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The Role of Primary Jets in the Dome Region Aerodynamics of a Model Can Combustor

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The role of the primary jets in the aerothermal behavior and overall performance of a gas turbine combustor is explored through an experimental study. The study is performed in a model laboratory combustor that possesses the essential features of practical combustors. The test bed is designed to accommodate optical access for laser diagnostics and overall flow visualization, and is capable of incorporating variable inlet geometries. In the present case, the combustor is operated on JP-4 at atmospheric pressure. A parametric variation in the number of jets per row and axial location of the jet row is performed. The aerodynamic and thermal fields are characterized using laser anemometry and a thermocouple probe, respectively. Species concentrations are acquired via extractive probe sampling. The results demonstrate the importance of primary jet location with respect to the dome swirler. The percent mass recirculated into the dome region, as well as the overall uniformity of mixing and combustion efficiency, are substantially influenced by jet row location. The momentum ratio of the incoming primary jet stream to that of the approaching crossflow of reacting dome gases has a direct impact on the mixing patterns as well. An increase in the number of primary jets leads, in the present case, to more uniform mixing.

Introduction

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 design of gas turbine combustors is today predicated on empirical data associated with the overall combustion performance of the system. Although experimental research has been conducted in both laboratory bench-scale and full-scale hardware (Brum and Samuelsen, 1987; Gouldin et al., 1985; Lilley, 1985; Bicen and Jones, 1986), little is understood about the detailed aerodynamics, the detailed mixing of fuel and 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 laboratory can combustor is employed with optical access and the essential features of gas turbine combustors (including spray injection, swirl stabilized dome aerodynamics, and wall jet injection). Second, nonintrusive optical diagnostics such as laser anemometry (LA) and phase Doppler interferometry are used for probing of the flow field. Third, data are acquired for use in the development and validation of numerical codes.

The penetration of the primary jets and subsequent mixing likely play a dominant role in fuel-air mixing in the dome region of gas turbine combustors. The primary jets penetrate the flow field to interact with the swirl-induced recirculation zone and provide additional air to the dome region as well as to the intermediate or "secondary" zone. In this paper the focus is on the role of the primary jets in dome region aerodynamics and fuel-air mixing.

Background

The combustors used in this study are based on a model combustor dubbed the Wall Jet Can Combustor, WJCC, developed at the UCI Combustion Laboratory (Rudoff, 1986). This combustor features dome swirl and two rows of discrete wall jets. Each row of jets consists of four individual jets with an injection angle of 90 deg. The original combustor was constructed of stainless steel with two windows along the length of the combustor for optical access. A schematic of this combustor is shown in Fig. 1(*a*). In previous work this combustor was characterized via detailed spatial maps of velocity, temperature, and droplet field statistics (Cameron et al., 1989a, 1986b), and found to produce an overall flow field and combustor performance that is representative of a gas turbine can combustor.

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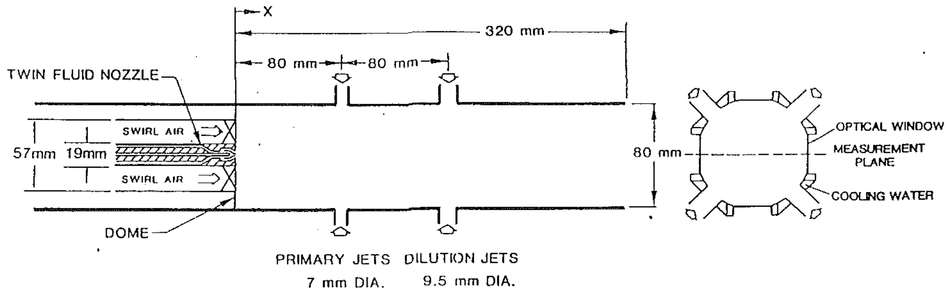
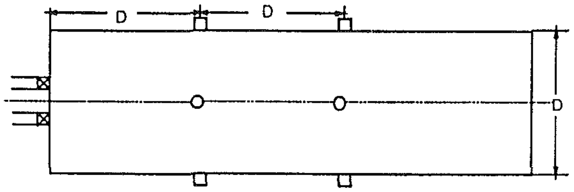
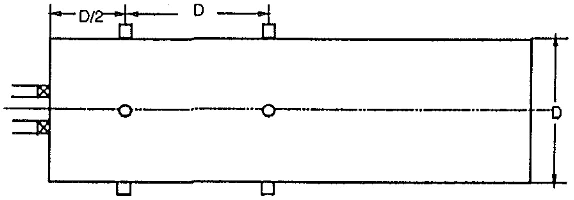
a) The Wall Jet Can Combustor (WJCC).



