NASA/CR—2000-209949

Effect of Jet Injection Angle and Number of Jets on Mixing and Emissions From a Reacting Crossflow at Atmospheric Pressure

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April 2000

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Prepared under Grant NAG3–1110

National Aeronautics and
Space Administration

Glenn Research Center

April 2000

Acknowledgments

The flow conditions for this experiment were specified by Pratt & Whitney Aircraft and the NASA High Speed Research Program. The authors wish to acknowledge the support of NASA Glenn Research Center through Grant NAG3–1110. Dr. J.D. Holdeman was the NASA Program Monitor. The authors also wish to thank Dr. Holdeman for his detailed involvement throughout this project. His experience and recommendations were most appreciated. This, coupled with his reputation and expertise, dramatically improved both the productivity of the program and the utility of the final products.

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EFFECT OF JET INJECTION ANGLE AND NUMBER OF JETS ON MIXING AND EMISSIONS FROM A REACTING CROSSFLOW AT ATMOSPHERIC PRESSURE

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ABSTRACT

The mixing of air jets into hot, fuel-rich products of a gas turbine primary zone is an important step in staged combustion. Often referred to as "quick quench," the mixing occurs with chemical conversion and substantial heat release. An experiment has been designed to simulate and study this process, and the effect of varying the entry angle (0°, 22.5°, and 45° from normal) and number of the air jets (7, 9, and 11) into the main flow, while holding the jet-to-crossflow mass-low ratio, MR, and momentum-flux ratio, J, constant (MR = 2.5; J = 25). The geometry is a crossflow confined in a cylindrical duct with side-wall injection of jets issuing from orifices equally spaced around the perimeter. A specially designed reactor, operating on propane, presents a uniform mixture to a module containing air jet injection tubes that can be changed to vary orifice geometry. Species concentrations of O_2, CO, CO_2, NO_X, and HC were obtained one duct diameter upstream (in the rich zone), and primarily one duct radius downstream of the orifice centers. From this information, penetration of the jet, the spatial extent of chemical reaction, mixing, and the optimum jet injection angle and number of jets can be deduced.

NOMENCLATURE

D	main duct diameter
DR	jet-to-mainstream density ratio
J	jet-to-mainstream momentum-flux ratio
MR	jet-to-mainstream mass-flow ratio
n	number of orifices
P	pressure
R	main duct radius (D/2)
Θ	jet entry angle

ϕ_o overall equivalence ratio

ϕ_r rich zone equivalence ratio

INTRODUCTION

Various systems, such as fuel injection and exhaust temperature control processes, rely on jet mixing with a crossflow of gas to mix streams of fluid rapidly and thoroughly. Jet mixing in a crossflow may also play a fundamental role in the next generation of low pollutant-emitting engines such as the Rich-burn/Quick-mix/Lean-burn (RQL) combustion concept. The formation of various pollutants is driven by high temperatures attained in near-stoichiometric reactions. Therefore, the strategy in this combustor design lies in minimizing the lifetime of, as well as preventing the formation of, near-stoichiometric fluid packets. As passing through stoichiometric regions is inevitable, rapid mixing reduces the lifetime of the stoichiometric packets, while the production of a uniform fuel-lean mixture precludes their formation.

A previous study (ref. 1) at the UCI Combustion Laboratory (UCICL) involved the construction of a facility that handled reacting tests at atmospheric pressure in a cylindrical crossflow configuration. A 10 round hole case was tested to explore the types of information that could be gathered from the experiment. The study in reference 2 expanded upon this initial work by addressing whether, for a given jet-to-crossflow momentum-flux ratio and mass-flow ratio, a configuration with an optimal number of orifices can yield rapid mixing of air jets into a rich crossflow, and result in a uniformly-lean mixture with minimal potential for pollutant formation.

NO_x reduction is a driving force in combustor design today. Previous studies motivated by the RQL scheme have shown several factors to be influential to the efficacy of the quick-mix section (refs. 1 and 2). The present study investigates the sensitivity of fuel-air mixing to geometric variation in a quick mixer for a given set of flow conditions.

BACKGROUND

The gas turbine combustor contains many examples of jet mixing in a reacting crossflow, as evidenced by the presence of air ports in the primary, intermediate, and dilution zones of conventional combustors. An understanding of the jet mixing process becomes important in guiding the design of the ports to obtain the desired mixing fields for given operating conditions. The prediction of jet mixing in combusting flows is especially important in an application such as the quick-mix section of the RQL combustor, where poor mixing of jet air with the rich, reacting crossflow can lead to hot pockets conducive to pollutant formation. Nonreacting multiple jet in crossflow mixingexperiments are a tool to address this problem, as they are an inexpensive and convenient tool for predicting mixing fields in combusting flows.

Numerous studies on the jet in crossflow problem have yielded insight on such flow field characteristics as the jet structure and penetration, the development of vortices, the jet entrainment of crossflow fluid, and the flow field distributions resulting from jet mixing. An extensive listing of documented jet-in-crossflow studies performed in the past few decades can be found in references 3 to 6. Note that many of the studies cited in these summaries are of a single jet in an unbounded crossflow or are otherwise inappropriate for direct application to a confined mixing

problem. Although the single jet is a key component in combustor flow fields, these flows are usually confined, and interaction between jets is critical. Also, because the references listed in references 3 to 6 are extensive, only those papers from which specific material is mentioned, or those publications that post-date the summaries, will be cited in this paper.

