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A Detailed Characterization of the Velocity and Thermal Fields in a Model Can Combustor With Wall Jet Injection

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This work represents a first step in the establishment of a data base to study the interaction and influence of liquid fuel injection, wall jet interaction, and dome geometry on the fuel air mixing process in a flowfield representative of a practical combustor. In particular, the aerodynamic and thermal fields of a model gas turbine combustor are characterized via detailed spatial maps of velocity and temperature. Measurements are performed at an overall equivalence ratio of 0.3 with a petroleum JP-4 fuel. The results reveal that the flowfield characteristics are significantly altered in the presence of reaction. Strong on-axis backmixing in the dome region, present in the isothermal flow, is dissipated in the case of reaction. The thermal field exhibits the primary, secondary, and dilution zone progression of temperatures characteristic of practical gas turbine combustors. A parametric variation on atomizing air reveals a substantial sensitivity of the mixing in this flow to nozzle performance and spray symmetry.

Introduction

Gas turbine combustors are receiving increased attention with respect to design, internal flowfield structure, and dome region mixing processes between the fuel and air. A greater understanding of the processes associated with gas turbine engine combustion is required as designers address problems due to increasing demands on combustor performance and the move toward the use of relaxed specification fuels and alternative fuels. Little is understood about the interaction between fuel spray injection and a swirl-induced aerodynamic field or the interaction of wall jets with a swirl-stabilized flowfield.

As an aid to understanding the complex flowfield, in-situ and nonintrusive, spatially resolved measurements of gas velocity, temperature, droplet size, droplet velocity, soot distribution, and species concentration must be provided. Although experimental research has been conducted in both laboratory bench-scale and full-scale hardware (e.g., Brum and Samuelsen, 1987; Gouldin et al., 1985; Lilly, 1985), the required data base is still not available. This is due to several factors. First, the relatively simple model combustors amenable to modeling and optical access for laser diagnostics typically do not exhibit some of the geometrical and operational features characteristic of practical combustors. Second, full-scale combustor beds preclude the use of optical diagnostics, have poorly defined boundary conditions, and have prohibitive operating costs.

In recent work at the UCI Combustion Laboratory, a model gas turbine can combustor has been developed that provides optical access for laser diagnostics and clean boundary conditions amenable to modeling, and also incorporates critical features of practical combustors such as discrete wall jets, swirl-induced flowfield, liquid spray atomization, and elevated pressure operation (Rudoff and Samuelsen, 1986). The primary objective of the present study was to characterize the performance of this model combustor.

Background

The present combustor evolved from a simplified configuration, dubbed the Axisymmetric Can Combustor (ASCC). The ASCC (Fig. 1*a*) is an atmospheric pressure combustor operated at bulk velocities up to 15 m/s. The design was developed in a series of tests (Brum and Samuelsen, 1982) and the module has been used for a number of turbulent transport (Brum and Samuelsen, 1987; LaRue et al., 1985) and fuel effects (Wood and Samuelsen, 1985; Wood et al., 1985; Smith et al., 1985) studies. The dilution air (nonswirling) is introduced through an annular shroud to provide closure to the swirl-generated recirculation zone, retain clean boundary conditions, maintain axisymmetry, and keep the optical windows cool and clean. As a result, the ASCC provides (1) an axisymmetric flowfield amenable to modeling, and (2) optical access. The geometric features of the ASCC result in a representative model of the primary zone of a practical gas turbine combustor: strong swirl, strong backmixing, and liquid fuel spray injection.