b) Module 1.



c) Module 2.



d) Module 3.

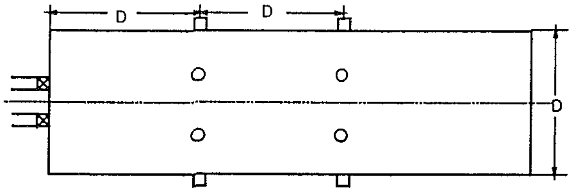


Fig. 1 Model combustors

The combustor modules used in this study feature the same general characteristics; namely, dome swirl and two rows of discrete wall jets. The new modules, however, are manufactured from quartz and thus provide full optical access to the highly three-dimensional flow field present in these reactors. In addition, three modules were manufactured so that a parametric variation of number of jets per row and axial position of jet row can be performed.

In the present study the role of the primary jets is evaluated through an experimental investigation. The goals of the study are to explore (1) the relative importance of primary jet location relative to the dome swirler, and (2) the effect of the number of jets in the primary row to the swirl-stabilized dome region aerodynamics.

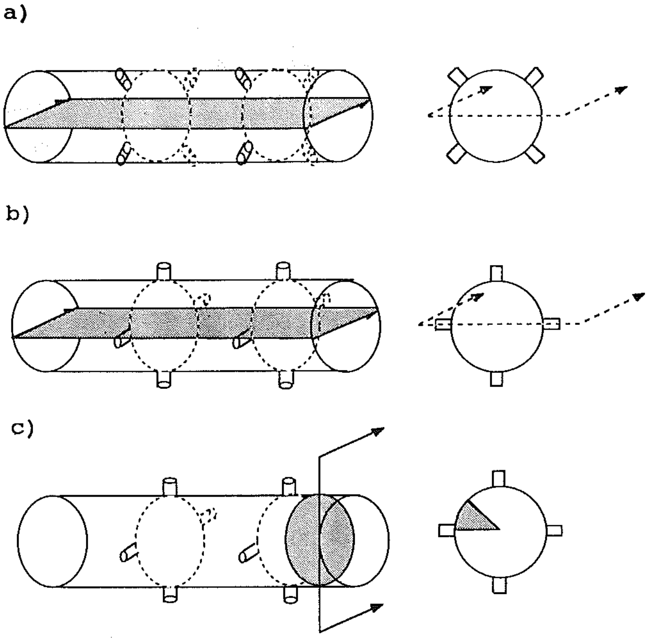
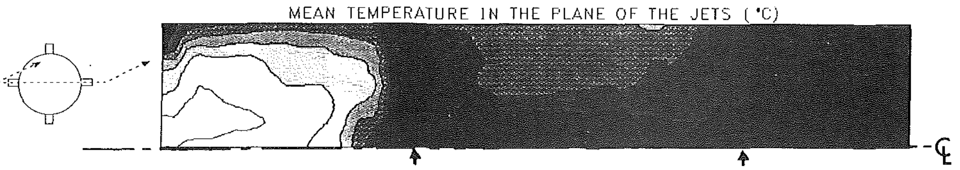


