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Authors
Cameron, CD
Brouwer, J
Samuelsen, GS

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A MODEL GAS TURBINE COMBUSTOR WITH WALL JETS AND OPTICAL ACCESS FOR TURBULENT MIXING, FUEL EFFECTS, AND SPRAY STUDIES

C. D. CAMERON, J. BROUWER AND G. S. SAMUELSEN
UCI Combustion Laboratory
Department of Mechanical Engineering
University of California
Irvine, CA 92717

A model laboratory reactor is presented and characterized for the study of spray-fired combustion in a swirl-stabilized, complex, three-dimensional flow representative of a gas turbine combustor. The reactor features optical access for non-intrusive diagnostics, and clean boundary conditions for modeling. The aerodynamic and thermal fields are characterized using laser anemometry and a thermocouple probe respectively. The droplet size and droplet velocity fields are resolved using phase Doppler interferometry. The performance of the reactor is found to be representative of a practical combustor with a well defined dome region primary zone, a secondary zone between the two rows of wall jets in which reaction persists, and a relatively well-mixed and cool dilution zone. A parametric study of the dome geometry indicates that the structure of the dome region recirculation is relatively insensitive to a change from a step to a 45° divergent dome expansion. A parametric study of the dome swirl, primary jet, and dilution jet flows shows that the primary air provides closure to the dome recirculation and enhances the turbulent mixing. The reactor is attractive for studies of turbulent mixing, fuel effects, and spray dynamics in this class of flows.

Introduction

The design of continuous combustion systems is today predicated on empirical data associated with the overall combustion performance of the system. Little is known about the detailed aerodynamics, the detailed mixing of the fuel and combustion air, and the relationship of these processes to the overall system performance. The reasons are associated with: (1) the absence of model reactors with optical access and clean boundary conditions in combination with the necessary features representative of practical systems, (2) key voids in diagnostic capability, and (3) the lack of data to develop and validate numerical codes for complex, two-phase flows.

The present program addresses all three of these voids. First, a model reactor is introduced for the study of fuel effects, turbulent mixing, and spray-aerodynamic interactions in a practical system of special interest to combustion technology. Second, a new diagnostic technique for the measurement of droplets is introduced in combination with conventional diagnostics for the detailed measurement of the aerodynamic, and thermal fields in a complex, two-phase flow reactor. Third, data are acquired for use in the development and validation of numerical codes.

The system selected for the model reactor is the gas turbine combustor. The design and operation of gas turbine combustors are relatively consistent from system to system in contrast to other continuous combustion systems (e.g., incinerators, boilers, and furnaces). In addition, substantial interest is now directed to gas turbine combustion as a result of: (1) a goal to double gas turbine engine performance, (2) the need to create combustor/nozzle systems that are fuel flexible, and (3) the initiative to expand combustor technology in support of hypersonic flight.

The objective of the present study is to present, and to characterize, a model laboratory reactor with optical access that is representative of gas turbine combustors including spray injection, swirl-stabilized dome aerodynamics, and wall jet injection.

Background

In recent work at the UCI Combustion Laboratory, a model gas turbine can combustor has been designed to provide optical access for laser diagnostics, clean boundary conditions amenable to modeling, and the critical features of practical combustors such as liquid atomization, dome region injection of swirl air, discrete wall jets, and elevated pressure operation.[1] This model reactor, the Wall Jet Can Combustor (WJCC), evolved from a two-dimensional Axisymmetric Can Combustor (ASCC).[2] Schematics of both model reactors are presented in Fig. 1. The major changes in the ASCC design incorporated in the final WJCC design are (1) the replacement of the front face injection of dilution air with two rows of discrete wall injection, (2) dome expansion, and (3) a smaller swirler.

While the ASCC has been useful in the evaluation of fuels effects,[3] the effect of inlet condition specification on the flowfield,[4] the formation of soot,[5] the effect of complex aerodynamics on atomizer performance,[6] and the acquisition of data for the development and verification of elliptic flow numerical codes,[7] the swirl-stabilized axisymmetric flow does not include the critical three-dimensional effects of discrete wall injection. The WJCC addresses this requirement. The design is based upon input and critical review of major engine manufacturers and end users.[1]

The present paper describes the WJCC and presents a characterization of the model reactor under both nonreacting and liquid spray-fired, reacting conditions. Insitu measurements of mean and rms velocities, mean temperature, droplet size, and droplet velocity are acquired. For the case of reacting flow, data are acquired for a parametric variation in dome geometry and wall jet to swirl air flow splits.

Approach

The approach is to first describe the final design of the WJCC and the experiment, and then to present a characterization of the flowfield structure via detailed maps of: (1) gas mean and rms velocities with a laser anemometer, (2) mean temperature with a thermocouple probe, and (3) droplet size, velocity, and data rate with a phase Doppler interferometer.

