NASA/TM—1999-209431

The Effect of Air Preheat at Atmospheric Pressure on the Formation of NO_x in the Quick-Mix Section of an Axially Staged Combustor

M.A. Vardakas, M.Y. Leong, J. Brouwer, and G.S. Samuelsen
University of California at Irvine, Irvine, California

J.D. Holdeman
Glenn Research Center, Cleveland, Ohio

September 1999

The NASA STI Program Office . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the Lead Center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA's counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized data bases, organizing and publishing research results . . . even providing videos.

For more information about the NASA STI Program Office, see the following:

- Access the NASA STI Program Home Page at ***http://www.sti.nasa.gov***

- E-mail your question via the Internet to help@sti.nasa.gov

- Fax your question to the NASA Access Help Desk at (301) 621-0134

- Telephone the NASA Access Help Desk at (301) 621-0390

- Write to:
  NASA Access Help Desk
  NASA Center for AeroSpace Information
  7121 Standard Drive
  Hanover, MD 21076

NASA / TM—1999-209431

The Effect of Air Preheat at Atmospheric Pressure on the Formation of NO_x in the Quick-Mix Section of an Axially Staged Combustor

M.A. Vardakas, M.Y. Leong, J. Brouwer, and G.S. Samuelsen
University of California at Irvine, Irvine, California

J.D. Holdeman
Glenn Research Center, Cleveland, Ohio

National Aeronautics and
Space Administration

Glenn Research Center

September 1999

Acknowledgments

This work was supported by a grant from the NASA Glenn Research Center (Cooperative Agreement NCC3–412).

Available from

NASA Center for Aerospace Information
7121 Standard Drive
Hanover, MD 21076
Price Code: A03

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22100
Price Code: A03

The Effect of Air Preheat at Atmospheric Pressure on the Formation of No_x in the Quick-Mix Sections of an Axially Staged Combustor

M.A.Vardakas, M.Y. Leong, J. Brouwer, G.S. Samuelsen
UCI Combustion Laboratory
University of California at Irvine
Irvine, California 92697–3550

and

J.D. Holdeman
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Summary

The Rich-burn/Quick–mix/Lean-burn (RQL) combustor concept has been proposed to minimize the formation of nitrogen oxides (NO_x) in gas turbine systems. The success of this combustor strategy is dependent upon the efficiency of the mixing section bridging the fuel-rich and fuel-lean stages. Note that although these results were obtained from an experiment designed to study an RQL mixer, the link between mixing and NO_x signatures is considerably broader than this application, in that the need to understand this link exists in most advanced combustors. The experiment reported herein was designed to study the effects of inlet air temperature on NO_x formation in a mixing section. The results indicate that NO_x emission is increased for all preheated cases compared to non-preheated cases. When comparing the various mixing modules, the affect of jet penetration is important, as this determines where NO_x concentrations peak, and affects overall NO_x production. Although jet air comprises 70 percent of the total airflow, the impact that jet air preheat has on overall NO_x emissions is small compared to preheating both main and jet air flow.

Nomenclature

DR	jet-to-mainstream density ratio
d	orifice axial height, or round hole diameter
f_{avg}	average planar jet mixture fraction derived from carbon mass fraction
f_{var}	planar jet mixture fraction variance
J	jet-to-mainstream momentum-flux ratio = $(\rho V^2)_{jets}/(\rho U^2)_{main}$
MR	jet-to-mainstream mass-flow ratio
n	number of round holes in quick-mix module
R	radius of the quick-mix module
r	radial distance from the module center
T_{jet}	average jet air temperature
T_{main}	average mainstream temperature
U	mainstream velocity

U_S spatial unmixedness
V jet velocity
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

Many processes involved in the injection of fuel and in the control of exhaust temperature rely on jet mixing with a crossflow of gas to mix fluid streams. One particular application in which jet mixing in a confined crossflow plays a fundamental role is the Rich-burn/Quick-mix/Lean-burn (RQL) combustor. The success of this combustor in producing lower emissions than conventional gas turbine combustors depends on the efficiency of the mixing section bridging the fuel-rich and fuel-lean stages of combustion. In this combustor design, the jets of air introduced into the quick-mix section should mix with the fuel-rich reacting crossflow as quickly as possible to bring the reaction to an overall fuel-lean equivalence ratio. It is hypothesized that rapid and spatially distributed mixing must occur in order to prevent the formation of hot pockets (consisting either of closer to stoichiometric species concentrations, higher temperatures, or both) which in turn drive pollutant formation.

Previous studies (refs. 1 and 2) involved the construction of a facility, and reported results for reacting tests in cylindrical crossflow configurations at atmospheric pressure. The current study expands upon this initial work by elevating the inlet air temperatures, testing various mixing module designs and studying the species concentrations, with particular interest in NO_x formation.

Background

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. 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 will be cited in this paper.

In previous studies (refs. 5 and 6), nonreacting experiments and modeling were often used as convenient tools to explore the mixing of air jets into the fuel-rich cross stream. The primary goal of these studies was to determine orifice configurations that lead to optimal mixing within a specified duct length. In a cylindrical duct geometry, experimental surveys of the effect of the jet-to-crossflow momentum-flux ratio and the shape, orientation, and number of orifices on mixing were performed in order to gain a mechanistic understanding of jet penetration and mixing dynamics (ref. 7). A systematic optimization scheme using a design of experiments statistical approach was applied to the experimental data to determine the round hole configurations leading to optimal mixing at various momentum-flux ratios. For jet-to-mainstream momentum-flux ratios of 36 and 70, the number of round holes leading to optimal mixing were identified as 10 and 15, respectively (ref. 8).

While extensive nonreacting confined jet mixing work has been performed (see refs. 3 to 6), research into reacting flows 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. 9 to 13), the model gas turbine combustors contained two sets of holes for primary and dilution air mixing typical of conventional combustors, as opposed to the single stage quick mixing scheme. These studies were also concerned with varying operating conditions such as fuel injection (ref. 9), air preheat (ref. 10), fuel-air ratio (ref. 11), or the momentum-flux ratio of the primary jets (ref. 12). 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. 12). 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. 13). 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.