While the jet mixing studies illustrate much activity with respect to a nonreacting system, research into reacting jet-in-crossflow systems has been limited. Tests on multiple jet mixing in reacting flows have been performed on model gas turbine combustors of a can-type, or cylindrical duct geometry. In many of these experiments (refs. 7 to 10), the model gas turbine combustors contained two sets of holes for primary and dilution air mixing typical of conventional combustors, as opposed to a single stage quick mixing scheme, such as that often found in an RQL configuration. These studies were also concerned with varying operating conditions such as fuel injection (ref. 7), air preheat (ref. 8), fuel-air ratio (ref. 9), or the momentum-flux ratio of the primary jets (ref. 10). In one study, a geometric parameterization was pursued, but was related to varying the positions of the rows of the primary and dilution jets rather than with changing the orifice configurations (ref. 10). An experiment performed on a model RQL combustor operating at various pressures and inlet temperatures did yield NO_x emissions measurements for a 20 round hole mixing section (ref. 11). The results from this RQL study also emphasized that the optimization of the quick-mixing section was integral to lowering the total NO_x emissions from the RQL combustor.

On the whole, these reacting tests varied operating parameters in order to affect the distributions of emissions and temperature. In reference 2, it was desired to vary the number of orifices at a set momentum-flux ratio in order affect the mixing and reacting fields. This study combines the diagnostic tools and analysis utilized in reference 1 and builds upon a series of related work performed on nonreacting jet mixing in a cylindrical duct. Nonreacting studies (refs. 12 and 13) surveyed the effect of the jet to crossflow momentum-flux ratio and the shape, orientation, and number of orifices on jet penetration and mixing. Optimal orifice configurations were designated as those that produced uniform mixing within a specified length (e.g., one duct radius from jet injection). Depending on the chosen jet to crossflow momentum-flux ratio J and the orifice spacing to duct height ratio S/H, different optimal orifice configurations can be obtained. However, it was unknown if an optimum configuration identified through nonreacting experiments would apply in reacting flows.

A recent study (ref. 14) investigated the effect of preheated inlet air on mixing and emissions for optimally penetrating jets, as well as under- and overpenetrating ones.

The orifice thickness, l/d, is a significant difference between the present and previous studies. In all previous studies at UCICL injection was through sharp-edge orifice ($l/d << 1$) whereas $l/d = 5$ in the current study. The interested reader should see reference 15.

The objectives for the study reported in reference 2 were to determine an effect between jet mixing and the achievement of desired outlet conditions, and to identify an orifice configuration leading to optimal mixing at a set jet-to-crossflow momentum-flux ratio and a set mass-flow ratio. It has been shown that the most important flow variable is the jet-to-mainstream momentum-flux ratio, J. For a given value of J, there are three gross geometric features which can be modified in a cylindrical (can-type) combustor section. These are the shape of the jet orifices, the number of orifices, and the angle of injection by which the jets are introduced into the main flow. Previous studies under nonreacting conditions have indicated an insensitivity of mixing to orifice shape. Hence, that leaves two variables to be explored, jet injection angle (Θ) and number of jets (n).

The goal of the present study is to identify the optimum value of Θ and n, in the mixing section in a cylindrical main duct, for a given set of fixed parameters.

EXPERIMENT

This section describes the facility, diagnostics, and test matrix used for the work. Figure 1 is a general depiction of the experiment and illustrates the variable parameters investigated in this study.

Facility

The experiment was conducted on a UCICL test stand described in reference 1, and slightly modified to accommodate the current experiment. A schematic of the modified test stand is shown in figure 2. The modular design of the mixing section allows for the testing of various geometries. Nine stainless steel quick-mix jet modules were fabricated in order to accommodate the jet injection angle and jet number variations explored in this study. The diameter of the main duct, D, is 80 mm, and the length-to-diameter ratio (l/d) of the jets is kept at a constant value of 5 for all of the modules. A typical quick-mix module is shown in figure 3 (n = 7, Θ = 45°).

The combustor is up-fired on premixed propane and air. Propane was injected and mixed with room air14 ft upstream of the ignition source. Main air was supplied to the system at a flow rate of 0.4 standard ft^3/min (SCFM), which ensured a 33 ft/s bulk flow velocity at the point of ignition. The plenum surrounding the mixing module section was fed by four equidistant, individually metered airports located toward the base of the plenum. By controlling appropriate flowrates, momentum-flux ratio is held constant at a value of J = 25 for each of the test cases.

The primary reaction zone of the combustor is stabilized by an on-axis recirculation region generated by a contracting quarl and a 45° vaned production engine cast swirler. Between the recirculation (rich) zone and the mixing module, products and reactants flow through an oxide-bonded silicon carbide ceramic foam matrix to remove the swirling component and provide a uniform plug-flow.

Diagnostics

A double-jacketed, water-cooled, stainless steel probe was mounted such that its 45° angled tip could be positioned on the measurement plane of interest. Pointwise measurements of carbon monoxide (CO), carbon dioxide (CO_2), unburned hydrocarbon (HC), oxygen (O_2), and the combination of nitrogen oxide and nitrogen dioxide (NO_x) concentrations were made by traversing the combustor in the horizontal plane (the extractive probe remains fixed) and drawing gas samples continuously through a bank of emission analyzers. A digital encoder monitors the position of the probe tip relative to the center of the quick-mix module.

