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Simultaneous Velocity and Temperature Measurements in a Premixed Dump Combustor

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Experimental measurements of velocity and temperature were made in a low-speed turbulent flowfield following an axisymmetric sudden expansion with and without combustion. The combustion case considered here used a lean, completely premixed propane-air mixture whose flame was stabilized by the recirculation zone present in this flow. Simultaneous two-component laser velocimeter measurements were made giving the mean axial and radial velocities and the Reynolds stresses throughout the flowfield. In addition, simultaneous time-resolved temperature measurements were made in the reacting flow using a fast response thermocouple. Velocity-temperature correlations were formed from the velocity and temperature measurements. The reacting flow case was found to have a shorter and stronger recirculation zone, and the turbulence intensity level was found to be suppressed over most of the flowfield when compared with the cold flow case.

Nomenclature

H = step height, 38.1 mm
$\dot{m}_f$ = fuel mass flow rate, kg/s
R_1 = inlet radius of sudden expansion, 38.1 mm
R_2 = outlet radius of sudden expansion, 76.2 mm
r = radial coordinate direction, $r = 0$ at centerline
T = instantaneous temperature, $T = \bar{T} + t'$, K
$\bar{T}$ = time-averaged mean temperature, K
T_0 = inlet temperature, 298 K
t' = fluctuating temperature, K
U_0 = inlet mean axial velocity, 22 m/s
$\bar{U}$ = time-averaged mean axial velocity, m/s
u = instantaneous axial velocity, $u = \bar{U} + u'$, m/s
u' = fluctuating axial velocity, m/s
$\overline{u'u'}$ = time-averaged axial turbulent normal stress, m^2/s^2
$\overline{u't'}$ = time-averaged axial velocity-temperature correlation, m-K/s
$\overline{u'v'}$ = time-averaged turbulent shear stress, m^2/s^2
$\bar{V}$ = time-averaged mean radial velocity, positive toward wall, m/s
v = instantaneous radial velocity, $v = \bar{V} + v'$, m/s
v' = fluctuating radial velocity, m/s
$\overline{v'v'}$ = time-averaged radial turbulent normal stress, m^2/s^2
x = axial coordinate direction
y = radial coordinate direction, $y = 0$ at centerline
μ = dynamic viscosity, kg/m-s
ρ = fluid density, kg/m^3
ρ_0 = inlet fluid density, kg/m^3
Φ = equivalence ratio

Introduction

THE effect of combustion on turbulence structure[1,2] and the effect of turbulence on combustion are of great interest to the combustion engineer. Much of the recent experimental work in turbulent flows has been carried out to obtain data for comparison with numerical prediction codes that model turbulence, combustion, and heat transfer.[3] Velocity, temperature, and species concentration measurements in reacting flows have been made in various geometries including coaxial jets, diffusion flame jets, bluff body flameholders in ducts, industrial furnaces, and two-dimensional rearward facing steps. High-turbulence intensities and well-defined recirculation zones are characteristic of these flows. Comparisons of mean velocities, turbulence intensities, temperature distributions, and recirculation zone sizes have been made with and without combustion. Although substantial literature exists, there is still an incomplete understanding of the turbulence-combustion interaction process. Turbulent combustion is highly nonhomogeneous, involving large fluctuations in temperature, composition, density, and velocity. There also can be a strong interaction between the aerodynamic and heat release mechanisms. The development of accurate models is dependent upon reliable experimental information concerning a large number of flow quantities. The extreme difficulty in making even a single reliable measurement in a confined turbulent reacting flow has made, and will continue to make, this a difficult task.

With these considerations in mind, the present study was designed to provide an accurate experimental mapping of the flowfield following an axisymmetric sudden expansion (dump combustor) with and without combustion. A lean ($\Phi = 0.5$), completely premixed propane-air mixture was used for the reacting flow part of this study. The combination of an axisymmetric geometry (i.e., two-dimensional in the mean flow) and a completely premixed inlet condition was chosen to provide benchmark data which can be used to test model predictions. Flowfield properties of interest included axial and radial mean velocities and turbulent normal stresses, as well as Reynolds stresses. In addition to these measurements, mean and fluctuating temperatures and temperature-velocity correlations were obtained for the reacting flow. Measurements of these quantities, and in particular the radial velocity, are virtually nonexistent in cylindrical-geometry confined flows due to optical access problems.