Archival journal publications of NO formation in the RQL concept have been few (refs. 13 and 14), however, the results of these studies have shown that momentum flux ratio and orifice configuration as being the leading factors in NO_x formation.

Initial reacting flow experiments studied by the authors included the flowfield of a row of jets mixing with rich reacting gases confined to a cylindrical crossflow (refs. 1 and 2). The work presented here expands upon the reacting flow investigation by using the diagnostic and analysis techniques developed in the previous study. The objective for this study is to examine orifice configurations that demonstrated optimal mixing in previous tests, and vary the inlet temperatures to measure the impact this change has on species concentrations.

Experiment

Facility

The experimental facility used consisted of a premixing zone, a fuel-rich combustion zone, and a jet-mixing section as shown in figure 1. In the premixing zone propane gas is mixed with air upstream of the ignition point. Fuel-rich combustion occurs downstream of the quarl in a zone stabilized by a swirl-induced recirculation zone. To dissipate the swirl in the flow and to introduce a uniform nonswirling flow into the jet-mixing section, the fuel-rich product was passed through an oxide-bonded silicon carbide (OBSiC) ceramic foam matrix (Hi-Tech Ceramics) with a rated porosity of 10 pores/in.

The jet mixing section was comprised of a modular quartz section to which jet air is supplied from a surrounding plenum. The plenum was fed by four equally-spaced, air ports located toward the base of the plenum. A high-temperature steel flow-straightener installed in the plenum conditioned and equally distributed, the jet air entering the mixing module.

To supply the necessary heated air, two recirculating heaters were utilized. The main-air line and jet-air line were heated by a 20 and 25 kW heater, respectively. Each heater is capable of supplying the required maximum of 260 °C (500 °F) air preheat temperature at the desired flowrates.

The quartz modules which comprised the jet mixing section were 280 mm (11 in.) in length, with inner and outer wall diameters of 80 mm (3.15 in.) and 85 mm (3.35 in.). The row of orifices was positioned with its centerline 115 mm (4.5 in.) downstream from the module entrance. An alumina-silica blend of ceramic fiber paper provides sealing between the quartz module and the stainless steel mating surfaces to form the air plenum for the jets. Modules tested were 8, 12, 14, and 22-orifice configurations.

Measurements

The purpose of the present investigation was to examine the impact of air preheat on species concentrations of O_2, CO_2, CO, HC and NO_x. Species concentrations are obtained downstream of the jet air injection plane.

Species concentration data were obtained in a sector grid for the plane at x/R = 1 (plane 5 in refs. 1 and 2) for each module. The x/R = 1 plane is measured from the leading edge of the orifices.

Each planar grid consisted of 16 points spread over a region that includes two orifices (fig. 2(b)). The points include one point located at the center, and five points along each of the arc lengths at r/R = 1/3, 2/3, and 1. The points along each arc are distributed such that two points are aligned with the center of the orifices and three are aligned with the midpoint between orifice centers for all cases.

Species concentration measurements are obtained by sampling through a water-cooled stainless-steel probe by routing the sample through a heated line connected to the emission analyzers. Water was condensed from the gas before the sample is analyzed by chemiluminesence for NO (nondispersed infrared) NDIR analysis for CO, and CO_2, paramagnetic analysis for O_2, and flame ionization detection (FID) for total hydrocarbons.

Experimental Conditions

The experiments were performed for a jet-to-mainstream momentum-flux ratio (J) of 57 and a mass-flow ratio (MR) of 2.5. The total effective area of the mixing module orifices is 9 cm^2 (1.4 $in.^2$). The ratio of the total effective jet area to cross-sectional area is 0.18. The rich equivalence ratio and overall equivalence ratio are 1.66 and 0.45, respectively. The operating pressure for the system is one atmosphere.

Various levels of preheat were applied to both the jet and main airflows. Inlet temperature operating conditions for the experiment are noted in table I. The results show comparisons between non-preheated air, preheated jet air only, and preheated jet and main air cases.

Analyses

The jet mixture fraction was derived from conserved scalar calculations of the mass fraction of carbon. As a step toward obtaining the carbon mass fraction at each datum point, the wet mole fraction was calculated from the dry species concentration measurements. The wet mole fractions were obtained by solving a system of eight linear equations for the measured dry species concentrations of CO, CO_2, O_2, and unburned HC (assumed to be comprised mainly of unburned C_3H_8), as well as for C_2H_4, H_2, N_2, and H_2O (ref. 15). The inclusion of C_2H_4, which is a prevalent intermediate species produced from the combustion of C_3H_8 (ref. 16) was necessary in order to form a closed set of equations. The calculated unburned hydrocarbon species C_3H_8 and C_2H_4 contributed, at most, to 1.4 percent of the overall wet mole fraction at each point. The concentration of H_2, a primary species of combustion produced under fuel-rich reactions, was assumed to be 65 percent of the concentration of CO (ref. 15). N_2 was assumed to make up the rest of the gas concentration in the sample.

Results and Discussion

The NO_x data are presented in the following sequence: (1) the effect of air preheat showing a comparison of NO_x emissions for each test condition, and (2) a comparison of the experimental configurations (i.e., the various mixing modules) for each preheat test condition. The former will show the general trends observed with all of the modules tested, and the latter will illustrate the contrast between the mixing modules for a given test condition.

Effect of Preheat

The effect of heating the inlet air on the measured NO_x values is illustrated in figure 3. Non-preheated air data was collected as a baseline to determine the effect air preheat has on NO_x, and to repeat the (unpublished) experiments of MYL in 1997 to ensure experimental repeatability. Mainstream measurements s of CO and CO_2, 11 and 5 percent respectively, were virtually unaffected by preheat, and were consistent with equilibrium values. NO_x measurements were also consistent with equilibrium calculations and were 2 ppmv without preheat, and 13 ppmv for 500 °F preheat. Due to the dilution through the mixing section, one would expect a NO_x concentration of only 4 ppmv at the exit for mainstream preheat if no NO_x were formed in the mixer.

