JOURNAL OF PROPULSION AND POWER
Vol. 10, No. 2, March–April 1994

Velocity Characteristics of Reacting and Nonreacting Flows in a Dump Combustor

Robert S. Gabruk*
ARAP Group of Titan Research and Technology, Princeton, New Jersey 08543
and
Larry A. Roe†
University of Arkansas, Fayetteville, Arkansas 72701

A two-component laser Doppler anemometer (LDA) was used to measure mean and turbulent velocities in an axisymmetric dump combustor. Data were acquired for the axial and tangential components and provide a comparison between combusting and isothermal flows. Inlet profiles were carefully documented to provide a suitable boundary condition for future comparison to predictive models. The results show significant differences between the reacting and nonreacting flows. One large-scale observable effect was the difference between the recirculation regions for each case. Combustion decreased the length of the region by approximately 50%, while increasing the maximum velocities. This made for a more compact, but stronger, recirculation region. The reduction in recirculation zone size is recommended as a benchmark criterion in modeling studies. The presence of reaction caused higher turbulent fluctuations near the expansion, and lower fluctuations in downstream regions. The turbulence was observed to be nonisotropic in both the reacting and nonreacting cases.

Introduction

DETAILED experimental data are required to evaluate the validity of numerical models currently under development. The application of models to complex turbulent flowfields continues to be the focus of many studies, as numerical modeling of turbulent flows provides a cost-effective and time-saving method of engineering design. Many experimental studies have concentrated on understanding the behavior of turbulent flows and have not been aimed at specifically improving the accuracy of computational modeling. Lower-order predictive codes require various assumptions in the solution of the Navier-Stokes equations, and experimental data must be available to determine the validity of these assumptions. The results presented herein are appropriate for such comparative purposes and also provide an analysis of the effects of heat release on a turbulent flowfield.

The sudden expansion (or dump) combustor provides a suitable vehicle for both experimental and numerical studies. This configuration models many important characteristics of practical combustion devices, including gas turbine burners and ramjet combustion chambers. The flowfield of a dump combustor is a complex combination of turbulent mixing, flow separation, recirculation, reattachment, and various other phenomena, as shown in Fig. 1. The recirculation region acts as the main flame holder (without physical interjection) by providing a low-velocity region and recirculation of hot combustion products and radical species into fresh reactants. Subsequent convection, diffusion, and decay of the structures developed in the recirculation zone and in the region of high shear between the recirculation zone and the main flow have a significant effect on the overall flowfield of the combustor. The scale, mean velocity profiles, and turbulence parameters associated with the recirculation zone are primary factors governing the development of the overall flowfield.

Received Feb. 27, 1992; revision received June 10, 1993; accepted for publication July 6, 1993.

*Engineer.

†Assistant Professor, Mechanical Engineering Department. Senior Member AIAA.

The main goal of this research effort was to provide a benchmark set of flowfield data that could be used in comparisons with numerical simulations. As a result, the inlet velocity profiles that have seldom been reported in past studies are specifically included to provide a boundary condition for modeling comparisons. The second goal of this research effort was to study the effects of heat release on the flowfield of a simulated ramjet engine. Understanding the effects of combustion on a particular flowfield should provide valuable insight that can be used in future experimental and numerical programs.

Many prior studies have concentrated on isothermal (cold) flows through dump combustors because of the difficulties involved with taking velocity measurements in highly turbulent reacting flowfields. Among the most significant of these are the results of Drewry,[1] Yang and Yu,[2] Samimy et al.,[3] and Nejad et al.[4] These studies generally show a recirculation zone extending approximately 8 step heights downstream from the dump plane, and peak turbulence levels located in the region of highest shear between the recirculation zone and the core flow.

Comparisons of reacting flows to nonreacting cases have been made in several different geometries, including the coaxial studies of Baker et al.,[5] Owen,[6] and Smith and Giel,[7] the two-dimensional step combustor experiments of Ganji and Sawyer,[8] Banhawy et al.,[9] and Pitz and Daily,[10] and the centerbody studies of Lightman et al.,[11] Schefer et al.,[12] and Roe and Proctor.[13] A common conclusion was that existing turbulence models were inadequate to accurately describe the physics of the combusting flowfields studied.

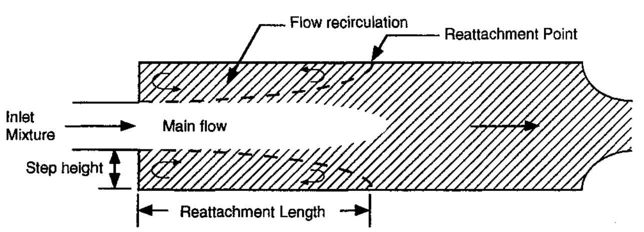

Fig. 1 Schematic illustration of a dump combustor flowfield. Shaded area indicates approximate hot region of the flow.

