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Mixing of Jet Air with a Fuel-Rich, Reacting Crossflow

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The mixing of jet air into hot, fuel-rich products of a gas-turbine primary zone is a critical step in staged combustion. Often referred to as quick quench, the mixing occurs instead with chemical conversion and substantial heat release. An experiment has been designed to simulate and study this process. The geometry is a crossflow confined in a cylindrical duct with a sidewall injection of jets issuing from round holes. A specially designed reactor, operating on propane, presents a uniform mixture to a module containing jet-air-injection orifices that can be varied in geometry. Temperature and species concentrations of O_2, CO_2, CO, and HC are obtained upstream, downstream, and within orifice planes. From this information, penetration of the jet, the spatial extent of chemical reaction, and mixing can be deduced. Results are presented for a mixing module containing 10 round holes that is operated at a momentum-flux ratio of 57 and a jet-to-mainstream mass-flow ratio of 2.5.

Nomenclature

d	= round hole diameter
f	= jet mixture fraction based on carbon mass fraction
J	= jet-to-mainstream momentum-flux ratio, $(\rho V^2)_{\text{jet}}/(\rho V^2)_{\text{main}}$
R	= radius of the quick-mix module
r	= radial distance from the module center
T_{main}	= mainstream temperature
T_{jet}	= jet-air temperature
U_S	= spatial unmixedness
V_{ref}	= reference velocity
x	= axial distance from leading edge of orifice
Y	= mass fraction of carbon
ϕ	= equivalence ratio, $(\text{fuel/air})_{\text{local}}/(\text{fuel/air})_{\text{stoichiometric}}$

Introduction

JETS in a crossflow play an integral role in practical combustion systems, such as can and annular gas-turbine combustors in conventional systems, and the rich-burn/quick-mix/lean-burn (RQL) combustor utilized in stationary applications and proposed for advanced subsonic and supersonic transports. The success of the RQL combustor rests with the performance of the quick-mixing section that bridges the rich and lean zones. The mixing of jet air with a rich crossflow to bring the reaction to completion in the lean zone must be performed rapidly and thoroughly to decrease the extent of near-stoichiometric fluid pocket formation. Fluid pockets at near-stoichiometric equivalence ratios are undesirable because the high temperatures that are attained accelerate pollutant formation kinetics associated with nitric oxide (NO). The present study develops a model experiment designed to reveal the processes that occur when jet air is introduced into hot effluent emanating from a fuel-rich reaction zone.

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Backgound

Jet mixing into a crossflow has been studied extensively because of its wide range of applicability to such diverse fields as gas-turbine cooling and staging, fuel–air premixing, vertical/short takeoff and landing aircraft, and pollutant discharge from stacks or pipes. For the confined crossflow problem, such as that encountered in the quick-mixing region of the RQL combustor, flow properties, such as the jet-to-mainstream density and momentum-flux ratios as well as the geometries constraining the jet and crossflow, influence the degree of mixing that occurs. In a confined subsonic crossflow, the most important flow variable is the jet-to-mainstream momentum-flux ratio J (Ref. 1). The momentum-flux ratio must be determined before a configuration, e.g., orifice number, shape, and placement, can be designed. For this experiment, a target J value of 60 was chosen to simulate a practical operating condition in an aircraft gas-turbine combustor.

Extensive experimental and numerical studies[1] on jets in a confined crossflow have been performed under nonreacting conditions to examine the effect of jet orifice configurations on mixing in different duct geometries at various momentum-flux ratios. Both rectangular and cylindrical ducts have been studied for annular and can combustor configurations, respectively.[2,3] Various orifice shapes of circular, square, elliptical, and slotted geometries have been tested under the premise that the shape of the jet entering the crossflow would affect jet mixing. In one study, round holes were found to be as effective as slotted orifice geometries in promoting jet mixing.[4] Because of this result and the fact that manufacturability considerations favor the circular orifice over the other orifice shapes, this study concentrated on testing the round hole configuration.

To date, reacting-flow component experiments have been avoided to benefit from the advantages of the nonreacting environment (less complicated, more amenable to diagnostic interrogation). Numerical analyses have been used to characterize the flowfield of jets entering a reacting cylindrical geometry by either 1) inference from nonreacting data or 2) numerical simulation.[3] The next step taken here is to conduct a reacting experiment.

The objectives of the present study are twofold: 1) design and construct an experiment for the study of jet mixing into a uniform, fuel-rich reacting crossflow; and 2) reveal the progress of penetration, reaction, and mixing for a specific mixing module configuration.

Experiment

This section describes the facility and data measurement protocol that were developed and used in the rich, reacting experiment.

