AIAA-83-0334
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AIAA 21st Aerospace Sciences Meeting
January 10-13, 1983/Reno, Nevada
INSTANTANEOUS TWO-COMPONENT LASER ANEMOMETRY
AND TEMPERATURE MEASUREMENTS IN A COMPLEX FLOW MODEL COMBUSTOR

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ABSTRACT

The use of a compensated thermocouple probe to measure time-resolved temperature simultaneously with time-resolved axial and azimuthal velocity is assessed in a complex flow Dilute Swirl Combustor (DSC). Results indicate that the measured values of the mean and root-mean-square temperature and velocity-temperature correlations are sensitive to the amount of compensation. Variation in the compensation coefficient of 25% leads to a variation of 20% in the indicated root-mean-square temperature and 50% in the axial heat flux. The effect of probe perturbation on the velocity field is also assessed and found to be (1) significant near the axis of the sensor and to become less significant off axis, and (2) not confined to the immediate area downstream of the probe but to extend up to one combustor diameter upstream. Finally, the Reynolds stress and azimuthal and axial heat fluxes as well as other statistical quantities of fluid mechanical interest obtained from simultaneous time-resolved measurements of the temperature and velocity are presented.

INTRODUCTION

Turbulent, recirculating flows are found in many practical engineering applications, notable of which are continuous combustion devices such as gas turbines and furnaces. These complex (i.e., turbulent and recirculating) flows are used to promote mixing and provide flame stabilization. As a result, they have a significant effect on combustion efficiency, blow-off limits, and gaseous pollutant production. Presently, experimental and computational techniques are being pursued to increase the understanding of the mixing and chemical processes associated with such flows, and to develop predictive codes. Earlier work by Brus et al. (1992) and Brum and Samuelson (1982a) has identified the Dilute Swirl Combustor (DSC) as a candidate flowfield for studies of complex recirculating flows. Brum and Samuelson (1982a) measured the time-resolved axial velocity component using a single-component laser anemometer and have since extended the measurements (Brum and Samuelson, 1982b) to include the time-resolved, simultaneous measurement of both the axial and azimuthal velocity components.

These two previous studies have provided the initial velocity field data base necessary to establish the overall performance and flowfield structure of the DSC. The goal is to develop a model laboratory complex flow combustor suitable for fundamental studies in continuous combustion such as predictive modeling validation, the development of optical diagnostics, and fuel effects studies. Not only are velocity field data necessary in the pursuit of this goal, temperature data are required as well. If the data are to be used for predictive modeling or to provide insight into turbulent mixing, then simultaneous, time-resolved measurements of velocity and temperature are also desirable. Thus the primary objective of the present study was to obtain simultaneous, time-resolved measurements of axial and azimuthal velocity and temperature \((u, w, T)\) respectively. A two-color laser anemometer system was used to measure the velocity while a bare wire, small diameter, electronically compensated thermocouple probe was used to measure the temperature.

Probe perturbation effects can be potentially significant in recirculating flows (Bilger, 1976; Hack et al., 1981). Therefore, a second objective of this study was to evaluate the effect of the thermocouple probe on the velocity field. Electronic compensation was used to extend the frequency response of the thermocouple so as to permit time-resolved temperature measurements. The correct amount of electronic compensation depends in part on the physical properties of the gas and the instantaneous velocity at the sensor location. Therefore, even when the sensor is accurately compensated corresponding to the mean flow conditions, the sensor will at times be over- or under-compensated in a flow with a fluctuating velocity. Thus, a third objective of the present study was to determine the effect on the temperature measurements of variations in the amount of compensation.

EXPERIMENT

Geometry

The DSC configuration, presented in Figure 1, features an aerodynamically controlled, swirl-stabilized recirculation zone and possesses the important features of practical combustors. It consists of an 80 mm I.D. x 50 cm long cylindrical stainless steel tube having rectangular optical
windows (30 mm x 310 mm) mounted perpendicular to the horizontal plane on both sides of the combustor tube. These flat windows provide clear optical access for laser anemometry measurements and allow accurate co-location of the u and w measurement volumes.

A set of swirl vanes (57 mm O.D.) is concentrically located within the tube around a 19 mm O.D. centrally positioned fuel delivery tube. Dilution and swirl air are metered separately. The dilution air is introduced through flow straighteners in the outer annulus. The swirl air passes through a set of swirl vanes which impart an angle of turn to the flow, 60° in the present case. For a swirl-to-dilution ratio of unity, the value used in the present study, the swirl number obtained by integrating across the swirl vanes is 0.8; that obtained by integrating the total inlet mass flux is 0.3. The combustor was operated at atmospheric pressure.

