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MOMENTUM AND HEAT FLUX IN A SWIRL-STABILIZED COMBUSTOR

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The use of a fine-wire compensated thermocouple probe and two-color laser anemometry to measure both heat and momentum fluxes in the axial and azimuthal directions is assessed for a complex flow, swirl-stabilized laboratory combustor. Thermocouple probe perturbation and time constant variation are evaluated and the former is found to be significant in the central region of the recirculation zone. To minimize the effect of perturbation, the configuration of the probe is varied. In the recirculating region, the mean temperature is uniform with peak, instantaneous temperatures approximating the maximum adiabatic flame temperature. The maximum rms temperature approaches 250° C and occurs off-axis, just downstream of the recirculation zone. The heat flux on the centerline is negative and becomes more negative with downstream distance. Correspondingly, the temperature time series and the probability density function of the fluctuating temperature indicate that neither is cool dilution air present near the centerline nor are hot fluid particles present near the wall. This is attributed to the preferential transport of hot, low velocity fluid particles towards the centerline and cool dense gas towards the wall by the swirl.

Introduction

Turbulent, recirculating (i.e., complex) and elliptic flows are found in many practical engineering systems, such as gas turbines, furnaces, and boilers. An increased understanding of these flows requires detailed, time-resolved measurements of flow properties. The principal objective of the present study was to measure simultaneously time-resolved temperature and velocity fluctuations and, from the computed statistical quantities, provide a qualitative and quantitative description of the flow with respect to the mixing processes and turbulent transport in a model laboratory, swirl-stabilized combustor. An electronically compensated fine-wire thermocouple probe was used to obtain the time-resolved temperature and a two-color laser anemometer was used to measure the two components of velocity.

Fine-wire thermocouple probes have been used

for more than two decades,^{1,2,3} and have been recently combined with single-component laser anemometry to provide simultaneous measurements of both temperature and velocity in relatively simple flows.^{4,5} The principal objections to fine-wire thermometry are durability, frequency response, and flow perturbation, each of which is exacerbated in a complex flow. In previous work, durability and frequency response,⁶ and probe perturbation⁷ have been assessed to establish the utility and limits of applicability of the use of fine-wire thermometry in a swirl-stabilized, complex flow combustor. The present study addresses the interpretation of the data set with respect to the mixing processes and turbulent transport.

The Experiment

Combustor Geometry

The model laboratory complex flow combustor (Fig. 1) has an aerodynamically controlled, swirl-

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FIG. 1. Dilute swirl combustor (DSC).⁸

stabilized recirculation zone.⁸ It consists of an 80 mm I.D. cylindrical stainless steel tube 32 cm long with rectangular optical windows (30 mm $\times$ 310 mm) mounted vertically on either side of the combustor tube. These flat windows provide the clear optical access necessary for the laser anemometer.

A set of swirl vanes (57 mm O.D.) is concentrically located within the combustor 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 and the swirl air passes through 60° swirl vanes. For a swirl-to-dilution ratio of unity, the value used in this study, the swirl number obtained by integrating across the swirl vanes is 0.8 while that obtained by integrating the total inlet mass flux is 0.3.

Propane is introduced at the end of the central fuel delivery tube through a cone-annular gas injector sized to emulate the directional momentum flux of a hollow-cone liquid spray nozzle. Data discussed herein corresponds to an overall equivalence ratio of 0.1 with a bulk reference velocity of 15 m/s. The combustor was operated at atmospheric pressure. Radial profiles were measured at four axial locations downstream of the exit plane: $x = 2.0, 7.0, 14.0,$ and 24.0 cm where x is measured relative to the exit plane and the radial position, r , is measured relative to the centerline of the combustor.

Temperature Measurements

For temperature measurements in combustor flows, the sensor should be as small as possible to maximize uncompensated frequency response but must be large enough to survive the hot, oxidizing conditions of the flame.^{1,3} The latter criterion sets a lower limit on the wire diameter for the present case of 25 μm . Although 25 μm diameter wires survived in many regions of the flow, larger diameters were required in the central region within and immediately downstream of the recirculation zone.