Fig. 2 Measurement locations

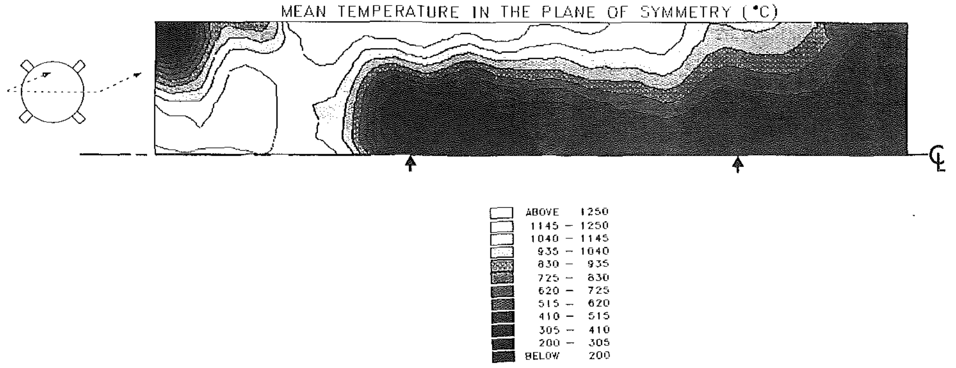
Experiment

Approach. The approach is to characterize the aerodynamic field of the combustor. Measurements of velocity are made across the diameter of the combustor in increments of 4 mm at selected axial locations as well as along the centerline. A thermocouple probe is used to obtain the average temperature at the same locations. An extractive probe and gas analyzers are used to determine species concentrations at an axial location 2.5 duct diameters downstream of the nozzle inlet plane.

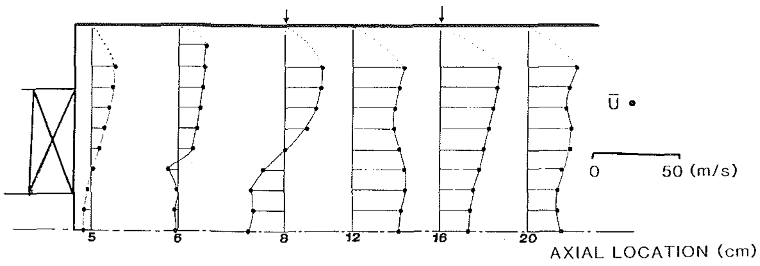
a) The thermal field in the plane of the jets.



b) The thermal field in the plane of symmetry.



c) Radial profiles of mean axial velocity.



d) Emissions profiles at the exit plane.

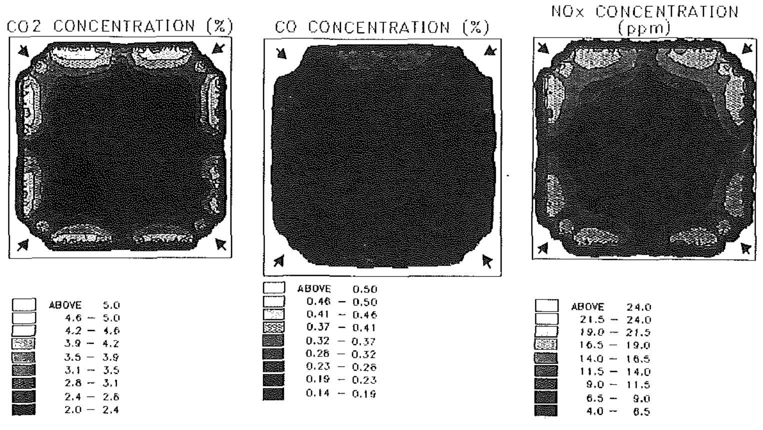


Fig. 3 Module 1 results

Test Bed. The combustor modules, as shown in Fig. 1, are 80 mm quartz circular ducts with an operating length of 32 cm. Air flow to the combustor is split into three separate lines delineated as the dome swirl, primary jets, and dilution jets. Each line is separately metered and controlled so that the flow splits may be varied. The swirl air enters the combustor at the inlet plane through a 34-mm-dia, 100 percent blockage, 45 deg swirler. Each of the wall jet lines is further split into six lines, which are individually controlled and metered. These lines feed the discrete wall jets.