Model Reactor

The WJCC (Fig. 1b) is an 80 mm stainless steel duct, with an operating length of 32 cm. Air flow to the combustor passes through a preheater section and is then split into three separate lines delineated as the dome swirl, primary jet, and dilution jet air lines. The swirl air enters the combustor at the inlet plane while the primary and dilution jet flows are sent to the discrete wall jets of the

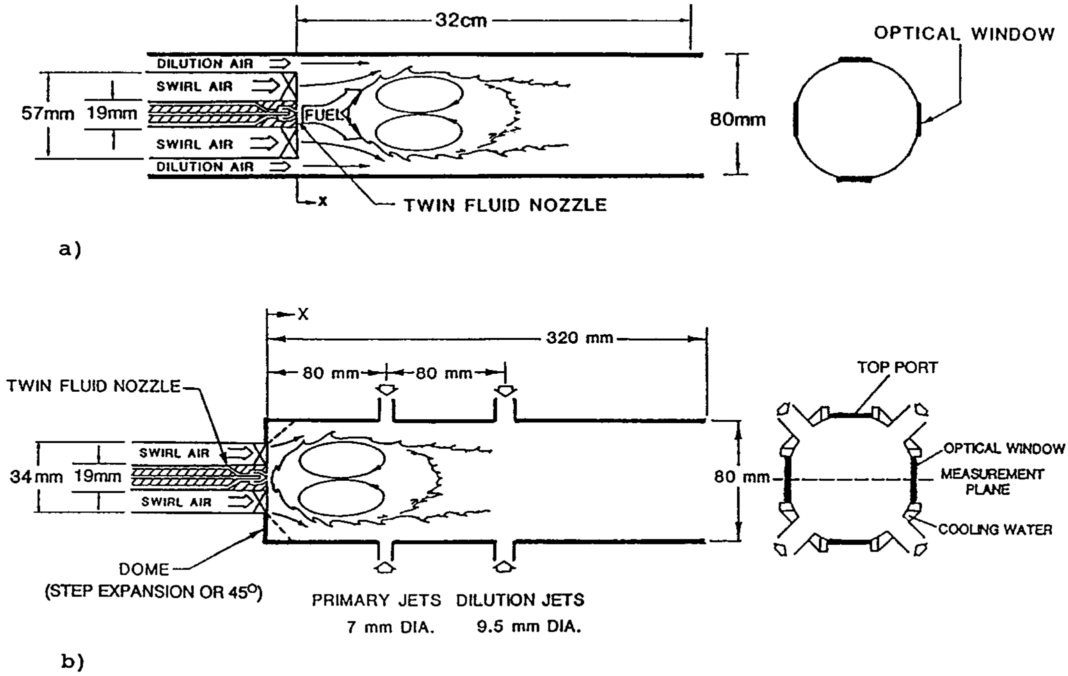


FIG. 1. Model Reactors
a) Axisymmetric Can Combustor (ASCC)[3]
b) Wall Jet Can Combustor (WJCC)[1]

WJCC. Each line is separately metered and controlled so that the flow splits may be varied.

As shown in the end view of Fig. 1b, four 25 mm × 306 mm rectangular ports are located longitudinally around the combustor for diagnostic access. The plane of optical measurements bisects the wall jets through the side ports (outfitted with flat, optical quality quartz windows) while the top port is available for wall thermocouple and/or radiometer measurements.

Two rows (primary and dilution) of discrete wall jets are included, each consisting of four orthogonally located jets positioned one and two combustor diameters downstream from the inlet. The locations are based on designer's inputs and experimental tests of combustion performance in a prototype model with multiple jet combinations.[1] The performance criteria considered included combustor efficiency calculated with exit plane gas species concentration and combustor stability as documented with high speed photography. The prototype testing also resulted in the selection of primary and dilution jet diameters of 7 mm and 9.5 mm respectively.

A 19 mm O.D. centrally positioned fuel delivery assembly is sized to house a twin fluid air-assist atomizer (Parker Hannifin) specially designed for the present application. The spray angle is measured (photographically) to be 60°. The dome swirl vanes are concentrically positioned within the combustor around the fuel delivery assembly. The vanes impart a 60° angle of turn to the flow with 100% solidity (i.e., percentage of blockage). Based on design criteria and the evaluation of alternate sizes in the prototype testing, the swirl vane outer diameter in the present configuration is 34 mm. The model combustor is equipped to accommodate variable inlet geometries. In the present work, two geometries are considered: a sudden expansion step and a 45° expansion.

Experiment

Diagnostics:

Laser Anemometer: A laser anemometer (LA) system is used to characterize the flowfield velocities. The LA system is described in detail elsewhere.[5] All air flows are uniformly seeded with nominally 1 micron alumina powder to scatter light while passing through the probe volume.[8]

Thermocouple Probe: The thermal field is established using a Type R thermocouple probe mounted on a three-axis positioning traverse.[5] The data are presented uncorrected for radiation loss.