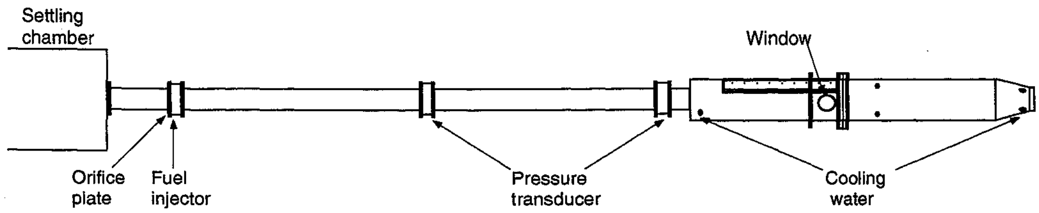

Fig. 2 Inlet duct and dump combustor.

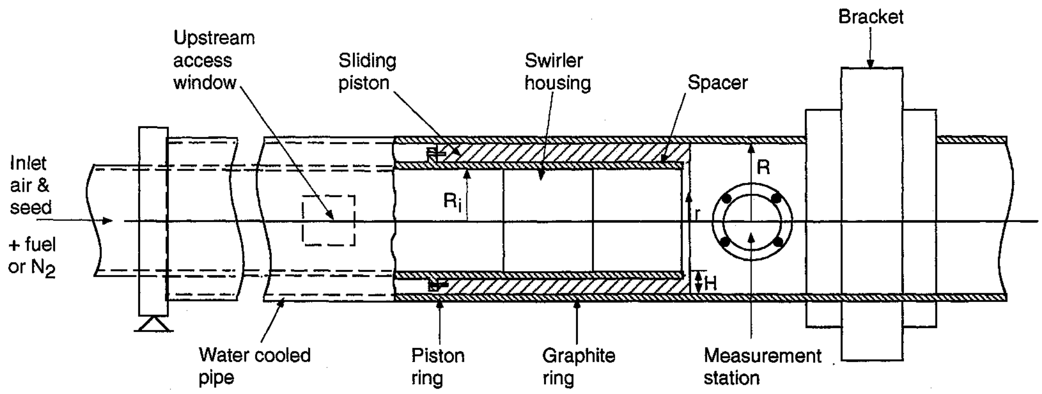

Fig. 3 Cross-sectional view of dump combustor.

Some information relevant to reacting flows in axisymmetric expansion combustors is available in the literature. Stevenson et al.[14] compared nonreacting and reacting flows in a combustor configuration similar to the one used in this research. Significant differences were observed between mean centerline velocities and the extent of the recirculation zones. Turbulent velocity fluctuations were similar in both cases. Nejad et al.[15] conducted a stability and flow-visualization study on the same combustor used for this study, and compared some limited reacting-flow velocity data to cold flow data obtained from a geometrically similar acrylic model. Evaluation of the velocity data led to observations generally similar to those of Stevenson et al.,[14] although the magnitudes of the flowfield changes accompanying the presence of reaction were different.

Dump Combustor

All experiments were conducted in a stainless steel model of a ramjet dump combustor as shown schematically in Figs. 2 and 3. This is the same combustor used in a stability analysis and preliminary flowfield investigation by Nejad et al.,[15] where a more detailed description may be found. The combustor wall contained a high-quality quartz window for optical access to the flow.

A 10.16-cm-diam inlet duct supplied air to the 15.24-cm-diam combustion section. The combustor had a maximum length of 162 cm, a minimum length of 132 cm, and terminated with an unchoked, 15.24-cm-long exit nozzle, with a 60% area reduction. The inlet air was supplied by high-pressure compressors to achieve a 18.3 m/s average velocity, corresponding to a 1.18×10^5 Reynolds number. Inlet pressure and temperature were ambient (300 K, 100 kPa) at the dump plane. A screen was located 46.4-cm upstream of the dump plane to guard against flashback. An orifice plate was mounted in the inlet duct downstream of the settling chamber and just upstream of the fuel injectors to reduce airflow-coupled instabilities and isolate the reaction region from the large acoustic resonant contribution of the settling chamber. Provisions for a swirler immediately upstream of the dump plane are incorporated into the design, although swirl was not utilized in this series of studies.

The propane fuel was injected 3.35 m upstream of the dump plane through four 0.318-cm-diam injector tubes. Each tube had a 1.65-mm-diam fuel orifice located in the side, intruded radially into the flow, and could be adjusted to inject at various radial positions. Overall equivalence ratio was 0.65; nitrogen was used in the nonreacting flow cases to simulate fuel injection.

Laser Doppler Anemometer

The LDA system was primarily composed of TSI Corporation components and utilized a Spectra Physics model 164 laser operating in the multiline mode at a total output power level of 1.5 W. The blue (488 nm) and green (514.5 nm) lines were used to measure flow velocities. Each of these beams (blue and green) was split into two beams, with one beam of each color receiving a frequency shift for directional sensitivity.

The optical system, which operated in the backscatter mode, consisted of a standard TSI beam splitter, a frequency shifter (TSI model 9180-3A) operating at 40 MHz for each channel, a 3.75× beam expander, and a transmitting/receiving lens with a focal length of 450 mm. The entire optical system was mounted on a three-axis traversing table. Fringe inclinations were aligned at 45.7 and 135.2 deg from the combustor centerline with the axial and tangential velocity components resolved geometrically.

