is found to be closely fitted by a Gaussian, and the area under the resulting curve provides a good estimate of $(1-\gamma)$. The normalized threshold density $\bar{\rho}/\rho_0$ determined using this method was 0.94.

In Fig. 10, the resulting intermittency profiles are shown on a probability scale as a function of normalized radial distance. Profiles are shown for $x/d = 30$, 50, and 70 with the solid line indicating the best fit to the data. The probability density of the interface position between the unmixed air and mixed fluid is nearly Gaussian over the range of axial positions shown. The results for a heated nonreacting jet,[11] indicated by the dotted lines for $u_j/u_0 = 1.9$ and 6.6, show that although the interface is again Gaussian, the mean position of the interface ($\gamma = 0.5$) shifts toward the centerline with respect to y/L_ρ as u_j/u_0 is increased. This shift was attributed to the fact that the turbulence structure is not self preserving and that the turbulence length scale, as given by the mean position of the interface, changes with respect to the length scale of the mean flow, as given by L_ρ.

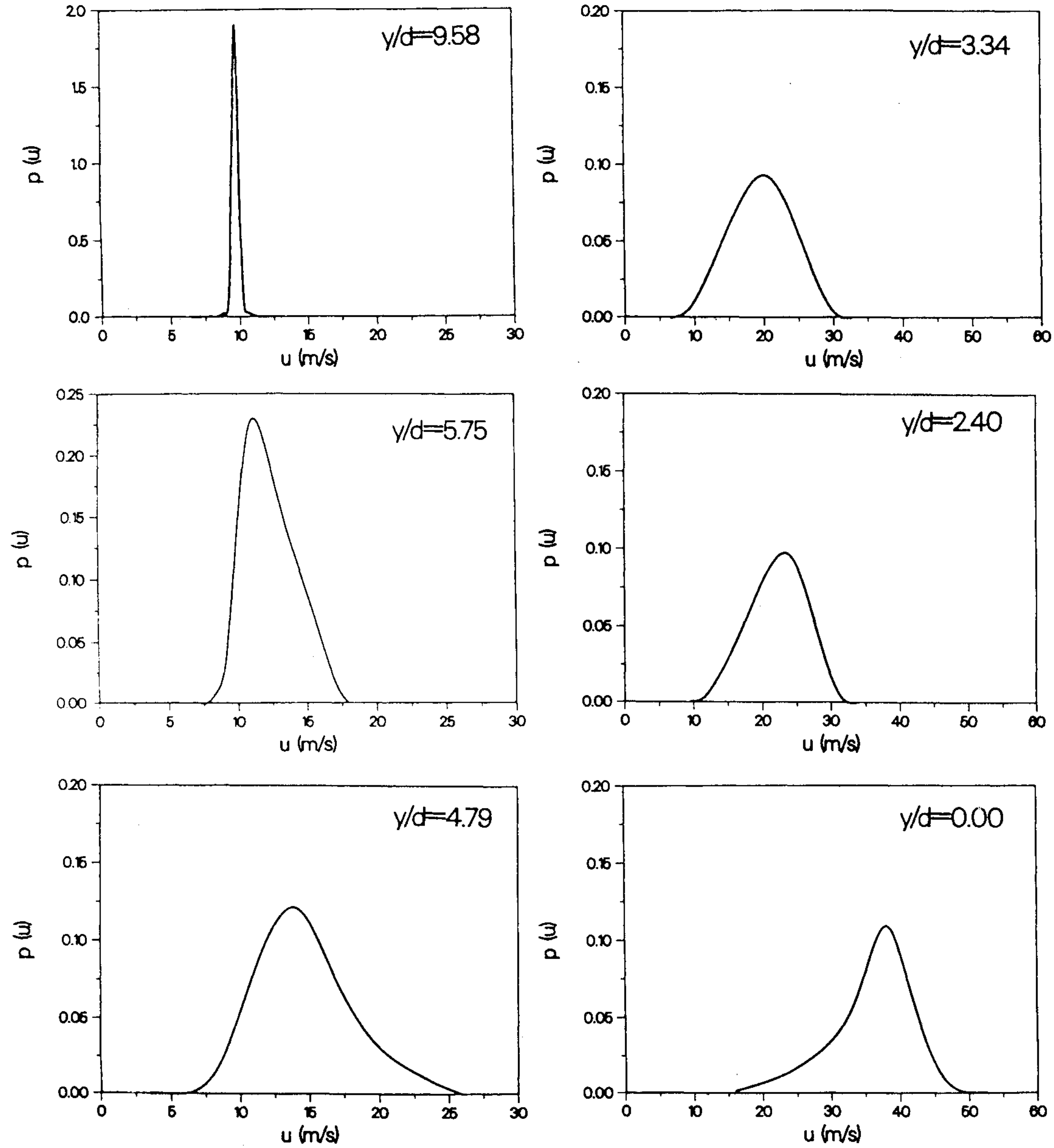

Fig. 9 Probability density distributions of axial velocity at an axial location of $x/d = 50$ in a turbulent nonpremixed flame.

At all axial locations in the present study a region exists near the centerline in which the intermittency is unity, indicating that turbulent mixing is insufficient to transport air into the central region. Only in a relatively well-defined mixing region for which γ is between 0 and 1 are both unmixed air and lower-density fuel and combustion products present. In contrast to these results, Starner and Bilger[24] noted significant intermittency on the flame centerline as far upstream as 50 jet nozzle diameters in a turbulent hydrogen-air diffusion flame. The reason for these differences is not certain at this time.