Experimental Apparatus

LDV System

A two-color, two-component laser Doppler velocimeter (LDV) system operating in forward scatter was used to make

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simultaneous measurements of the axial u and radial v velocity components. This system has been described previously by Gould et al.[4,5] The green and blue fringes are oriented with respect to the test section such that direct measurements of the axial and radial velocity components are made. A specially designed correction lens[4,6] was fabricated and used in this study to ensure that the two orthogonal probe volumes overlap at all measurement locations in the cylindrical tube test section. Measurements to a radial location of $r = 63.5$ mm were possible with this system. The LDV system includes Bragg cell modulators in the four beam paths to allow a net frequency shift of 5 MHz in both the green and blue beams. This permits an unambiguous measurement of negative velocities and also eliminates incomplete signal bias. Probe volume diameters of the green and blue beams are 250 and 150 μm, respectively. The probe volume lengths are approximately 2 mm.

Thermocouple Design

Temperature measurements in the reacting flow were made with fine uncoated Pt/Pt-13% Rh (R type) thermocouples. The thermocouple probe consists of a two-hole ceramic insulator containing two 0.25-mm-diam thermocouple posts. A 25-μm-diam wire is butt-welded to form the thermocouple junction suspended midway between the posts which are separated by approximately 3.2 mm. The thermocouple is mounted on a rigid arm fixed to the LDV system, all of which is mounted on a 3-axis mill table driven by servo-controlled motors. Probe volume locations can be positioned to an accuracy of ± 0.1 mm with this system. Once the thermocouple junction is positioned near the LDV probe volume (in-line with and ≈ 250 μm downstream of the probe volume for this study), it moves with the probe volume. Holes slightly larger than the ceramic probe diameter were drilled through the top wall of the quartz test section at each axial measurement plane. The holes not occupied by the thermocouple probe were plugged so as not to change the flowfield boundary conditions. The thermocouple orientation is shown in Fig. 1. Note also the correction lenses positioned between the LDV optics and the cylindrical tube.

The -3-db cutoff frequency of the 25-μm-diam thermocouples used in this study was found to be approximately 20 Hz. In order to extend the frequency response of the thermocouple, electronic compensation for the thermal inertia, similar to that described by Lockwood et al.,[7] was employed. The compensation network was designed using low-noise, precision analog electronic components to give the thermocouple a flat frequency response up to approximately 1000 Hz. Proper compensation requires knowledge of the thermocouple time constant, which varies with flow condition. Time constants were determined, using a modification of the technique described by Yule et al.,[8] at each measurement location in the flow prior to making instantaneous temperature measurements. This was accomplished by electrically heating the thermocouple using a square wave voltage signal and then recording the thermocouple cooling time history. Since the flow is turbulent, 20 cooling histories were averaged to give the average thermocouple time constant at each measurement location. A complete description of the compensation network circuit design, theory, and validation (using both electrical resistor-capacitor circuits as model thermocouples and placing the thermocouple in a pulsed heated jet) is given by Gould et al.[4] All temperature measurements were corrected for radiation loss by assuming the normal emissivity for platinum was 0.25 and the walls were cool using the expression: $T_{corr} = T_{meas} + \varepsilon\sigma T^4_{meas}/h$. The convection heat transfer coefficient h used in the previous expression was estimated using lumped capacitance analysis on the thermocouple and the measured time constant $\tau = \rho C_p d/4h$. An extensive discussion of problems associated with making time-resolved temperature measurements in a reacting flow is given by Heitor et al.,[9] whereas discussions concerning the response of fine wire thermocouples to fluctuating temperatures are given by Bradley et al.[10] and Yoshida et al.[11]

Data Acquisition System

The data collection and processing system consists of two Thermal System Inc. (TSI) Model 1990 counter-type processors (one for each channel), a TSI Model 1998 master interface with coincidence timing electronics, and a PDP 11/40 minicomputer with DMA capability. The digitized thermocouple signal was also interfaced through the TSI 1998 master interface so that coincident velocity-temperature data could be obtained. The coincidence window was set to 10 μs throughout this study. With this system it is theoretically possible to acquire velocity data from individual Doppler burst signals at rates up to 100,000 samples/s. In practice, the rates are less due to seed density limits. The minicomputer and counter processors are also interfaced so that sampling can be controlled. This is accomplished with a PDP 11 hardware clock (KW11-P) controlling the data ready-inhibit handshaking signals.

Flow System

The flow system is illustrated in Fig. 2. It consists of a converging inlet nozzle with an exit diameter of 76.2 mm followed by a 152.4 mm i.d. downstream section giving an area expansion ratio of 4. This inlet was chosen to give a uniform inlet velocity profile. The test section was extruded from optical quality fused quartz and had a wall thickness of 3.2 mm. This test section allows measurements throughout the flowfield for x/H values ranging from 0.2 to 14 where $H = 38.1$ mm is the expansion step height. Heat shields and the thermocouple mounting arm limited reacting flow measurements to the range $x/H = 0.9$ to 13. The test section design is shown in Fig. 3.