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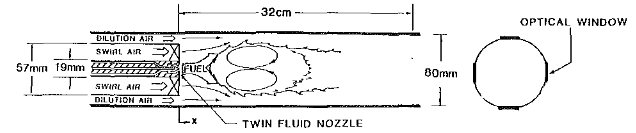

Fig. 1(*a*) The axisymmetric can combustor (ASCC)

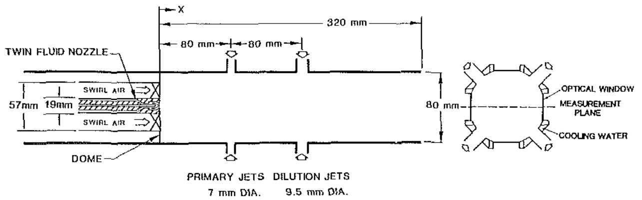

Fig. 1(*b*) The wall jet can combustor (WJCC)

The present combustor, the Wall Jet Can Combustor (WJCC), features introduction of primary and dilution air via discrete wall jets. This produces a more accurate representation of the aerodynamics of a practical combustor, namely primary, secondary, and dilution regions.

Major changes in the ASCC design (Fig. 1*a*), which led to the current WJCC design (Fig. 1*b*), were (1) the replacement of the front face injection of dilution air with discrete wall injection, and (2) the replacement of the front face dilution air shroud with a step expansion dome. Design decisions required in the development of the WJCC (e.g., number and location of wall jets, air flow ratios, and dome design) were made with the input from designers of practical combustors and design texts (e.g., Lefebvre, 1983). The design was refined and finalized based on the results of prototype testing (Rudoff, 1986).

The present work reports on a characterization of the WJCC for a select set of parametric variations. In particular, the aerodynamic and thermal fields of this model combustor are presented. Nonintrusive measurements of mean and rms velocity were made via laser anemometry. A thermocouple probe was used to map the average gas temperature inside the combustor. The goals are to (1) establish initial insights into the mixing processes associated with complex flowfields typical of can combustors, and (2) assess the utility of the WJCC for studies of gas turbine combustion processes.

Experiment

Approach. The WJCC was characterized operating at atmospheric pressure with a petroleum derived JP-4. A twin fluid air-assist Parker Hannifin nozzle was used for fuel injection. The combustor air was preheated to 100°C and the bulk flow rate was 163 kg/h. The fuel flow rate was 3.27 kg/h, which corresponds to an overall equivalence ratio of 0.3.

The approach was to characterize the aerodynamic field of the WJCC using laser anemometry to measure the gas mean and rms velocities in the axial and azimuthal direction. Measurements of velocity were made across the full diameter in increments of 4 mm at seven axial locations. A thermocouple was used to obtain the average temperature at the same locations.

Test Bed. The WJCC is an 80 mm stainless steel duct, with an operating length of 32 cm (Fig. 1b). A 57 mm diameter, 100 percent blockage, 60 degree swirler is located at the front face of the combustor. Air flow to the combustor passes through a stainless steel preheater section, where it is preheated to 100°C. After passing through the preheater the flow is split into three separate lines delineated as the swirl, primary jet, and dilution jet air lines. The swirl air is sent through a straightening section before entering the combustor at the inlet plane while the primary and dilution jet flows are sent to the discrete wall jets of the WJCC.

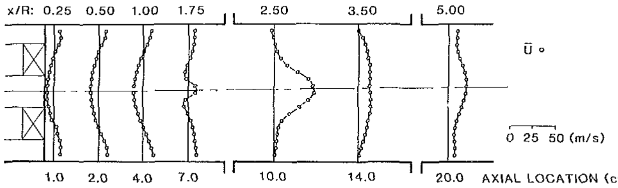

Fig. 2 The isothermal mean axial velocity field (25 percent swirl, 35 percent primary jet air, 40 percent dilution jet air)

As shown in the end view of Fig. 1(*b*), four ports for diagnostic access are located longitudinally around the combustor. The plane of optical measurements bisects the wall jets through the side ports while the top port is used for thermocouple and radiometer measurements. Also, as shown in Fig. 1(*b*), water cooling is provided to the walls in the nonwindow regions through four channels to preserve the integrity of the combustor and wall jet tubes and to prevent warpage around the window frames.