Kent and Bilger[25] have proposed that the Favre-averaged intermittency γ is related to the mixture fraction fluctuation intensity through an empirical correlation of the form $\gamma = (K+1)/(\xi''^2/\xi^2 + 1)$ where ξ and ξ''^2 are the Favre-averaged mean and variance in the mixture fraction, respectively, and K is an empirical constant. Here ξ is defined as the concentration of atoms originating from the jet nozzle fluid divided by the total atom concentration. Shown in Fig. 11 is the correlation between γ and the mixture fraction fluctuation intensity based on the results of Becker et al.[26] for a round jet into still air and Antonia et al.[11] for a heated round jet in a coflowing stream. The solid line ($K = 0.25$) indicates the assumed fit to the data used by Kent and Bilger in their calculations.

The density measurements obtained in the present study can be uniquely related to the mixture fraction ξ if it is assumed that 1) the rate of chemical reaction is fast relative to the rate of mixing, 2) that mixing is dominated by turbulence and, hence, all species and enthalpy are transported at the same rate (unity Lewis number), and 3) that the mixture fraction is less than the stoichiometric value.[27] Assumptions 1 and 2 have been shown experimentally by Dibble et al.[28] to be valid in the intermittent mixing region in the present system. Using the above assumptions, the Favre-averaged mean and fluctuating mixture fractions were calculated from the Rayleigh scattering data and the resulting correlation is shown in Fig. 12. Good agreement is obtained with the results of Becker et al.[26] for a jet in still air and the data yield a value of 0.46 for K.

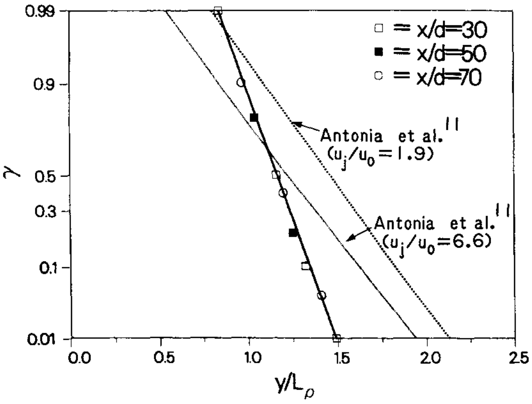

Fig. 10 Intermittency factor γ as a function of normalized radial distance.