The planes at which measurements were made are indicated in figure 3. The main experimental plane was located at an axial distance equal to one duct radius, R, (40 mm) downstream of the center of the orifice. Emissions were also measured at a second plane, one duct-diameter (80 mm) upstream of the jet centerline, in order to verify a uniform rich entry section.

Flow symmetry was verified for the primary plane, and data were taken from sampling points across a fraction of the entire plane, in order to reduce the volume of data. The primary plane of data (x/R = 1) consisted of 16 points distributed across a sector which includes two orifices. Therefore, the exact sampling region varies with n. Figure 4 shows the locations of the sampling points for each of the three primary planes (n = 7, 9, and 11), and the rich-zone sampling plane as well, which encompassed the entire cross-section, but at a courser distribution.

Test Matrix

Three values for each of the variable parameters (n and Θ) were selected to attempt to bracket the optimum case (n = 9 for J = 25 from nonreacting tests). Table 1 lists the fixed and variable design conditions. The test matrix is simply the nonreduced combination of each variable, and is shown in Table II.

Emissions measurements were made across the plane one radius, R, downstream of the jets, for each of the test conditions. The effect of jet injection angle and number of jets in the mixing zone on the mixing and emissions distributions one radius downstream can be assessed by comparing the resulting measurements of each test condition.

RESULTS AND DISCUSSION

An evaluation of the rich reacting product entering the mixing module zone was performed before collecting primary plane data in order to ascertain the uniformity of the flowfield exiting the rich recirculation zone. Following this verification, species concentration data were obtained at the primary measurement plane for each of the nine test cases.

Rich Zone Verification

Table III shows the species concentrations across the rich zone. The species concentrations present in this zone are consistent with chemical kinetics predictions. These measurements were repeated for several cases and the overall result was the same each time: The upstream conditions provide a rich product environment that is uniform and consistent enough to provide a practically fixed boundary condition.

Downstream Measurements

Figures 5 to 8 illustrate species concentration distributions at the sampling plane for CO, CO_2, O_2, and NO_x, respectively. Plots of HC are not shown because measurements were essentially zero in all cases. All species concentration distributions were generated from the pointwise data obtained using a geostatistical interpolation algorithm known as kriging.

The relative striations evident in the plots give a qualitative characterization of the extent to which mixing has occurred at this point. The area-weighted average values for each species

concentration at each condition are also shown on figures 5 to 8. These plots exhibit several points of interest.

First, the largest jet penetration was observed for the $\Theta = 0°$, n = 7 case. Increasing Θ and/or n decreases jet penetration so it is not surprising that the most underpenetrating case is for $\Theta = 45°$ and n = 11. There seems to be a trade-off between Θ and n such that jet penetration appears to be similar along diagonal lines such as for $\Theta = 0°$, n = 9 and $\Theta = 22.5°$, n = 7.

It also appears, within the ranges investigated, that jet injection angle, Θ, has a greater effect on mixing than do the number of jets, n. That is, the difference between adjacent plots is more pronounced in the direction of Θ, and less so along the n axis.

Also, the penetration of jets away from the wall is clearly observed in all cases. In fact, over-penetration is indicated for $\Theta = 0°$ and n = 7,whereas underpenetration is clearly indicated for $\Theta = 45$, n = 11. These cases are characterized respectively by unreacted fluid of jet origin near the center of the duct , and a core of rich products there. The overpenetration of the jets and the rich core region indicate that mixing has not progressed far in these cases.

Finally, it appears that the best mixing occurs for $\Theta = 0°$ and n = 9. The striations are few and the colors smooth, relative to the other cases. No over-penetration of the jets is apparent, and the core is not rich, both of which suggest good mixing. The area-averaged values support the qualitative results of the plots as well, indicating the optimum combination of parameters for this particular configuration is $\Theta = 0°$ and n = 9.

SUMMARY AND CONCLUSIONS

This work was an investigation into the effect of jet injection angle and number of jets on mixing and emissions in a cylindrical duct at atmospheric pressure. A uniform rich plug flow condition was established and the downstream emissions of 9 different geometric variations were evaluated and compared. The results indicate the following conclusions:

- Within the range of parameters investigated ($0° < \Theta < 45°$, $7 < n < 11$) jet injection angle has a greater relative effect on mixing than number of holes.
- The optimum case was observed to be $\Theta = 0°$ and n = 9.
- There appears to be a trade-off between the optimum number of jets and their injection angle. Note also that as Θ increases, the optimal number of jets decreases

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TABLE I.—FIXED AND VARIABLE DESIGN CONDITIONS.

Pressure, P	1 atm
Rich Zone Equivalence Ratio, Φ_r	1.66
Overall Equivalence Ratio, Φ_o	0.45
Density Ratio, DR	3.3
Momentum-Flux Ratio, J	25
Mass-Flow Ratio, MR	2.5
Duct Radius, R	40 mm
Variable	
Θ, Jet Injection Angle	0°, 22.5°, 45°
n, number of jets	7, 9, 11

TABLE II.—TEST MATRIX

Case	Θ	n
1	45.0°	7
2	22.5°	7
3	0.0°	7
4	45.0°	9
5	22.5°	9
6	0.0°	9
7	45.0°	11
8	22.5°	11
9	0.0°	11