Two rows of discrete wall jets are included (primary and dilution), each consisting of four orthogonally located jets. They are located one and two combustor diameters downstream from the inlet, respectively. The primary jets have a 7 mm diameter and the dilution jets have a 9.5 mm diameter.

Diagnostics

Laser Anemometer. A two-component, dual-beam laser anemometer (LA) system was used to characterize the axial and azimuthal velocity components of the flowfield. The green beam (514.5 nm) from a dispersion prism was focused by a lens onto a diffraction grating where it was split into ordered pairs. The first-order beam pair was collimated, then focused and crossed into a probe volume by a pair of lenses. Frequency shifting to eliminate directional ambiguity was provided by rotating the diffraction grating. By varying the speed of the precision motor that rotates the grating, shifts of up to 8 MHz were available.

The Doppler bursts were collected 20 deg off axis through a pair of collimating lenses and focused upon a photodetector. Pedestal and high-frequency noise removal were accomplished through adjustable high and low pass filters provided on a Macrodyne counter/processor. Data reduction was performed by an LSI 11/23 minicomputer. All air flows were seeded with nominally 1 μm alumina powder to scatter light while passing through the probe volume.

Thermocouple Probe. Temperature measurements in the WJCC were accomplished with the use of a thermocouple probe using a Type R exposed junction thermocouple. The thermocouple wire diameter was 250 μm. The thermocouple was supported by a 1.6 mm o.d. Inconel tube, 38 mm long, which was in turn mounted on a 6.4 mm o.d. Inconel tube for structural rigidity. Water cooling was provided through the larger Inconel tube to assure the structural integrity of the probe, but only to 41 cm from the thermocouple bead to minimize conduction losses down the length of the probe. The probe is mounted on a three-axis positioning traverse to place the bead in alliance with the beam crossing of the LA system. The probe is then traversed through the entire flowfield using the traverse of the LA system.

Results

Isothermal. The isothermal mean axial velocity field in the combustor module is shown in Fig. 2 for swirl, primary jet, and dilution jet air flows of 25 percent, 35 percent, and 40 percent, respectively. These flow splits are based on design criteria for practical combustors (Rudoff, 1986). A strong on-

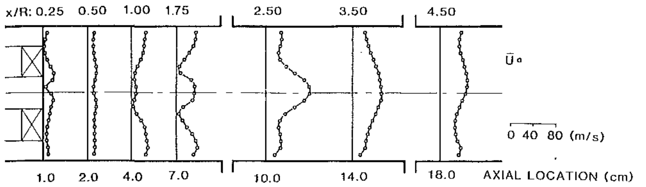

Fig. 3 The mean axial velocity field for a nozzle air-fuel ratio = 1.5 (25 percent swirl, 35 percent primary jet air, 40 percent dilution jet air)

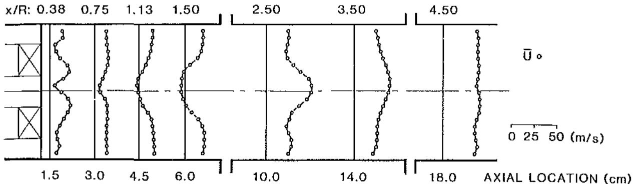

Fig. 4(*a*) Mean velocity

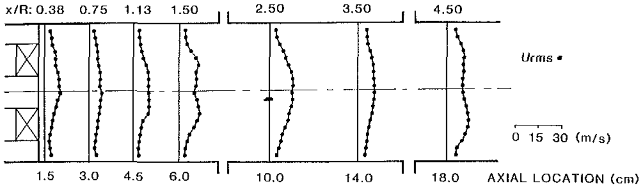

Fig. 4(*b*) Rms velocity

Fig. 4 The axial velocity field for a nozzle air-fuel ratio = 1.5 (45 percent swirl, 30 percent primary jet air, 25 percent dilution jet air)