The thermocouple junction was formed by overlapping and spotwelding a platinum and platinum/10% rhodium wire. The small diameter wires were then gas welded to larger support wires (of 250 μm or 500 μm diameter) of the same material. The support wires were cemented in a 0.159 cm or 0.318

cm O.D. alumina tube which in turn was placed in Inconel tubing of various diameters and shapes. Various probe configurations, consisting of small and large straight and curved probes, were evaluated. Measurements are reported for the probe that minimized perturbation at a specific measurement location.^{7,9}

The probe was inserted into the flow through the exhaust plane of the combustor and held in a mechanical traverse which moved with the laser anemometer optical table. The thermocouple junction was positioned one mm downstream of the laser anemometer probe volume.

The thermocouple frequency response necessary for accurate time-resolved measurements in the wake region can be estimated from the physical dimensions of the combustor and the bulk mean velocity. If the length scale of the energy-containing structure is taken to be one-half the combustor radius, the corresponding frequency for a mean velocity of 15 m/s is about 750 Hz. In order to accurately measure 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 to approximately 2 kHz. The uncompensated frequency response of the 25 μm sensor at this mean velocity is about 15 Hz. Thus, the frequency response must be increased by a factor of 130 and is accomplished using electronic compensation.

The frequency response required for accurate measurement of the temperature near and in the recirculation zone is more difficult to estimate but certainly depends on the flame zone thickness and its angle relative to the probe. Ion probe measurements made in and at the edge of the recirculation zone indicate that the minimum flame zone thickness corresponds to a time duration of about 1 ms while the average duration is 5 to 10 ms. (The average is relatively high due to the oblique passage of flame zones past the probe and the low velocities in the recirculation zone.) Thus, in and at the edge of the recirculation zone, a compensated frequency response of 2 kHz should be adequate for the accurate measurement of time-resolved temperature.

The compensation method used in this study is similar to the one used by Lockwood and Moneib³ and is described in detail by Seiler.⁹ The basic function of the compensator is to perform the operation $[1 + \tau(d/dt)]E$ to increase the low (~ 15 Hz) frequency response of the sensor. In that expression, τ is the mean time constant which is determined experimentally and in-situ at each measurement location, and E is the thermocouple voltage.

Briefly, the time constant is determined by electrically heating the thermocouple and, when the heating current is turned off, using the computer and appropriate software to monitor the tempera-

ture decay. First an ensemble average is obtained for nine individual realizations of the thermocouple decay. Second, the averaged temperature decay is linearized by taking the natural logarithm of the ensemble averaged decay. Finally, the slope of the resultant curve, which corresponds to the time constant, is determined by the method of least squares. This process is repeated a minimum of six times so that at least 54 individual realizations of the thermocouple decay are used to obtain the mean time constant at each position. Repeated determinations of the mean time constant obtained in this manner vary by about $\pm 10\%$. Also time constants obtained in this manner using AC or DC heating currents differ by no more than $\pm 10\%$.

Velocity Measurements

Velocity measurements are made using a two-color laser anemometry (LA) system. The beam from a 200 mW Argon-ion laser (LEXEL Model 75) is collimated and passes through a prism to separate the various wavelengths. The blue beam (488 nm) and the green beam (514 nm) are the most intense and are each polarized and then split into two beams of equal intensity spaced 50 mm apart. A 40 MHz frequency shift (TSI Model 915 Bragg Cell) is applied to each pair of beams to eliminate directional ambiguity that otherwise results from the turbulent, recirculating flow.

The four beams are focused at a common point within the combustor. A set of perpendicular interference fringes, spaced at 2.6 μm for the green beams and 2.5 μm for the blue beams, are oriented to yield the axial (u) and azimuthal (w) velocity components respectively.

Receiving optics consist of a 120 mm lens focused onto a 0.25 mm diameter photomultiplier tube aperture (via an appropriate dichromate filter to selectively pass either the blue or green light). These optics are placed at an angle of 20° off direct forward scatter which results in a probe volume of 0.022 mm³ and a 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 and azimuthal velocity components be obtained simultaneously, the effective probe cross-section is much less (approximately 0.03 mm²). The transmitting and receiving optics are mounted on an optical bench capable of placing (accurate to ± 0.3 mm) the measurement volume at points throughout the stationary combustor test section.