TABLE III.—RICH ZONE VERIFICATION

Point	CO (%)	CO2 (%)	HC (ppm)	O2 (%)	NO_x (ppm)
1	12.6	6.5	3420	0.1	9.9
2	12.5	6.5	5395	0.0	10.5
3	12.5	6.5	4205	0.0	10.6
4	12.6	6.5	2970	0.0	8.9
5	12.3	6.6	5540	0.0	10.2
6	12.3	6.6	3685	0.2	9.3
7	12.6	6.5	4570	0.0	10.3

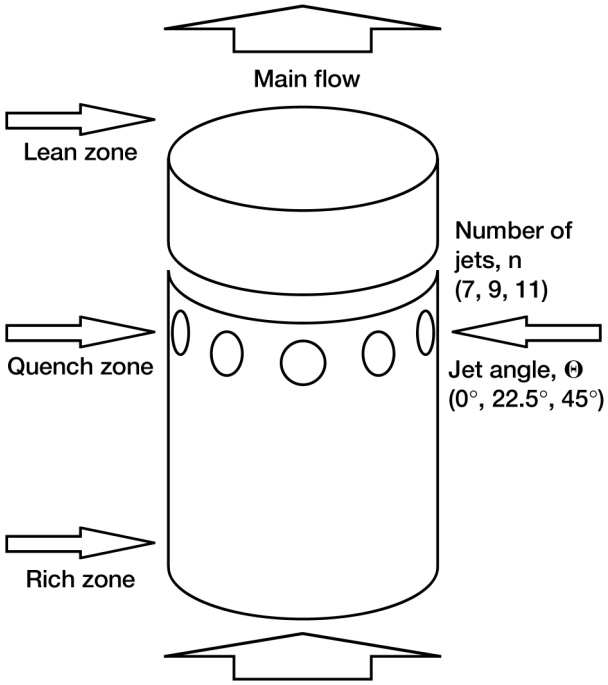

Figure 1.—RQL concept and variable parameters.

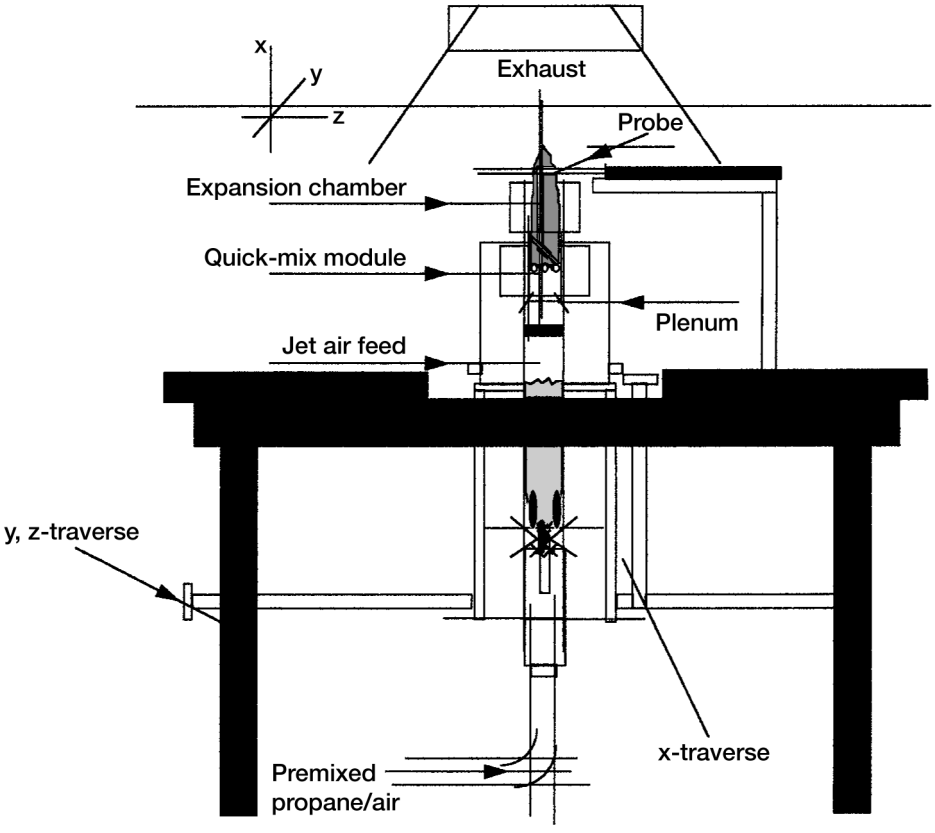

Figure 2.—Experimental facility schematic.

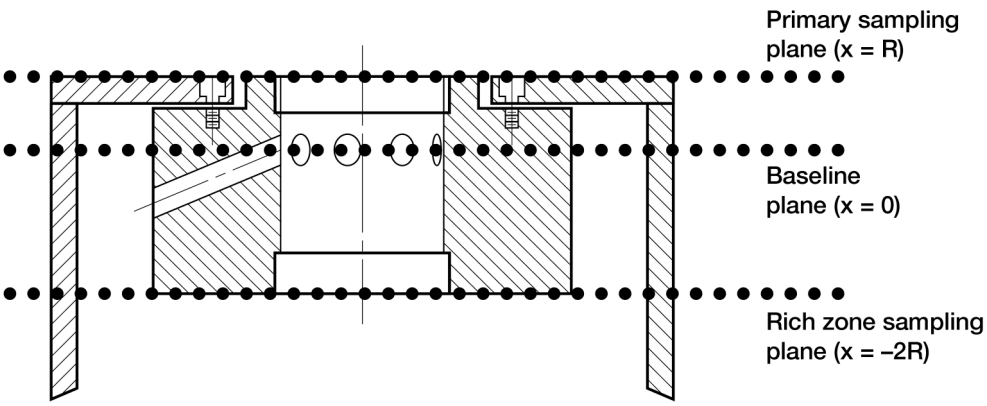

Figure 3.—Sampling point locations.