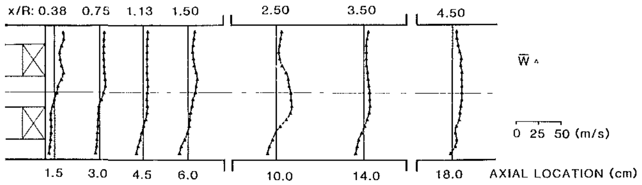

Fig. 5(*a*) Mean velocity

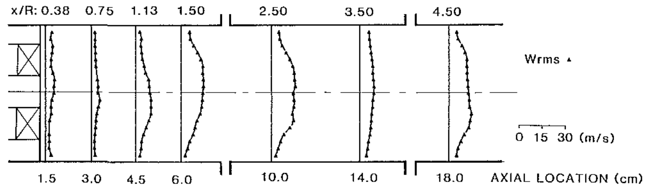

Fig. 5(*b*) Rms velocity

Fig. 5 The azimuthal velocity field for a nozzle air-fuel ratio = 1.5 (45 percent swirl, 30 percent primary jet air, 25 percent dilution jet air)

axis recirculation zone extends from $x/R = 0.25$ to $x/R = 1$. At $x/R = 1.75$, a small off-axis recirculation zone is formed. The strong axial acceleration of the flow along the centerline at $x/R = 2.5$ is due to the primary jet flow. At $x/R = 3.5$, the velocity profile is more uniform due to the on-axis flow of the dilution jets. At $x/R = 5$, a modest centerline acceleration occurs due to the dilution jet flow. The axial velocity profiles exhibit a reasonable degree of symmetry in the measurement plane.

Liquid Injection and Reaction. The mean axial velocity field, shown in Fig. 3, was obtained with the combustor operating on a petroleum-derived JP-4. The flow splits between the swirl and wall jets are identical to those of the isothermal case. The nozzle air-fuel ratio was 1.5 as per the manufacturer's recommended operating range for this atomizer.

The presence of fuel injection and reaction changes the character of the flowfield; notably, no mean on-axis recirculation zone is present.

In addition, the velocity profile displays a slight asymmetry ($x/R = 0.25$, 0.5) with respect to the centerline. This is attributed to a modest asymmetry in the spray produced by the nozzle since the flowfield demonstrates symmetry in the absence of fuel injection and reaction. Noteworthy is that nozzles generally display modest asymmetries (e.g., McDonell et al., 1987; Rosjford, 1987). The present data reflect the probable asymmetries in flowfield properties that can result from these asymmetries in fuel distribution.

Beyond $x/R = 1.75$, the aerodynamics again control and the flowfield displays reasonable symmetry about the centerline. In the region between the jets ($x/R = 2.5$, 3.5), the velocities near the centerline are quite high (as in the isothermal case); in addition, the velocities in the outer flow (near the walls) are substantial. This is likely due to a blockage effect created by penetration of the cold jets to the rapidly expanding reacting flow.

Increased Swirl Air. The common perception of the flowfield in a gas turbine combustor is the presence of an on-axis recirculation zone produced as a result of the interaction between the swirl air and the primary jet flow. Although present in the case of isothermal flow, as described above, the on-axis recirculation is absent in the case of reaction. Exploratory isothermal testing revealed that the backflow produced by the primary jets formed an *off-axis* recirculation zone. By increasing the swirl air, the recirculation zone was transformed to an on-axis configuration. A parametric study was conducted to establish the extent to which the proportion of air directed to the swirler needed to be increased to establish on-axis recirculation for the case of reacting flow. It was found that, for a given flow rate through the swirler, increasing the primary jet air always led to a weakening of the recirculation zone. Except to provide closure to the dome region, a condition was not found for which the primary jet flow played a role in enhancing the recirculation zone strength or size. Increased primary jet flow did however lead to higher levels of rms velocity in the dome region.