A 19 mm o.d. centrally positioned fuel delivery assembly is sized to house a twin-fluid air-assist atomizer. The dome swirl vanes are concentrically positioned around the fuel delivery assembly as shown in Fig. 1(*a*).

Each combustor module features two rows of discrete wall jets. The number of jets per row and the axial position of the jet rows vary between the modules. Module 1, the baseline case, consists of four jets per row positioned one and two duct diameters downstream from the inlet, as shown in Fig. 1(*b*). Module 2, shown in Fig. 1(*c*), also features four jets per row but they are positioned 1/2 and 3/2 duct diameters downstream from the inlet. Module 3 features six jets per row positioned one and two duct diameters downstream of the inlet, as shown in Figure 1(*d*).

Diagnostics

Laser Anemometer. A single component laser anemometer (LA) system is used to characterize the flow field velocities. The LA system is described in detail elsewhere (Brum and Samuelsen, 1987). To eliminate directional ambiguity, frequency shifting is provided by a Bragg cell. All flows are uniformly seeded with nominally 1 μm alumina powder to scatter light while passing through the probe volume.

Measurements of mean and rms axial velocities are acquired in the plane of symmetry between the jets as shown in Fig. 2(*a*).

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

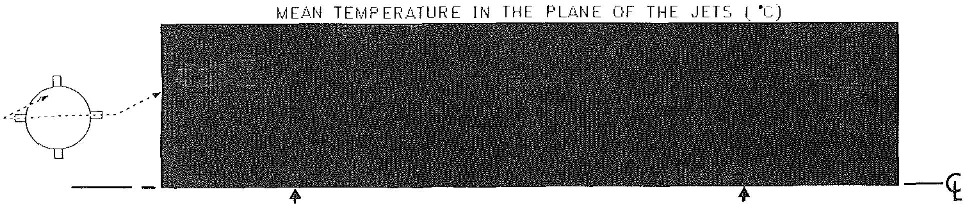
Temperature measurements are obtained in the plane of symmetry between the jets as well as in the plane of symmetry through the jets (as shown in Fig. 2*b*), across the radius of the combustor in 5 mm increments at 11 axial locations along the length of the combustor.

Species Measurement. Exit plane species concentrations are determined with a water-cooled extractive probe mounted on a three-axis positioning traverse. Concentrations of oxygen, carbon dioxide, carbon monoxide, and nitric oxide and nitrogen dioxide are acquired using a Beckman Model 755 O_2 analyzer, Horiba PIR 2000 analyzers for CO and CO_2, and a TECO Model 10 analyzer for NO_x concentrations.

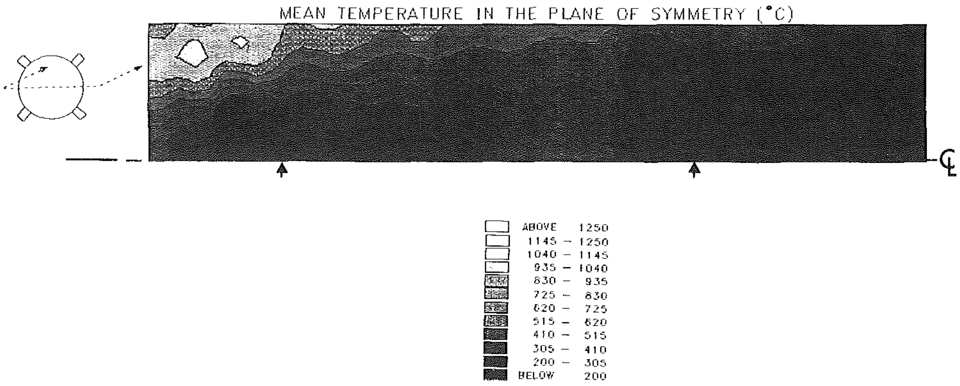
Species concentrations are obtained at an axial plane 2.5 duct diameters downstream of the inlet plane in a slice defined by the two planes of symmetry as shown in Fig. 2(*c*). The probe was traversed along radial lines in 5 mm increments. The axial plane was selected to be near the end but within the combustor duct.