Airflow was provided by a radial fan blower followed by a flow conditioning section consisting of honeycomb flow straighteners. Fuel (gaseous propane) was injected in the duct immediately following the blower through a multiport manifold (36-0.76-mm holes) to give a homogeneous fuel-air mixture at the entrance to the sudden expansion. The system was

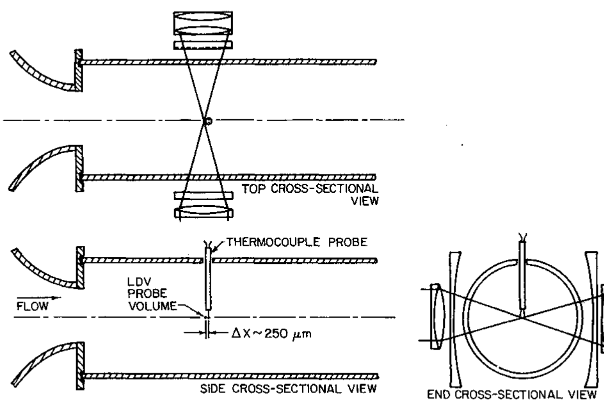

Fig. 1 Thermocouple orientation.

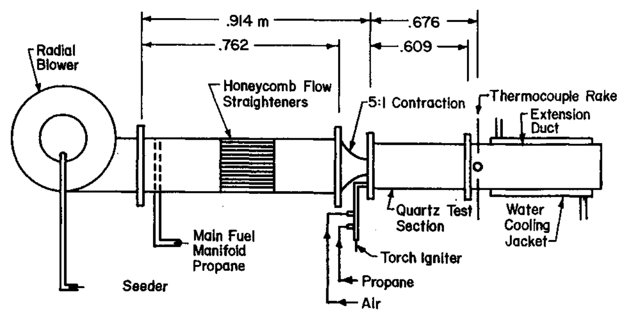

Fig. 2 Flow system.

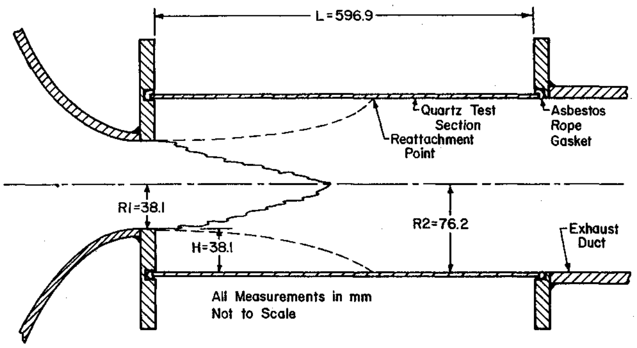

Fig. 3 Test section.

designed to operate at steady-state conditions using a lean, $\Phi = 0.5$, completely premixed propane-air mixture which keeps the peak wall temperature below the melting point of the quartz test section ($\approx$1700°C). The adiabatic flame temperature for a propane and air mixture having an equivalence ratio of 0.5, assuming ambient initial mixture temperatures, is approximately 1500 K. A torch mounted flush in the face of the sudden expansion was used to ignite the fuel and was extinguished once the flame was stabilized at the run operating condition.

The static pressure drop across the nozzle was used to monitor inlet flow conditions. In addition, the reacting flow run condition was controlled by monitoring the fuel flow rate using a calibrated rotometer and by monitoring the exit temperature using a thermocouple rake located downstream ($x/H = 17.7$) of the test section. The fuel flow rate was maintained constant to within $\pm 3\%$ and the exit temperature was maintained constant to within ± 15°C throughout this study. No combustion instabilities were observed during operation at the run condition used in this study.

Flow Seeders

Two different flow seeders were used, one for seeding the flow without combustion and one for seeding the flow with combustion. In both cases the seed was injected into the entrance of the radial blower. This insured a uniform seed density at the inlet to the sudden expansion. Seeding for cold flow measurements was supplied by two TSI model 3076 liquid atomizers each followed by a TSI model 3072 evaporation-condensation monodisperse aerosol generator. This produced seeding particles 1 μm or less in diameter using a 100% solution of dioctyl phthalate (DOP). Seed densities were sufficient to give data validation rates in excess of 30,000/s for both channels over most of the flowfield.

