NASA Technical Memorandum 107430
WCC/CI Paper No. 97S–034

Mixing of Pure Air Jets With a Reacting Fuel-Rich Crossflow

M.Y. Leong and G.S. Samuelsen
University of California
Irvine, California

J.D. Holdeman
Lewis Research Center
Cleveland, Ohio

Prepared for the
Spring 1997 Meeting of the Western States Section
sponsored by the Combustion Institute
Sandia National Laboratory, Livermore, California, April 14–16, 1997

National Aeronautics and
Space Administration

WCC/CI paper No. 97S-034

MIXING OF PURE AIR JETS WITH A REACTING FUEL-RICH CROSSFLOW

M.Y. Leong
G.S. Samuelsen*
UCI Combustion Laboratory
University of California
Irvine, CA 92697-3550 USA

J.D. Holdeman
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, OH 44135 USA

COMBUSTION LABORATORY

* Corresponding Author
(714)824-5468 (Phone)
(714)824-7423 (FAX)
email: gss@uci.edu

ABSTRACT

The mixing of air jets 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 side-wall injection of jets issuing from round orifices. A specially designed reactor, operating on propane, presents a uniform mixture to a module containing air jet 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 the orifice plane. 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, and operated at a momentum-flux ratio (J) of 57 and a jet-to-mainstream mass-flow ratio (MR) of 2.5.

NOMENCLATURE

DR	jet-to-mainstream density ratio
d	round hole diameter
f	jet mixture fraction based on carbon mass fraction
J	jet-to-mainstream momentum-flux ratio = $(\rho V^2)_{jet}/(\rho V^2)_{main}$
MR	jet-to-mainstream mass-flow ratio
r	radial distance from the module center
R	radius of the quick-mix module
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 = $(\text{fuel/air})_{local}/(\text{fuel/air})_{stoichiometric}$

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 in order to decrease the extent of near-stoichiometric fluid pocket formation. Fluid pockets at near-stoichiometric equivalence ratios are undesirable because the high temperatures 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.

BACKGROUND

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, VSTOL 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.[1] The momentum-flux ratio must be determined before a configuration (e.g., orifice number, shape, and placement) can be designed.

Extensive experimental and numerical studies on jets in a confined crossflow have been performed under non-reacting conditions to examine the effect of jet orifice configurations on mixing in different duct geometries at various momentum-flux ratios. Both rectangular ducts and cylindrical ducts have been studied for annular and can combustor configurations, respectively.[2,3]

To date, reacting-flow component experiments have been avoided to benefit from the advantages of the non-reacting 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 non-

reacting 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 flow experiment. Further information on the facility and experiment can be found in Ref. 4.

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 Figure 1. The reacting facility is up-fired to eliminate asymmetries due to buoyancy. Propane is injected and mixed into room temperature (72°F) air 14 ft. upstream of the contracting quarl section. Propane simulates the chemistry associated with the higher hydrocarbon composition of jet fuel without complicating the experiment with liquid fuel atomization.

The quarl provides a 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 0.4 standard cubic feet per minute (SCFM) ensures a 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° 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 (OBSiC) ceramic foam matrix (Hi-Tech Ceramics) in order to provide a uniform plug flow into the

mixing module. The 3 in. diameter, 1 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 10 pores per inch, is sufficient in allowing the required flow rate through the 1 in. thickness at a negligible, 0.3% pressure drop in the system. The ceramic is rated up to 2200°F and has withstood thermal shock and stress loading due to periodic testing.

The complete testing facility is shown in Figure 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 3.0 in. and 3.3 in., and a length of 11 in. The centerline of the circumferential row of orifices is positioned 4.5 in. downstream from the entrance of the module. Sealing between the quartz tube and stainless steel mating surfaces is provided by gaskets made of an alumina-silica blend of ceramic fiber paper.

Measurement Protocols

Data are acquired with a stationary probe while the experiment is moved to the desired data point. 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 (Figure 3a). The planes are positioned, with respect to the leading edge of the orifices, as follows:

Plane	Position
1	One module radius upstream, $x/R = -1$,
2	Orifice leading edge, $x/R = 0$
3	One-half the orifice axial height, $x/R = (d/2)/R$
4	Orifice axial height, $x/R = d/R$
5	One module radius downstream, $x/R = 1$
6	Two module radii downstream, $x/R=2$.

Assuming flow symmetry, a sector of data is obtained to represent the entire plane (Figure 3b). 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 at r/R=1/3, 2/3, and 1. For 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 0.315 in. outside diameter that tapers down to a 0.125 in. tip bent at a 45-degree angle. The plane of the probe tip is positioned such that the tip points toward, and is perpendicular to the sector wall. The angled-tip thermocouple probe design is the preferred configuration in quick-mixing jet flows.[5]

Temperature measurements are obtained with a type B platinum-rhodium thermocouple. The range of the type B thermocouple, which falls between 32° and 3300°F, is suitable for the reaction temperatures that were measured. The thermocouple, which is constructed from a set of bare wires 0.010 in. in diameter, is threaded through the sample extraction tube and positioned such that the junction extends 0.1 in. beyond the probe tip. A computer program records and returns an average of 100 readings after 20 seconds.

Species concentration measurements of CO_2, CO, O_2, H_2, and unburned total HC are obtained by conveying the sampled gas through the probe and through a 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 utilize non-dispersed infrared (NDIR), paramagnetic, and flame ionization detection (FID) to measure CO_2 and CO, O_2, and unburned HC species, respectively. H_2 is measured by gas chromatography. For the experiment, the measured H_2 concentration was 9.6%.

A measurement is obtained at a point when the readings on the console stabilize after approximately 45 seconds. Data are acquired with an acquisition program that reads 100 samples in 20 seconds and returns an averaged quantity.

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

$$f = \frac{Y_{main} - Y_{sample}}{Y_{main} - Y_{jet}} \qquad (1)$$

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

$$f = \frac{Y_{main} - Y_{sample}}{Y_{main}} . \qquad (2)$$

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 standard deviation value that is defined as

$$U_S = \frac{STD}{f_{avg}\left(1 - f_{avg}\right)} , \qquad (3)$$

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

Demonstration

The experiment was conducted for a 10-round hole mixing module. The round holes were sized (0.494 in. diameter) to yield a jet-to-mainstream momentum-flux ratio J of 60. The total geometrical orifice area of 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 fully-mixed jet mixture fraction is about 0.71. In the absence of chemical reactions, one would thus expect exhaust 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} (°F)	2200
T_{jet} (°F)	350
V_{ref} (ft/s)	60
momentum-flux ratio J	57
mass-flow ratio MR	2.5
density ratio DR	3.3

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 rich product flow uniformity 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. Figures 4a-c show the measured temperature and species concentrations of O_2, CO_2, CO, and HC measurements.