Fuel (propane) is introduced through a nozzle at the end of the central fuel delivery tube. The exit plane of the fuel nozzle is set at the same axial location as the exit plane of the swirl air to provide a clean, well defined boundary condition for the application of numerical models.

A cone-annular gas injector (Figure 1), sized to emulate the directional momentum flux of a hollow-cone liquid spray nozzle, was used for the present work.

Velocity Measurements

Axial and azimuthal, mean and rms velocity measurements were made using the two-color laser anemometry (LA) system shown in Figure 2. The beam from a 200 mW Argon-ion laser (Lexel Model 75) was collimated and passed through a prism to separate the various wavelengths. The two most intense beams, green (514 nm) and blue (488 nm) were each passed through a pair of optics in which they were polarized and split into two beams of equal intensity 50 mm apart. An upstream 40 MHz frequency shift (TSI model 915 Bragg Cell) was applied to one of each pair of beams in order to avoid directional ambiguity that would otherwise result from the highly turbulent recirculating flow. The four beams (blue pair in the vertical plane and green pair in the horizontal plane) were then focused through a 250 mm lens to a common point within the test section. This resulted in a set of perpendicular interference fringes spaced at 2.6 µm for the green beams (vertical fringes) and 2.5 µm for the blue beams (horizontal fringes) which were responsive to the axial and azimuthal velocity components respectively.

Receiving optics consisted of a 120 mm lens focused onto a 0.25 mm diameter photomultiplier tube aperture (via an appropriate dichromatic filter to selectively pass either the blue or green light). These optics were placed at an angle of 2° to direct forward scatter which resulted in a probe volume 0.023 mm² and cross-sectional area perpendicular to the axis of measurement of 0.10 mm². However, due to the requirement imposed by the processing electronics that both axial (u) and azimuthal (w) velocity components be obtained simultaneously, the effective probe cross-section was much less (approximately 0.03 mm²). The transmitting and receiving optics are mounted on an optical bench capable of placing the measurement volume at points throughout the stationary combustor test section.

The main and fuel jet flows were seeded independently but to the same levels of concentration with 5 µm alumina particles. A liquid suspension atomization seeding technique (Ikioka et al., 1982) was employed. Signal validation was obtained using two counter processors (Macromopyne Model 2098).

Temperature Measurements

At the present time, non-intrusive optical techniques for the measurement of time-resolved temperatures are still in the developmental stage. A sensor more amenable to measurement in a turbulent flow is the thermocouple. It has the advantage of relatively low cost, a history of use in the measurement of mean flame temperatures, but is subject with respect to durability, flow perturbation, and frequency response. In fluctuating temperatures in a combusting flow, the sensor must be small but at the same time must be sufficiently rugged to survive. This latter criterion establishes a lower limit on the wire diameter of approximately 25 µm. The thermocouple must also withstand the high temperature (1900°C), oxidizing environment in a reacting flow. Platinum and the alloy platinnum 10% Rhodium can operate satisfactorily under these hostile conditions and were chosen for the present study to serve as the thermocouple materials. The thermocouple junction was formed by overlapping and spot welding the two 25 µm wires which yielded a junction with a characteristic length of less than 4 µm. The small diameter wire used to form the junction was gas welded to a 250 µm diameter support wire of the same material. The support wires were cemented in a 0.318 cm O.D. alumina tube which in turn was mounted in a 0.635 cm O.D. inconel tube. Approximately 4 cm of the alumina tube projected in front of an aerodynamically smooth transition to the larger inconel tube. The inconel tube was held on a mechanical traverse which moved with the LA optical bench and was inserted into the flow through the exhaust plane of the combustor. The junction of thermocouple was positioned 1 mm downstream of the laser anemometer fringe volume.

The thermocouple frequency response necessary to make accurate time-resolved measurements can be estimated from the physical dimensions of the combustor and the bulk mean velocity. If the length scale of energy-containing structure in taken to be one-half the combustor radius, the corresponding frequency for a mean velocity of 15 m/sec is about 1750 Hz. Therefore, in order to accurately resolve the root-mean-square temperature, the sensor frequency response must extend to at least two or three times the frequency of the energy-containing structures or about 2 kHz. The uncompensated frequency response of the sensor at this mean velocity is about 15 Hz. Thus, the frequency response must be increased by a factor of 130. In order to do so, electronic compensation is required.