Phase Doppler Interferometer: The method used for droplet sizing and droplet velocity is phase Doppler (PD) interferometry.[9] The transmitter is identical to that used for the LA measurements, breadboarded by the UCI Combustion Laboratory using a 5 watt Argon Ion laser and rotating grating for beam splitting and frequency shift. The receiver (Aerometrics Model 2100) and processor (Aerometrics Model 3100) are the unique components that provide the droplet statistics. The droplet velocity is determined by standard fringe mode laser anemometry. Droplet size is established by measuring the phase shift of light encoded in the spatial variation of the fringes reaching three detectors after traveling paths of different lengths through the drop. The phase shift is measured directly by the three detectors; each looks at a spatially distinct portion of the collection lens. A detailed description of the configuration used for measurements in the combustor is available.[5]

Data reduction and analysis are performed via an AT class microcomputer. Size and velocity distributions, size-velocity correlations, and Sauter mean diameter (SMD) are acquired at the same axial and radial positions as the gas phase velocity measurements. Instrument processing restrictions limited acquisition in the present case to the azimuthal component of droplet velocity. Measurements are acquired in the absence of LA seeding to allow for the unambiguous discrimination of droplet velocity and size.

Although the PD data acquired under isothermal conditions can be quantitatively used for modeling and other forms of analyses with confidence, uncertainties persist in the application of the technique to reacting flows. Reservations in reacting flows include the effect of: (1) variations in gas phase index of refraction induced by thermal gradients, (2) variations in droplet index of refraction imposed by selective evaporation of practical fuels, and (3) increased noise due to flame luminosity. These questions are unanswered and remain subjects of active research. As such, the accuracy is not yet established, but experience to date suggests that the uncertainty associated with the droplet size and droplet velocity data presented in this study is within +/− 30%.

Test Conditions:

Measurements are made across the full diameter of the WJCC in increments of 4 mm at seven axial locations. The reactor is characterized at atmospheric pressure. The combustor air flow is preheated to 100° C and the bulk flow rate is 163 kg/h. Under reacting conditions, the combustor is operated on a petroleum derived JP-4 at a fuel flow rate of 3.27 kg/h (which corresponds to an overall equivalence ratio of 0.3), and a nozzle atomizing air-to-fuel mass ratio of 3.0. Air flow splits of 45%, 25%, and 30% are adopted for the dome swirl, primary jet, and dilution jet flows respectively.

Results and Discussion

The results section begins with a description of the basic flowfield structure for a step expansion dome geometry in the absence of reaction. Secondly, results are presented for the case of reacting flow. As a demonstration of the utility of the model combustor, results are then presented for a parametric variation on: (1) the dome geometry, and (2) the swirl-to-wall jet air flow splits.

Non-Reacting:

The aerodynamic flow structure of the combustor is presented in Fig. 2 in the absence of liquid fuel injection to establish, for the non-reacting (isothermal) case: (1) the basic flowfield structure, (2) the flowfield symmetry, and (3) a basis for assessing the effect of liquid spray injection and reaction. The profiles of mean axial velocity (Fig. 2a) show a strong on-axis recirculation zone in the dome region. The data also show a substantial axial acceleration of the flow in the core of the combustor at $x/R = 2.5$ due to the primary jet flow. At $x/R = 4.5$, the dilution jet flow is shown to also accelerate the core flow, although the centerline velocity is lower and the radial spread of the accelerated flow is larger. This is a direct consequence of the lower momentum of the dilution jets which have a larger injection diameter.

The ratio of rms-to-mean axial velocity ("axial turbulence intensity") profiles (Fig. 2b) show the elevated levels of turbulence intensity at the zero crossing of the mean velocity. Beyond the dome region, the penetration and splitting of the wall jets produce high absolute rms velocities (not shown) uniformly across the duct. Because the local mean velocities are relatively high and non-zero, the levels of axial turbulence intensity (shown) do not approach the peak levels observed in the dome region. The levels of axial turbulence intensity nonetheless generally exceed 50% in the wake region.