At Plane 1, a uniform temperature distribution is obtained in the bulk flow (Figure 4a). 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.

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 (Figure 4b). These species concentrations are then used to calculate the jet mixture fraction and equivalence ratios based on the carbon mass fraction (Figure 4c). The near-constant jet mixture fractions, having an average value of 0.018, further demonstrates flowfield uniformity by showing that the main reacting flow distributes carbon evenly throughout the plane. The equivalence ratio calculation, which is based on the jet mixture fraction, shows an average equivalence ratio of 1.64 which compares well with the operating condition of 1.66 set by the fuel and air mass flow rates.

Jet Penetration and Reaction

Visual Illustration Figure 5 shows a picture 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 holes. The blue emission denotes the border of the jet and reacting mainflow interface, and clearly illustrates the oxidation reaction of the rich section reducing species CO, H_2, and HC.

Temperature Profiles A temperature profile distribution of the 10-round hole module (Figure 6) illustrates the evolution of the reaction process occurring in the mixing module. At the orifice leading edge (Plane 2), the

temperatures do not differ greatly from the initial temperatures in the rich section (Plane 1), hovering near 2200°F in the bulk flow with the exception of Points 13 and 15. The lower temperatures at these points reflect the relatively cool entering jet fluid.

By the orifice half-plane (Plane 3), the temperatures at a majority of points remain near 2100°F. However, the jet trajectory is revealed with lower temperatures near 350°F occurring at Points 13 and 15. Jet penetration to 2R/3 is marked by lower temperatures of 1550°F and 2020°F occurring respectively at Points 8 and 10.

The temperatures at Points 8 and 10 would be equal if flow symmetry and probe alignment were perfect. To check flow symmetry, pitot tube measurements were obtained under non-reacting 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 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.

At the orifice trailing edge (Plane 4), all of the jet fluid has entered the module. The jets penetrate to 2R/3 but have not yet fully dispersed and mixed with the neighboring node points. The central core temperatures persist near 2100°F.

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 histogram profiles. At Plane 5, mixing and reacting processes have produced three stratified bands of temperature. The center and inner radial points 1-11 all show temperatures less than the initial mainflow temperature of 2200°F but higher than the 350°F jet fluid temperature. Temperatures higher than 2200°F occur in the outer band of points near the wall, and offer evidence of chemical reaction. In the absence of additional chemical reaction, one would expect 2200°F to be the highest temperature in the flow.

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

The contour plots in Figure 7 present a pictorial view of the temperature data. The temperature of the entering fluid at Plane 2 is nearly uniform. The two jets entering the crossflow are distinct. Downstream of the orifices, as seen in Plane 5, the jet fluid loses its coherency and disperses. Fully-stratified temperature ranges occur in the jet-crossflow mixture by Plane 6. The temperatures in the center region at Plane 6 are lower than the initial mainflow temperature, which suggests penetration and mixing of the cooler jet fluid at the center. The temperatures along the wall are higher than the initial mainflow temperature, which indicates the occurrence of reaction processes.

Species Concentration Profiles Inferences related to jet penetration and mixing can also be formed from the distribution of species concentrations. The O_2 concentrations indicate jet presence and dispersion because the air jets provide the only source of oxygen in the rich reacting field. The O_2 charts in Figure 8 show the evolution of jet penetration from the leading edge of the orifices (Plane 2). At the orifice mid-height plane (Plane 3), the jets fill the outer mixer radius R to near-21% concentrations at Points 13 and 15, which are aligned with the orifices. The jet fluid then penetrates to the second radial band 2R/3 by Plane 4 and begins to spread to neighboring regions, as shown by the presence of O_2 at Points 7 through 11. At 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 levels are between 10-16% in the core region while concentrations are less than 6% 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 9 shows the sector profiles of concentrations of O_2 as well as CO and CO_2. While the O_2 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 Planes 3 and 4 for 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 holes (between Planes 4-5) where the jets penetrate toward the center and begin to disperse throughout the crossflow. In this volume of reaction between Planes 4 and Plane 5, CO is consumed in oxidation reactions that convert CO to CO_2. CO levels at Plane 5 range between 0-6%, 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. Most of the reaction terminates by Plane 5 since the magnitude of the profiles measured at that plane and at Plane 6 do not change substantially.

Downstream of Plane 5 the penetrating jets displace the rich reacting fluid toward the wall, as evidenced by the pocket of relatively higher CO concentration at the wall. The small pockets of CO in the wake of the jets subsequently disappear as CO reacts with the jet to form CO_2. This source of CO_2 increases concentrations at the wall from Plane 5 to Plane 6.

Area-weighted values of O_2, CO, and CO_2 calculated per plane are shown in Figure 10. Each specie shows uniform concentration levels between Planes 1 and 2. In the orifice region, the entering jets raise the average planar O_2 level and decrease the CO and CO_2 values. After the orifice region, the O_2 level does not change greatly but CO decreases and 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 CO_2 levels 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%.

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. At Plane 1, U_s is 0.008 and at Plane 2, U_s is 0.011 (Figure 11). Because no jet fluid is present at these planes, the expected U_s value at these planes is zero. The values at Planes 1 and 2 are close, but not equal to zero because there is a small amount of spatial unmixedness associated with the distribution in the carbon mass fraction upon which the jet mixture fraction is based.

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 all the jet fluid has entered, and U_s decreases to 0.11. The unmixedness then decreases to 0.078 at Plane 6, which is 13% of the peak U_s value attained. The larger difference in U_s between Planes 4 and 5 (difference of 0.51) compared to that for Planes 5 and 6 (difference of 0.029) indicates that most of the jet mixing with the crossflow has been attained within one module radial length of the jet entrance.

The 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 12 shows the contour sector 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 at Plane 1. The jet fluid presence is seen in Planes 3 and 4 by the blue patches denoting near-zero equivalence ratio values. Near-stoichiometric equivalence ratios (denoted in orange) occur in bands surrounding the jet which suggest where the interface between jet and fuel-rich crossflow lies.

The fuel-rich gases still exist at Plane 4 because the jets have not fully dispersed and reacted yet, but disappear by Plane 5, indicating 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 Figure 7).