The compensation methods used in this study are based on the one proposed by Lockwood and Monieb (1981). A block diagram of the thermocouple signal processing electronics, shown in Figure 3, consists of five main subcircuits: 1) an electronic switch, a source of heating current, and a square-wave
function generator to control the switch, 2) a low noise, low drift, differential input preamplifier (gain = 106), a compensation circuit, 3) two low-pass filters, one to reduce noise from the differentiator and one to reduce overall noise in the compensated temperature signal, and 5) a gain and bias amplifier to match the dynamic range of the temperature signal to that of the analogue-to-digital converter.

The preamplifier consists of a battery-operated differential amplifier (AD524). This unit has a very low d.c. drift and an equivalent root-mean-square input noise of 1°C.

The compensation subcircuit consists of a differentiator and summing amplifier and performs the operation $[E + \int \frac{dE}{dt} dt]$ where $E$ is the thermocouple voltage and $T$ is the average time constant. The average time constant $T$ is determined by observing the decay of the temperature of the thermocouple when a d.c. heating current is shut off. The function generator is used to alternatively switch this heating current on and off from the probe and trigger a microcomputer (a DEC PDP 11/23) and associated analogue-to-digital converter to sample the time decay of the thermocouple temperature when the heating current is shut off. The computer determines a least square fit of the log of the voltage versus the time. The slope of this line is related to the time constant. The instantaneous values of the time constants are determined for ten or more different repetitions of the probe cooling cycle and are averaged to obtain the average time constant. The compensator is adjusted accordingly.

Yula, et al. (1978) suggested that the time constant determined using this method should be adjusted to account for the fact that the thermocouple junction is not the same diameter as the wire. Based on their results for a junction characteristic length-to-diameter ratio of less than 1.5, the error in the root-mean-square temperature is estimated to be less than 10% and no correction of the time constant is made for this effect.

Data Acquisition

Special electronics were built to interface the output of the two digital counter processor channels ($u,w$) and an analogue channel (temperature in this case) directly to a DEC PDP 11/23 computer system. This interface identifies whether or not the $u$ and $w$ events occur within a certain aperture time of each other. If so they are considered simultaneous, stored and then multiplexed into the computer via a parallel interface. The corresponding simultaneous measurement of temperature is obtained by means of a sample-and-hold circuit which is activated by the laser interface unit when it registered the simultaneous measurement of the axial and azimuthal velocities. The signal "hold" by the sample-and-hold unit is sampled, digitized and stored with the corresponding velocity signals by means of a Data Translation, 12 bit, analogue-to-digital converter which is controlled by appropriate software in the computer. Once the interface verifies that the computer has read the data, it simultaneously resets both processor channels and the sample-and-hold on the analogue data channel. The key feature of this system is that it permits the acquisition of simultaneous realizations of the two velocity components and temperature. An aperture time of 50μs was selected since at the maximum bulk velocity measured (15 m/s), an equivalent spatial resolution of less than 0.75 mm is obtained.

The computer is equipped with an internal clock having a resolution of 100 μs which is initiated at the beginning of each run cycle. As the $u,w,T$ data are received, the time of event $t$ is combined with the raw data ($u,w,T,t$) and the data are permanently stored on either a hard disc or floppy disc for future reference and analysis.

Accuracy

Sources of velocity inaccuracy evaluated were (1) sampling error resulting from a finite number of samples, (2) positional accuracy of the traversing system, and (3) digital resolution (i.e., the magnitude of the least significant bit output by the counter processors). Between 400 and 1000 samples were taken at all measurement points. This resulted (to a 95% confidence level) in a maximum sampling error of $\pm e_r$ on the mean velocity:

$$e_r = \frac{2(V_{rms})}{V n}$$

where $n$ is number of samples and $V_{rms}$ is the root-mean-square velocity. For the flows measured this error ranged from 1 to 3 percent of the bulk velocity. The translation of positional accuracy (+ 0.3 mm) into velocity error depends upon the local gradients and is at most $\pm 0.75$ m/s.

Finally, the resolution of the least significant bit was approximately 0.25 m/s resulting in a maximum bit resolution error of $\pm 0.125$ m/s.

Root-mean-square noise in temperature signal has been measured to be 6.5°C and the relative error in mean temperature is estimated to be $\pm 10%$. The thermocouple probe data are not corrected for radiation.