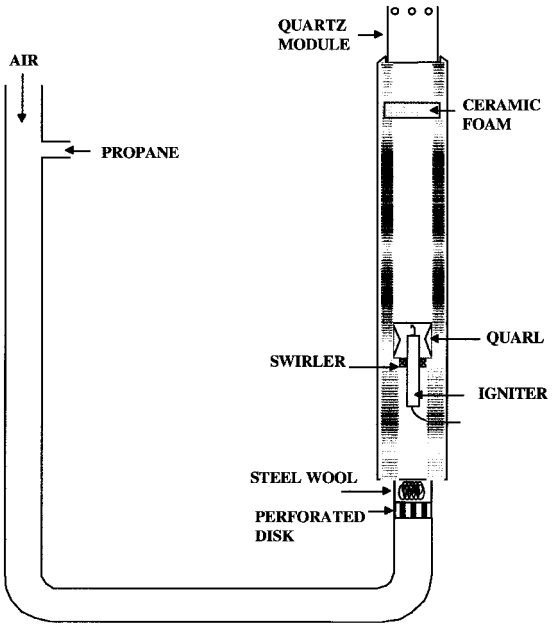

Fig. 1 Rich product generating system.

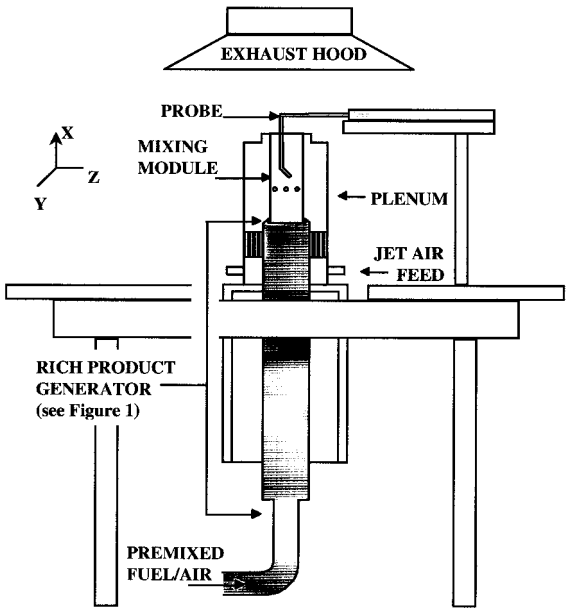

Fig. 2 Reacting flow test stand.

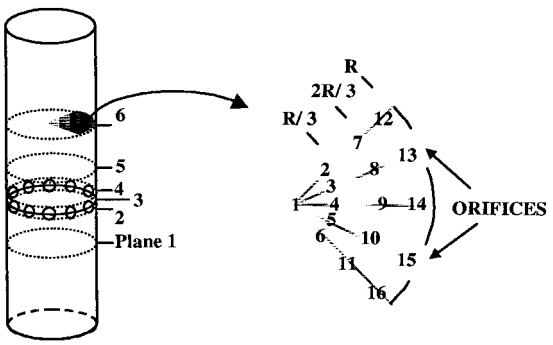

Fig. 3 Measurement locations.

Further information on the facility and experiment can be found in Ref. 5.

Facility

The facility consists of a reaction zone that supplies rich reacting effluent to the jet mixing section. The design of the rich-product generator was an iterative process to establish an experiment that generates a uniform rich combustion product, in the absence of swirl, into a cylindrical mixing module. Hardware durability and safety applied important constraints on the design.

The final design of the rich-product generator is shown in Fig. 1. The reacting facility is up-fired to eliminate asymmetries caused by buoyancy. Propane is injected and mixed into air at room temperature (20°C, 68°F) at a point that is 4.3 m (14 ft) upstream of the contracting quarl section. Propane simulates the chemistry associated with the hydrocarbon composition of jet fuel without complicating the experiment with liquid fuel atomization.

The quarl provides a 38-mm (1.5-in.) contraction to prevent the backflow of combustion products. An ignition source is provided by an industrial spark plug positioned in the center of the quarl. Main air supplied to the system at a flow rate of 11.3 SLPM (0.4 SCFM) ensures a 10-m/s (33-ft/s) bulk flow velocity at the quarl contraction.