By Plane 6 the orange band range disappears, but any change in the contour profiles compared to Plane 5 appears slight. This observation suggests that reaction still occurs, though not in the same magnitude as the reaction taking place between Planes 4 and 5. The average equivalence ratio for Planes 5 and 6 are 0.63 and 0.59, respectively. Given that the design lean equivalence ratio based on the fuel and air mass flow rates of the exiting section should be 0.45, the 10-orifice mixing module does not promote full jet reaction with the crossflow by Plane 6 since reaction may still be continuing beyond this plane.

SUMMARY AND 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-hole configuration. It was found that:

- 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 air jets.

- 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.

- 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).

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

ACKNOWLEDGMENTS

This work was funded under a grant from the NASA-Lewis Research Center (Grant NAG3-1110). Appreciation is extended to Dr. William A. Sowa for contributing to the initial stages of the reacting flow experiment. The authors are grateful to Professor Ron Matthews (University of Texas) and Professor Robert Peck (Arizona State University) for their guidance in the selection of the ceramic foam.

REFERENCES

[1]Holdeman, J.D. (1993). Mixing of Multiple Jets with a Confined Subsonic Crossflow. *Prog. Energy Combust. Sci*, v.**7**, pp.31-70. (See also AIAA-91-2458; NASA TM 104412).

[2]Holdeman, J.D., Liscinsky, D.S., and Bain, D.B. (1997). 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* (in press). (Also NASA TM 107417)

[3]Holdeman, J.D., Liscinsky, D.S., Oechsle, V.L., Samuelsen, G.S., and Smith, C.E. (1996). Mixing of Multiple Jets With a Confined Subsonic Crossflow: Part I—A Single Row of Orifices Around the Perimeter of a Cylindrical Duct. *Journal of Engineering for Gas Turbines and Power* (in press). (See also NASA TM 107185)

[4]Leong, M.Y. and Samuelsen, G.S. (1996). Quick-Mixing Studies Under Reacting Conditions. NASA Contractor Report 195375 (UCICL-ARTR-95-8).

[5]Sowa, W.A., Kroll, J.T., Samuelsen, G.S., and Holdeman, J.D. (1994). Optimization of Orifice Geometry for Cross-Flow Mixing in a Cylindrical Duct. AIAA-94-0219 (Also NASA TM 106436).

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

[7]Vranos, A., Liscinsky, D.S., True, B., and Holdeman, J.D. (1991). Experimental Study of Cross-Stream Mixing in a Cylindrical Duct. AIAA-91-2459 (Also NASA TM 105180).

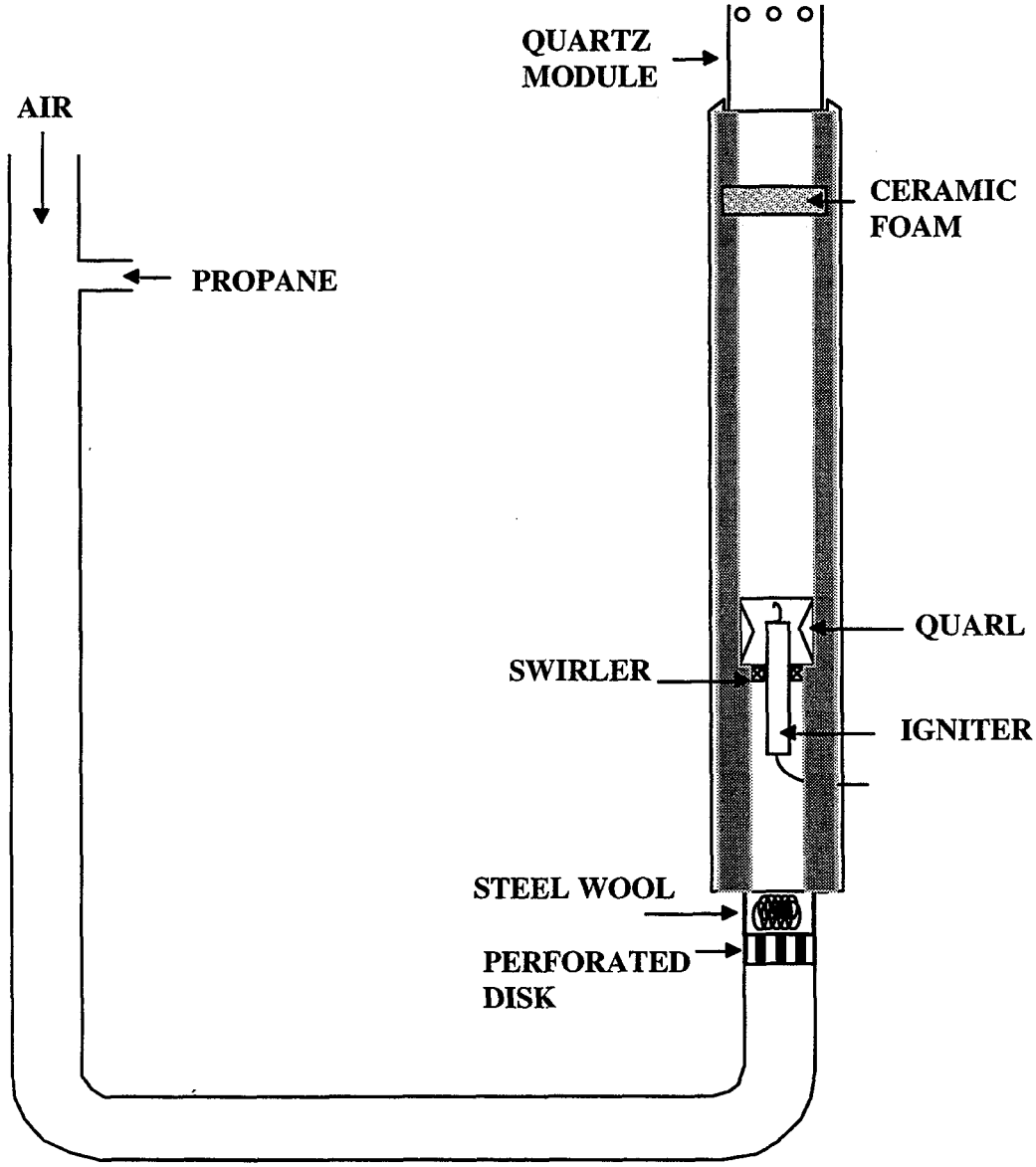


Figure 1. Rich product generating system.