Most notable of the comparison between the preheated jet air case, and the preheated main and jet air case of figure 3, is the small impact of preheated jet air on NO_x. The jet air comprises over 70 percent of the total airflow, but preheating jet air results in relatively small increases in NO_x emissions compared to the main and jet preheated air case.

Figure 4 presents the corresponding NO_x distribution plots. These plots also show the effect that jet penetration has on determining the locations for peak NO_x formation. Both the linear and contour plots indicate peak NO_x formations occurring near the orifices of the module (in the wakes of the jets).

The distributions of equivalence ratio are given in figure 5. Note that preheat has very little effect on jet penetration, and that the equivalence ratio distributions (refs. 12 and 13) better reflect the mixing than do to the NO_x distributions, as the latter are similar for each module.

To account more accurately for the overall effect of preheated air on NO_x formation for a given case, area weighted averages were calculated. The overall effect of preheating only jet air, and both main and jet air preheat on the production of NO_x is shown in figure 6. This figure shows clearly that the affect of jet air preheat, with a NO_x value of 16 ppmv (for the 14 hole module), is relatively smaller than that of the main and jet air preheat case, with a NO_x value of 24 ppmv.

Round Hole Module Comparisons

Overall Combustion Performance.—Figures 7 to 9 present the concentrations of O_2, CO, CO_2 and hydrocarbons for the four modules that were tested (8, 12, 14, and 22 round hole modules) for no preheat (fig. 7), jet air preheat (fig. 8), and jet and main preheated air (fig. 9) conditions. The corresponding distribution plots are shown in figures 10 to 12. In each case, the trends are very similar and the differences that do exist are a result of jet penetration for that particular module (see also fig. 5). The penetration of the jets for the 12 and 14 hole module cases is observed to be different than that of the 22 hole module case as indicated by the flatness, or smoothness, of the data. Similar measurements were observed for the non-preheat air condition and the jet air preheat condition with relatively small differences in the major species concentrations as shown in figures 7 to 12.

Jet Air Preheat.—Previous studies indicated optimal mixing configurations for round hole modules (refs. 1 and 2). The current work compares the various modules for given experimental conditions (nonpreheat, jet air preheat, and main and jet air preheat) to determine which modules produce lower NO_x emissions. The data presented in figures 13(a) to (c) were obtained for the jet air preheat experimental condition and shows that the various modules have similar overall NO_x performance. Similar spatial distributions of NO_x are observed for each module with the exception of the center region where the 14 round hole module shows slightly higher NO_x emissions. This difference is illustrated in the area weighted average chart (fig. 13(c)) with the 14 round hole module producing slightly higher NO_x than the 12 and 22 round hole module cases. It should be noted that the differences are only 2 to 4 ppmv.

Main & Jet Air Preheat.—The results of the main and jet air preheat experimental conditions are similar to the jet air preheat results. The data for each module, figures 14(a) and (b), follow almost identical paths with the exception of the 22 round hole module. In this case, the NO_x seems to be a little less near the center region. This may be due to the fact that the 22 round hole module is considered a very overpenetrating mixing module, and thus may have lower NO_x formation in this region.

The overall effect of main and jet air preheat experimental conditions is presented in figure 14 showing a slightly different trend than the jet air preheat case. The data indicates that the 12 round hole module has highest NO_x concentrations compared to the 14 and 22 round hole modules. As with the jet air preheat cases the difference between the largest and smallest overall NO_x emissions is only 3.5 ppmv.

Summary and Conclusions

An experiment was performed to expand upon earlier work by incorporating preheated inlet air, and examining the effect it has on NO_x production. The following was revealed in the experiment:

- Jet penetration determines where NO_x concentrations peak and affects overall NO_x production.
- Jet air comprises over 70 percent of the total airflow, however the impact of preheating jet air alone on overall NO_x emissions is small compared to preheating both main and jet air. This is likely due increased sensitivity of NO_x kinetics to increases in the fuel rich zone temperatures leading to increased production of fixed nitrogen species.

- Overall NO_x concentration varies little with mixing configuration. However, there is a trade-off with CO production especially for under-penetrating configurations such as the 22 round hole module.

These results show that preheating both main and jet air increases NO_x significantly more than preheating only the jet air. Also, the four mixing strategies investigated showed a small difference in overall NO_x concentration although these configurations ranged from those giving under- to overpenetrating jets.

References

1. Leong, M.Y., Samuelsen, G.S., and Holdeman, J.D.: Mixing of Air Jets With a Fuel-Rich, Reacting Crossflow. *Journal of Propulsion and Power,* Vol. 2, No. 2, March-April 1999. (See also NASA TM–107430, 1997.)
2. Leong, M.Y., Samuelsen, G.S., and Holdeman, J.D.: Optimization of Jet Mixing in a Rich, Reacting Crossflow. Accepted for publication in *Journal of Propulsion and Power*. (See also NASA TM–97–206294, 1997.)
3. Margason, R.J.: "Fifty Years of Jet in Cross Flow Research," Presented at Computational and Experimental Assessment of Jets in Cross Flow, AGARD Conference Proceedings 534, April 1993.
4. 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. (See also NASA TM–104412, 1991.)
5. 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. (See also ASME 96-GT-482, NASA TM–107185, 1996.)
6. 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* (in press), Vol. 121, 1999. (See also ASME 97-GT-439 and NASA TM–107461, 1997.)
7. Hatch, M.S., Sowa, W.A., Samuelsen, G.S., and Holdeman, J.D.: (1995), Jet Mixing into a Heated Cross Flow in a Cylindrical Duct: Influence of Geometry and Flow Variations. *Journal of Propulsion and Power*, **11**, pp. 393–402. (See also NASA TM–105390.)
8. Kroll, J.T., Sowa, W.A., Samuelsen, G.S., and Holdeman, J.D.: (1993), Optimization of Circular Orifice Jets Mixing into a Heated Cross Flow in a Cylindrical Duct, AIAA–93–0249 (Also NASA TM–105984.)
9. Noyce, J.R., Sheppard, C.G.W., and Yamba, F.D.: "Measurements of Mixing and Species Concentration Within a Gas Turbine Type Combustor," *Combustion Science and Technology*, Vol. 25, 1981, pp. 209–217.
10. Bicen, A.F., Tse, D.G.N., and Whitelaw, J.H.: "Combustion Characteristics of a Model Can-Type Combustor," *Combustion and Flame,* Vol. 80, 1990, pp. 111–125.
11. Heitor, M.V. and Whitelaw, J.H.: "Velocity, Temperature, and Species Characteristics of the Flow in a Gas-Turbine Combustor," *Combustion and Flame*, Vol. 64, 1986, pp. 1–32.
12. Richards, C.D. and Samuelsen, G.S.: "The Role of Primary Jet Injection on Mixing in Gas Turbine Combustion," *Twenty-Third Symposium (International) on Combustion*, Vol. 23, 1990, pp. 1071–1077.