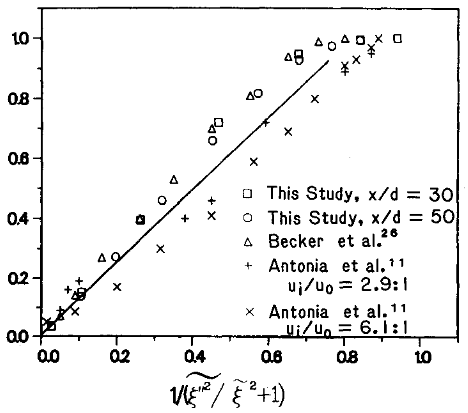

Fig. 11 Correlation between Favre-averaged intermittency and mixture fraction fluctuation intensity. □, ○ this study: □, $x/D=30$; ○, $x/D=50$; △ Becker et al.,[26] isothermal jet in still air; +, × Antonia et al.,[11] heated jet in coflowing stream: +, $u_j/u_0=1.9:1$; ×, $u_j/u_0=6.6:1$; solid line, $\tilde{K}=0.25$.

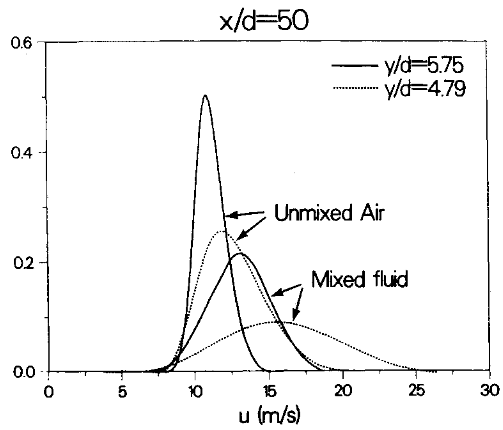

Fig. 12 Conditional probability density distributions of axial velocity for a turbulent nonpremixed flame at an axial location of $x/D=50$.

Conditional Sampling

Conditionally sampled zone-averaged results are presented in Figs. 12-14. The threshold criterion previously used for the determination of intermittency was used to identify the passage of unmixed air and lower-density mixed fluid. The conditionally sampled results were found to be insensitive to variations in threshold value over the range of expected uncertainty. Mean and fluctuating velocities and densities and the length scales corresponding to the passage time of these zones then were determined. Conditionally sampled probability density distributions of the axial velocity are shown in Fig. 12 for $y/d=5.75$ and 4.79. The distributions for the unmixed air are represented by relatively narrow distributions at both radial locations. Closer to the centerline ($y/d=4.79$) the distribution is broader and the peak value has shifted to a higher velocity. For the mixed fluid the distributions have broadened considerably at $y/d=4.79$ due to the higher turbulence levels existing nearer the centerline from which the mixed fluid originates.

The difference between zone-averaged mean and fluctuating axial velocities for various values of γ are shown in Table 1. Here the subscripts u and m denote values for the unmixed air and the mixed fluid, respectively. Presented for comparison are results for a heated jet[11] and for an H_2-air diffusion flame.[20] In all cases the trend with intermittency is consistent, i.e., the zone-averaged mean velocity difference decreases with decreasing intermittency and the zone-averaged turbulence intensity difference increases with decreasing intermittency. The zone-averaged mean velocity differences obtained in the present study agree well with the reacting jet data of Starner,[20] while values for the heated jet are 40-60% higher. Some inconsistency is apparent in the zone-averaged velocity fluctuations in that the results of the present study fall below that of the heated jet, while the results of Starner are considerably higher. This inconsistency has been attributed by Starner[20] to the difference in diffusivity between hydrogen and the seed particles which could cause a significant underestimation of the intermittency. The

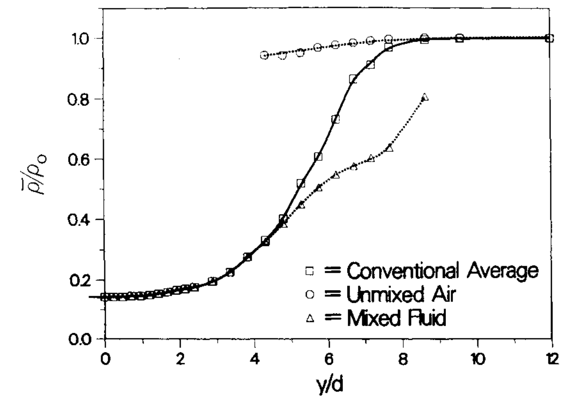

Fig. 13 Radial profiles of conventional and conditional normalized mean density for a turbulent nonpremixed flame at an axial location of $x/D=50$. □, conventionally averaged density; △, conditionally averaged density in mixed fluid; ○, conditionally averaged density in unmixed air.