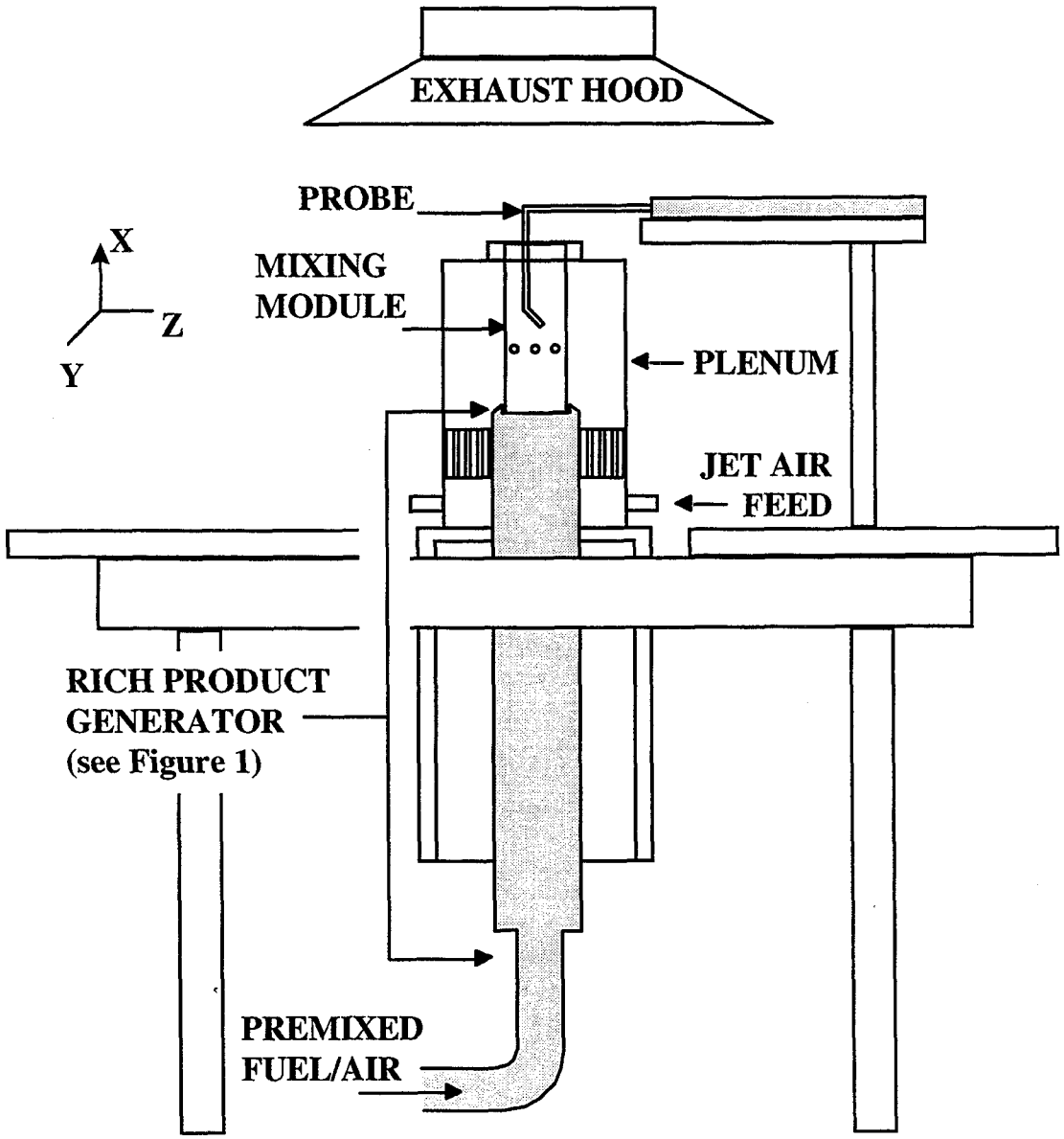
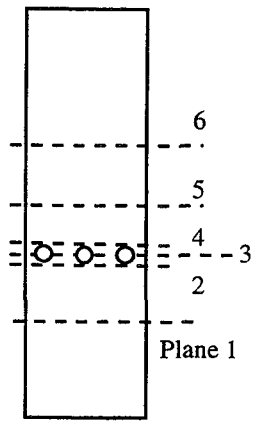
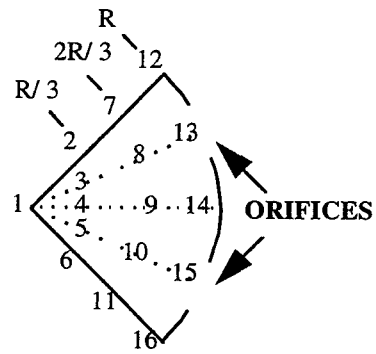


Figure 2. Reacting flow test stand.

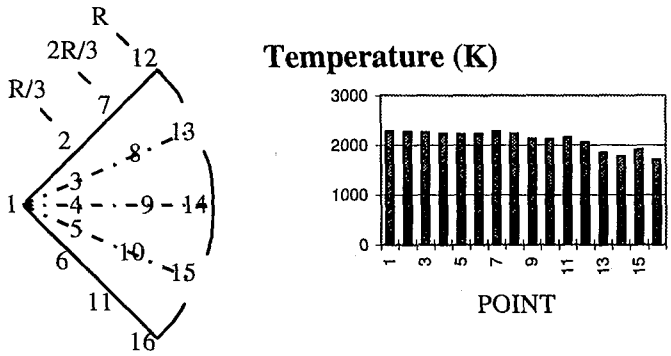


(a) Data plane locations

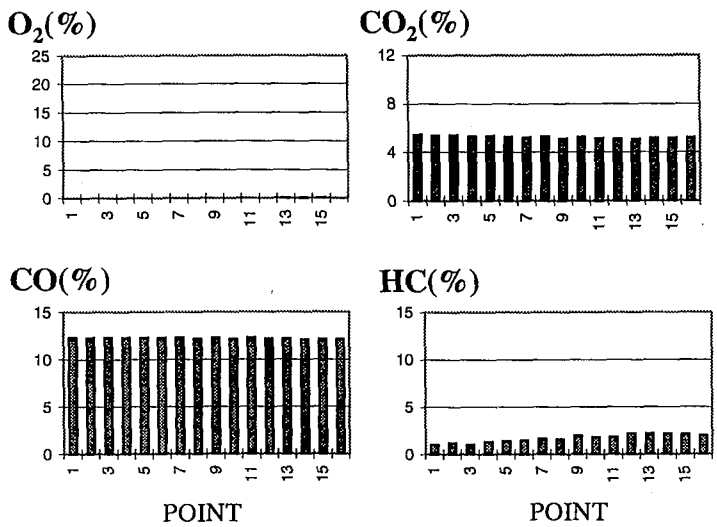


(b) Data point locations

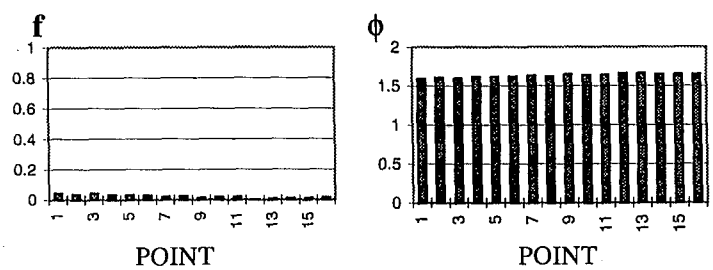
Figure 3. Measurement locations.