In the reaction zone, a recirculation region promotes the stable continuous combustion of the fresh incoming fuel and air mixture. A production engine cast swirler with 45-deg vanes and axially directed holes dispersed around the outer circumference of the vanes is used to create an on-axis recirculation zone. Before the gases reach the mixing module, the swirling component is dissipated by an oxide-bonded silicon carbide ceramic foam matrix (Hi-Tech Ceramics) to provide a uniform plug flow into the mixing module. The 76-mm– (3.0-in.)-diam, 25-mm– (1.0-in.)-thick matrix is positioned five duct diameters downstream of the quarl section and one duct diameter upstream of the module. The porosity of the foam, rated at four pores per cm (10 pores per inch), is sufficient in allowing the required flow rate through the 25.4-mm (1-in.) thickness at a negligible, 0.3% pressure drop in the system. The ceramic is rated up to 1200°C (2192°F) and has withstood thermal shock and stress loading caused by periodic testing.

A schematic of the complete testing facility is shown in Fig. 2. The plenum surrounding the mixing section is fed by four equidistant, individually metered air ports located toward the base of the plenum. A high-temperature steel flow straightener conditions and equally distributes the jet air entering the mixing module. A pressure tap and thermocouple mounted on the plenum chamber monitor the pressure drop across the mixing module and the temperature of the jet air, respectively.

The modular design of the mixing section allows for the testing of varying orifice sizes and geometries by interchanging different quartz tubes. The quartz tubes have inner and outer diameters of 80.0 mm (3.15 in.) and 85.0 mm (3.35 in.), respectively, and a length of 279 mm (11.0 in.). The centerline of the circumferential row of orifices is positioned 114 mm (4.50 in.) downstream from the entrance of the module. Gaskets made of an alumina–silica blend of ceramic fiber paper are used to provide sealing between the quartz tube and stainless-steel mating surfaces.

Measurement Protocols

Data are acquired with a stationary probe while the experiment is moved to the desired spatial coordinate. A digital encoder (Mitutoyo) monitors the position of the probe tip with respect to the center of the quick-mix module. Temperature and species concentration data are obtained at each of six planes situated throughout the length of the module (Fig. 3). The planes are positioned, with respect to the leading edge of the orifices, as follows: plane 1 = one module radius upstream, $x/R = -1$; plane 2 = orifice leading edge, $x/R = 0$; plane 3 = one-half the orifice axial height, $x/R = (d/2)/R$; plane 4 = orifice axial height, $x/R = d/R$; plane 5 = one module radius downstream, $x/R = 1$; plane 6 = two module radii downstream, $x/R = 2$.

Assuming flow symmetry, a sector of data is obtained to represent the entire plane (see Fig. 3). Each plane of data consists of 16 points distributed across a sector that includes two orifices. One point is located at the center while the rest of the points are positioned along

the arc lengths of three radii that are $R/3$, $2R/3$, and R distance away from the center. Along each radial arc, two points are aligned with the center of the holes, and three are aligned with the midpoint of the wall region between the holes.

Temperature and gas concentration measurements are made using a double-jacketed water-cooled stainless-steel probe. The probe dimensions consist of an 8.0-mm (0.315-in.) o.d. that tapers down to a 3.2-mm (0.125-in.) tip bent at a 45-deg angle. The plane of the probe tip is positioned such that the tip points toward, and is perpendicular to, the sector wall. In quick-mixing jet flows, the angled-tip thermocouple probe design is the preferred configuration.[4]

Temperature measurements are obtained with a type-B platinum–rhodium thermocouple. The range of the type-B thermocouple, which falls between 0°C (32°F) and 1820°C (3308°F), is suitable for the reaction temperatures that were measured. The thermocouple, which is constructed from a set of bare wires 0.254 mm (0.010 in.) in diameter, is threaded through the sample extraction tube and positioned such that the junction extends 2.54 mm (0.1 in.) beyond the probe tip. A computer program records and returns an average of 100 readings after 20 s. The temperature measurements are corrected for radiation losses. The uncertainty associated with the temperature measurement is ±10 K.

Species concentration measurements of CO_2, CO, O_2, H_2, and total unburned HC are obtained by conveying the sampled gas through the probe and through a 15.2-m (50-ft) heated line connected to the emission analyzers. After the water is condensed from the gas sample, the gas is routed to the analyzers. The analyzers (Horiba Instruments, Inc., models AIA-210/220 and FIA-220/MPA-220) utilize nondispersed infrared, paramagnetic, and flame ionization detection to measure the concentrations of CO_2 and CO, O_2, and unburned HC, respectively. H_2 is measured by gas chromatography. For the experiment, the measured H_2 concentration was 9.6% in the rich section.

A measurement is obtained at a point when the readings on the console stabilize after approximately 45 s. Data are acquired with an acquisition program that reads 100 samples in 20 s and returns an averaged quantity. An uncertainty corresponding to 1% of the full-scale reading of the analyzer range is used to determine the uncertainty in calculations that depend on the species concentration measurements.