RESULTS

Simultaneous time-resolved measurements of temperature and axial and azimuthal velocities were made in a reacting flow involving propane and air. The overall equivalence ratio was 0.1 and the reference bulk velocity was 15 m/s. The first results reported describe the velocity field and the streamline structure of the complex flow as measured by the two-color laser anemometry. The second set of results discussed pertain to a study of the effect of the thermocouple probe on the velocity field.

Most of the temperature measurements reported herein were made in the wake region of the flow downstream of the main recirculation region. Since the flowfield involves both recirculation and swirl, significant perturbation of the flowfield by the thermocouple probe is possible. It is interesting to note that Bilger (1976) points to the dearth of perturbation effects data and states that "though the problem is obvious, it appears to have been addressed in the literature, not even to the extent of saying that visual observations indicated no effect." One of the few studies of probe perturbation effects in complex, recirculating turbulent flows is reported by Hack, et al. (1981) who found that the local soot number
density can be reduced in excess of 100% when an
extractive sampling probe is placed in the
flowfield.

A second concern relating to the use of compensated thermocouple sensors corresponds to the fact that the "time constant" is not a constant. The turbulent temperature fluctuations are associated with fluctuations in the velocity, density, species concentration, and viscosity. All these fluctuations affect the heat transfer coefficient and thus the time constant. For the compensated data presented herein, the compensation is chosen to correspond to the average time constant. Thus at certain times in space, the probe may be over- or under-compensated, and the temperature signal will be in error. The possible error due to the use of a fixed average time constant can be estimated at each sampling position by determining the sensitivity of the various statistical quantities of interest to variations in the time constant. This analysis is accomplished in the third section of the results.

Statistical quantities of fluid mechanical interest such as mean and root-mean-square axial and azimuthal velocities and temperature are presented in the final section, in addition, the normalized Reynolds stress, \( \frac{\langle w' \phi' \rangle}{\text{rms}} \), and the normalized axial and azimuthal heat fluxes, \( \frac{\langle u' \theta' \rangle}{\text{rms}} \) and \( \frac{\langle w' \theta' \rangle}{\text{rms}} \), are described. The results of the first two sections are applied to these data to indicate those regions of the flow where probe perturbation and time constant variation have an negligible effect on the measured data.

Velocity Profiles and Streamlines

Axial and azimuthal mean and root-mean-square velocity profiles are shown in Figure 4a. A detailed discussion of these profiles is presented in Brum and Samuelsen (1982) and it is sufficient here to discuss only those features pertinent to the present study. Evidence of the recirculation zone is indicated by the negative mean axial velocities at the 2 and 7 cm stations. The relative large mean axial velocity component at the 24 cm station is indicative of a large-scale swirl velocity component over the length of the combustor axis from the algebraic reduction resulting from the mixing of swirling and non-swirling inlet streams. Axial turbulence intensities on the centerline at the 24 cm station are about 40% which is considerably higher than for isothermal pipe flow.

The mean streamlines, \( \psi \), are shown on Figure 4b. The streamlines are obtained using the continuity equation and integrating the profiles of mean axial profiles shown in Figure 4a (and additional profiles not shown):

\[
\int_0^r \frac{x}{r} \, dx = \int_0^R \frac{r}{R} \, dx
\]

where \( r \) is the radial location of interest and \( R \) is the radius of the DSC. Integration at each profile allows streamlines to be drawn through points of constant \( \psi \). The closed streamlines correspond to the recirculation zone. Clearly, the flow is complex (i.e., recirculating with very high turbulent intensity) and is vulnerable to perturbation by the insertion of a physical probe.

Probe Perturbation

The method used to assess the effect of probe perturbation is based on a comparison of the velocity field obtained earlier by Brum and Samuelsen (1982b) in the absence of a probe in the flow to data obtained in the present study in which the thermocouple probe was placed at 1 mm and selected additional locations downstream of the laser fringe volume.

Figure 5 shows the ratio of various statistical quantities obtained with the thermocouple probe junction located 1 mm downstream of the fringe volume (subscript "p") to those obtained in the absence of a probe (no subscript). At the 14 cm station, the mean and root-mean-square profiles for both the axial and azimuthal velocities differ by less than 20% in the two cases for radial positions 0.2 \( \leq r/R \leq 0.65 \). Closer to the axis, the mean axial velocity is reduced by as much as 35% when the probe is present. At the 24 cm station, probe perturbation is even more pronounced near the axis where the presence of the probe reduces the mean axial velocity by as much as 50%. Away from the axis, however, the perturbation is significantly less. For 0.25 \( \leq r/R \leq 0.65 \) the mean and the mean and root-mean-square velocities differ by less than 10%.