Some in-house modifications were made to the TSI system and the alignment procedure. These included micrometer adjustment screws for the field stop lens system and both receiving optic modules, which allowed for adjustment to provide the highest possible data rates and best Doppler signal. A 20-μm aperture was used in the alignment procedure to ensure all four beams crossing at the same point.

Signal processing was accomplished with two TSI counter-type systems. The high filter limits were 100 MHz and the low were 20 MHz; the actual data frequency range was approximately 30–40 MHz, well within the filter settings. Sixteen cycles of each burst were evaluated to determine the Doppler frequency and were validated by comparison to an 8-cycle count, with a maximum deviation of 1% permitted between the two timings. A 20-μs channel-to-channel coincidence window was used to guarantee properly correlated velocity data.

A custom-made interface linked the two LDA processors to the data analysis computer. Double-precision calculations of all statistical moments using standard formulas[16] were made at each measurement location. Postprocessing cutoff limits of three standard deviations were made on the calculated velocity histograms.

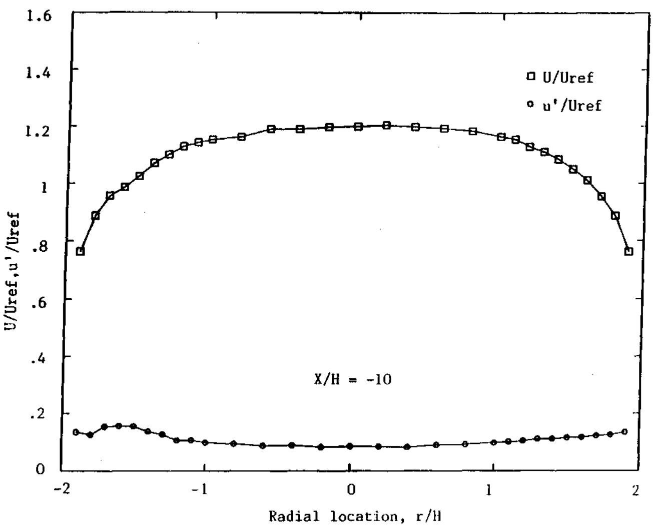

Fig. 4 Inlet velocity profiles.

The seeding material, TiO_2, was produced from the chemical reaction between $TiCl_4$ and the moisture in the ambient air. The seed size, as determined from samples extracted from the recirculation zone, was approximately 1 μ. $TiCl_4$ injection occurred just upstream of a flow settling chamber located 3.12 m from the expansion plane. Since the seed was injected far upstream of the combustor in a low velocity settling chamber and then accelerated through a long section of inlet duct, the seed distribution was assumed to be uniform at the combustor inlet.

In any interpretation of LDA velocity data, the method of acquisition and analysis must be considered. Edwards,[17] in a report of the special panel session on statistical biasing problems in LDA systems (held at the 1985 International Symposium on Laser Anemometry), gives recommendations on how LDA measurements should be treated and reported. This work follows these guidelines as closely as possible, although some of the suggested parameters, specifically the Taylor time microscale, particle arrival rate, and trigger rate were not readily available.

Stored data rates (coincident pairs of realizations from each signal processor) ranged from 15 to 500/s for hot flows, and 100–1000/s for cold flows. The data acquisition capability of the interface/computer system is much faster than this, so the "validation rate" is the same as the stored data rate. Although the Taylor time microscale (which is a measure of the time that the flow needs to change one standard deviation) could not be determined, the data density is expected to be in the low category. For the majority of flowfield locations, 4096 velocity measurements were taken. In the near-wall regions, where data rates were typically low, 1024 measurements comprised a data set.

Biasing was minimized by both hardware constraints and data acquisition techniques. Angle bias was virtually eliminated by the 40-MHz Bragg cells since this frequency is much greater than the Doppler frequency of the flow. Filter settings well outside the Doppler frequencies eliminated filter bias problems caused by roll-off. In an effort to minimize velocity bias, particle interarrival time weighting (also referred to as time-between-data-points, or TBD weighting) was implemented. The particle interarrival time method uses the time between each realization as the weighting factor. The specific method is described in depth by Nejad and Davis.[16]

Estimated maximum uncertainties in the experimental results were established through a series of repetitive experiments at (nominally) fixed conditions, and by comparison of these data to previous investigations using the same instrumentation, seeding system, and combustor dimensions.[4,15,16] For the mean velocities, the repeatability was within 5%, with the major contribution (2.5%) coming from control of the airflow rate. The turbulent fluctuations were also repeatable within 5%. Contributors to the uncertainty include seeding nonuniformity, spatial averaging in regions of high velocity gradients, and contamination of the window. The sensitivity of the results to the number of velocity measurements was also established through repetitive testing, with the number of data points ranging from 1024 to 4096. Repeatability was again within 5%.

Experimental Results

Graphical results for mean axial velocities and turbulent fluctuations in both the axial and tangential directions are presented and discussed. Velocity data are normalized by Uref, the average velocity at the inlet section (18.3 m/s), while radial and axial positions are normalized by the step height H (2.54 cm). The mean tangential velocities were zero (within the accuracy of the instrumentation) since swirl was not used in this series of baseline studies. More detailed profiles and local histograms may be found in Gabruk.[18]

Inlet Conditions

The inlet velocity profile at 25.4 cm (10 step heights) upstream of the dump plane is shown in Fig. 4. The reacting and nonreacting cases had identical profiles. Both the streamwise mean and turbulent velocities (normalized with the average inlet duct velocity) are shown. As can be seen from the figure, the mean velocity profile is fairly symmetrical about the inlet duct centerline, and the turbulent velocities are approximately 15% of the average inlet duct velocity.