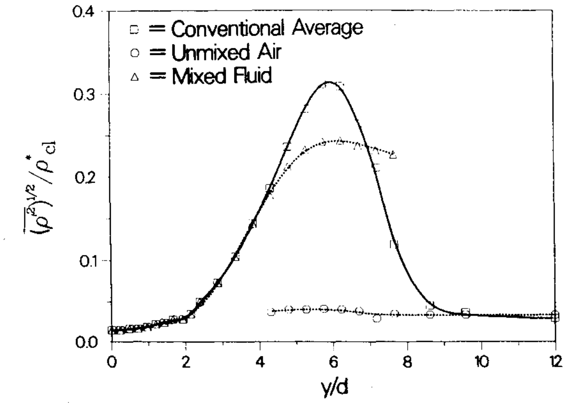

Fig. 14 Radial profiles of conventional and conditional gas density fluctuations for turbulent nonpremixed flame at an axial location of $x/D=50$. □, conventionally averaged density fluctuations; △, conditionally averaged density fluctuations in mixed fluid; ○, conditionally averaged density fluctuations in unmixed air.

Table 1 Difference between turbulent and nonturbulent zone velocity

	$\left(\frac{\bar{u}_u - \bar{u}_n}{u^*_{cl}}\right)$			$\frac{(\overline{u'^2})^{1/2}_u - (\overline{u'^2})^{1/2}_n}{(\overline{u'^2})^{1/2}_{cl}}$		
γ	This study $x/d=50$	Heated jet (Ref. 11)	H_2-air diffusion flame (Ref. 20)	This study $x/d=50$	Heated jet (Ref. 11)	H_2-air diffusion flame (Ref. 20)
0.75	0.09	0.15	0.11	0.07	0.10	0.23
0.50	0.05	0.11	0.04	0.10	0.22	0.49
0.25	0.02	0.06	—	0.17	0.26	—

Table 2 Turbulent and nonturbulent fluid length scales

			Nonturbulent fluid		Turbulent fluid	
Author	y/d	γ	ℓ	σ_ℓ	ℓ	σ_ℓ
This study	6.71	0.36	0.67	0.64	0.32	0.24
	6.23	0.55	0.38	0.37	0.47	0.42
Chevray and Tutu[9]	5.75	0.76	0.25	0.22	0.83	0.81
	—	0.28	0.54	0.69	0.21	0.22
	—	0.58	0.28	0.34	0.39	0.45

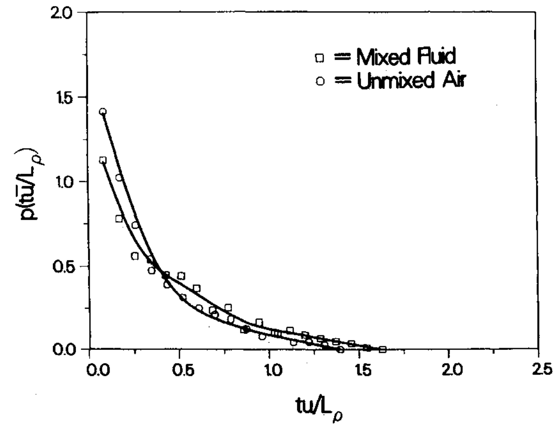

Fig. 15 Probability density distributions of the length of mixed fluid and unmixed air durations at a radial location of $y/D=6.23$.

values obtained by Starner should thus be viewed as an upper limit and the actual values are probably somewhat less.