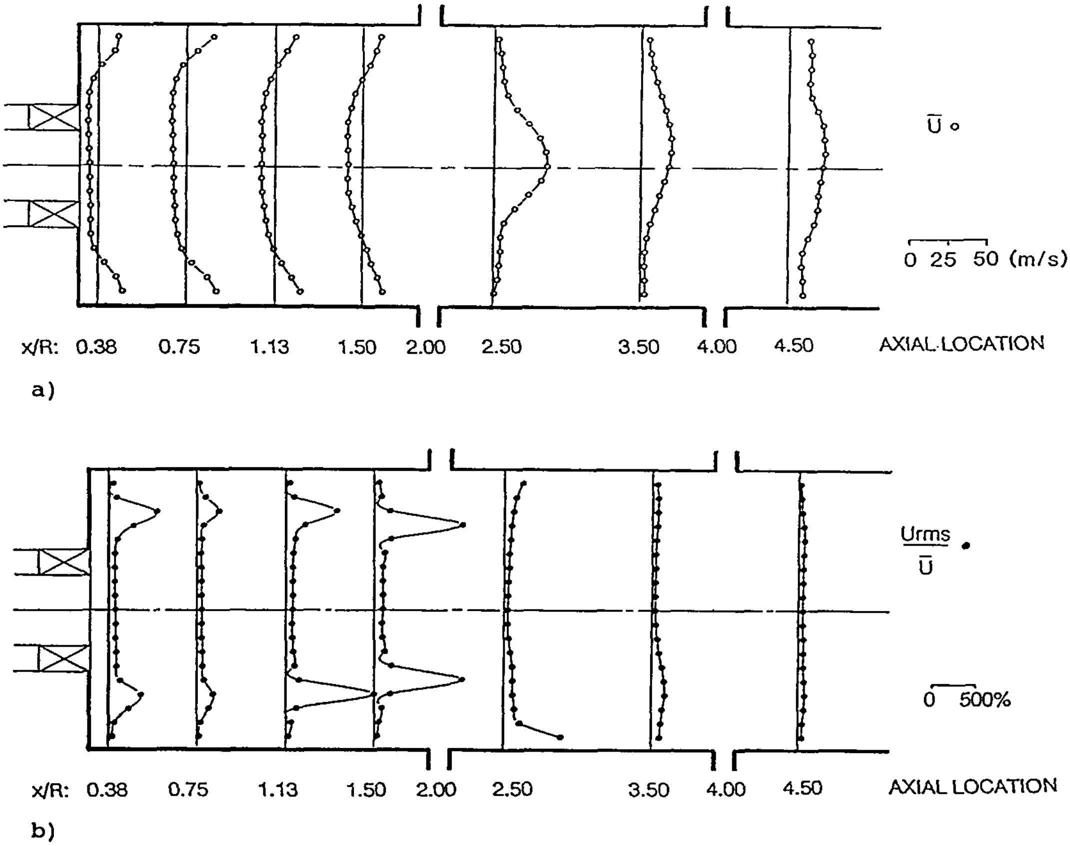


FIG. 2. Baseline Aerodynamic Field (Non-Reacting)
a) Mean Axial Velocity
b) Axial Turbulence Intensity

Reacting:

In Fig. 3a, the mean axial velocity profiles are presented for reacting flow. The presence of fuel spray injection and reaction substantially changes the character of the flowfield in the dome region. In particular, the recirculation zone is narrower, shorter, and weaker than in the isothermal case. In addition, the velocity profile displays an asymmetry with respect to the centerline at $x/R = 0.75$. This is attributed to a modest asymmetry in the spray produced by the nozzle. Noteworthy is that nozzles generally display asymmetries.[6,10] (The asymmetry is not evident at $x/R = 0.38$ and 1.13 due to the swirl component of the flow which rotates the asymmetry, in a "corkscrew" manner, in and out of the plane of measurement.) Beyond the plane of primary jet injection, the aerodynamics again dominate and the isothermal and reacting profiles have a similar character except for the distinctly higher velocities in the case of reaction. Immediately downstream of the primary jets ($x/R = 2.5$), the flow near the centerline is accelerated (as in the isothermal case). The profile at $x/R = 4.5$ is more uniform, again consistent with the isothermal case.

The profiles of axial turbulence intensity (Fig. 3b) reveal the substantial difference between the isothermal and reacting flow structures. Specifically, the turbulence intensity peaks that identify the core of the recirculation zone show that the width and length is reduced with respect to the non-reacting case. The flow asymmetry at $x/R = 0.75$ is again revealed. Between the jets, the absolute rms velocities (not shown) are higher in the reacting case even though the axial turbulence intensity (shown) is less than that for the isothermal case (30% vs. 50%).

The mean temperature field is shown in Fig. 3c for the baseline condition. In the dome region, the temperature profiles are relatively uniform across the combustor except at the wall. The temperatures remain high downstream of the primary jets, providing evidence of further reaction in the secondary zone. Noteworthy are the depressed temperatures in the core of the reactor, reflecting the deep penetration of the primary wall jets. At $x/R = 4.5$, the gases are cooled by the dilution jets. Consistent with the mean velocity profiles, the temperature profile at this location is more uniformly spread and substantiates, as a result, the conjecture that the dilution jet penetration is more diffuse due to the larger diameter of the jet inlets.

The radial profiles of droplet data rate, which provide a qualitative description of the distribution of fuel in the combustor, are presented in Fig. 4a for three axial locations. (A droplet data rate of 5 Hz was arbitrarily selected to represent the boundary of the spray.) Droplets are not present in the combustor beyond $x/R = 1.13$. The data rate profile at $x/R = 0.75$ reveals the small asymmetry in the spray distribution. At $x/R = 0.75$ and 1.13, the profiles develop into a hollow cone spray structure (i.e., no droplets are present in the spray core).