Jet mixture fraction values are calculated from the species concentration values by the method of Jones et al.[6] Because carbon is conserved throughout the reaction, the jet mixture fraction can be calculated based on the mass fraction of carbon. The jet mixture fraction is defined as

$$f = \frac{Y_{\text{main}} - Y_{\text{sample}}}{Y_{\text{main}} - Y_{\text{jet}}} \tag{1}$$

where the carbon mass fractions are calculated on a wet sample basis for the initial mainflow at plane 1 (Y_{main}), the jet air (Y_{jet}), and the sampled point (Y_{sample}). Assuming a negligible carbon content in the jet air, the jet mixture fraction equation reduces to

$$f = \frac{Y_{\text{main}} - Y_{\text{sample}}}{Y_{\text{main}}} \tag{2}$$

An index of the degree of mixing in the system is given by the spatial unmixedness value U_S. The spatial unmixedness parameter is a normalized variance value that is defined as

$$U_S = \frac{f_{\text{var}}}{f_{\text{av}}(1 - f_{\text{av}})} \tag{3}$$

where f_{av} refers to the planar area-weighted average of the calculated jet mixture fraction. A U_S value of 0 indicates a perfectly mixed system, whereas a value of 1 indicates a totally unmixed system.[7]

Demonstration

The experiment was conducted for a 10-round hole mixing module. The round hole diameters were sized at 12.5 mm (0.494 in.) to yield a jet-to-mainstream momentum-flux ratio J of 60. The total geometrical orifice area of 1237 mm^2 (1.917 in.^{2}) for the mixing module was based on a discharge coefficient of 0.73. The experimental operating conditions are noted in Table 1. The measured momentum flux ratio was 57, and the mass-flow ratio was 2.5. For this condition, the expected jet mixture fraction value for a fully mixed system is about 0.71. In the absence of chemical reactions, one would thus expect any nonreacting mainstream constituents that are not present in the jets to be near 30% of their mainstream value.

Table 1 Operating conditions

Parameter	Value
Ambient pressure, atm	1
Rich equivalence ratio ϕ	1.66
Overall ϕ	0.45
T_{main}, K	1500
T_{jet}, K	400
V_{ref}, m/s	18
J	57
Mass-flow ratio	2.5
Density ratio	3.3

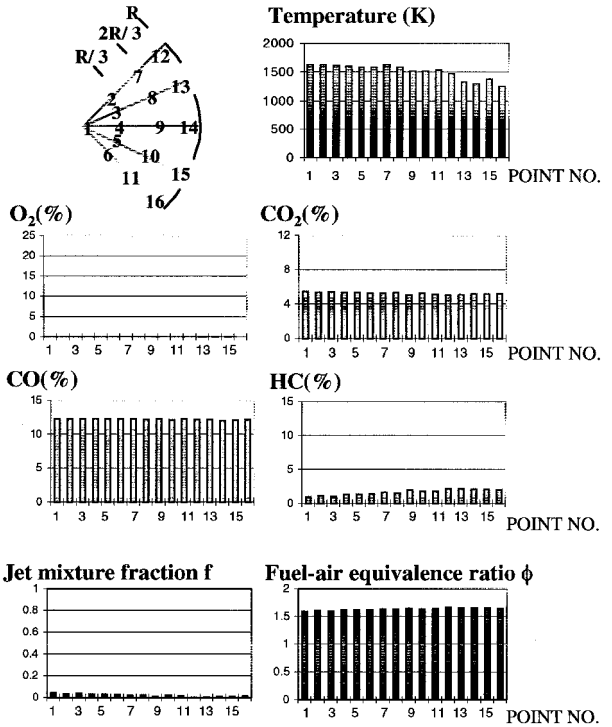

Fig. 4 Rich product data distributions at plane 1.

Results and Discussion

An evaluation of the rich reacting product entering the mixing module was first performed to ascertain the uniformity of the flowfield exiting the generator. Once the uniformity of the rich product flow was established, temperature and species concentration data were obtained at the six measurement planes within the mixing module.

Rich Inlet Flow Uniformity

Measurements upstream of the jets (plane 1) were made to evaluate the uniformity of the rich reacting product entering the jet-mixing module. Figure 4 shows the measured temperature and species concentrations of O_2, CO_2, CO, and HC.

At plane 1, a uniform temperature distribution averaging 1500 K is obtained. Lower temperatures in the immediate vicinity of the wall are attributed to the convective cooling of the outer quartz module wall by the plenum air.