(a) Temperature distribution

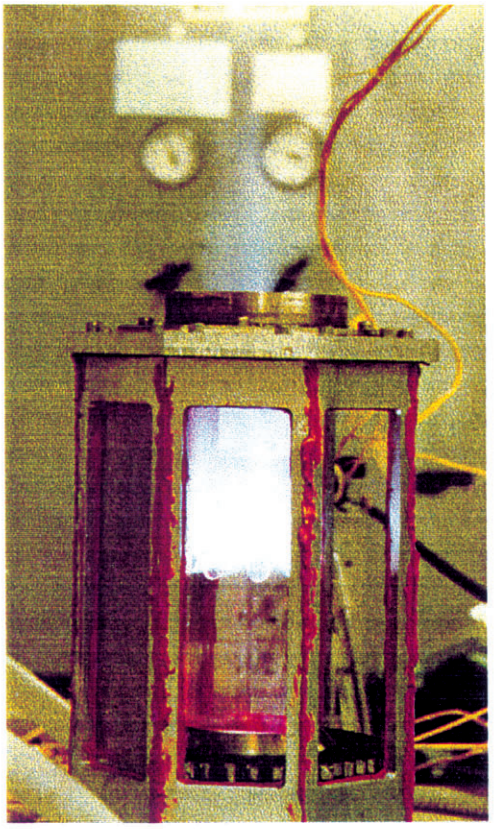


(b) Species concentration distributions



(c) Mixture fraction f and equivalence ratio ϕ distributions

Figure 4. Rich product data distributions at Plane 1.



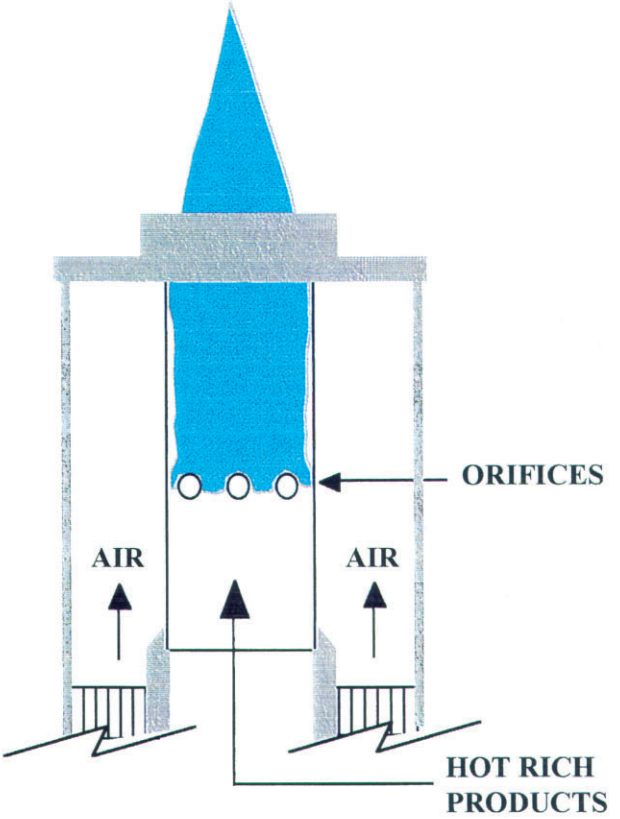


Figure 5. Jet mixing and reaction with a hot rich crossflow.