The air and fuel jet flows are seeded independently but to the same levels of concentration with 1 μm alumina particles. A liquid suspension atomization seeding technique (Ikioka et. al.¹⁰) is employed. Signal validation is obtained using two counter processors (Macrodyne Model 2098).

Data Acquisition

For simultaneous temperature and velocity data acquisition, a sample and hold op amp (AD 583) is used in conjunction with special electronics built to interface the output of the two channel digital counter processor channels with a DEC PDP 11/23 computer. The interface determines whether the two (u and w) velocity events occur within 50 μs of each other which corresponds to a spatial resolution of 0.75 mm.⁶ If so, the data are stored and multiplexed into the computer by means of a parallel interface. Once a u realization and a w realization are determined to have occurred simultaneously, the sample and hold is activated by the interface and the thermocouple signal corresponding to the simultaneous velocities is held. The thermocouple signal is then sampled, digitized and stored with the u, w pair along with the event time (t) relative to the initiation of the run cycle. The raw data sets consisting of u, w, t, T are stored for data reduction and analysis. A detailed discussion of the data acquisition system is available.^{9,11}

Uncertainty

Uncertainty in the velocity data has several sources including statistical convergence due to the finite amount of data, bias error due to particle-averaging versus time-averaging, digital resolution, repeatability of flow conditions, and probe volume positioning accuracy. Seiler⁹ and Brum¹¹ have evaluated these uncertainties and shown that the error in the mean and rms velocity are a few percent. Velocity bias is avoided by using a low seeding rate and thereby operating the counter processors in the unsaturated mode with sample times more than an order of magnitude above the flow correlation time.¹² (The absence of velocity bias is verified by analysis of the time-marked archived data base in uniform time steps of differing intervals.) The collection of 5000 data triplets (u, w, T) requires 30 to 90 minutes. (The time to collect 5000 axial velocity samples is about half that required to collect the data triplets.) A doubling of the sample rate, accomplished by increasing the particle generation rate, reduces the data collection time for 5000 samples by 45 percent for both the axial velocity alone as well as for the data triplets, thereby providing a verification that the data rate is proportional to seeding rate and not a result of misalignment of the laser sampling volumes.

The uncertainty in the temperature data depends as well on repeatability of flow conditions, positioning accuracy of the probe, and finite number of samples. Based on independent realizations of at least 5000 samples, the uncertainties in the mean and rms temperature, due to lack of statistical convergence and not including probe perturbation and

time constant effects, are found to be $\pm 10\%$ and ± 10 to $\pm 30\%$ respectively. The effect of probe perturbation and variation in time constant are discussed separately in the following section.

Results

First, a brief discussion of the probe perturbation study is presented where the perturbation caused by the use of probes of various shapes is reviewed. Second, the effect of time constant variation is discussed followed by a presentation of the temperature time series and the probability density function (PDF) of the temperature. The section concludes with the statistical properties of the combined velocity and temperature field. A tabulated data base, including measured inlet conditions, is available.¹³

Probe Perturbation

The thermocouple probe, while inexpensive and relatively easy to fabricate, must be placed in the flow. Unfortunately, the presence of a physical probe in a recirculating or elliptic flow (cf., Reference 14) can cause local and global flow field perturbation.

Probe perturbation was assessed by separately placing various probe configurations in the flow and determining statistical properties of the velocity field in the presence and absence of the probe.^{7,9} The probe perturbation effects are both small scale (local) and large scale (global). The former is associated with the size of the probe, especially near the probe tip, while the latter is related as well to the overall shape of the probe. Based on this perturbation study, probe configurations were selected to minimize the perturbation. In the central region, the perturbation is both local and global, and a curved probe is required to minimize the perturbation. In the outer regions, perturbation is limited to local effects and a straight probe is acceptable. In both cases, it is necessary to make the probe tip as small as possible.

Using probe sizes and shapes that minimize the perturbation, the perturbation as measured by laser anemometry was found to be significant but within reasonable limits for both the mean and rms velocities except within the recirculation zone itself. Perturbation effects outside the recirculation zone are less than 10% at all axial locations for $r/R \geq 0.2$, less than 20% at $r/R = 0.1$, and 30% on the centerline. At the edge of the recirculation zone, perturbation is less than 20%. Perturbation in the recirculation zone, however, led to differences exceeding 100%. As a result, the acquisition of time-resolved temperature measurements is precluded within the recirculation zone.