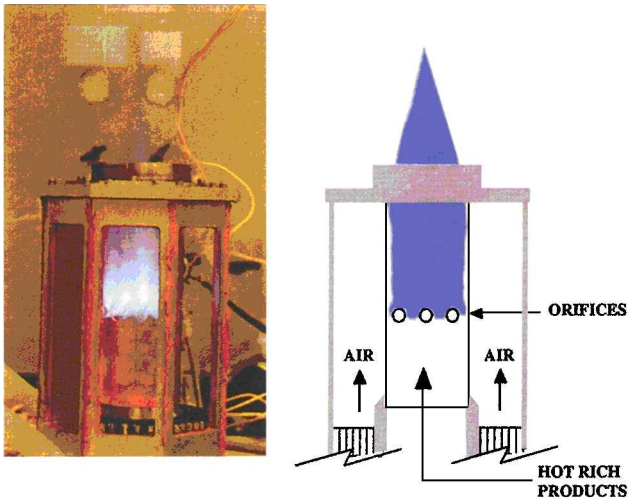

Fig. 5 Jet mixing and reaction with a hot rich crossflow.

Histogram distributions of O_2, CO_2, CO, and HC concentrations reveal uniform rich zone concentrations averaging 0% O_2, 5.2% CO_2, 12.1% CO, and 1.8% HC. These species concentrations are used to calculate the jet mixture fraction and equivalence ratios based on the carbon mass fraction. The near-constant jet mixture fractions further demonstrate flowfield uniformity by showing that the main reacting flow distributes carbon evenly throughout the plane. The average jet mixture fraction of 0.018, with an associated uncertainty of ± 0.017, is close to the value of 0 that is expected for the rich section.

The equivalence ratio calculation, which is based on the jet mixture fraction, yields an average equivalence ratio of 1.64. This value is within the 0.03 uncertainty range associated with the equivalence ratio of 1.66 that is set by the fuel and air mass flow rates.

Jet Penetration and Reaction

Visual Illustration

Figure 5 shows a photograph and an accompanying schematic of the mixing module during operation of the reacting experiment. The rich, hot flow that enters the module from the bottom is colorless. (The reddish tinge is caused by the radiative glow of the generator refractory lining below.) The jet air trajectory is illuminated by the blue emission emanating from the round holes. The blue emission denotes the border of the jet and reacting mainflow interface, and clearly illustrates the oxidation reaction of the reducing species CO, H_2, and HC in the rich section.

Temperature Profiles

In Fig. 6, contour plots showing the distribution of temperatures in the 10-round hole module illustrate the evolution of the reaction process occurring in the mixing module. Because of the uniform temperature and species concentrations measured at plane 1 (see Fig. 4), contour plots will not be presented for this plane.

At the orifice leading edge (plane 2), the temperatures do not differ greatly from the initial temperatures in the rich section (plane 1). Temperatures of at least 1500 K occur in the bulk flow, except for the regions where the jet fluid begins to enter the mixing module. By the orifice half-height (plane 3), the temperatures at a majority of points remain near 1500 K. At this plane, two distinct jets of fluid can be seen penetrating into the fuel-rich crossflow.

The distribution of the two jets in plane 3 appears uneven, which may be attributed to flow asymmetry. To check flow symmetry, pitot tube measurements were obtained under nonreacting conditions at the entrance of both orifices as well as across two diameters at plane 1. The measurements suggest that the jet flow entering the two orifices is uniform to within 5% and that the crossflow velocity profile is uniform to within 15%. As a result, no gross flow asymmetry exists, and the temperature results at plane 3 reveal the extent to which symmetry can be achieved in this highly dynamic, reacting, and mixing domain.

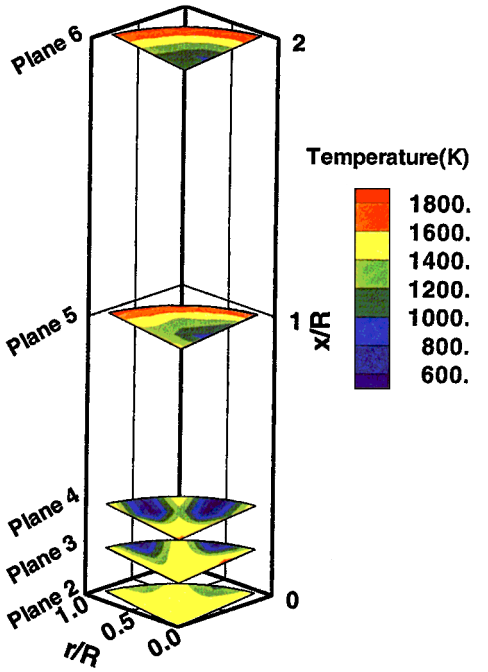

Fig. 6 Temperature profile.