The mean azimuthal droplet velocity profiles in Fig. 4b demonstrate that the droplets have a strong swirl component imposed by the nozzle and dome swirler, both of which rotate the flow in the same direction. The data show the swirl component is substantially reduced between $x/R = 0.38$ and 0.75.

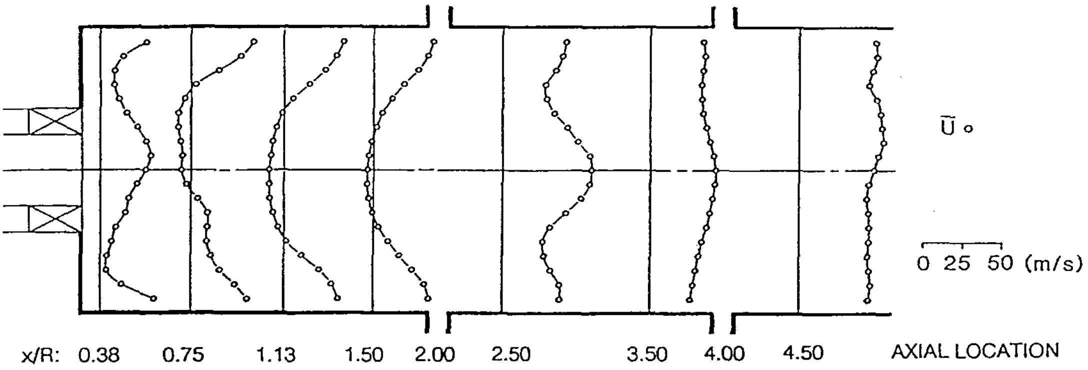
Temporal SMD data are presented in Fig. 4c. Close to the nozzle, the SMD is relatively uniform across the combustor although the SMD is distinctly elevated in the center of the combustor. This is attributed to the strong azimuthal velocity imparted to the droplets (Fig. 4b). The smaller droplets are, as a result, preferentially entrained and transported out to the wall region. At $x/R = 0.75$, larger droplets persist in the core region as a result of disproportionately rapid evaporation of the smaller droplets.

Parametric Variation:

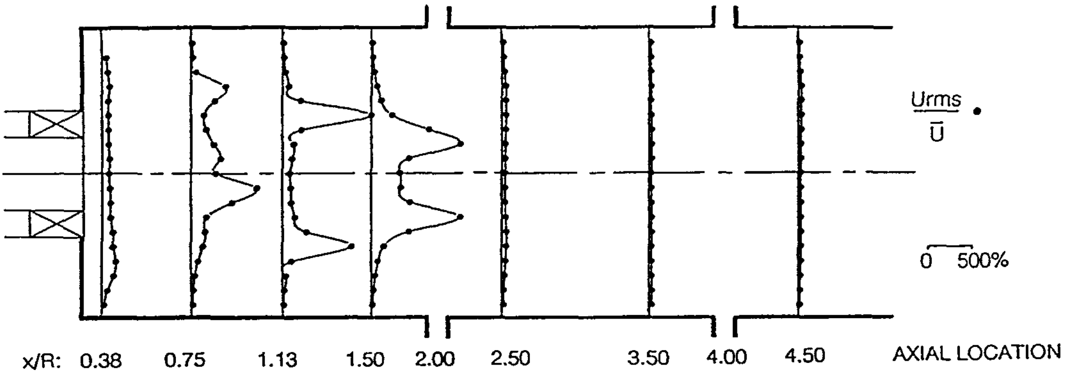
Dome Geometry: The step expansion may affect the development of the flow since secondary corner recirculation regions can effectively extract energy from the developing swirl flow. In recent studies conducted in the gaseous-fired axisymmetric can combustor (Fig. 1a), the substitution of the step expansion with a 45° diverging expansion dramatically strengthened the on-axis recirculation.[11] The impact of this geometry change in the present, liquid-fired reactor with wall jets, was much less dramatic. The results are presented in Fig. 5. (Note that, due to the addition of the gradual expansion insert, the closest axial station to the nozzle with optical access is $x/R = 0.63$.) Essentially, the mean flowfield is unchanged.

These results show that a mechanism, in addition to the dome swirl, is acting to influence backmixing in the dome region. In particular, the primary jets may contribute to the dome region recirculation. Although the primary jets provide closure to the dome region recirculation, the splitting of the primary jet flow is uncertain. For example, as the opposed primary jets collide, a fraction of the air is represented in most flowfield schematics to be entrained in the dome region recirculation zone.[12] To investigate the interaction in the present reactor of the primary jets with the swirl induced dome region recirculation, the flow splits between the primary jet, dilution jet, and dome swirl were varied.