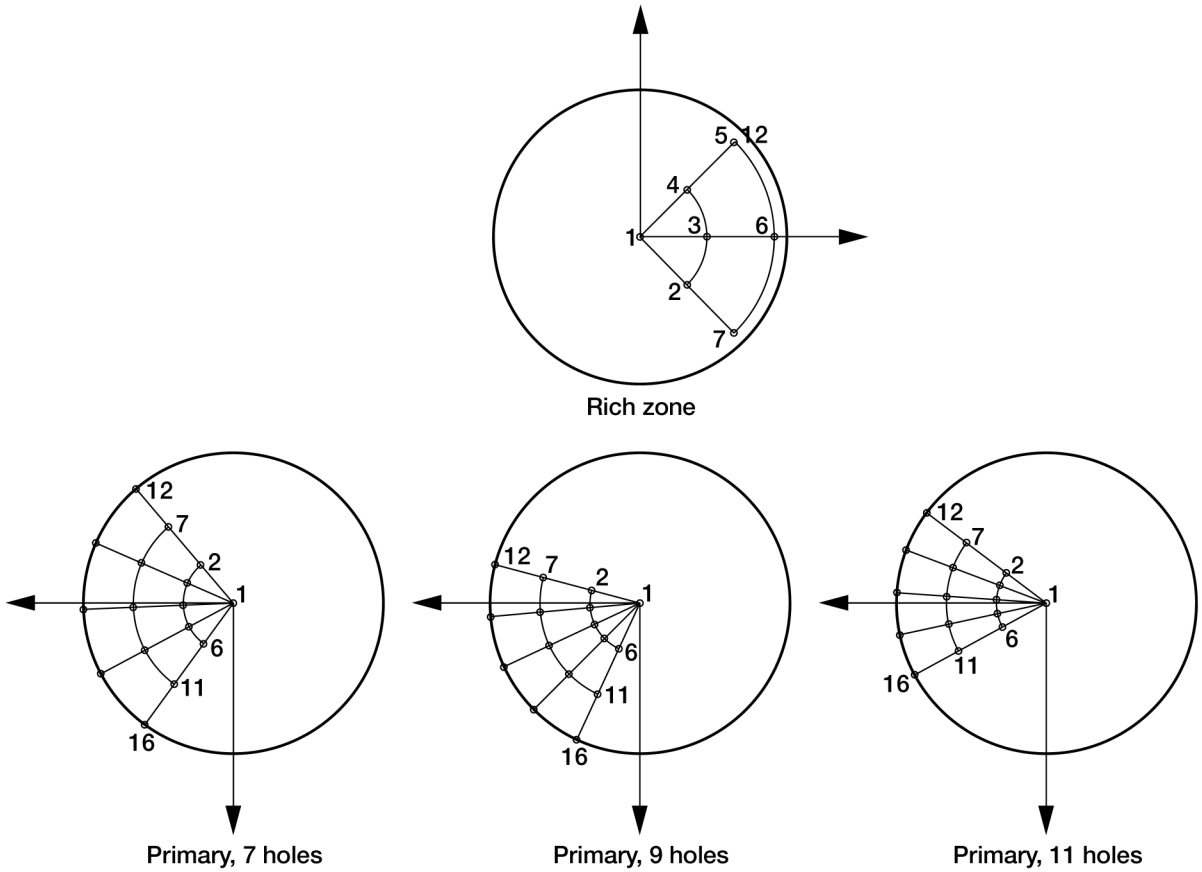

Figure 4.—Sampling point locations.