The reacting flowfield was seeded using titanium dioxide (TiO_2) particles generated by reacting dry titanium tetrachloride ($TiCl_4$) with moist air. The reaction chamber was designed using specifications provided by Nejad.[12] Craig et al.[13] measured the particle sizes generated by this device and found that they were fairly uniform and in the 0.2–1-μm-diam range. Data validation rates in excess of 50,000/s were obtained in the nonreacting flowfield with this seeder. However, the rates were much lower ($\approx$10,000/s for clean test section walls) in the reacting flowfield. Part of this reduction in seed concentration is expected due to the volumetric expansion of the gases ($\rho/\rho_0 = T_0/T$) across the flame front. A factor of three reduction in seed concentration due to fluid expansion is a reasonable estimate. Studies by Witze and Baritaud[14] and Moss[15] have found additional reductions in data rate when TiO_2 seed particles were used in high-temperature flames. They concluded that the scattering efficiency of the TiO_2 particles decreased severely in the combustion environment. A reduction in data validation rate may also result due to fluctuating refractive index gradients present in the reacting flowfield which could cause beam wandering and/or beam spreading. Both of these effects would reduce the signal-to-noise ratio, and therefore, the data validation rate. A study to investigate this possibility indicated that beam wandering (more specifically probe volume wandering) did not occur at the reacting flow conditions used in this study. It should also be mentioned that the TiO_2 seeder coated the test section walls rather quickly, and consequently, reduced the data validation rate even further.

Experimental Procedure

All flow conditions were maintained at near constant values throughout the testing procedure. The inlet centerline velocity U_0 was maintained at 22.0 $\pm$ 0.1 m/s. For the reacting flow case, the fuel flow rate $\dot{m}_f$ was maintained at 0.00410 $\pm$ 0.00013 kg/s, and fuel was injected well upstream of the sudden expansion to ensure that a fully premixed fuel-air mixture entered the test section. This fuel flow rate gives an overall fuel-air ratio of 0.032 and an overall Φ of 0.5. T_0 was maintained at 298 $\pm$ 5 K.

In all cases 6400 individual realizations were accumulated for each velocity component at each measurement point to form velocity histograms. In addition, 6400 temperature measurements were made at each point in the reacting flowfield. The coincidence timing logic on the TSI master interface ensured that simultaneous (within 10 μs) data were measured. In the cold flow case the simultaneous axial and radial velocities were sampled at 100 Hz using the equal interval sampling technique for velocity bias elimination proposed by Stevenson et al.[16] Briefly, this technique eliminates velocity bias by inhibiting the counter processors for a fixed time interval between samples, thus approximating equal time sampling. This method's effectiveness has been confirmed in subsequent studies by Gould et al.,[17] Durrett et al.,[18] Johnson et al.,[19] and Gould et al.[20] In the reacting flow case the simultaneous axial and radial velocities and temperature were sampled at 400 Hz. This sampling rate was chosen to reduce the total sampling time from 64 s for the cold flow case to approximately 16 s so that data at a reasonable number of measurement locations could be obtained before the quartz tube had to be cleaned.

In computing statistical parameters any individual measurement deviating more than 3σ from the mean was discarded as noise, and revised statistics were calculated. Typically, less than 50 data points out of the 6400 were discarded. This number is higher than the theoretical number of discards for a 3σ cutoff (i.e., 20) because if any one of the three simultaneous measurements (i.e., two velocities plus temperature) were discarded the two accompanying samples were also discarded. Using statistical analysis and assuming Gaussian distributions and local turbulence intensity levels of 70%, the expected sampling errors for the 6400 sample size were found to be less than 1.8% for both mean and standard deviation values for a 95% confidence level.[21]

Experimental Results and Discussion

Simultaneous velocity-temperature measurements were made at 19 radial locations across the test section and at 4 axial positions located at nondimensional distances based on step height of x/H = 1, 3, 5, and 12. These measurements were made on the vertical radius from the centerline of the tube to the top of the tube which, as mentioned earlier, required a specially designed correction lens system. Axial symmetry was assumed in this study based on results from previous studies[5,17,18] where velocity measurements on both sides of the centerline and circumferential static pressure measurements indicated that this was a good assumption. Additional measurements of mean and fluctuating temperatures were made in the test section at nondimensional distances of x/H = 2, 4, 6, 8, 10, and 14, but will not be presented here due to space limitations (see Ref. 4). Measured cold flow results are also presented here with the reacting flow measurements for comparison. A more complete presentation of the cold flow measurements can be found in the publications by Gould et al.[4,5] Separate measurements of the inlet flow conditions could not be made for the reacting flow case due to interference between the test section flange and the thermocouple support system. However, since the temperature in the central core region was found to be nearly room temperature, it is believed reasonable to assume that the inlet flow conditions for the reacting flow case are very close to those measured for the cold flow case. Cold flow measurements at $x/H = 0.2$ are included with the reacting flow measurements and should be considered very good estimates of the inlet flow condition. The mean inlet temperature ($T_0 = 298$ K) and inlet centerline velocity ($U_0 = 22$ m/s) were used to normalize the measurements.