At the orifice trailing edge (plane 4), all of the jet fluid has entered the module. The jet fluid penetrates even farther, but has not yet fully dispersed. The central core temperatures persist near 1500 K.

Substantial reaction and mixing between plane 4 and the plane situated one duct radius downstream (plane 5) is revealed by major differences between the two profiles. At plane 5, the jets of air disperse and the jet structure disappears. In addition, mixing and reacting processes have produced three stratified bands of temperature. The core temperatures are lower than the initial mainflow temperature of 1500 K, but are higher than the 400-K jet fluid temperature. In plane 5, temperatures higher than 1500 K occur in the outer band of points near the wall and offer evidence of chemical reaction. In fact, in the absence of chemical reaction, the maximum temperature in the flow should not exceed 1500 K.

The temperatures measured at plane 6 show the same stratification as in plane 5. The similar profiles in planes 5 and 6, which show a lack of extensive mixing and reacting activity between the two planes, indicate that the bulk of the reaction is completed within one duct radius of the jet leading edge.

Species Concentration Profiles

Inferences related to jet penetration and mixing can also be formed from the distribution of species concentrations. The O_2 concentration profiles indicate jet presence and dispersion because the jets of air provide the only source of oxygen in the rich reacting field. The O_2 plot in Fig. 7 shows the evolution of jet penetration from the leading edge of the orifices (plane 2). At the orifice midheight plane (plane 3), O_2 concentrations near 21% occur where the jets enter and indicate jet penetration to a distance that is one-third of the mixing module radius. In plane 4, the jet fluid then penetrates beyond the midradius and begins to spread to neighboring regions. By plane 5, all of the jet mass has been added, and jet penetration, as indicated by high O_2 concentrations, appears to have reached the center. The O_2 concentrations are between 10 and 16% in the core region, whereas concentrations less than 6% are found near the wall and are lowest in the wake of the jets. By plane 6, O_2 concentrations are stratified in three regions with the higher concentrations tending toward the center and the lower concentrations tending near the wall.

Figure 7 also shows sector profiles of concentrations of CO and CO_2. While the O_2 concentration profiles show the entrance and dispersion of the jets into the crossflow, the regions of near-zero concentrations of CO and CO_2 also indicate jet fluid presence (compare

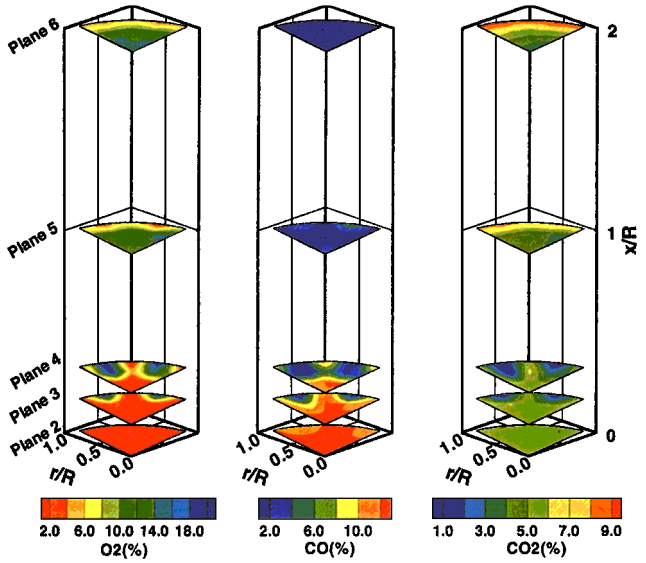

Fig. 7 Species concentration profiles.

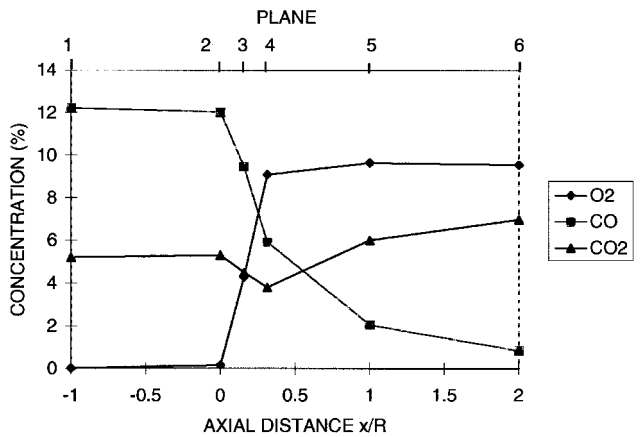

Fig. 8 Area-weighted planar-averaged species concentration values.