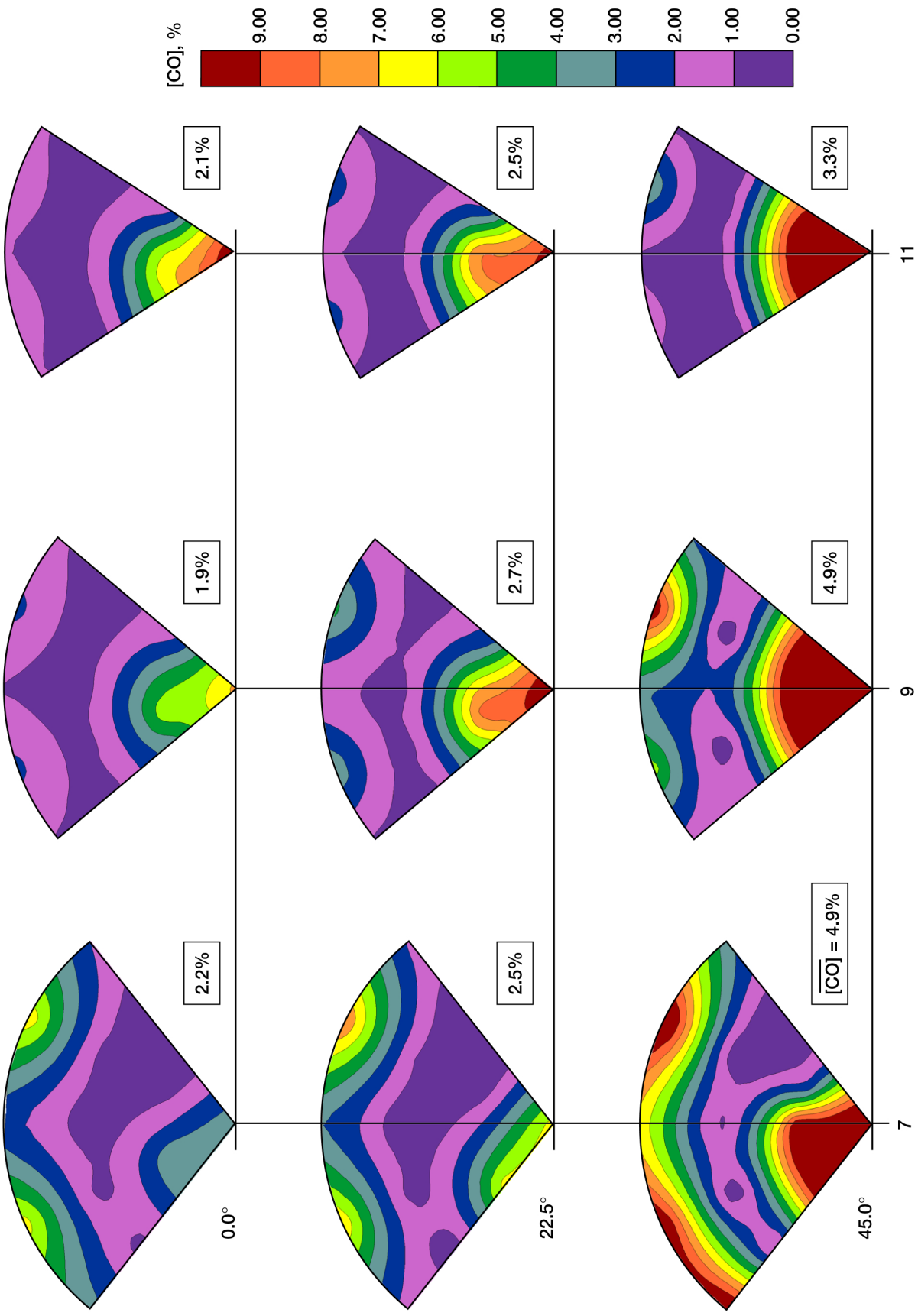

Figure 5.—CO concentration profiles.