Centerline Measurements

Centerline mean velocity and turbulence results (for both reacting and nonreacting cases) are shown in Figs. 5–7. These figures are designed to illustrate the effects of heat release on the flowfield of the dump combustor. Figure 5 shows a gradual decay of cold flow centerline axial velocity throughout the length of the combustor. Other experimental data[3,4,14,15] show similar trends. This is consistent with mass continuity principles, i.e., when given constant density, an increase in flow area will cause a decrease in flow velocity.

It can be seen in Fig. 5 that heat release has little effect on the mean centerline velocity for axial locations less than approximately 10 step heights from the dump plane. The similarity between the hot and cold flow velocities is due to the lack of combustion occurring in the high-speed potential core in the center of the flowfield. The potential core is a region of the flow where the inlet centerline velocity is maintained. The length of the potential core is on the order of 9–10 step heights for the reacting case, and 7–8 step heights for the nonreacting flow. These potential core lengths are in agreement with the values reported by Stevenson et al.[14] It should also be noted that the end of the potential core is marked by a regional deceleration in the cold flow case and an acceleration in the hot flow case.

Downstream of the noncombusting potential core, heat release has a significant effect in the center of the combustor flowfield. After $X/H = 10$, the mean axial velocities (for the reacting case) begin to increase rapidly as the density decreases, as expected from continuity requirements.

The cold flow centerline axial and tangential turbulence intensities (Figs. 6 and 7), on the other hand, increase in the downstream direction until approximately 18 step heights. This trend is also typical of the results of other researchers.[3,4,14,15] This increase in turbulence intensity is believed due to the convection and diffusion of high turbulent energy created in the shear layer during flow separation. After 18 step heights, however, the turbulence decreases as the flow becomes more developed. The maximum turbulence level (based on inlet duct average velocity) is about 20%, at 18 step heights from the dump plane.

One observation to be made from the turbulent velocity data is that the axial turbulence levels are always greater than

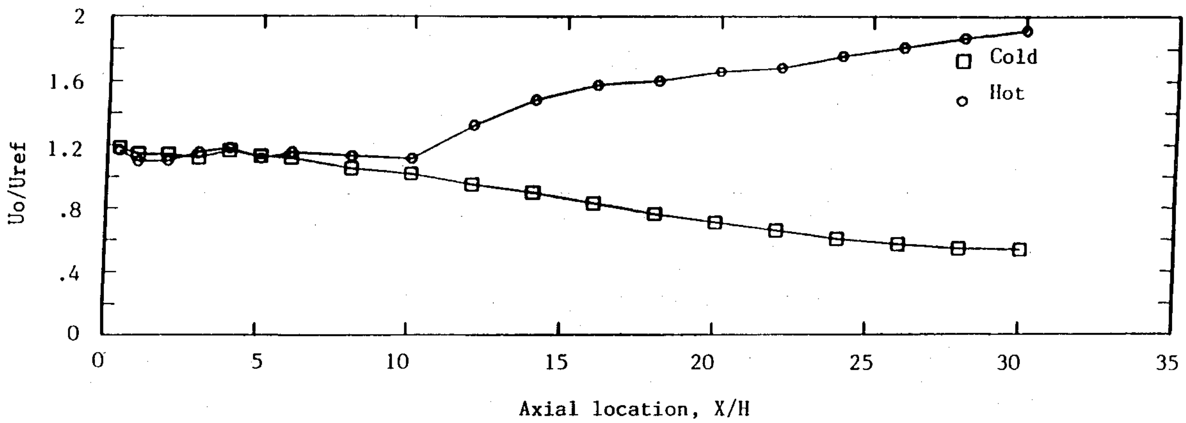

Fig. 5 Mean axial velocity along combustor centerline.

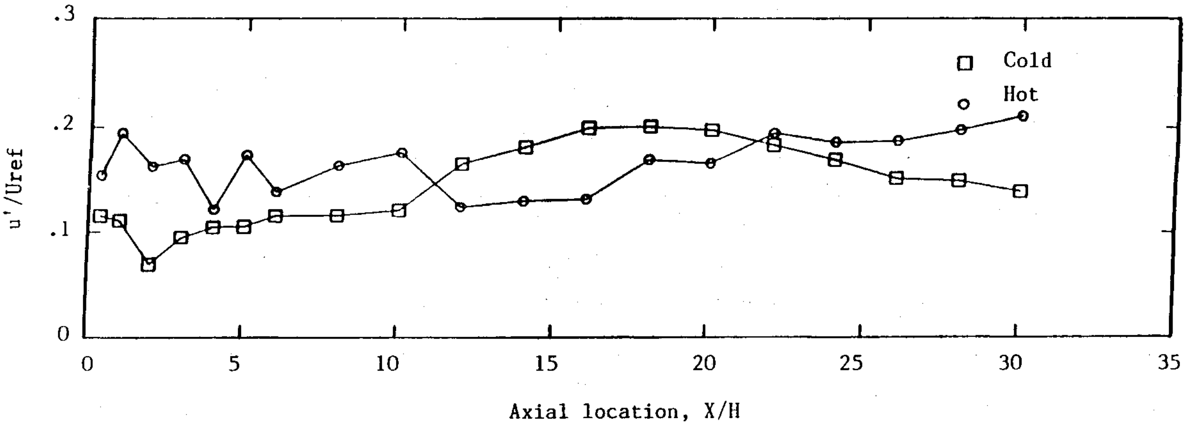

Fig. 6 Centerline distribution of axial turbulence component.