The practice of obtaining a velocity-temperature correlation by using a LDV to measure the velocity and a thermocouple to measure the temperature in a recirculating flow is open to question, since the thermocouple probe obviously disturbs the flowfield, and therefore, affects the result. In order to determine the magnitude of this flow disturbance, velocity measurements were made across the shear layer at one axial location ($x/H = 3$) with and without the thermocouple probe in place in the cold flow case only. These measurements, included in Ref. 4, indicated that the standard turbulent velocity statistics were affected very little by the thermocouple probe. Maximum absolute errors (value with probe in minus value with probe out) at this axial location were found to be $\Delta\bar{U} = -0.4$ m/s, $\Delta\bar{V} = -1.5$ m/s, $\Delta\overline{u'u'} = -2.6$ m²/s², $\Delta\overline{v'v'} = -0.5$ m²/s², and $\Delta\overline{u'v'} = -0.6$ m²/s². The largest normalized error occurred in the mean radial velocity measurement in the central core region, where the axial velocity is high and the turbulence level is low. Essentially, the large axial velocity is obstructed by the probe and turns along the probe direction. Since the maximum radial velocity in this flowfield is one-tenth the axial velocity, this flow turning has the largest effect on the radial velocity. The true mean radial velocity is, of course, zero in this central region.

Mean Velocity Measurements

Figure 4 shows the normalized measured mean axial velocities in the sudden expansion flow with and without combustion. The central core region upstream of $x/H = 5$ in the reacting flow case was virtually unchanged from that of the cold flow case because the temperature in this region was near the inlet temperature as will be shown later. Higher mean axial velocities in the shear layer are found in the reacting flow case due in part to volumetric expansion. At the downstream measurement location ($x/H = 12$), the reacting flow mean axial velocity was found to be approximately 1.7 times greater than the cold flow mean axial velocity across the entire tube diameter. It is interesting to note that the reacting flow centerline velocity does not decay as rapidly as the cold flow centerline velocity does. The relatively low temperature on the centerline at all measurement locations in the reacting flow would suggest that this result is not due to volumetric expansion alone. A comparison of the axial momentum flux ($\int \rho u^2 r\, dr$) at $x/H = 5$ and 12 indicates that the axial centerline pressure gradient in the reacting flow is approximately one-half that which exists in the cold flow, which may be why the centerline velocity does not decay as rapidly in the reacting flow case. The increased velocity in the radially growing shear layer, which is due to heat release, tends to preserve the central core region. The recirculation zone, defined by the streamline having the same value as the step face and the tube wall and indicated in Fig. 4 by the horizontal lines (dots for cold flow, dash-dots for reacting flow), was found to be thinner and shorter in the reacting flow case. This finding is in agreement with previous studies performed by Gould et al.[17] and Pitz and Daily.[22] Measured mean radial velocities for the cases with and without combustion are shown in Fig. 5. The relatively high negative radial velocities in the central core region (i.e., $r/R_2 < 0.5$) for the reacting flow case seen in this figure are due to flow turning introduced by the thermocouple probe as mentioned earlier, and thus should not be misinterpreted as measurement system error or as flowfield asymmetry. These velocities were found to be very near zero if the probe was removed as shown in Ref. 4. Fortunately, turbulent transport (i.e., advection, production, diffusion, dissipation) is not important in the central core region of this flowfield.[5] Measured radial velocities in the reacting flow case were found to be higher in the recirculation zone when compared to the cold flow case.

Mean Temperature Measurements

Figure 6 shows the normalized mean temperature measurements made while making simultaneous velocity-temperature measurements. The maximum normalized temperature achievable in this study (where $\Phi = 0.5$) is bounded by the adiabatic flame temperature and is approximately 5. Measurements show that the core region stays relatively cool and that maximum temperatures are achieved in the recirculation zone and the developing boundary layer downstream of the reattachment point. These profiles indicate that the mean temperature gradient in the radial direction is positive through most of the shear layer. Note that the central region well downstream of the core ($x/H = 12$) remains relatively cool, and thus, may contain large amounts of unburned fuel and oxidant.

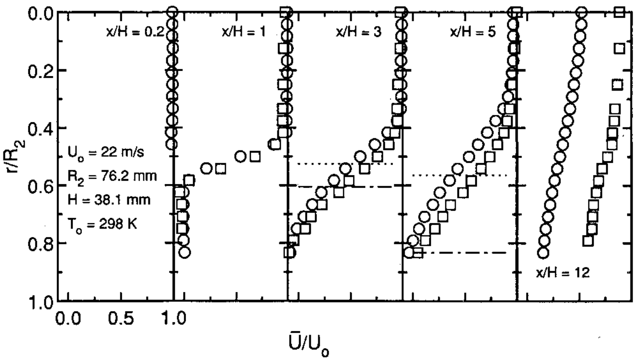

Fig. 4 Mean axial velocity profiles: ○—cold flow, □—reacting flow.