The variation in the ratio of the mean and root-mean-square velocities at different radial positions suggests that probe perturbation is due not only to local aerodynamic effects but also to a large-scale change in the flowfield. The data presented in Figure 6 support this hypothesis. The mean and root-mean-square axial and azimuthal velocity are plotted as a function of separation distances between the thermocouple junction and the laser fringe volume, the latter of which is positioned at axial locations of either 14 or 24 cm, and at radial locations of either r/R = 0 or 0.5. At the 24 cm station and on the centerline, there is a continuous variation in axial mean velocity and in root-mean-square azimuthal velocity as the thermocouple probe is moved to various positions downstream of the laser fringe volume. At a 1 mm separation, the mean axial velocity is reduced by 44% compared to the value when the probe is not in the flow. Even at a separation distance of 80 mm, which is near the exit plane of the combustor, there is still an effect on the mean axial velocity. Thus, at this particular position in the flow, the flowfield is affected over long distances. Probe perturbation effects can also be seen to exist at \( x = 24 \) cm and \( r/R = 0.5 \) but the effect is much smaller with a maximum difference in the mean axial velocity of 7.5%. Evidence of
localized perturbation of the velocity field can also be seen in the corresponding data obtained at the 14 cm station. The mean axial velocity and azimuthal root-mean-square velocity are again the most affected by the presence of the probe at r/R = 0 but at this position, a 1 mm separation corresponds to a difference of about 20% compared to the data for a separation of 80 mm. Again probe perturbation effects are much less significant at r/R = 0.5. Possible explanations for the relatively higher probe perturbation observed along the centerline include:

1. A suppression of the fluid momentum. The probe may cool (via re-radiation) the hot gases in the combustor core as well as provide a local source of skin friction drag. The net effect is to decelerate the axial and azimuthal transport of the flow. This effect is less evident at radial stations due to (a) significantly lower temperatures, (b) higher axial momentum flux, and (c) the centerline nature of the recirculation zones. The insertion of the probe along the center line may suppress the spiraling action and thereby reduce the local root-mean-square and mean axial velocities.

2. An occasional occurrence of negative axial velocities on axis with the probe in the flow. The occurrence of negative velocities on axis is much lower, hence, the flow is more 'elliptic' on axis which induces a path for projecting probe disturbances upstream.

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Effect of Time Constant Variation

The effect of time constant variation on the statistical features of the flow involving the temperature signal are exhibited in Figure 7. There it can be seen that a 10% variation in the time constant can have as much as a 20% variation in the measured axial heat flux and a 50% variation in the measured azimuthal heat flux. This high sensitivity may well be due to the fact that there is a correlation between the velocity and the sensor response. For example, if high velocities are associated with high temperatures, the increased frequency response of the sensor's high velocity and corresponding over-compensation will lead to a higher indicated temperature and a larger contribution to the u'-T' correlation. The root-mean-square temperature is much less sensitive to variation in the time constant where a 10% variation has less than a 5% effect on the measured root-mean-square temperature. This will be due to the fact that over- and under-compensation due to variation in velocity affects that portion of the temperature power spectrum which contributes a relatively small amount to the root-mean-square temperature. Finally, it was found that the measured value of the mean temperature varied by less than 10% for a ± 50% variation in the time constant.

Mean and Root-Mean-Square Temperature

The mean and root-mean-square temperature are indicated in Figure 6. The mean temperature has a maximum as expected on the centerline and decreases monotonically with increasing r. At both axial stations, the root-mean-square temperature has a maximum in the vicinity of the maximum gradient in the mean temperature. The off-axis minimum of the root-mean-square temperature at the 14 cm station is anticipated and may be an indication of the uncertainty in the data.

Velocity Statistics and Correlations

Radial plots of the u'-w' correlation coefficient (normalized Reynolds stress) appear in Figure 9. Velocity and azimuthal heat flux correlations in Figure 9a (top and bottom) along with the axial (u, top) and azimuthal (w, bottom) velocity profiles. The two radial stations (2.0 and 7.0 cm) are without the probe in the flow, the last two stations (14.0 and 24.0 cm) are with the temperature probe placed 1 mm downstream of the laser volume. The occurrence of these cutouts are to show the effect of the cooling of the hot gases in the combustor core. The magnitudes of the correlation coefficients also go to zero. In complex flows, the direction of the coherent changes as the direction of local gradients. For example, when both the u and w gradients with respect to r are positive (du/dr > 0, dw/dr > 0), the correlation is positive, and when both are negative, the correlation is positive. However, when the magnitude is positive and the w gradient is negative, or vice versa, the correlation is negative. In areas where there is little or no gradient in either u or w, the correlation goes to zero.