13. Meisl, J., Koch, R., Kneer, R., and Wittig, S.: “Study of NO_X Emission Characteristics in Pressurized Staged Combustor Concepts,” *Twenty-Fifth Symposium (International) on Combustion*, Vol. 25, 1994, pp. 1043–1049.
14. Hatch, M.S., Sowa, W.A., Samuelsen, G.S., and Holdeman, J.D.: (1995), Influence of Geometry and Flow Variation on the NO Formation in the Quick Mixer of a Staged Combustor. Accepted for publication in the *Journal of Engineering for Gas Turbines & Power*. (See also NASA TM–105639, 1997.)
15. 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.
16. Glassman, I.: *Combustion*, Academic Press, Inc., Orlando, 1987.

TABLE I.—OPERATING CONDITIONS

Description	Inlet air temperature, °C (°F)
Nonpreheated air	22 (72)
Jet air preheat	260 (500)
Main and jet air preheat	260 (500)

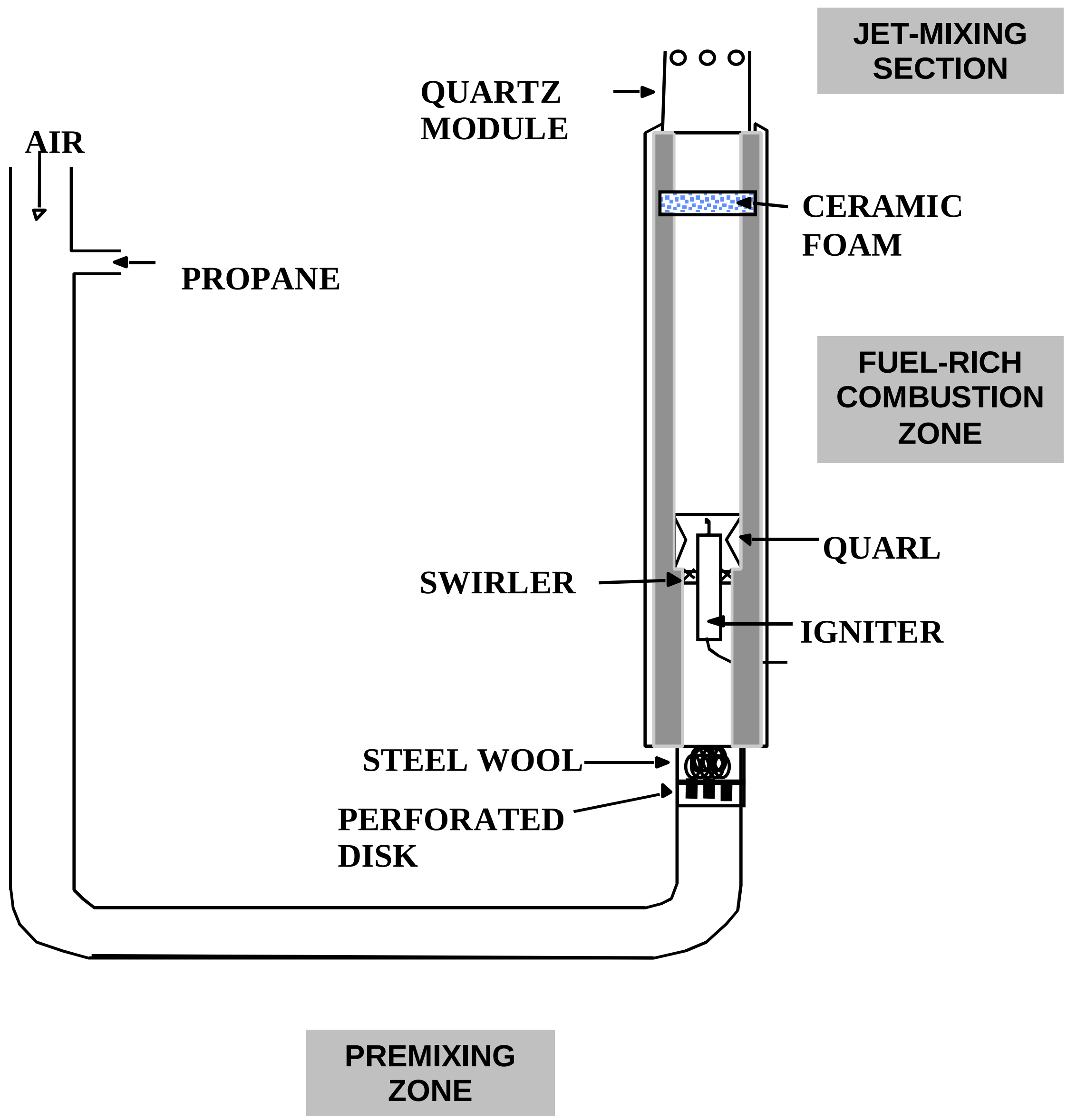
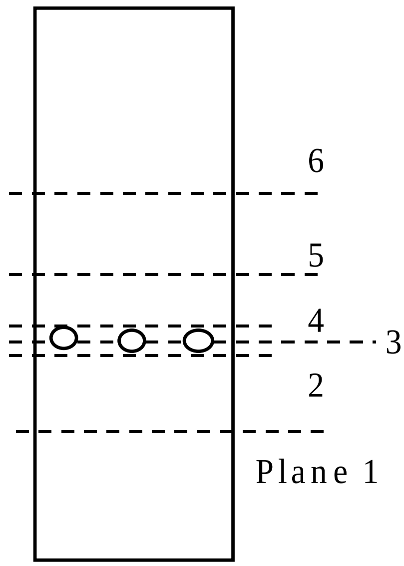
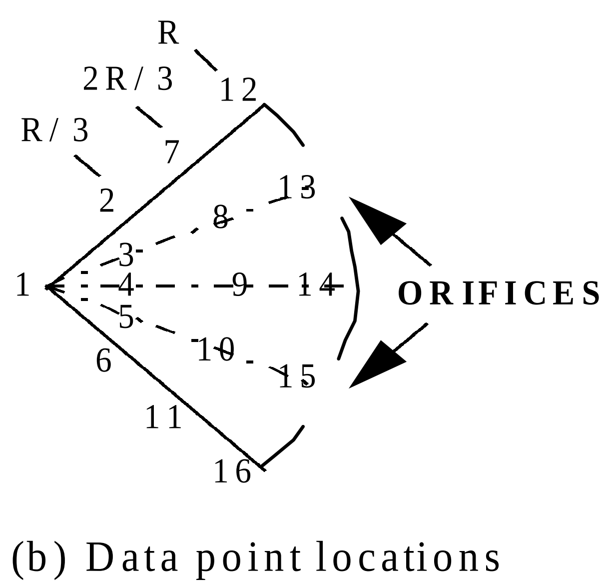