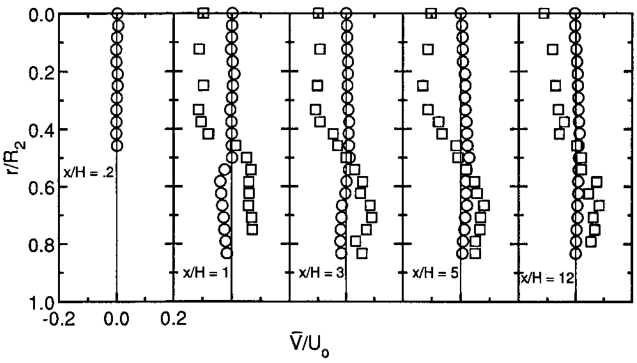

Fig. 5 Mean radial velocity profiles: ○—cold flow, □—reacting flow.

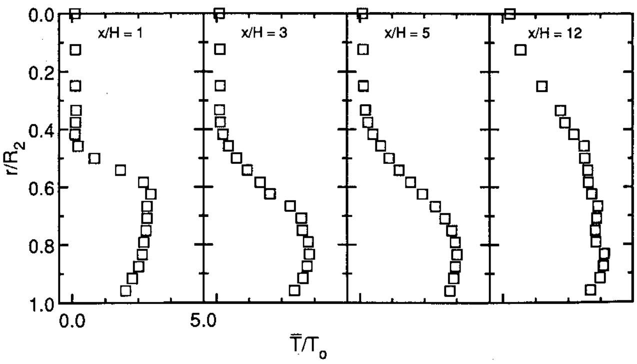

Fig. 6 Mean temperature profiles.

Turbulent Stresses

Figures 7 and 8 show the measured normalized axial and radial normal stresses, respectively, with and without combustion. Turbulence levels were found to be lower in the reacting flow case over most of the flowfield, indicating either reduced production and/or increased dissipation of turbulent kinetic energy. Peak turbulence levels in the reacting flow case are shifted radially outward, which is consistent with the location of the dividing streamline defining the thinner recirculation zone in the reacting flow. These results are also in general agreement with previous studies by Gould et al.[17] and Pitz and Daily.[22] The reacting flowfield was also found to be more isotropic (i.e., $\overline{u'u'} \approx \overline{v'v'}$) than the cold flow. Fujii and Eguchi[23] found this same result in the flow downstream of a bluff body flame stabilizer. This near isotropic behavior may allow for the use of simpler turbulence models.

Figure 9 shows measured normalized Reynolds stress $\overline{u'v'}$ in the flowfield with and without combustion. Maximum values of $\overline{u'v'}$ in the reacting flow were approximately a factor of 6 less than those measured in the cold flow case whereas maximum values of $\bar{\rho}\overline{u'v'}$ were approximately a factor of 13 less than those measured in the cold flow case. Repeated measurements gave Reynolds stress values to within 10% of the ones reported here. In addition, removing the thermocouple probe, while giving a slightly different value for $\overline{u'v'}$, indicated that this low value of $\overline{u'v'}$ was not due to probe interference effects. These low values of Reynolds stress raised concerns that beam wandering, due to fluctuating refractive index gradients, may be uncorrelating the $\overline{u'v'}$ measurement. To investigate this concern the beam blocks were removed to determine if the laser beams passed through the pinhole in front of the photomultiplier (PM) tube. Beam wandering would cause fluctuating light level through the pinhole. No beam wandering was detected either visually (the PM tube was removed and the beams were imaged on a screen) or electronically (the PM tube voltage was reduced) using an oscilloscope. It has been suggested[14,15] that the scattering efficiency of TiO_2 is reduced at high temperatures giving a reduced data

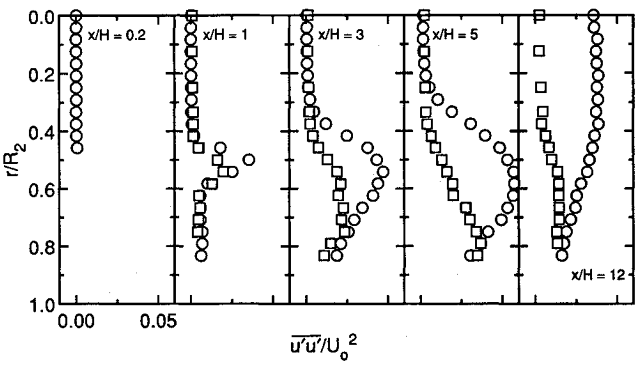

Fig. 7 Normalized axial turbulent normal stress profiles: ○—cold flow, □—reacting flow.