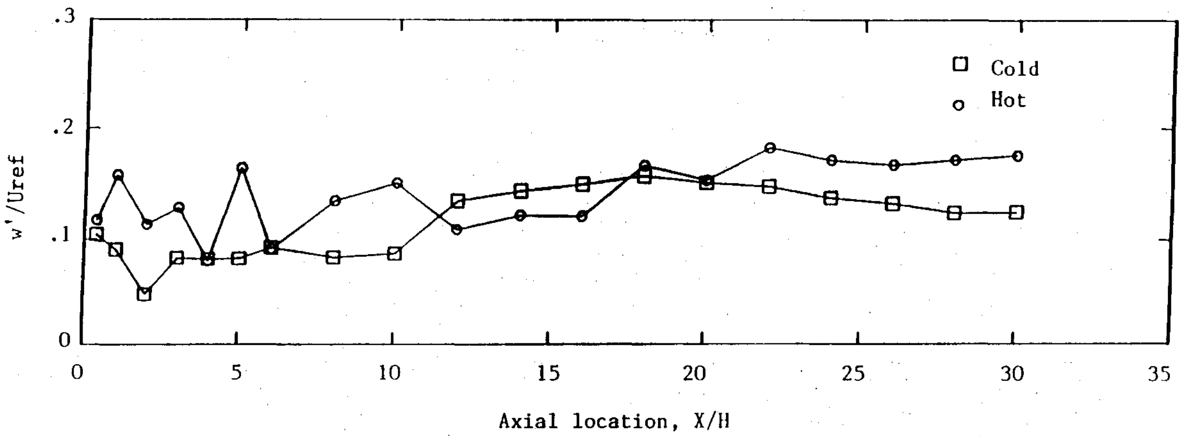

Fig. 7 Centerline distribution of tangential turbulence component.

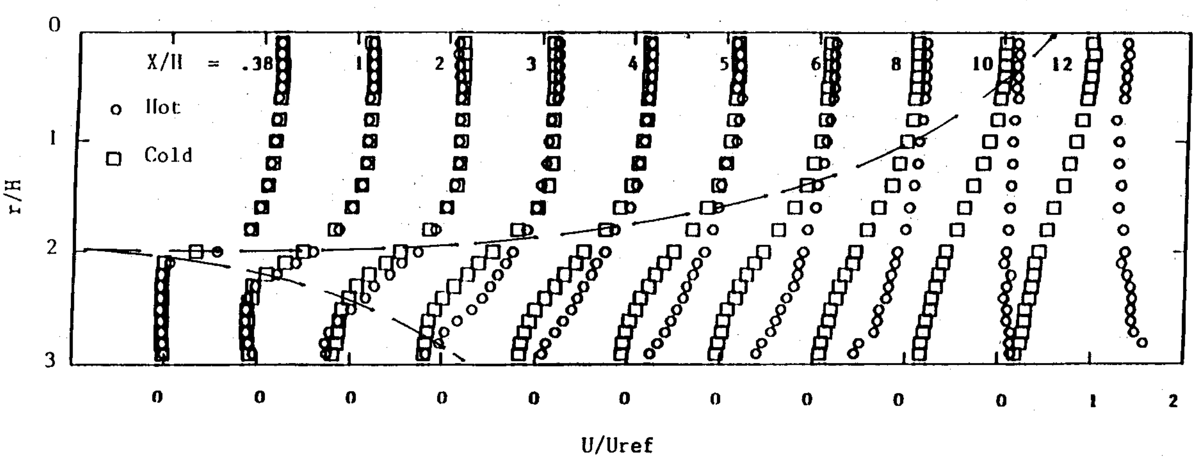

Fig. 8 Evolution of the mean axial velocity profiles. Heavy line approximately separates cold reactants (upstream) from hot regions of the flow.