Figure 1. Schematic of Experimental Rich Product Generator with Quartz RQL module.



(a) Data plane locations



(b) Data point locations

Figure 2. Measurement Locations

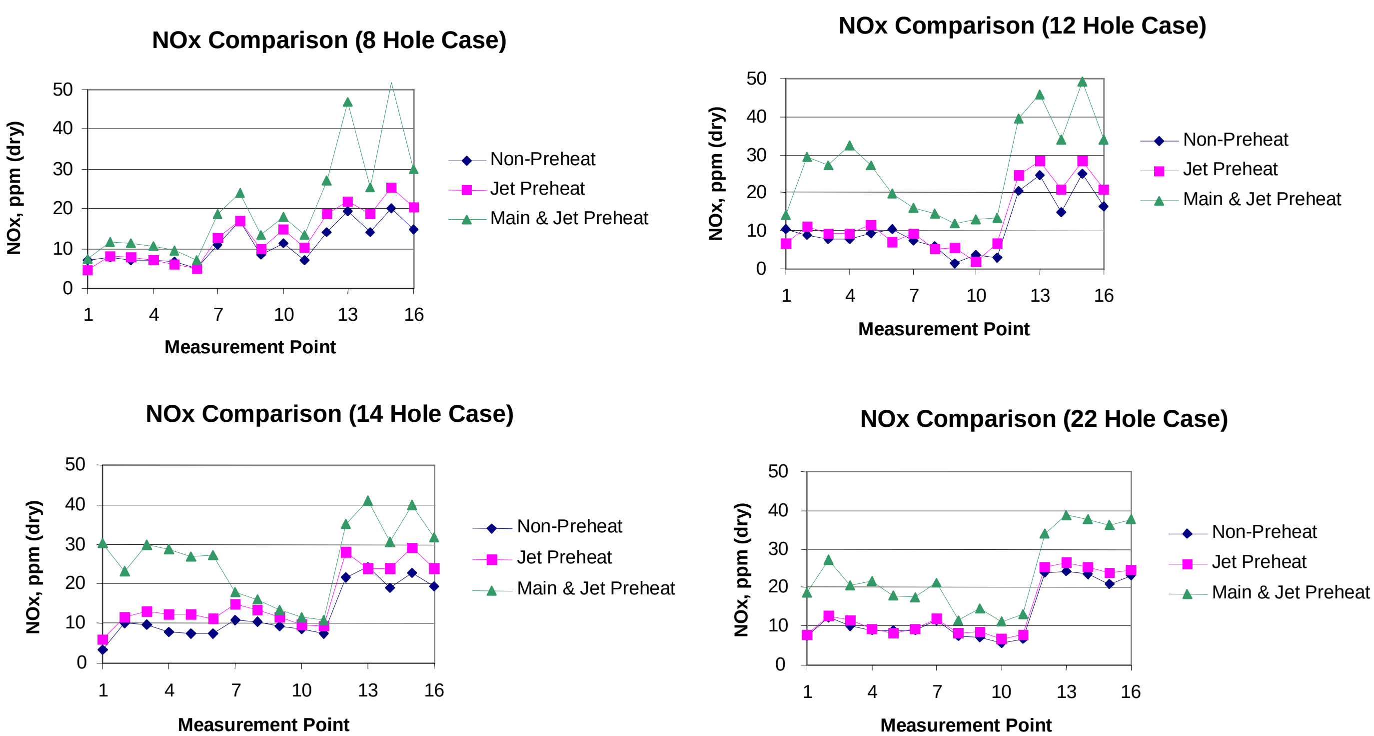


Figure 3. NO_X Measurement Plots

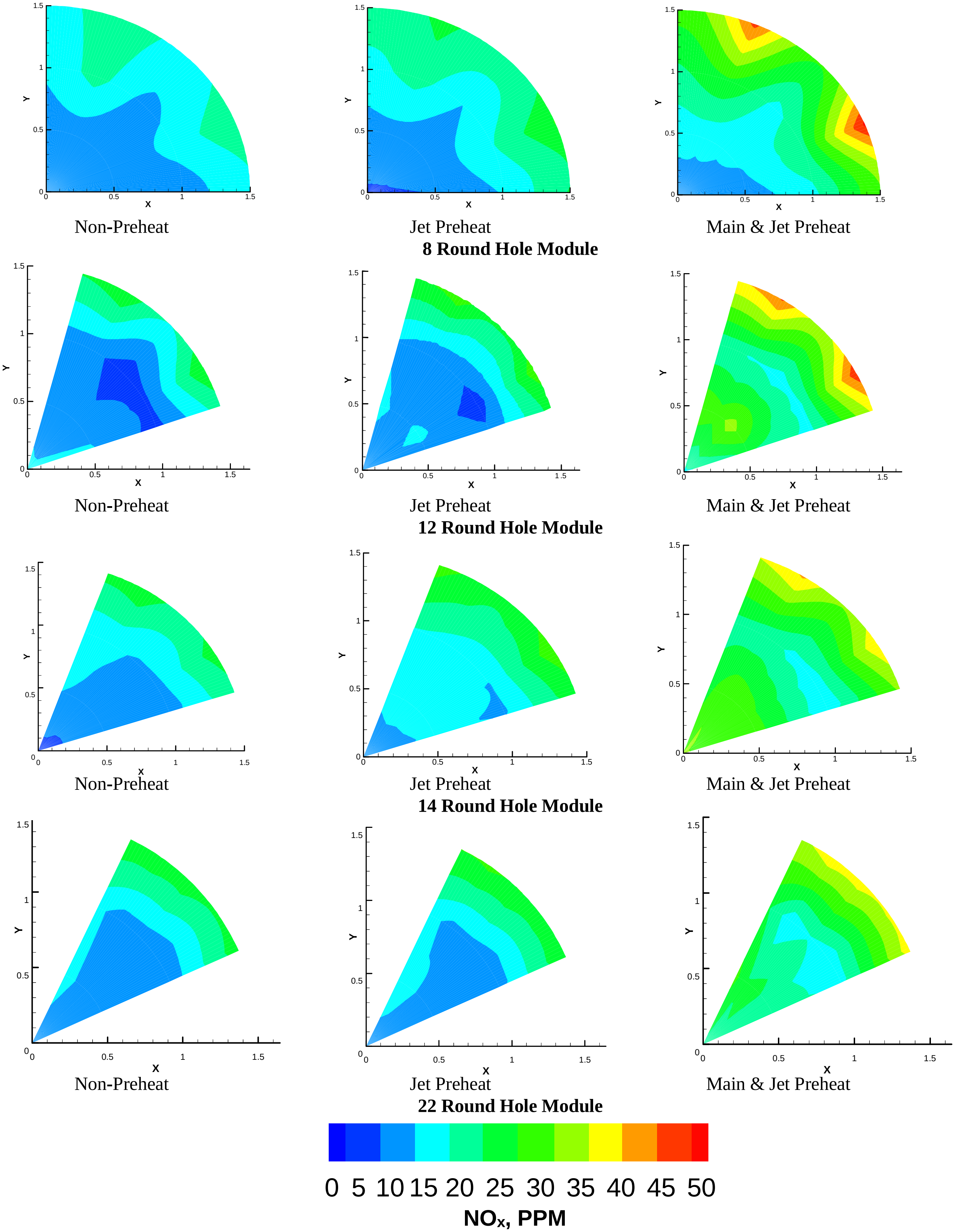


Figure 4. NO_X Distribution Plots for Non-Preheated, Jet Air Preheat, and Main & Jet Air Preheat Conditions for the four modules tested