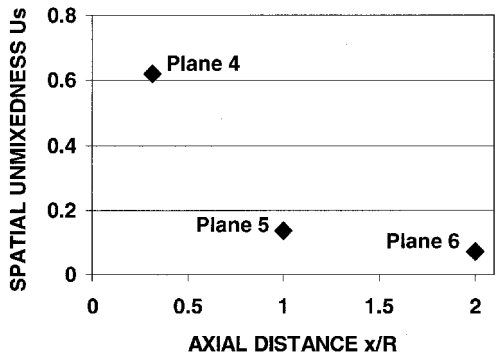

Fig. 9 Spatial unmixedness values calculated per plane.

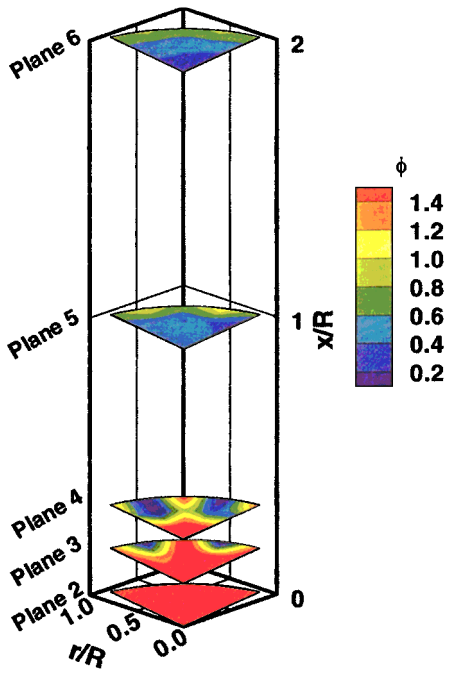

Fig. 10 Equivalence ratio profile.

the plots at planes 3 and 4 between the three species). The CO and CO_2 profiles also show the extent of reaction in the flow. The bulk of the reaction takes place in the zone downstream of the round holes, where the jets penetrate toward the center and begin to disperse throughout the crossflow. In this volume of reaction between planes 4 and 5, CO is consumed in oxidation reactions that convert CO to CO_2. CO levels at plane 5 range between 0 and 6%, which is a large decrease from the 12% initial CO concentration in the fuel-rich crossflow. The CO_2 profiles show a corresponding increase in concentration, particularly in the wall region. The small pockets of CO in the wake of the jets at plane 5 subsequently disappear as CO reacts with the jet air to form the CO_2 along the wall. Most of the reaction terminates by plane 5 because the magnitudes of the profiles measured at that plane and at plane 6 do not change substantially.

Area-weighted planar-averaged values of O_2, CO, and CO_2 calculated per plane are shown in Fig. 8. Each species shows uniform concentration levels between planes 1 and 2. In the orifice region, the entering jets raise the average planar O_2 concentration and decrease the CO and CO_2 values. Downstream of the orifice region, the O_2 concentration does not change greatly. However, the concentration of CO decreases and the concentration of CO_2 increases because of chemical reaction. Comparing planes 2 and 5, there is a large drop in CO concentration from 12 to 2%, which is accompanied by an increase in the average CO_2 level from 5.2 to 6%. O_2 levels are initially 0% in the rich section, but eventually attain a 9.6% concentration. These reaction processes begin to taper off between planes 5 and 6, where the average CO level drops by 1.3%, O_2 drops by 0.1%, and CO_2 increases by 1%. These average concentrations confirm the observations that the orifice region within one duct radius is full of chemical and mixing activity, and that downstream of this region this activity still occurs but begins to diminish.

Jet Mixing

Jet mixture fraction values at each point were calculated from the measured species concentrations. The spatial unmixedness values were then calculated per plane from the jet mixture fractions (Fig. 9).

At the orifice trailing edge (plane 4), where all of the jet mass has been added, the spatial unmixedness reaches a peak value of 0.62. By plane 5, U_S decreases to 0.14. The unmixedness then decreases to 0.073 at plane 6, which is 12% of the initial U_S value. The larger difference in U_S between planes 4 and 5 (difference of 0.48) compared with that between planes 5 and 6 (difference of 0.067) indicates that most of the jet mixing with the crossflow has been attained within one module radial length of the jet entrance.

The fuel–air equivalence ratio is a conserved scalar that can also be used as an index of mixing, since it is directly associated with the jet mixture fraction. Figure 10 shows the contour plots of the calculated equivalence ratio for the 10-orifice case. Up to the plane at the orifice leading edge (plane 2), the calculated average planar equivalence ratio is 1.60, which is close to the design equivalence ratio of 1.66, and which does not deviate greatly from the 1.64 average equivalence ratio obtained at plane 1. The blue patches denoting near-zero equivalence ratio values represent the jet fluid

presence in planes 3 and 4. Near-stoichiometric equivalence ratios (denoted in yellow) occur in bands surrounding the jet, which suggest where the interface between the jet and fuel-rich crossflow lies.