Radial profiles of the conditionally averaged mean and fluctuating density are compared with the conventionally averaged profiles in Figs. 13 and 14, respectively. In both figures the mean and fluctuating densities are normalized by conventionally averaged quantities. The mean mixed fluid density is considerably lower than the conventionally averaged value across the mixing zone, with the difference increasing toward the outer edge. The unmixed air density remains nearly constant across the mixing zone and indicates excursions of coflowing air well into the mixing zone. Conditionally averaged density fluctuations in the mixed fluid increase less rapidly in the inner region of the jet than the conventionally averaged values but are higher in the outer part of the flow. The small variations in the mean and fluctuating unmixed air density across the mixing zone toward the centerline are a consequence of the fitting procedure used to determine the noise contribution to the air distribution. Under conditions where the relative contribution of the mixed fluid to the total probability distribution is greater, the Gaussian curve fitting process and subsequent area determination become less accurate. The higher conventionally averaged fluctuations across most of the mixing region emphasize the three sources which contribute to the conventionally averaged value, i.e., 1) fluctuations in the unmixed air, 2) fluctuations in the mixed fluid, and 3) fluctuations that result from the passage of the unmixed air and mixed fluid parcels past the measurement volume. Qualitatively similar results were obtained for the conditionally averaged mean and fluctuating temperature distributions in a nonreacting turbulent heated jet.[11] Based upon these results it might be expected that a model for turbulent flows which accounts for the difference in turbulent and nonturbulent zone properties has a much firmer physical basis and is potentially more accurate for reacting flows where the chemical reaction rates are strongly dependent on the local flow properties such as temperature.

Probability density distributions of the length scales for the unmixed air and the mixed fluid parcels at $x/d=50$ are shown in Fig. 15. These results were obtained from the Rayleigh scattering data by determining the time durations during which the fluid density was above (corresponding to unmixed air) and below (mixed fluid) the threshold level as defined previously. Measurements of time durations and length scales shorter than those shown were limited by the maximum data rate of the Rayleigh system (5.5 kHz). The time durations have been nondimensionalized by u/L_ρ (u is the local mean axial velocity and L_ρ the previously defined density half-radius at $x/d=50$) to obtain an estimate of the length scales involved. Results are shown for $y/d=6.23$, corresponding to a value for the intermittency of 0.55. In general, moving radially inward toward the inner part of the mixing region, the duration lengths for air become shorter and the mixed fluid duration lengths increase. Conversely, moving radially outward, the unmixed air duration lengths increase and the mixed fluid lengths become shorter. A comparison of the mean length scale ℓ and the standard deviation σ_ℓ with those obtained by Chevray and Tutu[9] at $x/d=15$ in a heated round jet flowing into still air for various values of γ is shown in Table 2. Although the locations and flow conditions differ considerably in the two studies, the nondimensionalized length scales and standard deviations for a given intermittency show good agreement. The general shapes of the probability density distributions also agree well and indicate that similar mixing processes dominate both flows.

Joint Probability Density Distributions

Joint probability density distributions of axial velocity and normalized density at $x/d=50$ are shown in Fig. 16. The distributions were calculated from between 1000 and 2000 velocity-density pairs at each spatial location using 20 velocity and 20 density bins spaced over the 3σ limits of the velocity and density data. Due to the limited number of data points at each location, it should be noted that the joint probability distributions shown provide only a qualitative description of the flowfield. The distribution at $y/d=5.75$ corresponds to an intermittency of 0.75 (see Fig. 11) and is characterized by a relatively narrow velocity distribution, particularly at higher densities. At lower densities, an increase in the turbulent fluctuation level is indicated by some skewing in the velocity distribution toward higher velocities. Contributions to the probability density distribution from