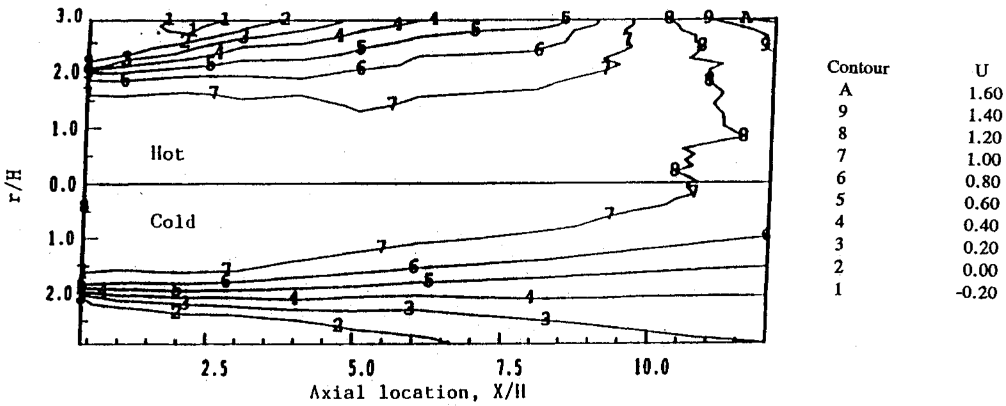

Fig. 9 Lines of constant axial velocity for both hot and cold flow cases.

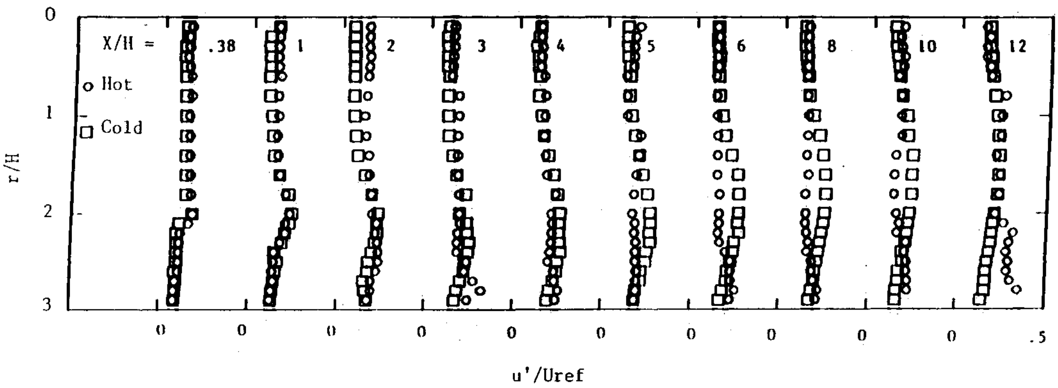

Fig. 10 Evolution of the axial turbulence profiles.

the corresponding tangential levels in both reacting and nonreacting cases (Figs. 6 and 7), although the general trend of turbulence level with axial location is almost identical. Similar observations have been made previously.[5–7,14,15] This is an important observation since this means that the flow demonstrates little turbulence isotropicity. Since many numerical models assume turbulence isotropicity, the results obtained from these models cannot generally be expected to show good agreement with experimental data from separated flows, especially in the presence of reaction.

The differences between the hot and cold flow turbulence intensities can be partially attributed to changes in the mean flowfield. It will be seen later in this section that the reacting case has a considerably shortened region of recirculation, associated with higher recirculation velocities. Downstream of the potential core, the reacting flow turbulence levels show a sharp decline just across the flame front (at $X/H \approx 11$), and then a gradual rise throughout the remainder of the combustor as the mean velocities increase.

Mean and Turbulent Velocity Profiles

Radial profiles of mean axial velocities at various axial locations are presented in Fig. 8. At axial locations of 0.38–6 step heights from the dump plane, there is very little difference between the nonreacting and reacting cases in the potential core (r/H less than 0.5). This is expected since there is very little combustion occurring in the high-speed core near the dump plane. The reaction zone originates at the step ($r/H = 2.0$), and propagates both radially inward and outward to form a hot, accelerated, annular region, which surrounds the potential core. At axial locations greater than (about) 10 step heights, however, a rapid acceleration of the flow due to local energy release is evident, marking the propagation of the reaction to the centerline and the end of the potential core flow in the reacting case. This is also seen in Fig. 5. Some acceleration of the core flow for the reacting case is evident in the region between $X/H = 6$ and 10. This is not due to local expansion of the gases caused by reaction, as the reaction has not yet reached the centerline. The core acceleration in this region is caused by a combination of mechanisms; momentum transport from flow in the rapidly accelerating annular reaction zone, and local expansion due to temperature increases caused by heat transfer from the surrounding, reacting region.

There are significant differences between the hot and cold flow mean axial velocities outside of the potential core (r/H greater than 2). This becomes even more apparent as the flow progresses downstream. At axial locations less than 4 step heights from the dump, the high shear region between the potential core and the recirculation region (near the combustor wall) can be clearly identified by the high-velocity gradient. Measurements near the combustor wall show rapid velocity decay and a region of flow reversal in the corner recirculation zone.

The corner recirculation region can be more clearly identified in a contour plot of constant velocity lines (Fig. 9). Contour 2 indicates the line of zero axial velocity, with the recirculation length defined by the intersection of this contour with the combustor wall. The recirculation length is much shorter for the reacting flow, although the maximum negative velocity is greater. For the hot flow, the recirculation length is approximately 3.5 step heights from the dump plane, opposed to 6.75 for the cold. The trend in these results is consistent with the experience of other researchers.[10,14,15] It is expected that the extent of the reduction in recirculation zone length caused by reaction will be related to the specific geometry and the inlet flow conditions to the combustor section. Differences in geometry and the unavailability of inlet data make direct numerical comparisons to the referenced work infeasible.