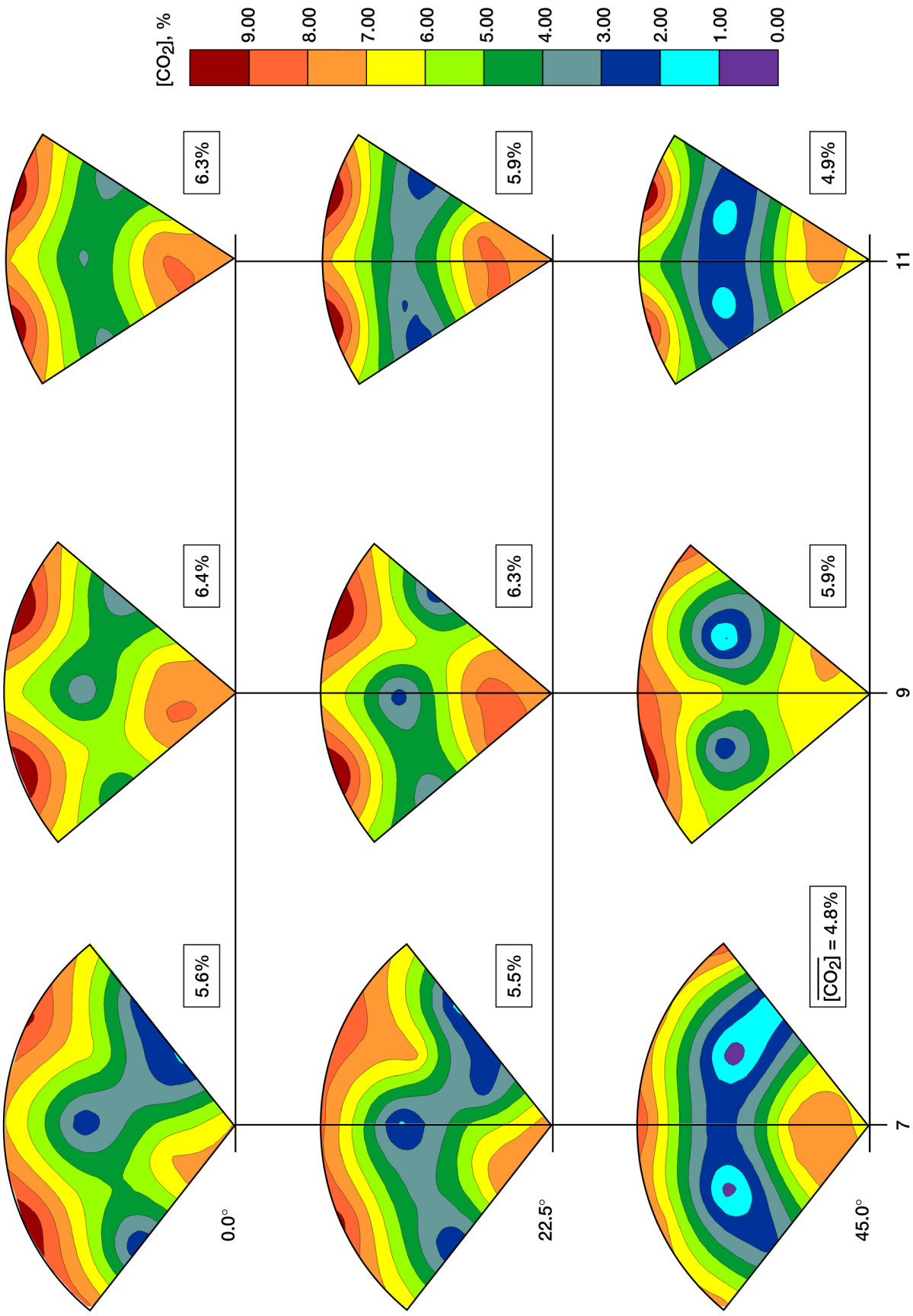

Figure 6.—CO_2 concentration profiles.

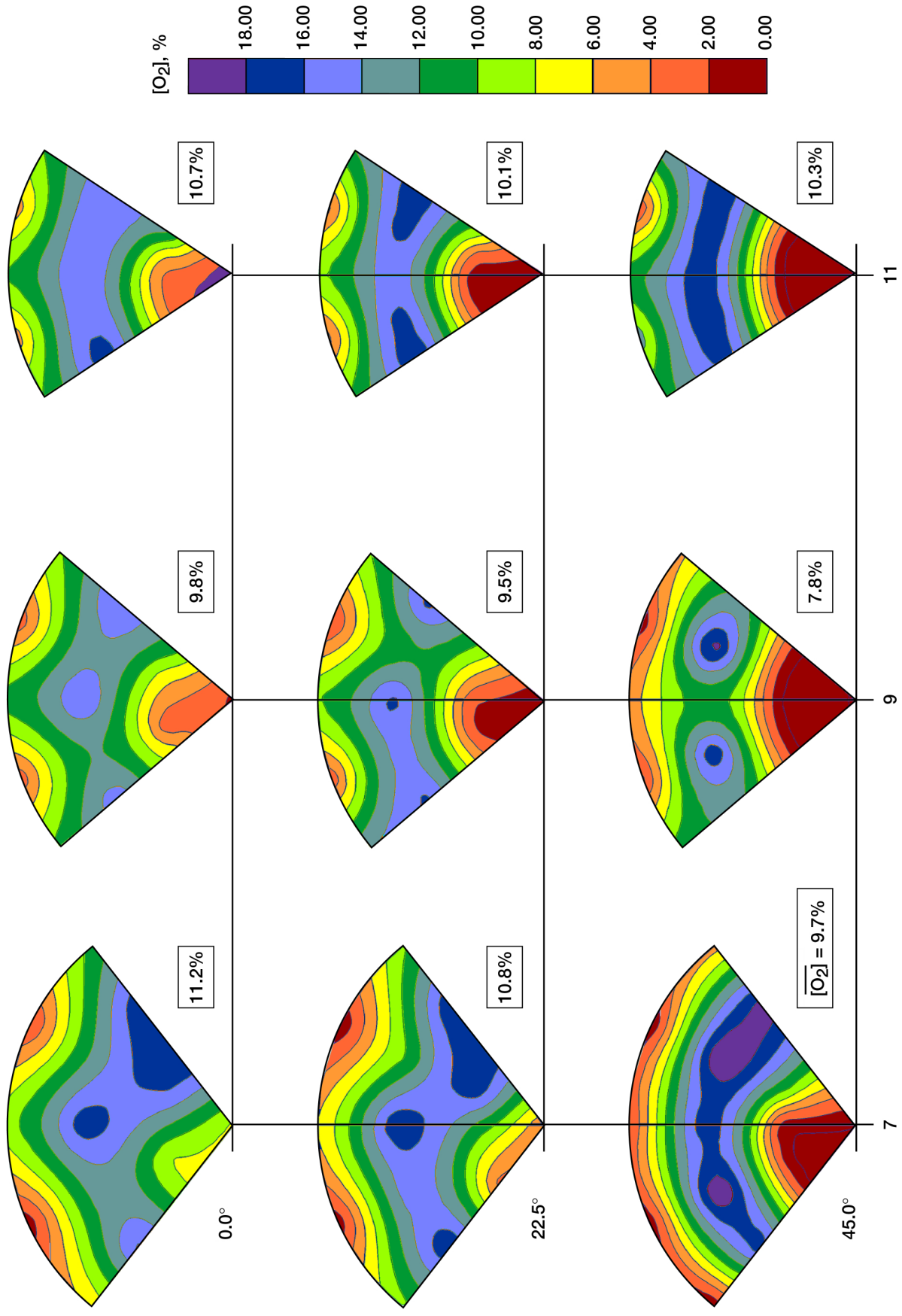

Figure 7.—O_2 concentration profiles.