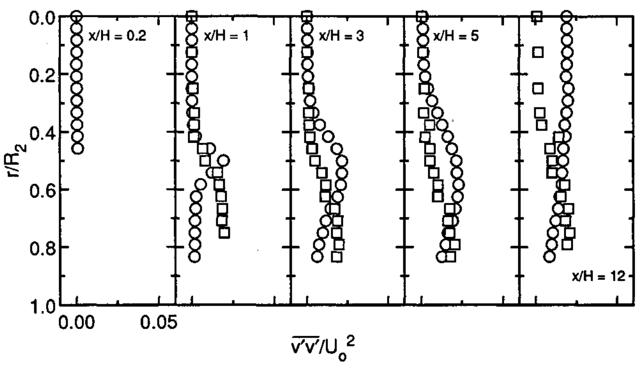

Fig. 8 Normalized radial turbulent normal stress profiles: ○—cold flow, □—reacting flow.

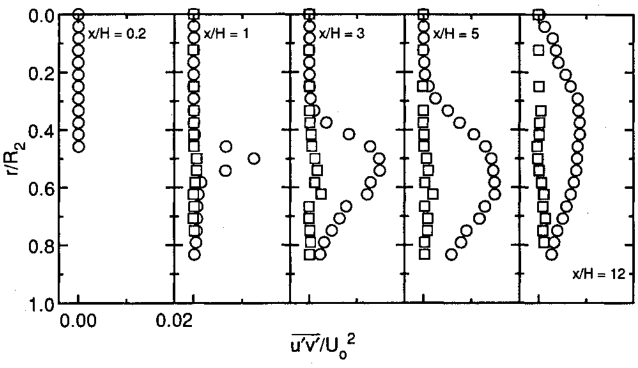

Fig. 9 Normalized shear stress profiles: ○—cold flow, □—reacting flow.

validation rate. It is conceivable that a loss in signal-to-noise ratio may also give rise to skewed statistical parameters, if e.g., only large particles (which would be more easily detected) moving nearly the same way are detected. In order to test this hypothesis a separate study would have to be undertaken using different seed materials. Somehow the velocity bias effects would have to be separated from the scattering efficiency effects. The reduction in $\bar{\rho}\overline{u'v'}$ is due both to the decrease in density and to the decrease in $\overline{u'v'}$. Fujii and Eguchi[23] reported that $\overline{u'v'}|_{max}$ decreased by a factor of 2 in their reacting flow, whereas Ng et al.[24] reported that $\bar{\rho}\overline{u'v'}|_{max}$ decreased by a factor of 2 in the turbulent boundary layer over a hot surface. One conclusion from these results is that the production of turbulence generated by shear (i.e., $\overline{u'v'}\partial\bar{U}/\partial r$) is much less in the reacting flow case than in the cold flow case. This may explain why the measured turbulence level (i.e., $\overline{u'u'}$ and $\overline{v'v'}$) is low in the reacting flow (i.e., very little is produced), but does not explain why the shear is low. One possible explanation is that the turbulent dissipation rate increases in a reacting flow due to the temperature dependent viscosity.[25] Dynamic viscosity μ increases by a factor of approximately 3 at the elevated temperatures present in this combustion chamber. Likewise, the kinematic viscosity defined as $\nu = \mu/\rho$, increases by a factor of approximately 15 (density decreases by a factor of 5), which reduces the local Reynolds number of the flow by an equivalent amount. Increased fluid viscosity and turbulent dissipation rates in reacting flows may be why some researchers[22,23] have found reduced eddy coalescence and structure in reacting shear layers. Ballal[1] suggests that the question of whether turbulence will be enhanced or suppressed does not have a simple answer because the mechanisms of turbulent kinetic energy production, diffusion, advection, and dissipation are very geometry dependent. Turbulent dilatation and viscous dissipation processes suppress flame-generated turbulence, whereas diffusion and shear-generated production enhance flame-generated turbulence.