Test Conditions. The swirl, primary jet and dilution jet flows comprise 26, 30, and 39 percent, respectively of the total

a) The thermal field in the plane of the jets.



b) The thermal field in the plane of symmetry.



c) Emissions profiles at the exit plane.

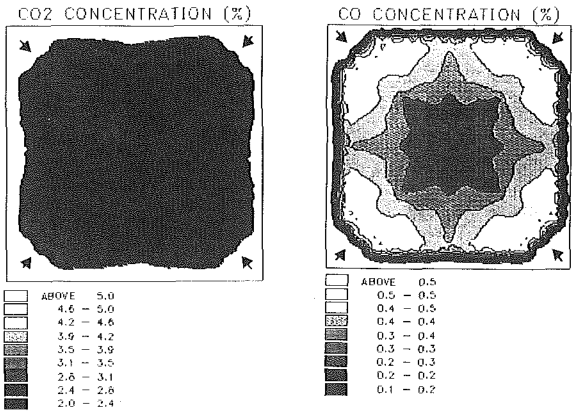


Fig. 4 Module 2 results

flow. The atomizing air in the nozzle circuit accounts for the remaining 5 percent. The swirl air plus the atomizing air alone are sufficient to provide a near-stoichiometric ($\phi = 0.95$) mixture. Lean combustion is desirable in this combustor due to the thermal limitations of the quartz. These flow split conditions are based on previous studies (Cameron et al., 1989a, 1986b; Richards and Samuelsen, 1990).

The combustor is operated at atmospheric pressure. The bulk flow rate of air 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.

Results and Discussion

Baseline Condition. The mean temperature field in the plane of the jets for Module 1 is shown in Fig. 3(*a*). The trajectory of the jets is evident, and the containment of the dome region reaction by the penetration of the primary jets to the centerline can be clearly deduced. In contrast, the dilution jets are more diffuse and their penetration is not as well defined.

In Fig. 3(*b*), the mean temperature field in the plane of symmetry between the jets is shown. A cold region occurs at the front corner of the combustor. This is a zone of recirculation due to the step expansion from the swirler to the duct and, because of the heat sink provided by the walls (and likelihood of a lean mixture as well), a reaction cannot be sustained.

The influence of the jets can be seen in the cold regions along the centerline as well. The hot reacting gases in the dome region move around the jets and are directed toward the wall in the secondary region between the jets as a result of the air injected to the centerline. The core of the combustor remains relatively cool beyond the primary jets.

Radial profiles of mean velocity data for this condition are shown in Fig. 3(*c*). At the first two axial locations (x = 5, 6 cm), the profiles are characteristic of the recirculation zone induced by the aerodynamic swirler. At the location x = 8 cm (corresponding to the primary jet location), the influence of the jet penetration is clearly detectable. Negative velocities are increased at the centerline. High velocities near the wall result from diversion of the hot gases to the wall. At x = 16 cm (the axial location of the dilution jets), evidence of the dilution jet penetration is seen in a slight deficit near the centerline, and a modest increase in the centerline mean velocity downstream of the dilution jets at x = 20 cm.

Emissions data are presented in Fig. 3(*d*). The data acquired have been rotated through 360 deg to provide a full cross-sectional view. The jet positions are marked for reference by arrows. In general CO, CO_2, and NO_x emissions are depressed at the centerline and increase toward the wall and correspondingly O_2 profiles exhibit the reverse behavior. O_2 profiles are not presented for brevity. This is in agreement with the trend observed in the temperature profiles for the dome region effluent to move around the jets toward the wall regions. NO_x concentrations tend to be highest on the wall at the circumferential locations that correspond to the jet locations. Conversely CO_2 and CO concentrations are highest between the jets.