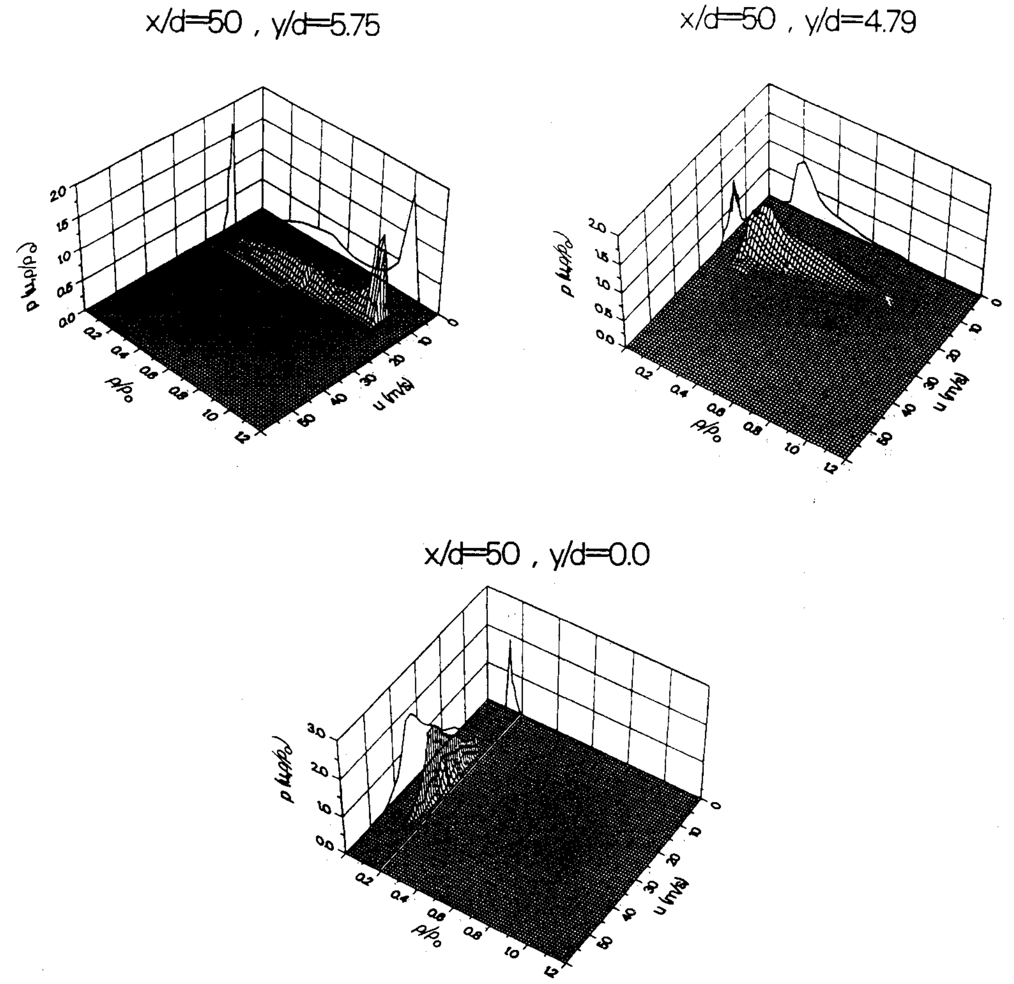

Fig. 16 Joint probability density distributions of axial velocity and density in a turbulent nonpremixed flame at an axial location of $x/D = 50$ in a turbulent nonpremixed flame.

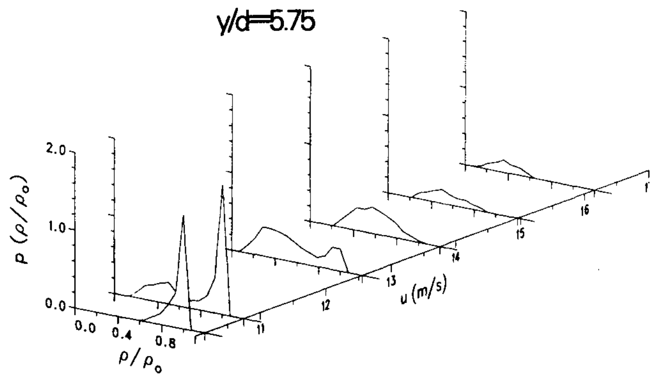

Fig. 17 Joint probability density distributions of gas density and axial velocity for a turbulent nonpremixed flame at a radial location of $y/D = 5.75$ and an axial location of $x/D = 50$.