The turbulent velocity profiles are shown in Figs. 10 and 11. Although a direct comparison between these figures is somewhat difficult, it can be recognized that the axial turbulent velocities are generally greater than the corresponding

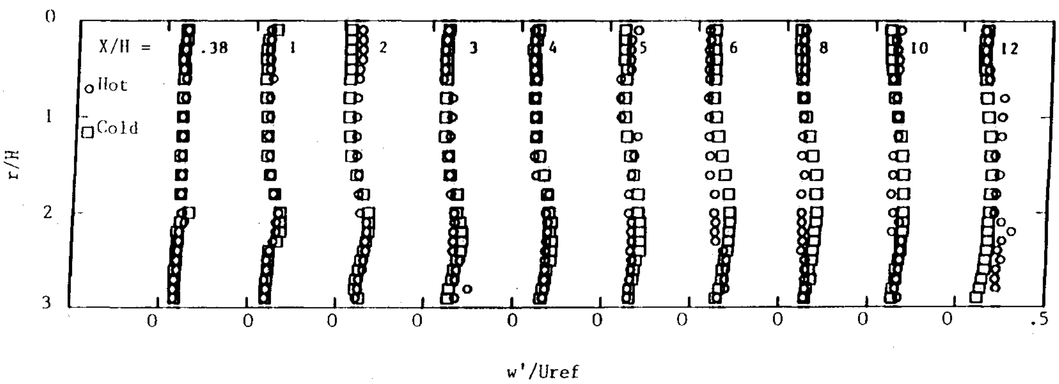

Fig. 11 Evolution of the tangential turbulence profiles.

tangential turbulent velocities, although the maximum turbulence levels occur at the same radial position. Furthermore, in the beginning region of the core flow (where X/H is less than 5), heat release has only a small effect on both the axial and tangential turbulent intensities, with the exceptions of higher intensities at $X/H = 1$ and 2. Examination of Fig. 9 indicates that this region of the core is in close proximity to the area of maximum negative velocity in the recirculation zone, which may provide a source for high turbulent energy transport into the core. It should also be recognized that the length of the recirculation zone is a time-averaged concept, and temporal fluctuations in the reattachment length will lead to velocity fluctuations in adjacent regions of the flowfield. A relatively sparse data matrix in the results of Stevenson et al.[14] makes a direct numerical comparison to these results difficult.

In the vicinity of the high shear region, the reacting and nonreacting turbulence levels differ significantly. As the flow progresses downstream from the dump plane, the location of the maximum turbulence level (which usually corresponds with the high shear region) shifts towards the wall much sooner for the reacting flow, consistent with the smaller recirculation region.

Further downstream, where X/H is greater than 4, the turbulence is observed to be lower in the reacting case. This is not surprising since the recirculation zone length for the reacting case is only 3.5 step heights, while recirculation continues until nearly 7 step heights for the nonreacting case. This essentially changes the scale of the flowfield. In fact, some consideration of scaling the overall results based on recirculation length rather than step height should be considered in future modeling and experimental comparisons. After the flame front penetrates the potential core (at locations greater than 10 step heights from the dump) the axial and tangential turbulent velocities increase with the mean velocities.

The turbulent levels near the combustor wall also seem to be affected by combustion, with an apparent increase at some downstream locations (where X/H is greater than 6). Stevenson et al.[14] also encountered this trend. One possible explanation for this is that the turbulence in the near-wall region downstream of the reattachment point is more intense for the reacting flow. Not only are the mean velocities greater (at these locations) for the reacting case, but so is the distance from the reattachment point, allowing more development to occur. Some of the turbulent energy is being convected radially inward and appears as an increase in turbulence in the near-wall region.

Conclusions

The main concerns of this study were to provide flowfield data, with inlet conditions, sufficient for eventual modeling comparisons and to document the effects of heat release on the combustor flowfield. Subsonic, recirculating flow experiments were conducted in an axisymmetric dump combustor with a combustor-to-inlet diameter ratio of 1.5. The fuel/air mixture was supplied at an inlet velocity of 18.3 m/s with an equivalence ratio of 0.65. From the velocity measurements, it is possible to make specific observations and conclusions.

1) Heat release has a significant effect on the corner recirculation region. The reattachment length is about 6.75 step heights for the isothermal flow and 3.5 for the combusting flow, a 52% reduction. Furthermore, maximum negative velocities are greater for the reacting case. Hence, the combusting flow has a shorter, but more intense, recirculation region. The recirculation zone extent is suggested as a primary criterion for evaluation of modeling studies.

2) The mean and turbulent velocity measurements clearly identify the potential core for both the nonreacting and reacting flows. The potential core is a region in the flowfield where the inlet centerline velocity is maintained and, for the reacting case, little combustion occurs. The potential core persists for approximately 10 step heights for the reacting flow and 8 step heights for the nonreacting flow. The potential core lengths are similar for the two cases because only a small amount of local expansion occurs in the hot flow case.

3) In the far field, at axial positions greater than 4 step heights from the dump, the reacting flow has lower turbulence levels than the isothermal flow. This suggests that heat release causes a substantial decrease in turbulent mixing and transport in this geometry. This may also be related to the fact that this region is farther downstream from the recirculation zone and associated high shear region in the reacting case. The turbulence was nonisotropic in all cases.