Fuel-rich gases (represented by the red color band) still exist at plane 4 because the jets have not yet fully dispersed and reacted. The fuel-rich regions disappear by plane 5, and indicate substantial reaction between the two planes. Near-stoichiometric pockets of fluid exist close to the wall in the wake of the jets, suggesting that reaction processes continue to occur at the jet–crossflow interface on the lee side of the jets. The near-stoichiometric mixture of fluid near the wall also corresponds to the higher temperature band along the periphery of the wall in the same plane (see Fig. 6).

By plane 6, the yellow band range disappears, but any change in the contour profiles compared with plane 5 appears to be slight. This corroborates the observation that reaction still occurs, though not in the same magnitude as the reaction taking place between planes 4 and 5. The average equivalence ratios for Planes 5 and 6 are 0.63 and 0.59, respectively. However, the design lean equivalence ratio based on the fuel and air mass flow rates of the exiting section should be 0.45. In this case, the decrease in the plane-averaged equivalence ratio with increasing downstream distance indicates the persisting presence of velocity gradients in the jet–crossflow mixture; a lean-burning plug flow in this experiment should otherwise yield a plane-averaged equivalence ratio of 0.45.

Conclusions

An experiment has been designed and successfully demonstrated to provide a test bed for the study of jet mixing in a rich reacting environment. In this demonstration, jet penetration, mixing, and reacting processes were observed for the 10-round hole configuration. The following facts were found:

1) A facility capable of producing a uniform flow of hot, fuel-rich gases for reacting jet mixing studies can successfully reveal the reaction and mixing processes associated with the crossflow injection of jets of air.

2) Temperature and species concentration measurements depict the jet–mainflow reaction occurring in the system and describe the jet dispersion process. Mixing fields are inferred from the jet mixture fraction, or equivalence ratio profiles.

3) Jet air mixing with a reacting stream of fuel-rich gases produces substantial reaction within one duct radial length from the entrance of the jets ($x/R = 1$). Reaction processes continue to occur up to and possibly beyond a distance from the jet entrance equivalent to one duct diameter ($x/R = 2$).

4) The bulk of the mixing between the jet air and reacting mainflow occurs by the $x/R = 1$ plane, although additional mixing does occur between $x/R = 1$ and 2.

Acknowledgments

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References

[1]Holdeman, J. D., "Mixing of Multiple Jets with a Confined Subsonic Crossflow," *Progress in Energy and Combustion Science*, Vol. 19, No. 1, 1993, pp. 31–70; also AIAA Paper 91-2458, 1991, and NASA TM 104412, 1993.

[2]Holdeman, J. D., Liscinsky, D. S., and Bain, D. B., "Mixing of Multiple Jets with a Confined Subsonic Crossflow: Part II—Opposed Rows of Orifices in a Rectangular Duct," *Journal of Engineering for Gas Turbines and Power* (to be published); also NASA TM 107417, June 1997.

[3]Holdeman, J. D., Liscinsky, D. S., Oechsle, V. L., Samuelsen, G. S., and Smith, C. E., "Mixing of Multiple Jets with a Confined Subsonic Crossflow: Part I—Cylindrical Duct," *Journal of Engineering for Gas Turbines and Power*, Vol. 119, No. 4, 1997, pp. 852–862; also NASA TM 107185, June 1996.

[4]Sowa, W. A., Kroll, J. T., Samuelsen, G. S., and Holdeman, J. D., "Optimization of Orifice Geometry for Cross-Flow Mixing in a Cylindrical Duct," AIAA Paper 94-0219, Jan. 1994; also NASA TM 106436, Jan. 1994.

[5]Leong, M. Y., and Samuelsen, G. S., "Quick-Mixing Studies Under Reacting Conditions," NASA CR-195375, Sept. 1996.

[6]Jones, W. P., McDonell, V., McGuirk, J. J., Milosavljevic, V. D., Taylor, A. M. K. P., and Whitelaw, J. H., "The Calculation of Mean Mixture Fractions in Turbulent Non-Premixed Methane Flames from Aspiration-Probe Measurements," Mechanical Engineering Dept., Imperial College of Science, Technology and Medicine, Thermofluids Section Internal Rept. TF/93/13, London, 1993.

[7]Liscinsky, D. S., True, B., and Holdeman, J. D., "Experimental Investigation of Crossflow Jet Mixing in a Rectangular Duct," AIAA Paper 93-2037, June 1993; also NASA TM 108152, July 1993.