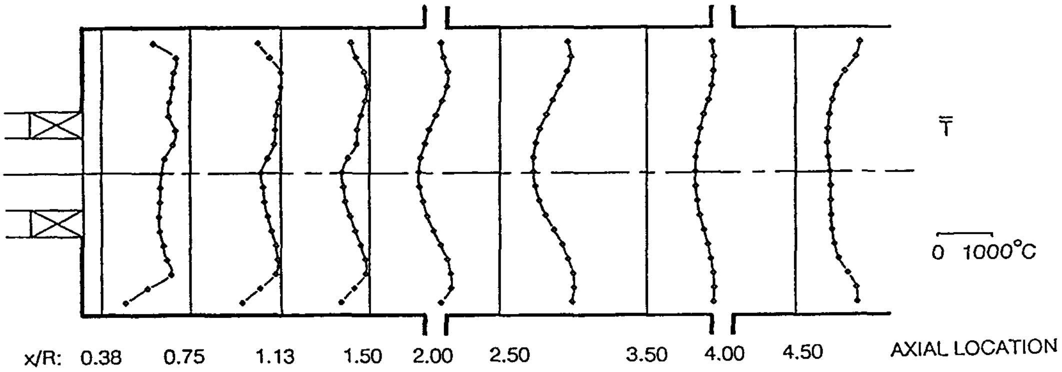
Flow Splits: The results are presented in Fig. 6 for the configuration with the gradual expansion dome. Two axial positions are selected to assess the influence of the primary jets on the recirculation zone: $x/R = 1.13$ which lies within the recirculation zone and gives a measure of width and back-



a) Mean Axial Velocity



b) Axial Turbulence Intensity



c) Temperature

FIG. 3. Baseline Aerodynamic and Thermal Fields (Reacting)
a) Mean Axial Velocity
b) Axial Turbulence Intensity
c) Temperature

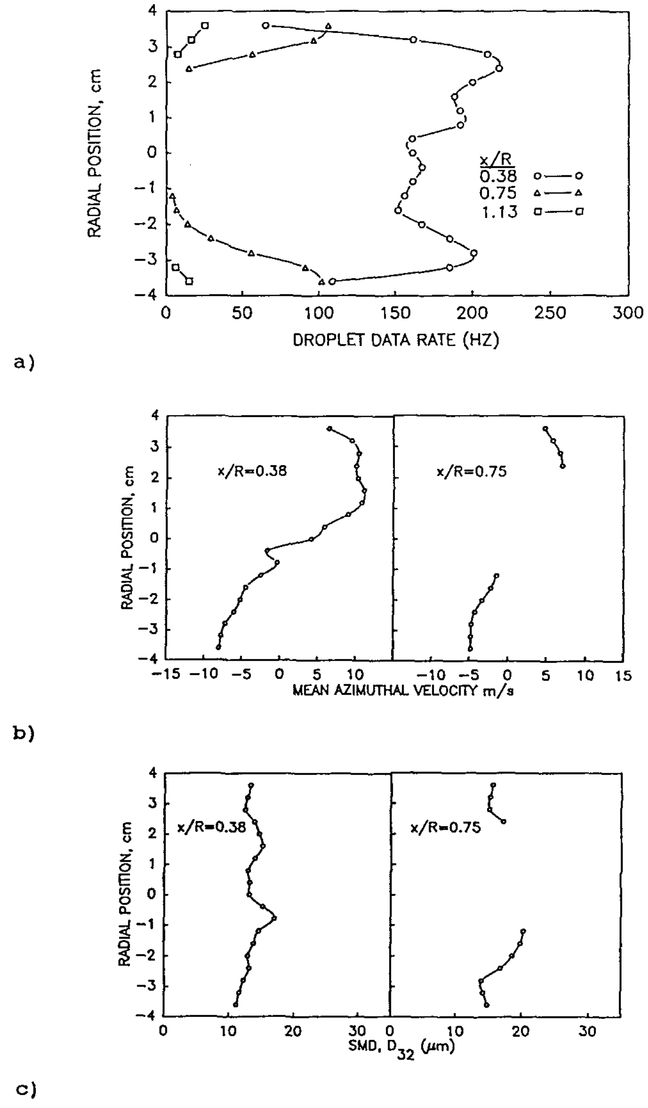


FIG. 4. Baseline Droplet Field (Reacting)
a) Data Rate
b) Azimuthal Velocity
c) Sauter Mean Diameter

flow strength; and $x/R = 1.75$ which lies just upstream of the primary jets, located at $x/R = 2.00$.

In the upper panel of Fig. 6a, a case of 50% swirl and 50% dilution jet flow (0% primary jet flow) is shown. For this case, the strong recirculation zone produced is solely due to the aerodynamically induced swirl, and the dilution jets provide closure to the flow. In the lower panel of the figure, the primary jet air is increased from 0% to 20% (the dilution jet air is reduced to 30%). At $x/R = 1.13$, the strength of the backflow is reduced. The on-axis recirculation at $x/R = 1.75$ is virtually eliminated.