The axial and azimuthal heat flux correlations (u'T'/u_rms T_rms and w'T'/w_rms T_rms), presented in Figure 9b for the 24 cm station, appear to correspond to the same sign convention rules as the velocity correlations. Peak correlation coefficients on the order of 0.3 are observed for both the u'-T' and w'-T' correlation in comparison to 0.2 for the u'-w' correlations. As the temperature gradients go toward zero at the outer radius, the correlation coefficients also go to zero.

A possible physical interpretation of the negative sign of the axial heat flux correlation coefficient is that the mean velocity near the axis is shown to be lower at upstream stations than the mean velocity far from the axis. This is consistent with the existence of the recirculation region indicated in Figure 4a. The recirculation zone also corresponds to the reaction zone and is in a region of high mean temperatures. Turbulent fluid particles which have their origin in the recirculation zone will on average be associated with relatively high temperatures and low velocities while particles with their origin outside the hot recirculation zone will be associated with relatively high velocities and low temperatures. Particles with either origin would lead to a negative axial heat flux. The positive
correlation at $r/R > 0.5$ might be associated with fluid particles originating from the wall region.

**CONCLUSIONS**

1. A compensated thermocouple probe can be used to measure time-resolved temperature with time-resolved axial and azimuthal velocity in a complex, model combustor. Precautions are required, however, with respect to probe perturbation, and compensation.

2. A physical probe introduced into a swirl-stabilized, complex flow combustor can significantly perturb the velocity field. The perturbation is not limited to the area in the immediate vicinity of the probe, but can extend up to one combustor diameter upstream. The perturbation has a greater effect on mean quantities than on fluctuating components.

3. For the combustor and probe configuration assessed in the present study, the perturbation is significant for the probe located at the centerline. For probe positions away from the centerline, the effect of perturbation drops to levels acceptable for many engineering applications.

4. The minimum thermocouple wire diameter that can withstand the high temperature, oxidizing, and turbulent environment encountered in the present study is 25 μm. Flows with a higher heat release may require larger diameter wires. In either case, compensation is necessary to increase the frequency response of the wire to that appropriate for the flow. Evidence from the present experiment demonstrates that electronic compensation must be employed with care. For example, a fixed electronic compensation corresponding to the average time constant can produce significant error in the azimuthal heat flux.

5. The values of axial on azimuthal heat flux exhibit peaks in the regions of maximum temperature and velocity gradients which is consistent with a gradient transport model. These first direct measurements of heat flux in a complex reacting flow indicate peak values of the axial and azimuthal heat flux correlation coefficient $(\overline{u'T}/\overline{u_T s_T} \overline{\tau_{rms}}/\overline{\tau_{rms}})$ on the order of 0.3.

**ACKNOWLEDGEMENTS**

This study is supported by the National Science Foundation under Grant No. CPE-8013742 and the Air Force Office of Scientific Research, Air Force Systems Command, USAF, under Grant Number AFOSR 79-3586. Any opinions, findings, and conclusions or recommendations expressed in this paper are those of the authors and do not necessarily reflect the views of the National Science Foundation. The United States Government is authorized to reproduce and distribute reprints for Governmental purposes notwithstanding any copyright notation thereon. The efforts of Denis Brockus in developing the data acquisition software and plotting routines and those of Vince Roman and Roger Rudoff in collection of the data are gratefully acknowledged.

**REFERENCES**


Figure 1 Dilute Swirl Combustor

Figure 2 Two-Component Laser Anemometer

Figure 3 Thermocouple Signal Processing Electronics
a) Mean and Root-Mean-Square Velocity Profiles

![Diagram of mean and RMS velocity profiles](image)

**Figure 4** DSC Velocity Field

b) Mean Streamlines

![Diagram of mean streamlines](image)

**Figure 5** Probe Perturbation—Local Field

a) 14 cm Axial Station

![Graphs of velocity profiles at r/R = 0 and r/R = 0.5](image)

b) 24 cm Axial Station

![Graphs of velocity profiles at r/R = 0 and r/R = 0.5](image)

**Figure 6** Probe Perturbation—Far Field
Figure 7 Effect of Time Constant Variation

Figure 8 Mean and Root-Mean-Square Temperatures

Figure 9 Velocity Statistics and Correlations