Parametric Variations

Module 2. In this module the jet rows are located closer to the inlet plane. As shown in Fig. 1(*c*), the primary jets are one half duct diameter from the swirler exit. The air flow rates and fuel loading are identical to those run in Module 1.

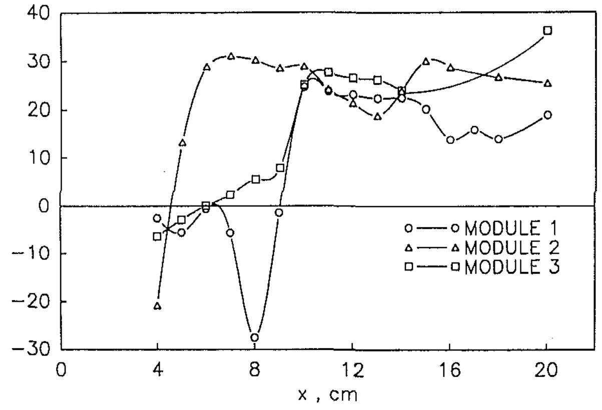
The mean temperature field in the plane of the jets, shown in Fig. 4(*a*), reveals overall lower temperatures. The substantially cooler temperatures in the dome region, for example, indicate a much larger air contribution from the jets and, as a consequence, leaner combustion than in Module 1. The temperature profiles in the plane of symmetry between the jets show that reaction takes place along the walls and that the cold core provided by the jets results in substantial quenching.

Emissions data are presented in Fig. 4(*c*). The levels of CO and CO_2 are high and low, respectively, compared to Module 1, an indication of relatively degraded combustion performance. CO_2 concentrations range from 2.2 to 3.1 percent compared to 2.4 to 5.1 percent in Module 1. Temperatures in this condition were not sufficiently high to produce a significant level of NO_x.

The centerline profile of mean axial velocity is shown in Fig. 5(*a*). The negative velocity at the position of the jets for Module 2 (at x = 4 cm) is close to that in Module 1 (at x = 8 cm). In Fig. 5(*b*), a radial profile of mean axial velocity acquired at the axial position of the primary jets is shown. Again the profiles are similar to those of Module 1. These data indicate that the penetration of the jets in the two cases is not substantially different.

Although the aerodynamic field near the jets is similar, the thermal fields and effluent are substantially different. This is attributed to the way in which the jets interact with the swirl induced recirculation zone. In Module 2, the primary jet axial location corresponds to approximately the middle of the extent of the recirculation zone. The jets penetrate to the centerline, impact, and feed directly into the swirl-induced recirculation bubble, providing a substantial amount of cold air to the reaction. In Module 1, the primary jets are close to the end of

a) Centerline profiles of mean axial velocity.



b) Radial profiles of mean axial velocity.

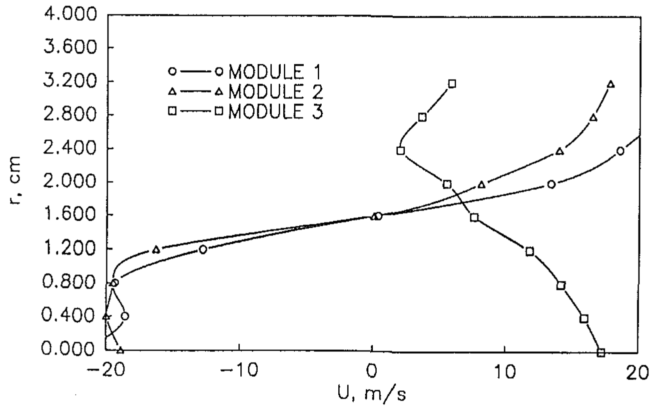


Fig. 5 Comparison of mean axial velocities

the recirculation bubble and, although backflow is produced by the impact of the jets, very little of the cold air is recirculated into the dome region.