Through an iterative process, a flow split in which the swirl air exceeds 45 percent was found to produce a flowfield in the present combustor that represents the flow structure described as representative of a gas turbine combustor (i.e., strong dome region, and on-axis recirculation) (Lefebvre, 1983).

The mean axial velocity field for this condition is shown in Fig. 4(*a*). On-axis recirculation is present at $x/R = 1.13$ and 1.5. A modest asymmetry again appears in the axial velocity profile near the nozzle ($x/R = 0.38$); otherwise, symmetry is maintained throughout the flowfield. The lower percentage of primary air in this case (25 versus 35 percent) results in lower centerline velocities in the region between the jets. The effect of a weaker dilution stream can be seen in the profile at $x/R = 4.5$; in the present case, the velocity profile is essentially uniform.

High rms velocities generated by the penetration, splitting, and resultant velocity gradients produced by the high velocity wall jets are present throughout the flow (Fig. 4*b*).The rms values are generally higher in the region between the jets. The slightly higher rms values near the centerline suggest a strong intermittency flow.

The azimuthal mean flowfield is presented in Fig. 5(*a*). Near the nozzle ($x/R = 0.38$), strong swirl is evident in the velocity profile. The swirl persists until $x/R = 1.13$, where the nonswirling central core created by the jets begins to dominate the flow. A small swirl component remains on the edge of the flow until it is completely dissipated by $x/R = 4.5$. The general upward tendency of the flow on centerline may be due to two possible effects: buoyancy and/or slightly unequal flow distribution to the jets, yielding a general upward flow. The az-

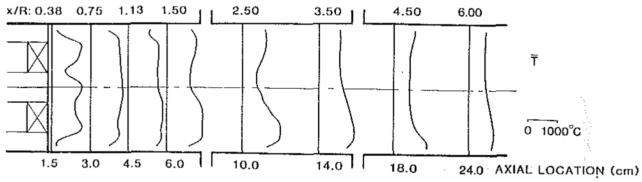

Fig. 6 The mean temperature field for a nozzle air-fuel ratio = 1.5

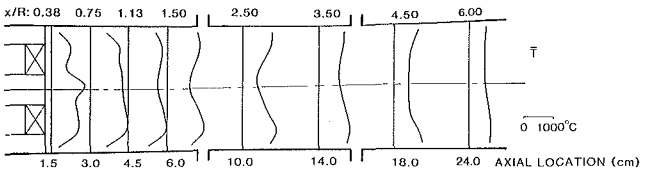

Fig. 8 The mean temperature field for a nozzle air-fuel ratio = 3.0

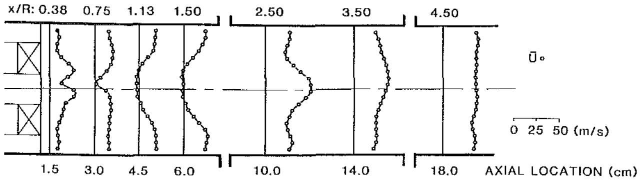

Fig. 7 The mean axial velocity field for a nozzle air fuel ratio = 3.0 (45 percent swirl, 30 percent primary jet air, 25 percent dilution jet air)

imuthal rms velocities are shown in Fig. 5(*b*). As for the axial case, the rms values are higher in the regions where the jet flows dominate, and near the centerline due to the flow intermittency.

The mean temperature field in the WJCC is shown in Fig. 6. Near the nozzle, the spray pattern is evident from the dips in the temperature profile and the correspondingly cooler temperatures on either side of the centerline. Evidence of an asymmetry in the spray distribution can be deduced from the data, namely a greater depression on the positive side of centerline.