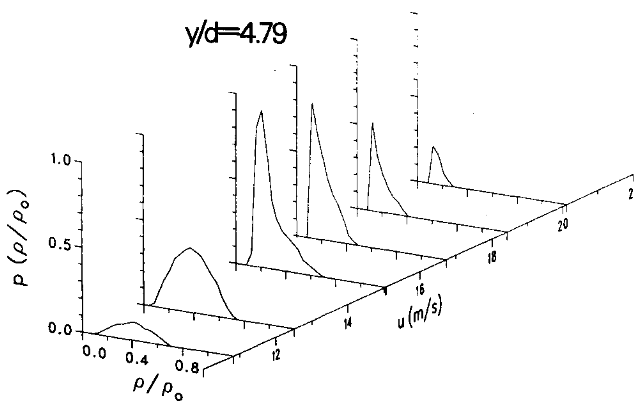

Fig. 18 Joint probability density distributions of gas density and axial velocity for a turbulent nonpremixed flame at a radial location of $y/D = 4.79$ and an axial location of $x/D = 50$.

both the air and the fuel and the product gas mixture are apparent. At $y/d = 4.79$, the primary contribution to the joint probability distribution is due to low-density product gases with very little high-density air present. The velocity distribution has broadened considerably, particularly for the lower-density gases, and is slightly skewed toward higher velocities. At the centerline the gas density is narrowly distributed about the stoichiometric equilibrium density and the peak in the velocity distribution has shifted to higher velocities.

The probability density distributions for gas density at various velocities are shown in Figs. 17-19. At $y/d = 5.75$, the distributions at low velocities are dominated by a relatively narrow spike corresponding to the coflowing airstream density and are skewed toward lower densities. With increasing velocity the contribution of lower-density fuel and product gas mixture increases and the density distributions become bimodal. For mean velocities greater than approximately 14 m/s, no evidence of air is present and the maximum in the distribution shifts to lower densities with increasing velocity. At $y/d = 4.79$, the density distributions narrow considerably with increasing velocity and the maximum approaches the stoichiometric equilibrium gas density. At the centerline, the distribution consists of a narrow spike with a width independent of velocity.

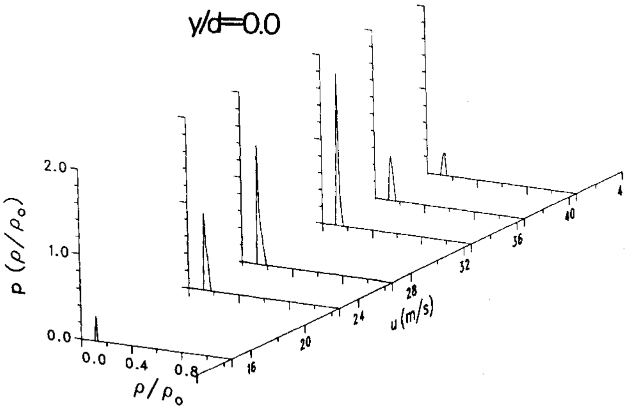

Fig. 19 Joint probability density distributions of gas density and axial velocity for a turbulent nonpremixed flame at a radial location of $y/D=0$ and an axial location of $x/D=50$.

Summary

The effect of combustion heat release on the mean and fluctuating flowfields varies considerably. The mean axial velocity profiles are similar to those found in nonreacting jets, while suppression of the centerline velocity fluctuations is observed in the heat release zone of the reacting jet. A region is also observed in the mixing region near the flame tip where velocity fluctuations are higher than those found in nonreacting jets. A decrease in gas density occurs along the centerline due to heat release in the reaction zone which is not observed in nonreacting jets.

The conventionally averaged intermittency profiles are closely Gaussian and exhibit good similarity for axial positions up to $x/d=70$. Favre-averaged intermittency correlates well with the mixture fraction fluctuation intensity and agrees with results in isothermal jets.

Conditionally sampled zone-averaged velocities are similar to nonreacting jet data. However, differences between zone-averaged mean and fluctuating velocities are 30-50% lower than those found in nonreacting jets. Mixed fluid densities are considerably lower than conventionally averaged densities in the outer part of the flow, while nonturbulent gas densities remain close to that of the coflowing air and indicate excursions of entrained air well into the mixing zone.

The joint probability distributions for velocity and gas density consist of contributions from various mixtures of fuel and reacted gases, and entrained air and reacted gases across most of the intermittent mixing zone. At low velocities the probability distributions of gas density are dominated by a relatively narrow spike corresponding to coflowing air. With increasing velocity, the contribution of lower-density fuel and product gas mixture increases and the gas density distributions become bimodal. At the highest velocities no evidence of air is present and the maximum in the distribution shifts to lower densities.

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