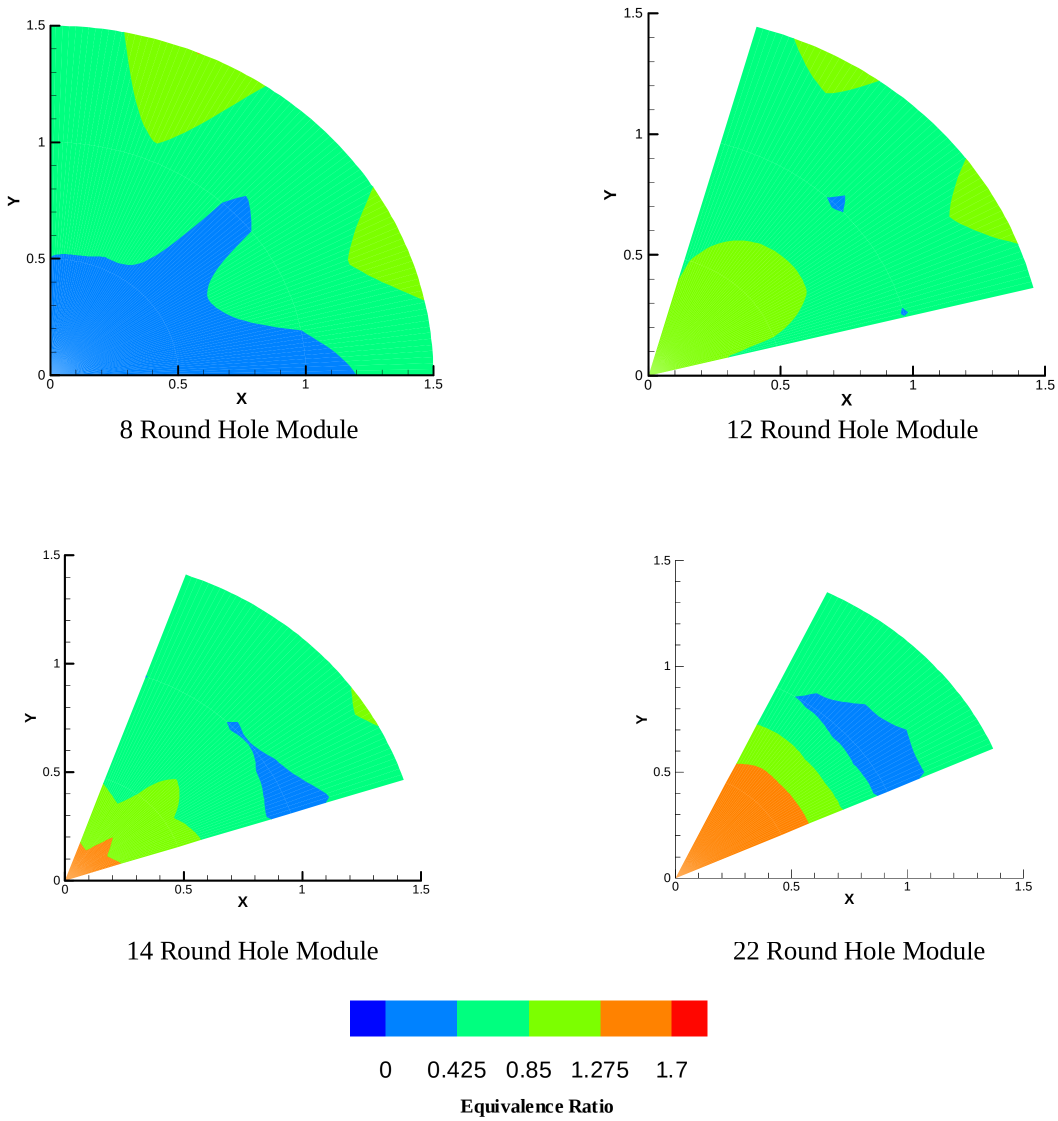


Figure 5. Non-Preheat Case Equivalence Ratio Distribution Plots

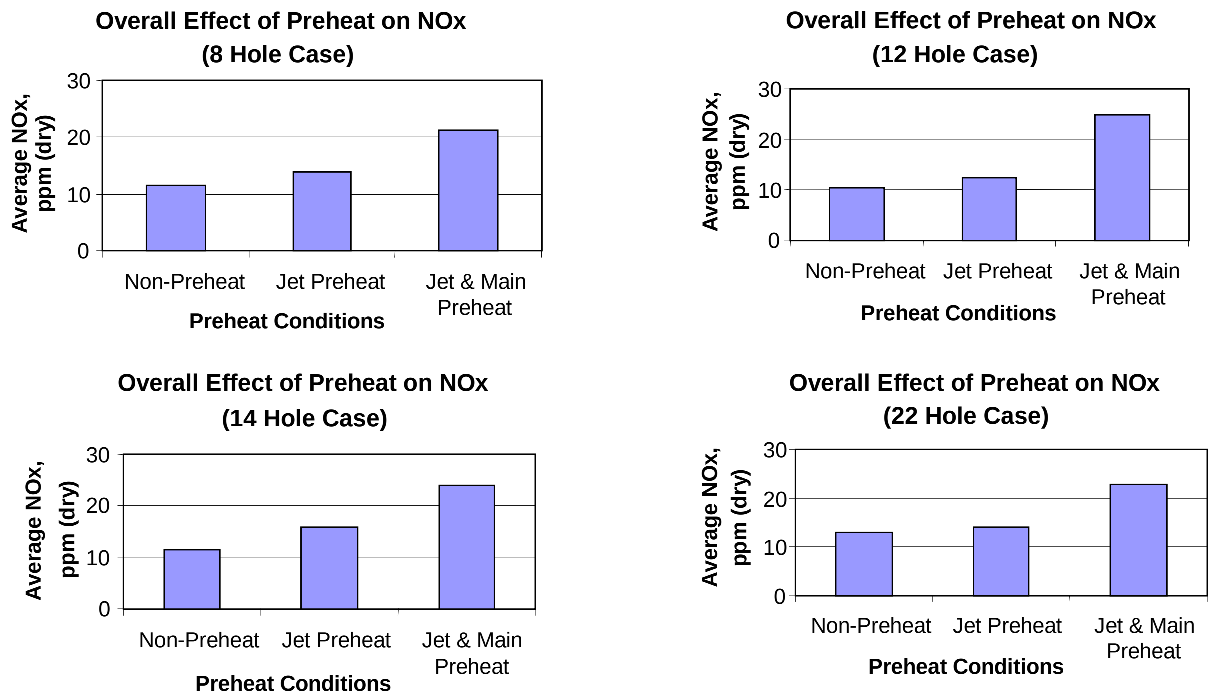