Time Constant Sensitivity

Another source of uncertainty is the amount of electronic compensation required to extend the frequency response of the fine-wire thermocouple probe. The correct amount of compensation depends on the physical properties of the gas and the instantaneous velocity and is therefore a fluctuating quantity. Thus, even when the sensor is accurately compensated for mean flow conditions, it will at times be over- or under-compensated. Variations in the time constant will affect statistical quantities associated with the temperature field (e.g., root-mean-square temperature) and introduce a phase shift in the temperature signal which will affect the value of the heat flux.

Time constant sensitivity was assessed by deliberately over- or under-compensating the sensor relative to the value obtained with the sensor compensated for the mean flow conditions.⁶ The effect on mean temperature is not significant. For example, the measured value of the mean temperature varies by less than 10% for a 50% variation in the time constant. The root-mean-square temperature is also relatively insensitive to variation in the time constant. A 10% variation in time constant has less than a 5% effect on the measured root-mean-square temperature which suggests that over- and under-compensation affects that portion of the temperature power spectrum that contributes a relatively small amount to the root-mean-square temperature. However, a 10% under-compensation in the time constant yields a 20% variation in the measured axial heat flux and a 50% variation in the azimuthal heat flux. In contrast, over-compensation has relatively little effect on the value of the heat fluxes. This observation is consistent with that of Yanagi and Mimura.⁴ It is clear that both phase shift and variations in the amplitude response that are correlated with the temperature and velocity affect the value of the heat fluxes, but the difference between the effect of over- and under-compensation is difficult to explain.

Temperature Time Series

Representative samples of the compensated temperature signal are presented in Fig. 2 at different radial positions for the 14 cm axial station. A peak-to-peak temperature of about 500° C is found at the centerline (Fig. 2a) distributed about a mean temperature of 1560° C. The fluid on the centerline is well mixed with no evidence of unheated dilution air reaching the centerline. Peak instantaneous values of temperature approximate the maximum adiabatic flame temperature of 1996° C. The peak instantaneous temperature recorded was as high as 2094° C. Excursions above the maximum adiabatic

FIG. 2. Temperature time series ($x = 14$ cm); a) $r/R = 0.0$ ($\bar{T} = 1560^\circ\text{C}$, $T_{\text{rms}} = 152^\circ\text{C}$); b) $r/R = 0.5$ ($\bar{T} = 580^\circ\text{C}$, $T_{\text{rms}} = 242^\circ\text{C}$); c) $r/R = 0.7$ ($\bar{T} = 135^\circ\text{C}$, $T_{\text{rms}} = 95^\circ\text{C}$).

temperature, which occurred less than 1% of time, are attributed to uncertainties associated with the effects of thermocouple radiation loss and catalysis, and time constant specification.

The temperature time series at the mid-radius position (Fig. 2b) indicates that the temperature signal has positive skewness due to the presence of relative short duration, high temperature peaks. The average rate of occurrence of hot particles (defined as the average rate at which the temperature signal crosses a threshold temperature) is 42 Hz for a threshold of 1000°C . The crossings are not periodic but appear to be distributed randomly in time, and are evidence that a periodic structure is not associated with the passage of the high temperature fluid particles. Power spectral measurements of the temperature signal show a relative increase in the

"energy" of the temperature signal at a frequency of 90 Hz. This corresponds to the frequency of longitudinal oscillation of the recirculation zone observed in high speed photography.¹⁵

Near the wall (Fig. 2c), the temperature signal is dominated by high amplitude, short duration, temperature spikes which correspond to a positive skewness. The average rate of occurrence of hot particles crossing a threshold of 400°C is 25 Hz. Again, the crossings are not periodic. The minimum temperature corresponds to about 40°C . The data obtained at the 24 cm station are similar, indicating that the sheath of dilution air near the wall of the combustor remains intact through the length of the combustor.