A condition of 35% dome swirl air is shown in Fig. 6b for varying percentages of primary and dilution jet flows. The top panel shows a case with no primary jet flow. As before, recirculation and strong mixing is evident at both stations. In the next panel, 25% primary jet air is added. The size of the recirculation zone and strength of backflow at $x/R = 1.13$ is reduced and the on-axis recirculation zone at $x/R = 1.75$ is transformed to off-axis. A further

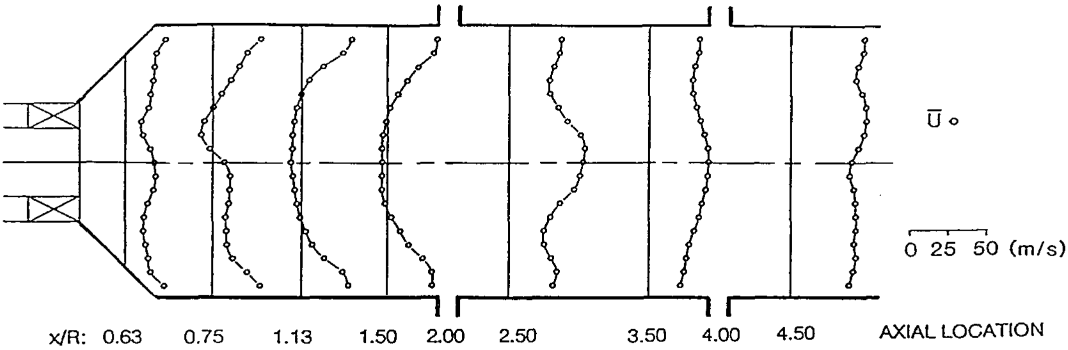


FIG. 5. 45° Dome Expansion: Mean Axial Velocity (Reacting)

increase in primary jet air (30%) shown in the bottom panel follows the same trend. At this point, recirculation at $x/R = 1.75$ is eliminated. Thus, for the case of reaction and this particular operating condition, increasing the primary jet air flow, for a given swirl air flow rate, leads to a weakening of the recirculation zone strength in the dome region.

Conclusions

The present study describes a model laboratory reactor with optical access and wall jets for the study of turbulent transport, fuel effects, and spray dynamics in gas turbine combustor type flows. The paper includes a characterization of the reactor including a sensitivity assessment of the reactor to: (1) the inlet dome geometry, and (2) the relative proportions of swirl air and wall jet flows.

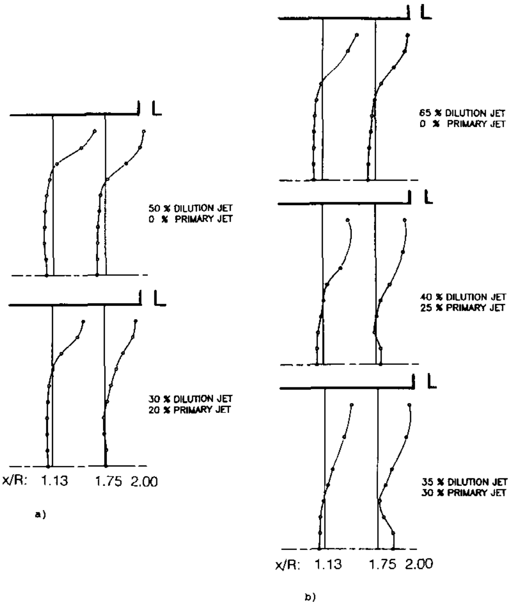


FIG. 6. Effect of Wall Jet Flow: Mean Axial Velocity (Reacting; 45° Dome Expansion)
a) 50% Dome Swirl
b) 35% Dome Swirl

From the characterization of the aerodynamic, thermal, and droplet fields, the model reactor is found to provide the attributes of a practical combustor. An on-axis recirculation zone is formed, and both the primary and dilution jets penetrate to the centerline. The temperature field reveals the location of a dome region primary zone upstream of the primary jets, a secondary zone where the reaction continues between the primary and secondary jets, and a dilution zone subsequent to the dilution jet injection where the hot gases are cooled. Overall, the WJCC is found to be a representative model of a gas turbine can combustor.

In direct contrast to a gaseous-fired combustor in the absence of wall jets, the substitution of a 45° expansion in the WJCC yields no significant change.

The formation of an on-axis recirculation zone in the reacting flowfield of this combustor is produced by the dome swirl. For a given swirl air flow rate, an increase in the primary jet flow leads to a weakening of the recirculation zone. Thus, in this combustor, the major role of the primary jets at the operating condition explored is to (1) provide closure to the dome region recirculation, (2) provide the necessary air to oxidize products of incomplete combustion, and (3) promote global turbulent mixing.