Downstream of the nozzle, the temperature profiles are relatively uniform across the combustor until $x/R = 1.5$, where the influence of jet penetration is evident from the colder centerline temperatures. The temperatures remain high downstream of the primary jets; this is evidence of further reaction in the secondary zone. At this point a modest asymmetry in the temperature profile or "hot streak" can be detected on the outer edge of the flow on the negative side of centerline. A probable explanation for the hot streak is the asymmetry in the spray field noted above. The relatively depressed temperature and buildup of carbon on the thermocouple is evidence of a locally high concentration of fuel. This is likely transported downstream in a corkscrew manner within the dome region, and is manifested as a hot streak. The effect is undetected until the reacting fuel streak moves into the measurement plane at this location. The hot streak persists for the rest of the field due to the fact that the swirl is very weak beyond this position and thus transport is primarily in the axial direction. At the final axial position of $x/R = 6.0$, the temperature profile is tending toward uniformity, with some evidence of the hot streak remaining.

Increased Atomization Air. The combustor was also characterized at the baseline air flow splits for a nozzle air-fuel ratio of 3.0. The combustor performance is notably improved for this condition as visually evidenced by the absence of yellow streaks and a more uniform and stable flowfield. Isothermal measurements of the line-of-sight Sauter mean diameter (SMD), via laser diffraction, in the spray field produced by this nozzle showed that 5 cm from the nozzle (corresponding to $x/R = 1.25$), the SMD decreased from 22 μm to 9 μm for nozzle air-fuel ratios of 1.5 and 3.0, respectively.

The mean axial velocity field for this condition is depicted in Fig. 7. The effect of increased atomization air is most evident near the nozzle ($x/R = 0.38$ and 0.75). Although the characteristics of the profiles are similar to those obtained with a nozzle air-fuel ratio of 1.5, the magnitudes of the velocities are much higher, reflecting the increased nozzle air flow. Throughout the remainder of the flowfield ($x/R = 1.13$ to $x/R = 4.5$), this effect has diminished and the velocity profiles for the two cases (nozzle air-fuel ratio = 1.5 and 3.0) are virtually identical.

The average temperature profiles for this condition are shown in Fig. 8. The asymmetry in the temperature profile is again evident near the nozzle. Although there is still evidence of a hot streak, the effect is greatly diminished. The temperature profiles appear relatively symmetric about the centerline. The cold core due to jet penetration appears at $x/R = 1.5$ and persists throughout most of the flow. At $x/R = 6.0$, the temperature profile is relatively uniform.

Summary and Conclusions

In-situ measurements of mean and rms velocities and mean temperature have been performed in the nonreacting and reacting environment of a model gas turbine combustor with wall injection. In the absence of liquid injection and reaction, flow splits typical of practical combustors produce a strong on-axis recirculation zone. The presence of liquid injection and reaction significantly alters the flowfield characteristics. Noteworthy is the absence of on-axis recirculation.

The formation of an on-axis recirculation zone in reacting flow is dominated by the swirl air flow. Except to provide closure to the dome region, the primary jet flow does not appear to interact with the swirl to enhance the strength or size of the mean on-axis recirculation zone. The rms velocity levels are, however, significantly increased with an increase in flow velocity in the region dominated by the primary jets.

The temperature field reveals the location of a primary zone upstream of the first row of jets, a secondary zone between the two jet rows where reaction continues, and a dilution zone downstream of the second row of jets where the gases are cooled. Evidence of a hot streak was identified, most likely associated with a nozzle asymmetry. An increase in the nozzle air-fuel ratio from 1.5 to 3.0 resulted in more symmetric temperature profiles throughout the combustor, and a more uniform exit temperature profile.

This first characterization suggests that the model combustor employed in the present study has attractive features (optical access, wall jet injection, twin fluid atomizer) for studies of gas turbine combustion. Refinements are worthy of exploration, namely: (1) A reduction in the effective area of the swirl vanes should be considered to represent practical designs more accurately; (2) nozzle asymmetries, while a reflection of practical hardware, should be minimized for the acquisition of data for modeling verification and development; and (3) operation at elevated pressures and elevated inlet temperatures should be provided.

Acknowledgments

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