4) The turbulent fluctuations near the dump plane and in the potential core were higher for the reacting flow cases. This can be attributed to the fact that the hot flow had a more intense and turbulent recirculation region that convected more turbulent energy into the potential core.

Acknowledgments

The support of the Experimental Research Branch, Advanced Propulsion Division, Aeropropulsion and Power Directorate, Wright Laboratories, is greatly appreciated. Special acknowledgment is made of the support and assistance of A. S. Nejad, S. A. Ahmed, and Charlie Smith. This research was sponsored by the Air Force Office of Scientific Research/AFSC, United States Air Force, under Contract F49620-88-C-0053. The United States Government is authorized to reproduce and distribute reprints for governmental purposes notwithstanding any copyright notation thereon.

References

[1]Drewry, J. E., "Fluid Dynamic Characterization of Sudden-Expansion Ramjet Combustor Flowfields," *AIAA Journal*, Vol. 16, April 1978, pp. 313–319.

[2]Yang, B. T., and Yu, M. H., "The Flowfield in a Suddenly En-

larged Combustion Chamber," *AIAA Journal*, Vol. 21, Jan. 1983, pp. 92–97.

[3]Samimy, M., Nejad, A. S., Langenfeld, C. A., and Favaloro, S. C., "Oscillatory Behavior of Swirling Flows in a Dump Combustor," AIAA Paper 88-0189, Jan. 1988.

[4]Nejad, A. S., Favaloro, S. C., Vanka, S. P., Samimy, M., and Langenfeld, C., "Application of Laser Velocimetry for Characterization of Confined Swirling Flow," American Society of Mechanical Engineers Paper 88-GT-159, Amsterdam, The Netherlands, June 1988.

[5]Baker, R. J., Hutchinson, P., Khalil, E. E., and Whitelaw, J. H., "Measurements of Three Velocity Components in a Model Furnace with and Without Combustion," *Fifteenth Symposium (International) on Combustion* (Tokyo), The Combustion Institute, Aug. 1974, pp. 553–558.

[6]Owen, F. K., "Laser Velocimeter Measurements of a Confined Diffusion Flame Burner," AIAA Paper 76-33, Jan. 1976.

[7]Smith, G. D., and Giel, T. V., "An Experimental Investigation of Reactive, Turbulent, Recirculating Jet Mixing," Arnold Engineering Development Center TR-79-79, May 1980.

[8]Ganji, A. R., and Sawyer, R. F., "Experimental Study of the Flowfield of a Two-Dimensional Premixed Turbulent Flame," AIAA Paper 79-0017, Jan. 1979.

[9]El Banhawy, Y., Sivasegaram, S., and Whitelaw, J. H., "Premixed Turbulent Combustion of a Sudden Expansion Flow," *Combustion and Flame*, Vol. 50, No. 2, 1983, pp. 153–165.

[10]Pitz, R. W., and Daily, J. W., "Combustion in a Turbulent Mixing Layer Formed at a Rearward-Facing Step," *AIAA Journal*, Vol. 21, Nov. 1983, pp. 1565–1570.

[11]Lightman, A. J., Richmond, R. D., Krishnamurthy, L., Magill, P. D., Roquemore, W. M., Bradley, R. P., Jr., Stutrud, S., and Reeves, C. M., "Velocity Measurements in a Bluff-Body Diffusion Flame," AIAA Paper 80-1544, July 1980.

[12]Schefer, R. W., Namazian, M., and Kelly, J., "Velocity Measurements in a Turbulent Nonpremixed Bluff-Body Stabilized Flame," AIAA Paper 87-1349, June 1987.

[13]Roe, L. A., and Proctor, C. L., II, "Velocity Measurements in a Turbulent Centerbody Diffusion Flame," *AIAA Journal*, Vol. 28, No. 4, 1990, pp. 655–660.

[14]Stevenson, W. H., Gould, R. D., and Thompson, H. D., "Laser Velocity Measurements and Analysis in Turbulent Flows with Combustion," Pt. II, Air Force Wright Aeronautical Labs. TR-82-2076, July 1983.

[15]Nejad, A. S., Ahmed, S. A., Roe, L. A., and Gabruk, R. S., "Experimental Studies of Reactive and Non-Reactive Flows in Dump Combustors," American Society of Mechanical Engineers Paper 90-GT-82, June 1990.

[16]Nejad, A. S., and Davis, D. L., "Velocity Bias in Two-Component Individual Realization Laser Doppler Velocimetry," *Proceedings of the 5th International Congress on Application of Lasers and Electro Optics*, Arlington, VA, Nov. 1986, pp. 78–88.

[17]Edwards, R. V. (ed.), "Report of the Special Panel on Statistical Particle Bias Problems in Laser Anemometry," *Journal of Fluids Engineering*, Vol. 109, No. 2, 1987, pp. 89–93.

[18]Gabruk, R. S., *The Characterization of the Flowfield of a Dump Combustor*, M.S. Thesis, Virginia Polytechnic Inst. and State Univ., Blacksburg, VA, Sept. 1992.