Module 3. In this module, the primary jets are positioned one duct diameter downstream of the swirler (as in module 1) but, instead of four jets per row, the number of jets is increased to six. Air flows and fuel loading are kept the same in this case as well. It is important to note, however, that because the same flow must now be divided among six jets instead of four, the jet injection velocity is reduced. In Module 1, the primary jet velocity is 60.7 m/s, whereas in Module 3, the jet velocity is reduced to 40.5 m/s.

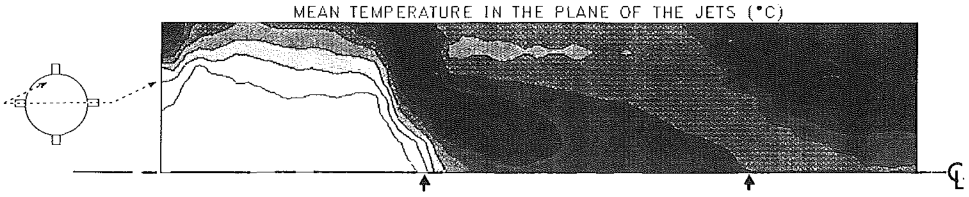
The ratio of the primary jet momentum to the approaching crossflow momentum is important to the resulting penetration and trajectory of the jets. In this case, because the momentum ratio has been reduced, the jets do not penetrate as deeply. This is demonstrated by the mean temperature in the plane of the jets (Fig. 6*a*).

The dome region temperature map of Module 3 is similar to that of Module 1; the reaction is contained in the central region of the combustor and a small cold corner is present. In contrast to Module 1, temperatures are substantially higher and the high-temperature region extends into the region downstream of the jets. Although it is clear the jets are deflected by the approaching crossflow, the presence of steep thermal gradients near the centerline in the axial region of the primary jets indicate cooling is influenced by the jets. The mean temperature profiles in the plane of symmetry, Fig. 6(*b*), also show this effect. Relative to the other modules, the hot gases from the dome region flow are not preferentially directed to the wall region. Instead, the hot gases are more uniformly mixed in the secondary region (between the primary and dilution jets) and the core of the combustor is, as a result, relatively hot.

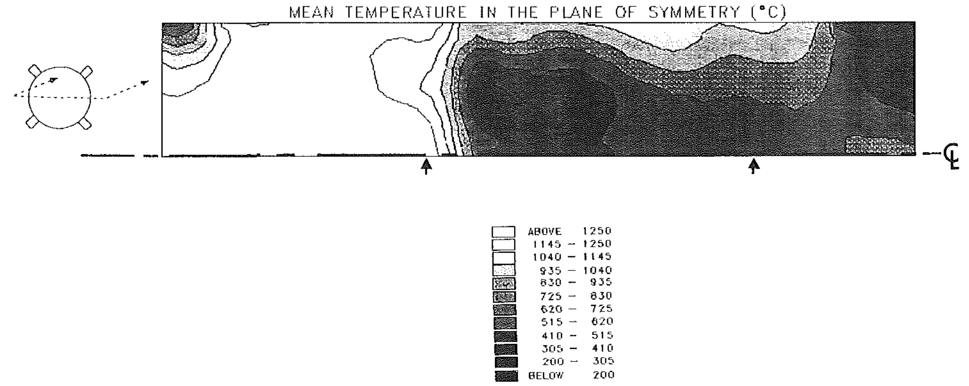
Emissions data for this combustor are shown in Fig. 6(*c*). In general the pattern for this combustor is reversed from the other two modules. Levels of CO_2 and NO_x are high at the central core and drop off near the walls, except very near the walls where levels are again high. In contrast CO levels are low in the core and rise toward the wall.