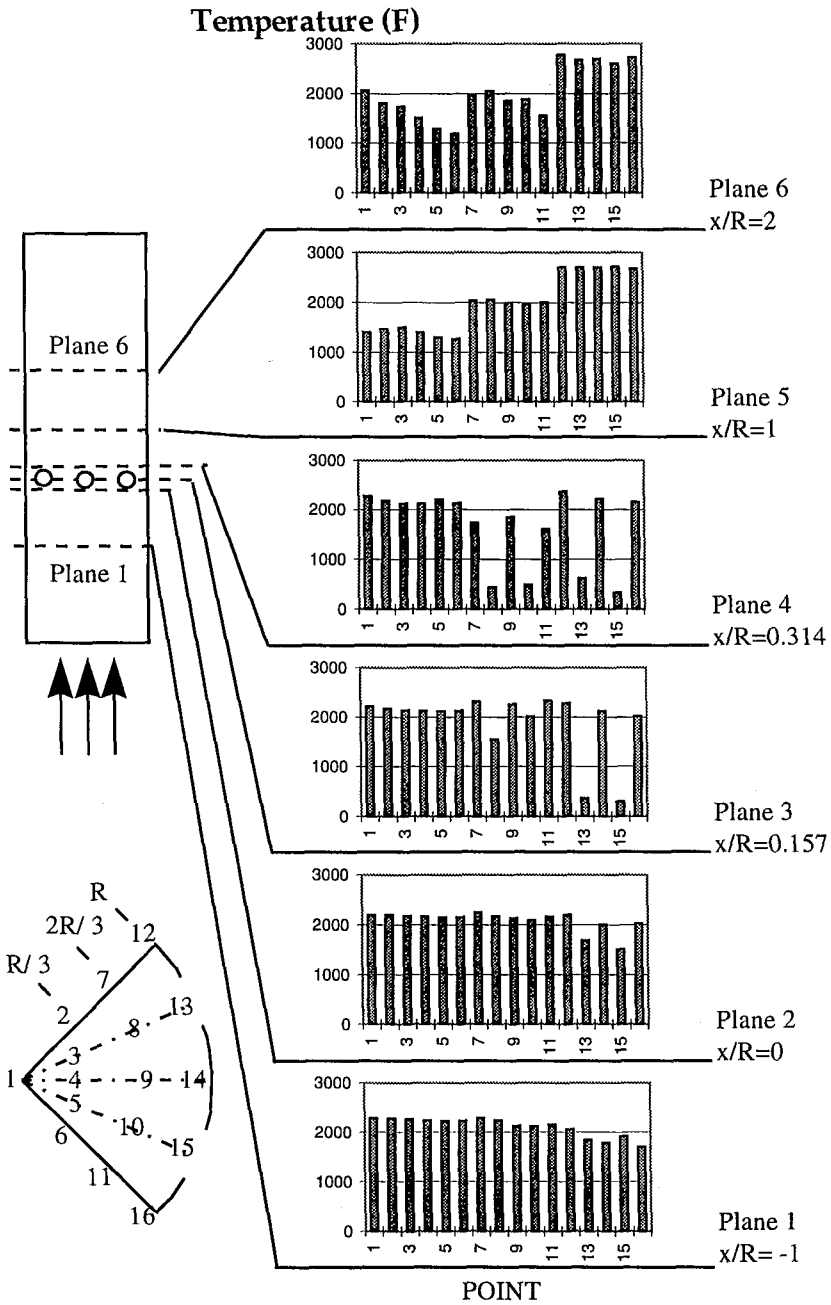


Figure 6. Temperature distribution for the 10-round hole module.

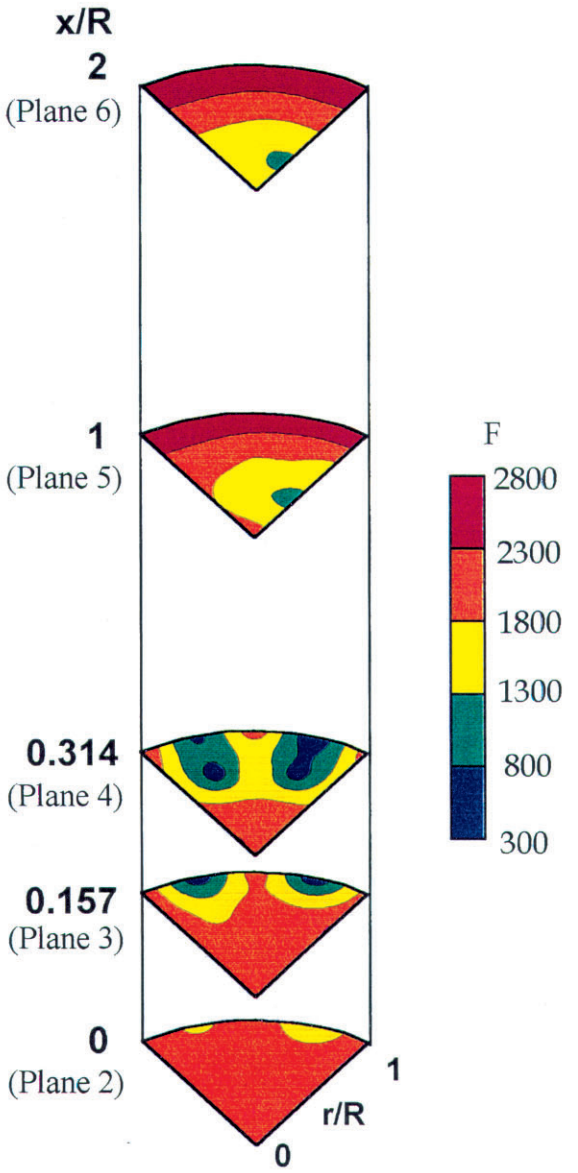


Figure 7. Temperature profile.

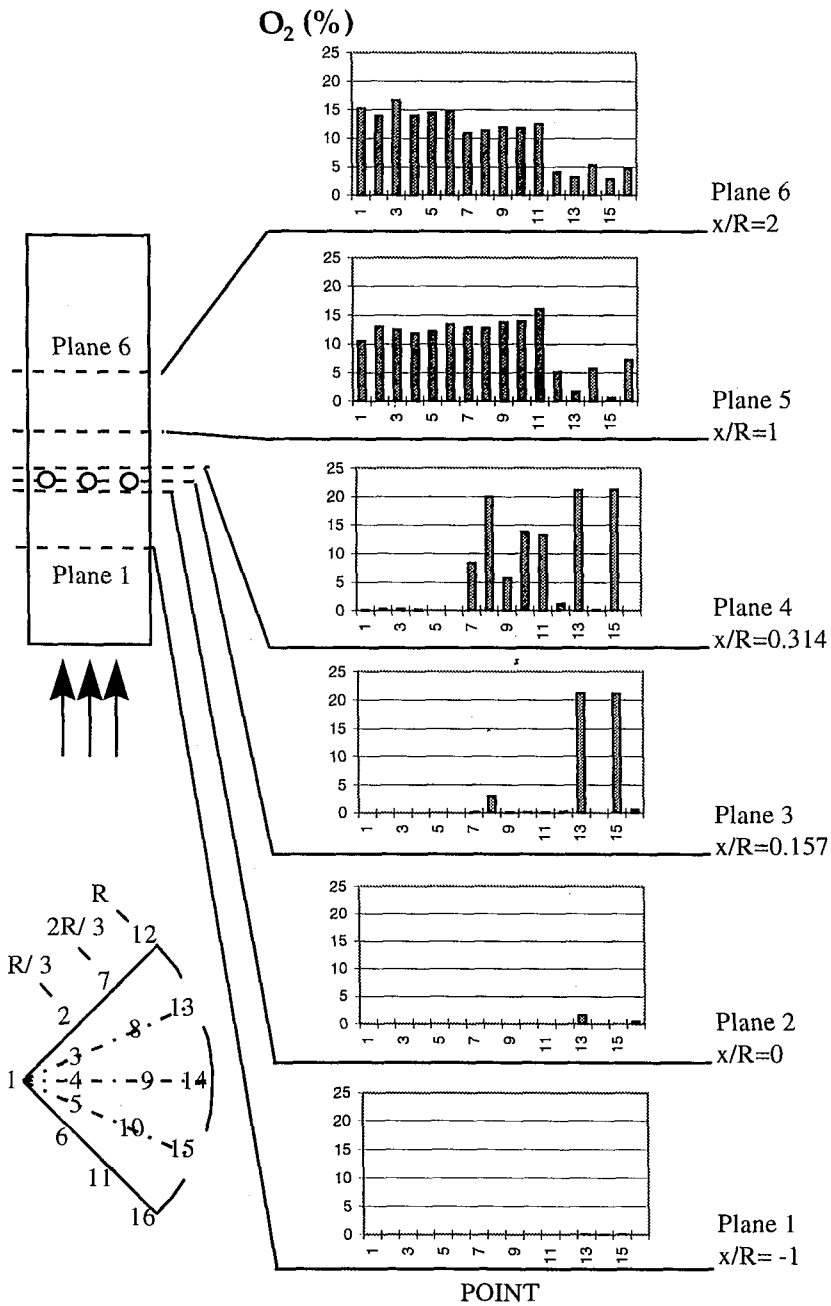


Figure 8. O_2 concentration distribution.