Probability Density Function of Temperature

Representative probability density functions (PDF) are presented in Fig. 3 for the axial location, $x = 14.0$ cm. The data are normalized by the maximum adiabatic temperature ($T_{\text{ad}} = 1996^\circ\text{C}$). The PDF's show positive skewness at locations well displaced from this centerline ($r/R \geq 0.6$). This was obtained at all four axial stations and indicates that cool, unreacted gas predominates in this region of the flow throughout the length of the combustor. In addition, the PDF's are narrow in this outer region of the flow which corresponds to low rms temperatures and indicates that only a limited amount of fluid from the hot recirculation zone mixes with the cool dilution air. The PDF's are very broad at the intermediate radial locations of $r/R = 0.4$ and $r/R = 0.3$ with peak-to-peak temperatures on the order of 1100°C , indicating the alternating presence of cool and hot and mixed fluid parcels. Maximum rms temperatures are also found at these ra-

FIG. 3. Temperature probability function, $x = 14$ cm.

dial locations. At $r/R \leq 0.2$, the gas is mainly high temperature (1160° C to 1750° C) combustion products with no evidence of unheated dilution air. The PDF's are similar at the 24 cm station. However, additional mixing between the hot products of combustion and cool dilution and unreacted swirl air is clearly evident. In particular, the PDF's at $r/R \leq 0.2$ are broadened relative to the upstream 14 cm station, and the peak temperatures of the PDF's at the intermediate radial locations ($r/R = 0.3, 0.4$) are reduced.

Characteristics of the Velocity and Temperature Field

Velocity data obtained without the thermocouple probe in place are shown in Fig. 4a. The mean and rms temperature, the axial velocity, and the normalized axial heat flux are shown in Fig. 4b. The velocity data indicate that the statistical features of the flow field remain essentially unchanged from those found in the absence of a probe (Fig. 4a). The mean temperature, at all axial locations, has a maximum near or on the centerline. The maximum

mean temperature in the recirculation region at $x = 2.0$ and 7.0 cm is nearly constant and equal to 1750° C which is approximately 200° C less than the maximum adiabatic flame temperature (1996° C). Radiation losses are estimated to account for approximately 90° C of the 200° C. The nearly constant mean temperature in the recirculation region indicates that the fluid in this region is relatively well mixed. For $r/R \geq 0.7$, the mean temperature is less than 150° C and consequently the flow corresponds to slightly heated dilution air.

Downstream of the recirculation zone (at $x = 14.0$ and 24.0 cm), the mean temperature profile exhibits a maximum of 1400° C on the centerline with a monotonic decay to a minimum near the wall of 125° C.

The axial heat fluxes at the 14.0 and 24.0 cm stations are negative in the central region of the flow ($r/R \leq 0.3$ and 0.4 respectively), and are either relatively small or slightly positive at the midradius positions ($0.4 \leq r/R \leq 0.7$ and $0.5 \leq r/R \leq 0.7$ respectively) and negative at the dilution air interface, $r/R = 0.8$. The negative sign of the axial heat flux in the central region of the flow may be attributed to either high velocity, low temperature or low velocity, high temperature fluid particles. The temperature time-series data (Fig. 2a) precludes the former. Hence, the negative sign corresponds to high temperature, low velocity fluid particles which, most likely, originate in the recirculation zone. The growth of the region of negative axial heat flux in the central region as the axial distance increases downstream is associated with the normal mixing and mean azimuthal velocity which preferentially transports low temperature, high density fluid away from the central region and high temperature, low density fluid toward the centerline. The low values of the axial heat flux at the midradius position corresponds to the fact that fluid is well mixed on this region. At the dilution air interface, the axial heat flux becomes negative because of the occasional presence of high temperature, low velocity particles from the central region of the flow. Evidence of these particles can be seen in Fig. 2c where fluid particles with temperatures as high as 800° C occur.

The mean azimuthal velocity at the 2.0 cm station (Fig. 4c) is relatively low in the recirculation region, with the peak mean azimuthal velocity, as expected, in line with the outer circumference of the swirl vanes. This sharp peak is quickly suppressed ($x = 7.0$ cm) by the interaction with the non-swirl dilution air. The azimuthal heat flux at the $x = 14.0$ and 24.0 cm stations exhibits relatively sharp, positive peaks at radial positions ($r/R = 0.2$ and 0.4 respectively) corresponding to the maximum values of the mean and rms azimuthal velocity.

FIG. 4. Statistical properties of velocity and temperature fields:

- Velocity field without thermocouple probe;¹⁵
- Mean and RMS temperature, axial velocity, and axial heat flux with thermocouple probe;
- Mean and RMS temperature, azimuthal velocity, and azimuthal heat flux with thermocouple probe.