The following conclusions have resulted from this study:

1) The WJCC configuration and operating conditions produce an overall flowfield and combustor performance that is representative of a gas turbine can combustor.
2) The WJCC provides an attractive test bed for the exploration of turbulent mixing, fuel effects, and sprays in gas turbine type combusting flows. The configuration is attractive

as well for the acquisition of data to develop and verify numerical codes for three dimensional elliptic flows. A data set from the present study is available[13] following the format of Faeth and Samuelsen.[14]

Acknowledgments

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COMMENTS

C. Presser, National Bureau of Standards, USA. Please remark on the details of your temperature measurements (i.e., wire thickness, shield, coating, etc.). Are the temperature measurements overall values (i.e., gas and droplets, etc.)? How are such measurements useful? Do you plan to investigate different dome configurations in order to optimize the presence of the wall recirculation zone? Similar studies in furnaces that have been carried out in the past may be useful for this purpose.

Author's Reply. Temperature measurements were made with a Type R (platinum-13% rhodium vs. platinum) exposed junction thermocouple. The wire diameter was 250 μm. The thermocouple is supported by a 1.6 mm O.D. inconel tube, 38 mm in length, which is in turn mounted to a 6.4 mm O.D. inconel support to provide structural rigidity. Water cooling is provided in the larger inconel tubing to retain the structural integrity of a probe bend necessary to clear the exhaust stream, but only with

41 cm of the thermocouple bead to minimize conduction losses down the length of the probe.

The temperature data presented are values obtained in the presence of soot and droplets (near the nozzle). Estimates of radiation, catalytic effects, or droplet impingement are not made. The authors feel the uncertainty in the corrections do not warrant their application. The presence of the probe also introduces an unknown perturbation in the flowfield. CARS measurements of temperature will be obtained in this combustor in the near future. At that time, the two techniques (CARS vs. thermocouple) can be compared and the effects of soot, droplets, and flow perturbation on the thermocouple measurements addressed.

The measurements are useful in that they provide a qualitative picture of the thermal structure in the combustor. For example, the measurements demonstrate the presence of three thermal zones in the combustor: (1) the dome region where most of the reaction occurs, (2) the secondary zone between the jet rows where oxidation of CO occurs, and (3) the dilution zone where reaction has ceased and the gas stream has been cooled.

Following the protocol of Reference 14 in the text, we will investigate in more depth in future studies the influence of inlet conditions on the thermal structure, aerodynamics, and fuel air mixing in the combustor. Data, for example, have been recently acquired for a diverging inlet case.

●

H. May, Univ. of Kaisaslantern, Fed. Rep. of Germany. Did you measure also NO_x-emissions as it can be assumed that the variation of flow and injection conditions will influence these?

Author's Reply. We did not measure either NO or NO_2 in this study. We do expect that the variation of inlet conditions and dome geometry, both of which have a significant impact on the aerodynamic and thermal fields and fuel air mixing, will influence the formation of NO and NO_2. One use of a combustor of this type is to conduct such studies, and the investigation of NO and NO_2 formation and emission is formally planned as one of the first applications of the combustor, both at atmospheric and elevated pressures.

●

B. Q. Zhang, Beijing Univ., China. How can you define the velocity of the boundary of recirculation force in primary zone?

Because the pressure & velocity near the boundary of the recirculation zone is fluctuated quite large. It is very difficult to define its value.

By your slides the airflow rate on primary zone is 45 percent total. (This means very lean mixture approximately equivalent ratio is 0.7) and the recirculation zone is quite small. So, I think, ignition performance and lean blowout limit of your combustor model is quite narrow.

Author's Reply. Laser anemometry was used to obtain measurements of mean and rms velocity throughout the flowfield. The mean and rms values presented are based on a statistically converged sample. In locations where the fluctuations are large, more samples are typically required to achieve a converged value. In general, the mean value requires fewer samples than the rms. The Reynolds stress ($u'w'$), when measured (e.g., Reference 2 in the text), requires substantially more samples than the rms.

For the case of 45% dome swirl, the primary zone mixture is indeed lean. However this is only one possible operating condition for this combustor. The flow splits between the swirler, primary jets, and dilution jets may be varied, as well as the total air flow, to produce a wide range of mixtures in the primary zone.

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R. Weber, The International Flame Research Foundation, The Netherlands. I understand that your experimental rig is a scaled down version of a typical gas turbine combustor. Consequently, the experimental swirl generator is of a vane type and it generates vorticies of a substantial radial velocity. Due to practical difficulties associated with LDV measurements of the radial velocity you have measured just axial and tangential velocities together with the Reynolds stresses.

The lack of numerical value of inlet radial velocity makes the experimental results more difficult to analyze. Moreover, those who will be using your experimental results for validation of mathematical models will have to guess the inlet value. Therefore, I believe, it would be advantageous to design an experimental swirler which would generate vortices of zero inlet radial velocity. The International Flame Research Foundation[1] for example, has been using a solid body rotation swirler, which has got this feature.

REFERENCE

1. Magiwara, A. and Bortz, S., "Studies on the Near Field Aerodynamics of Swirl Burners," IFRF doc. no. F 259/a/1, 1989.