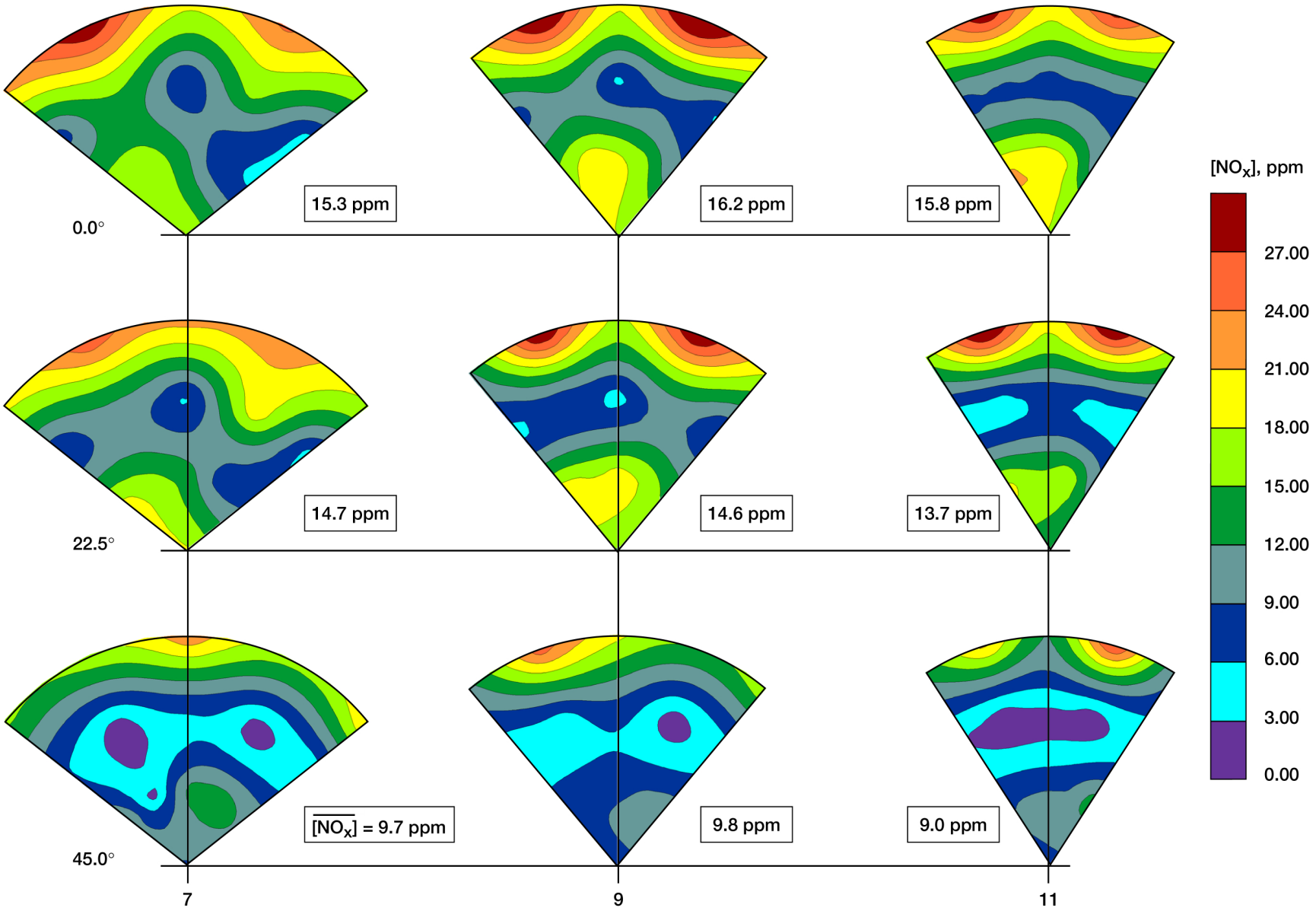

Figure 8.—NO_x concentration profiles.

REPORT DOCUMENTATION PAGE

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1. AGENCY USE ONLY (*Leave blank*)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	April 2000	Final Contractor Report

4. TITLE AND SUBTITLE

Effect of Jet Injection Angle and Number of Jets on Mixing and Emissions From a Reacting Crossflow at Atmospheric Pressure

5. FUNDING NUMBERS

WU–714–02–20–00
NAG3–1110

6. AUTHOR(S)

D. St. John and G.S. Samuelsen

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

University of California at Irvine
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8. PERFORMING ORGANIZATION REPORT NUMBER

E–12202

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field
Cleveland, Ohio 44135–3191

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA CR—2000-209949

11. SUPPLEMENTARY NOTES

Project Manager, J.D. Holdeman, Turbomachinery and Propulsion Systems Division, NASA Glenn Research Center, organization code 5830, (216) 433–5846.

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

The mixing of air jets into hot, fuel-rich products of a gas turbine primary zone is an important step in staged combustion. Often referred to as "quick quench," the mixing occurs with chemical conversion and substantial heat release. An experiment has been designed to simulate and study this process, and the effect of varying the entry angle (0°, 22.5° and 45° from normal) and number of the air jets (7, 9, and 11) into the main flow, while holding the jet-to-crossflow momentum-flux ratio constant (J = 25). The geometry is a crossflow confined in a cylindrical duct with side-wall injection of jets issuing from orifices equally spaced around the perimeter. A specially designed reactor, operating on propane, presents a uniform mixture to a module containing air jet injection tubes that can be changed to vary orifice geometry. Species concentrations of O_2, CO, CO_2, and HC were obtained one duct diameter upstream (in the rich zone), and primarily one duct radius downstream. From this information, penetration of the jet, the spatial extent of chemical reaction, mixing, and the optimum jet injection angle and number of jets can be deduced.

14. SUBJECT TERMS

Dilution jet mixing; Gas turbine; Injection angle; Emissions

15. NUMBER OF PAGES

20

16. PRICE CODE

A03

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	