Summary and Conclusions

Compensated fine-wire thermocouples can be used to measure time-resolved temperature along with axial and azimuthal velocity in a complex flow, swirl-stabilized combustor but precautions are required, especially with respect to probe perturbation and survivability. Different probe configurations must be used in the various regions of the flow to minimize probe perturbation. The sensor size required to survive in the flow depends on the mean temperature and velocity intensity and must be increased in high temperature, highly turbulent regions. In the recirculation zone, the time-resolved measurements of temperature are impractical due to severe perturbation of the probe.

The mean temperature is nearly constant in the recirculation zone with instantaneous peaks approximating the maximum adiabatic flame temperature. Further downstream, mixing of hot products with unreacted swirl and dilution air takes place and a gradient in the mean temperature develops in the central region. Axial heat fluxes in the central region are negative, reflecting a large population of high temperature, low velocity fluid from the recirculation region. The azimuthal velocity is shown to increase this population by inducing a transport of low density, high temperature fluid to the axis.

Acknowledgments

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REFERENCES

1. KUNAGI, M., AND JINNO, H.: Seventh Symposium (International) on Combustion, p. 942, The Combustion Institute, 1959.
2. YOSHIDA, A., AND TUSJI, H.: Seventh Symposium (International) on Combustion, p. 945, The Combustion Institute, 1959.
3. LOCKWOOD, F. C., AND MONEIB, H. A.: *Combust. Sci. and Tech.* 22, 63 (1980).
4. YANAGI, T., AND MIMURA, Y.: Eighteenth Symposium (International) on Combustion, p. 1031, The Combustion Institute, 1981.
5. TAMAKA, H., AND YANAGI, T.: *Combust. Flame* 51, 183, 1983.
6. BRUM, R. D., SEILER, E. T., LARUE, J. C., AND SAMUELSEN, G. S.: Instantaneous Two-Component Laser Anemometry and Temperature Measurements in a Complex Flow Model Combustor. Paper presented at AIAA 21st Aerospace Sciences Meeting, AIAA Paper 83-0334, Reno, Nevada, January 1983.
7. SAMUELSEN, G. S., LARUE, J. C., AND SEILER, E. T.: Instantaneous Two-Component Laser Anemometry and Temperature Measurements in a Complex Reacting Flow. Paper presented at the Second Symposium on Applications of Laser Anemometry to Fluid Mechanics, Paper 11.3, Lisbon, Portugal, July 1984.
8. BRUM, R. D., AND SAMUELSEN, G. S.: Assessment of a Dilute Swirl Combustor as a Bench Scale, Complex Flow Test Bed for Modeling, Diagnostics, and Fuel Effects Studies. Paper presented at AIAA/SAE/ASME Joint Propulsion Conference, AIAA Paper 82-1263, Cleveland, Ohio, June, 1982.
9. SEILER, E. T.: Compensated Thermocouple Measurements in a Complex, Reacting Flow, M.S. Thesis, University of California, Irvine, 1983; also available as UCI Combustion Laboratory Report ARTR-83-11, Mechanical Engineering, University of California, Irvine, Ca, 92717.
10. IKIOKA, L. M., BRUM, R. D., AND SAMUELSEN, G. S.: *Combust. Flame* 49, 155 (1983).
11. BRUM, R. D.: Evaluation of a Candidate Model Complex Flow Combustor Using Instantaneous Two-Color Laser Anemometry, Ph.D. dissertation, University of California, Irvine, 1983; also available as UCI Combustion Laboratory Report ARTR-83-5, Mechanical Engineering, University of California, Irvine, Ca, 92717.
12. EDWARDS, R. V., AND JENSEN, A. S.: *J. Fluid Mech.*, 133 (1983).
13. SEILER, E. T.: Tabulated and Documented Data Base: Momentum and Heat Flux for a Propane-Fired, Swirl-Stabilized Complex Flow Combustor (15 mps, $\phi = 0.1$), UCI Combustion Laboratory Report ARTR-83-13, Mechanical Engineering, University of California, Irvine, Ca, 92717, 1983.
14. BILGER, R. W.: Experimental Diagnostics in Gas Phase Combustion Systems (B. T. Zinn, Ed.),

- p. 49, American Institute of Aeronautics and Astronautics, 1977.
15. BRUM, R. D., AND SAMUELSEN, G. S.: Two-Component Laser Anemometry Measurements in a Non-reacting and Reacting Complex Model

Combustor. Paper presented at the Fall Meeting of the Western States Section of The Combustion Institute, Paper WSS/CI 82-53, Livermore, Ca., October, 1982.