Figure 6. Area Weighted Planar Average NO_X Data

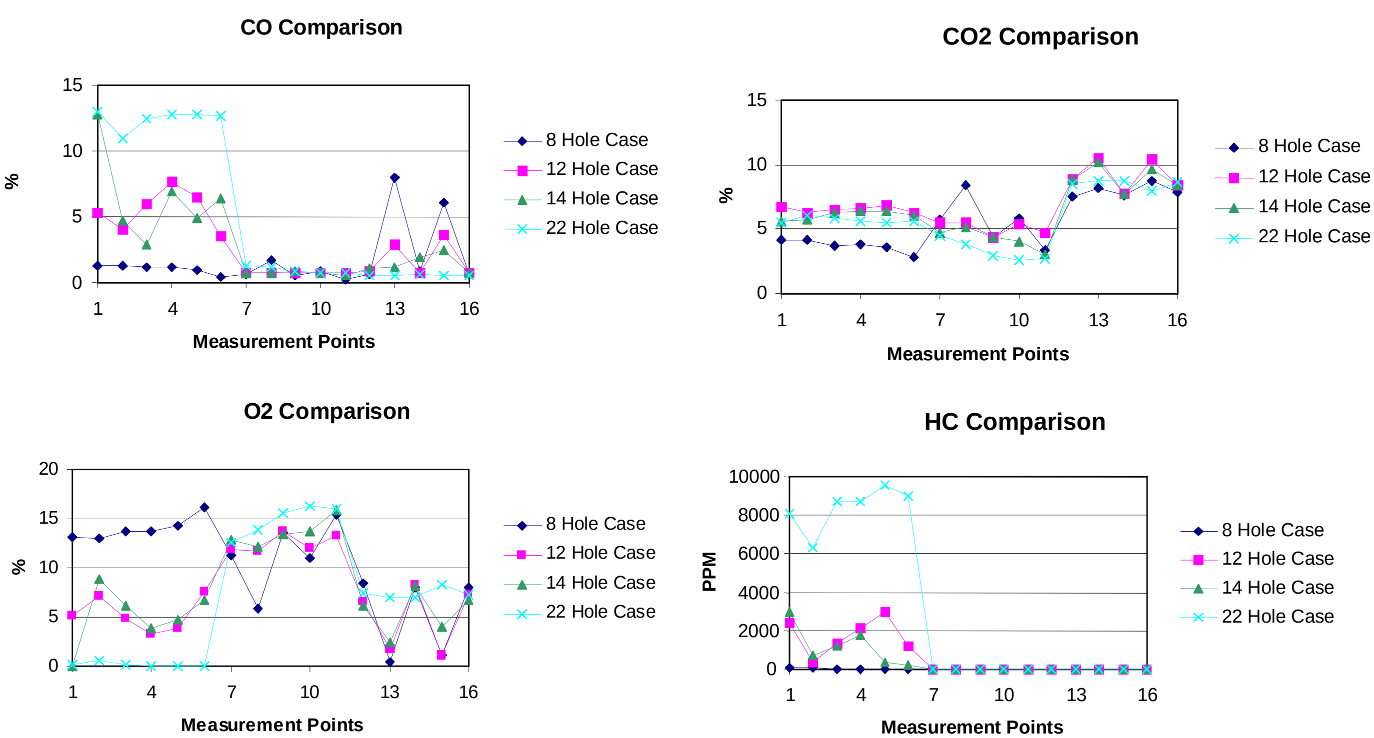