Fluctuating Temperature Measurements

Figure 10 shows the measured normalized fluctuating temperatures in the reacting flowfield. Peak fluctuations were found to coincide with the maximum mean temperature gradients and agreed in magnitude with results published by Yoshida and Tsuji[26] and Tanaka and Yanagi.[27] Peak temperature fluctuations also occurred where peak turbulence levels occur, as can be seen in Figs. 7–9. The relatively high values of fluctuating temperature near the centerline at x/H locations downstream of 10 step heights (only $x/H = 12$ is shown here) were not initially expected. Further investigation revealed that these were a result of bimodal temperature probability distributions at these locations. Oscilloscope traces of the temperature time history at these locations showed intermittent, almost square wave, behavior indicative of large-scale structure passage. This bimodal behavior is characteristic of premixed combustion and has been reported by many researchers.[15,28,29] Unfortunately, the fluctuating temperature power

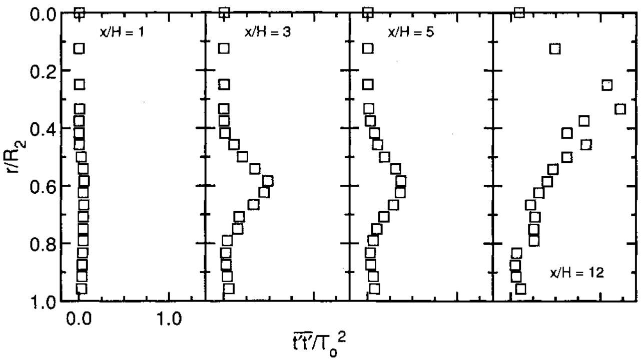

Fig. 10 Normalized fluctuating temperature profiles.

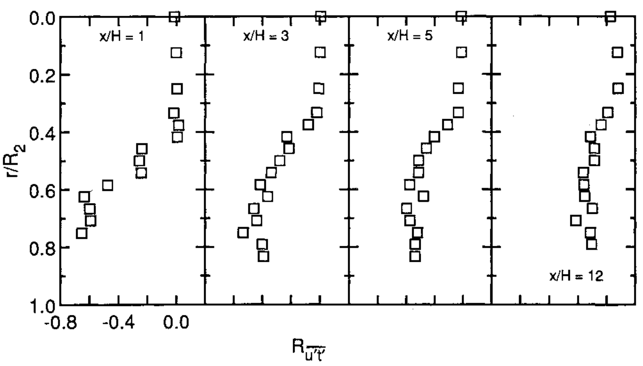

Fig. 11 Axial velocity-temperature correlation coefficients.

spectra could not be obtained since the data acquisition system could not record the temperature time history separately. The LDV data validation rate limited the sample rate below that which was considered necessary to obtain reliable spectra. Clearly, these time-dependent and possibly asymmetric phenomena cannot be predicted correctly when using simple two-dimensional, steady flow, gradient transport model based codes.

Temperature-Velocity Correlations

Figure 11 shows the axial velocity-temperature correlation coefficient in the reacting flow. The results of this study indicate that the correlation coefficients are negative throughout most of the flowfield, reaching a maximum value of -0.65 for the axial velocity-temperature correlation. Maximum values of radial velocity-temperature correlation coefficients (see Ref. 4), which are believed less reliable than the axial correlation due to probe induced flow disturbances, were less, reaching a peak value of -0.2. The negative sign of these correlations and the fact that mean temperature gradients were found to be positive indicates that gradient transport modeling applies in most regions of this combustion chamber. This is in agreement with the results obtained in a premixed jet flame by Yanagi and Mimura.[29] Small positive values of velocity-temperature correlations are found at the downstream location ($x/H = 12$) near the centerline, which again, may be due to the bimodal structure in this region.

Summary and Conclusions

The primary objective of this work was to make reliable measurements in a well-characterized flow (i.e., completely premixed combustion and axisymmetric geometry). Results of this study provide new insights on the interactions of flow and combustion and represent a data base for modelers interested in code validation. A summary of the results from this investigation is given below:

1) The reacting flow mean axial velocities were higher due to heat release, and the recirculation zone was shorter and thinner than observed in the cold flow case.

2) The centerline mean axial velocity in the reacting flow decays at a much slower rate than in the cold flow. An axial momentum balance indicated that the mean axial pressure gradient was approximately two times less in the reacting flow case.

3) Turbulent normal stresses were found to be nonisotropic in the cold flow ($\overline{v'v'} \approx \frac{1}{2}\overline{u'u'}$), but nearly isotropic in the reacting flow.

4) Maximum temperatures in the reacting flow are located in the shear layer and in the developing boundary layer downstream of reattachment.

5) Maximum temperature fluctuations are located at the point where the maximum mean temperature gradient exists, indicating that conventional gradient transport modeling may be useful.

6) The temperature-velocity correlations also indicate that gradient transport modeling may be acceptable.

7) Bimodal fluctuations of velocity and temperature were found to exist near the centerline at downstream locations in the reacting flow, possibly indicating that large-scale structures exist there. In agreement with the recent study by Broadwell and Dimotakis,[30] modelers must consider this unsteady large scale structure for accurate predictions.

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