The mean axial velocity profile along the centerline is shown in Fig. 5(*a*). The end of the swirl-induced recirculation zone is located approximately 2 cm upstream of the primary jets. The radial profile of axial velocity at $x = 8$ cm (corresponding

a) The thermal field in the plane of the jets.



b) The thermal field in the plane of symmetry.



c) Emissions profiles at the exit plane.

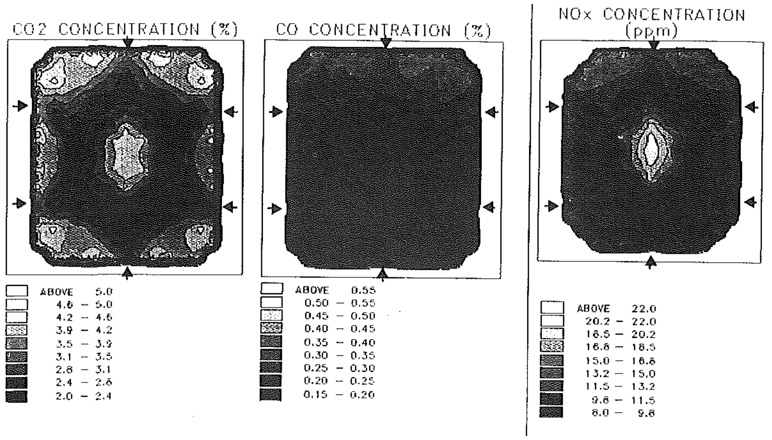


Fig. 6 Module 3 results

to the axial position of the primary jets) in Fig. 5(*b*) shows no evidence of jet penetration to the centerline. The slight deficit off centerline at $r = 0.8$ cm is probably an indication of where the primary jets penetrate to the plane of symmetry between the jets. Because the jets do not penetrate to the centerline, the jets do not contribute to the air mass entering the recirculation zone. Thus the dome region mixture ratio in this case is close to the stoichiometric conditions dictated by the ratio of fuel and swirl air injected, and the dome region temperatures are correspondingly higher.

Summary and Conclusions

This study delineates the importance and complexities associated with the primary jets in controlling combustor aerothermal behavior, and the overall performance.

The relative position of the primary jets to the swirl injection plane is of paramount importance. Although the two cases produce similar primary jet trajectories into the combustor core, the percent mass recirculated into the dome region is substantially different. This is attributed to the way in which the primary jets feed into the recirculation zone. In this study the location of the feed point was found to influence the mass recirculated. In parallel isothermal studies (Richards and Samuelsen, 1990), increasing the jet to crossflow ratio is found to produce a similar effect for primary jets located one duct diameter downstream of the swirler.

The number of primary jets also impacts the combustor aerothermal behavior in two ways. First, for the case in which fuel loading and equivalence ratio are maintained constant, increasing the number of jets per row results in decreased jet injection velocities. Second, the increased number of jets spread the mixing more uniformly about the duct circumference. Hence Module 3, with six jets per row, produces exit temperature and emissions profiles that are more uniform than those produced by the four jet combustors.

The next series of tests will explore the impact of jet to crossflow momentum and its relative impact compared to primary jet location and number. Experiments at elevated pressure are planned as well.

The conclusions of the present study are as follows:

- Years of combustor design, combustor development, and combustor research have demonstrated that the location and number and size of the primary jets are important to combustor performance. The present work is able to contribute the measurements and data presentation formats that quantify these empirically and intuitively held perceptions. In addition, the data base established should prove useful for the validation and development of the three-dimensional codes developed for can and annular combustor design.
- The percent mass recirculated into the dome region, as well as the overall uniformity of mixing and combustion efficiency, is substantially influenced by jet row location. The momentum ratio of the incoming primary jet stream to that of the approaching crossflow of reacting dome gases has a direct impact on the mixing patterns as well. An increase in the number of primary jets leads, in the present case, to more uniform mixing due to a reduced penetration and a more uniform distribution of mixing about the duct circumference.

Acknowledgments

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