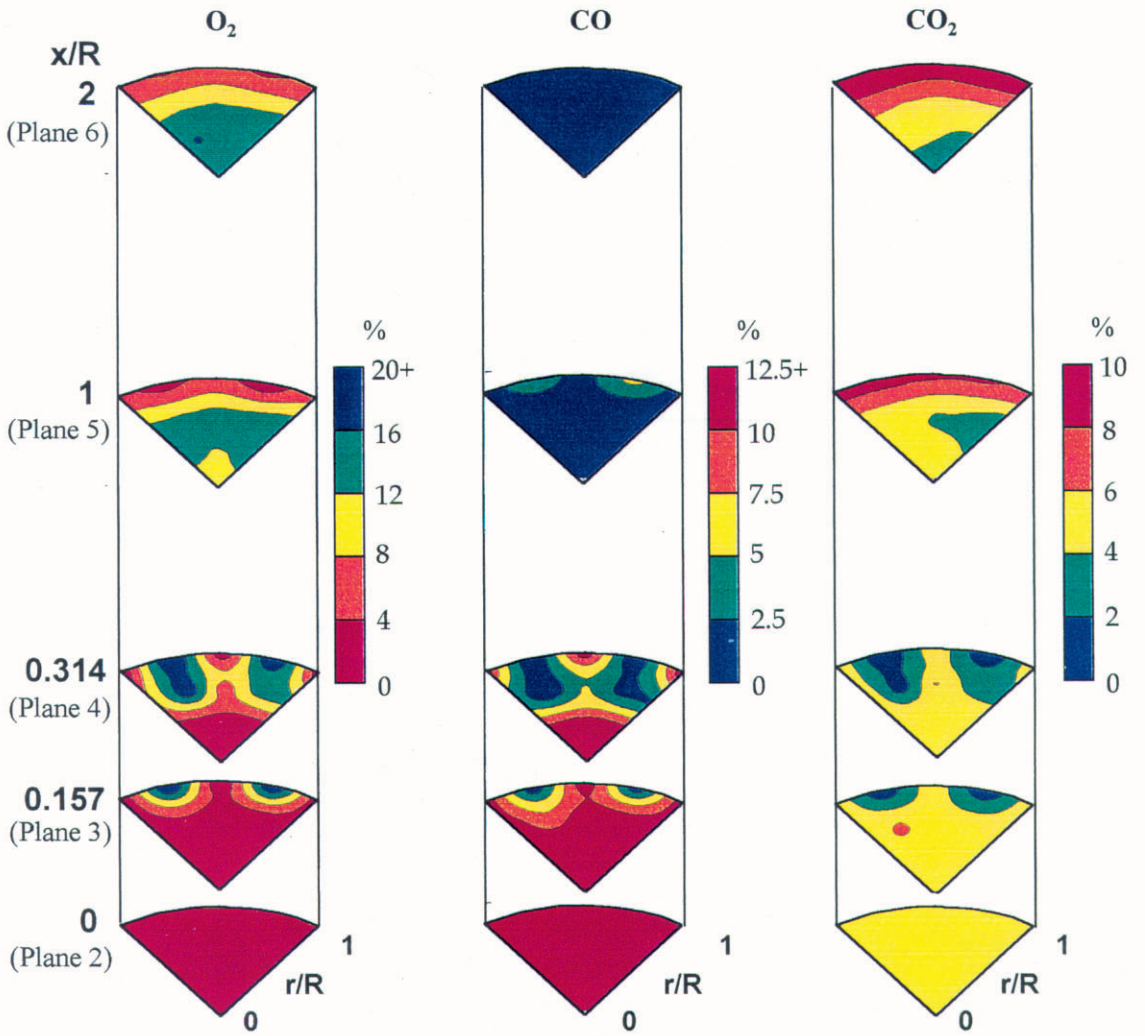


Figure 9. Species concentration profiles.

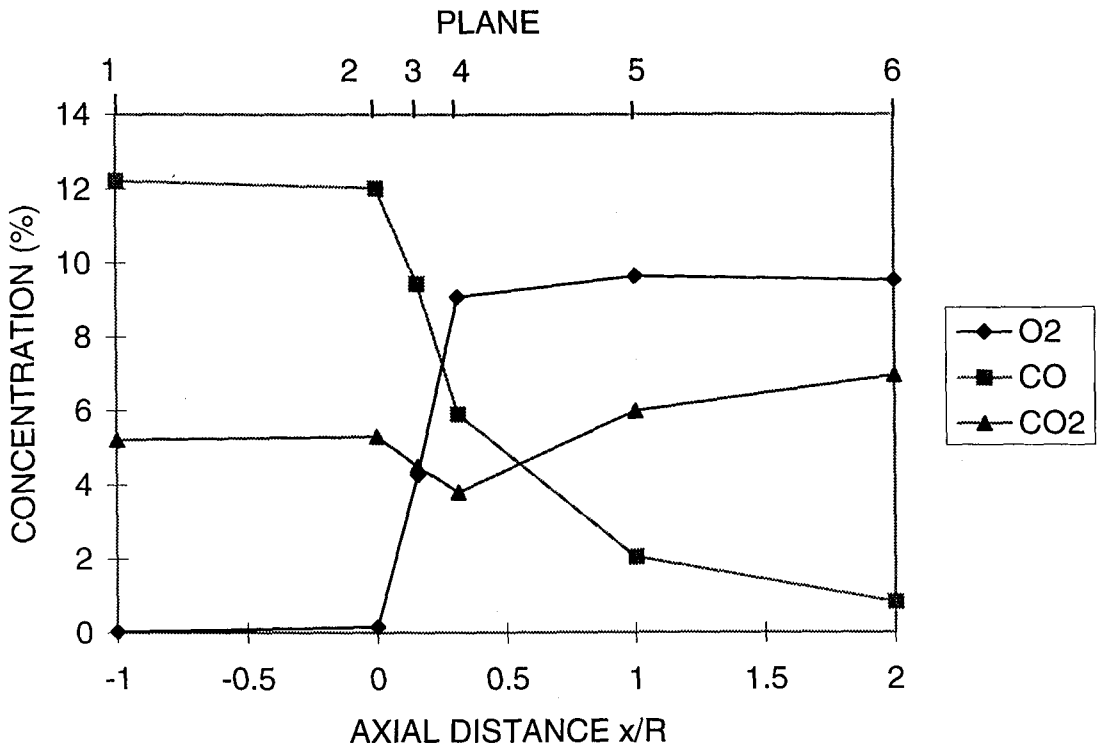


Figure 10. Area-weighted planar average species concentration values.