COMMENTS

I. M. Kennedy, Aeronautical Research Laboratories, Australia. Does soot buildup on the thermocouple bead in the re-circulation zone, and what are the implications for the frequency compensation of the temperature measurements?

Authors' Reply. No evidence of soot buildup on the probe was found. First, the time constant was determined in-situ at each measurement point in the present work, and no systematic change in the constant was noted over the duration of the experiment. Second, no evidence of soot deposition was detected upon visual inspection of the wire. The reason for this is due to the fact that the overall equivalence ratio is 0.1, and the estimated recirculation zone equivalence ratio is 0.2. As a result, the local fuel concentration is not conducive to the production of soot, as confirmed by optical measurements for soot. In other flows or under other conditions (e.g. different fuels, higher fuel loadings) where soot deposition is a problem, the time constant would increase in time. The compensation would then increase in error with corresponding errors in the temperature statistics and probability density functions.

G. E. Andrews, University of Leeds, Great Britain. Your results show that probes can be used in flames outside recirculation zones without significant flow perturbations. However, you implicitly assume that laser techniques involve no flow perturbations. Your objective was to study a swirl stabilized flame. However, to gain optical access and protect your windows you had to provide an annular dilution flow for flow area greater than that of the swirler. Also you inserted flat windows in a curved wall creating recesses that would generate flow disturbances. These are both major flow perturbations to the system you set out to study, in comparison with which probe disturbances are relatively minor.

Authors' Reply. The dilution flow is introduced to provide closure on the recirculation zone (Reference B in the text). Rather than introducing this

flow through wall jets, as in the case in a gas turbine combustor, the dilution flow is introduced symmetrically at the inlet plane to provide boundary conditions which are amenable to modeling. Secondary benefits of the dilution air are to (1) prolong the clean conditions of the windows, and (2) provide a buffering, soft "wall" interface between the flame zone and the pipe wall, thereby suppressing any wall irregularity. However, the window interface is designed to specifically preclude recesses and, as a result, an associated flow perturbation. Because transitions between the pipe and the windows at both the longitudinal and lateral interfaces are smooth, the effect of the windows on a curved surface is taken to be of second order. A cross-sectional view is shown in Reference 1.

REFERENCE

1. WOOD, C. P., SMITH, R. A., AND SAMUELSEN, G. S., Twentieth Symposium (International) on Combustion.

J. H. Whitelaw, Imperial College, Great Britain. Please state the diameter of the thermocouple wire, the data rate of particles and their type and size. Did these particles influence the time constant of the thermocouple? With 15 μm wire thermocouples in premixed flames and with both Al_2O_3 and TiO_2 particles, particle size is an SMD of around 2 μm , we found significant effects after 10 minutes with less than 60 particles/sec measured by the laser velocimeter control volume which had dimensions of around 1 mm $\times$ 0.15 mm.

Authors' Reply. For measurements in the wake region, the thermocouple junction was formed by spot welding 25 m diameter Pt-Pt/10%Rh wire. As a result, the length scale of the junction was about 1.4 times the wire diameter. Due to lack of probe durability in the recirculation zone, 125 m diameter Pt-Pt/10%Rh wire was required to measure mean temperature.

No evidence for seed particle deposition was found in the present experiment. Repeated measurement of the time constant at a reference position in the wake region of the flow, for example, resulted in measured variations of the time constant of less than +10%. These variations were random and a general trend of the variation, as would be expected if particle buildup had occurred, was not observed. Fi-

nally, particle buildup was not evident in visual inspections of the wires. The absence of particle deposition in the present case is attributed to (1) a low particle seeding rate (10 to 1 particles/sec), and (2) suppressed local temperatures (as a result of the lean conditions) which are conducive to maintaining the alumina particles in a refractory state.