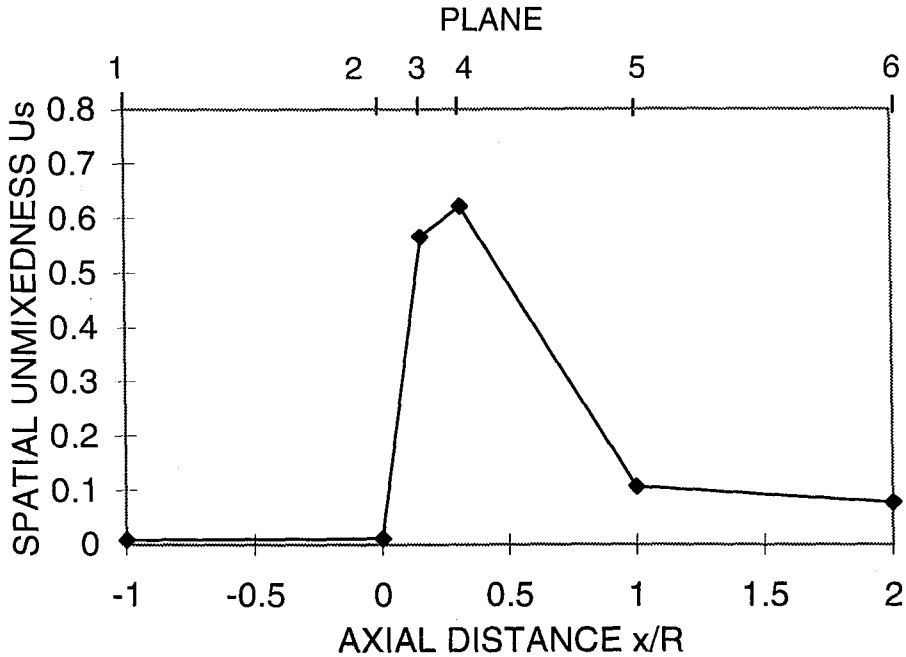


Figure 11. Spatial unmixedness values calculated per plane.

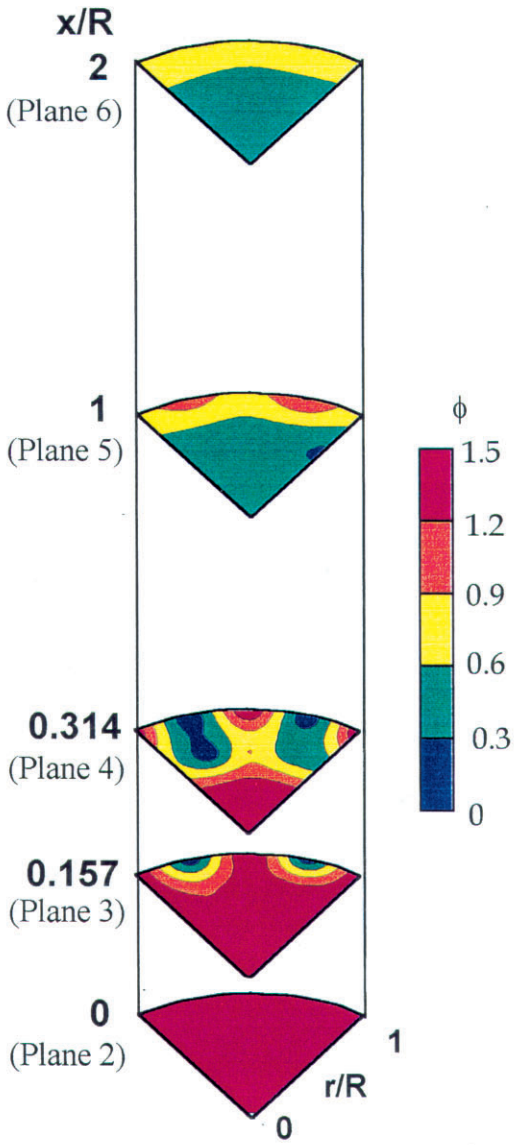


Figure 12. Equivalence ratio profile.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (*Leave blank*)

2. REPORT DATE
April 1997

3. REPORT TYPE AND DATES COVERED
Technical Memorandum

4. TITLE AND SUBTITLE
Mixing of Pure Air Jets With a Reacting Fuel-Rich Crossflow

5. FUNDING NUMBERS
WU–537–02–20–00

6. AUTHOR(S)
M.Y. Leong, G.S. Samuelsen, and J.D. Holdeman

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135–3191

8. PERFORMING ORGANIZATION REPORT NUMBER
E–10684

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA TM–107430
WCC/CI paper No. 97S–034

11. SUPPLEMENTARY NOTES
Prepared for the Spring 1997 Meeting of the Western States Section sponsored by the Combustion Institute, Sandia National Laboratory, Livermore, California, April 14–16, 1997. M.Y. Leong and G.S. Samuelsen, UCI Combustion Laboratory, University of California, Irvine, California 92697–3550; J.D. Holdeman, NASA Lewis Research Center. Responsible person, J.D. Holdeman, organization code 5830, (216) 433–5846.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Category: 07
Available electronically at http://gltrs.grc.nasa.gov/GLTRS
This publication is available from the NASA Center for AeroSpace Information, (301) 621–0390.

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***

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 ring the reaction to completion in the lean zone must be performed rapidly and thoroughly in order to decrease the extent of near-stoichiometric fluid pocket formation. Fluid pockets at near-stoichiometric equivalence ratios are undersirable because the high temperatures 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.

14. SUBJECT TERMS
Dilution; Jet mixing; Gas turbine; Emissions; Combustor

15. NUMBER OF PAGES
26

16. PRICE CODE
A03

17. SECURITY CLASSIFICATION OF REPORT
Unclassified

18. SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

19. SECURITY CLASSIFICATION OF ABSTRACT
Unclassified

20. LIMITATION OF ABSTRACT