Figure 7. Species Concentrations for Non-Preheat

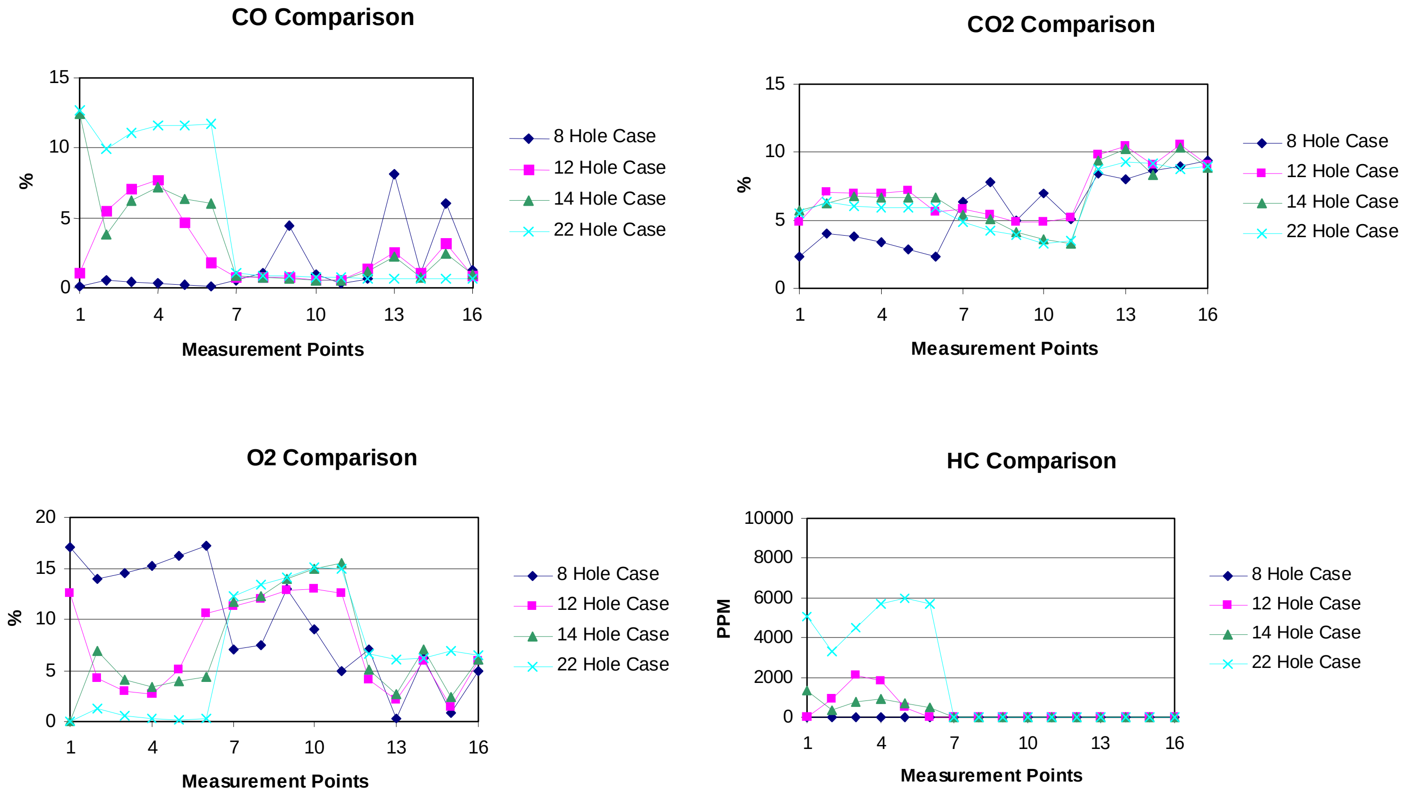


Figure 8. Species Concentration for Jet Air Preheat

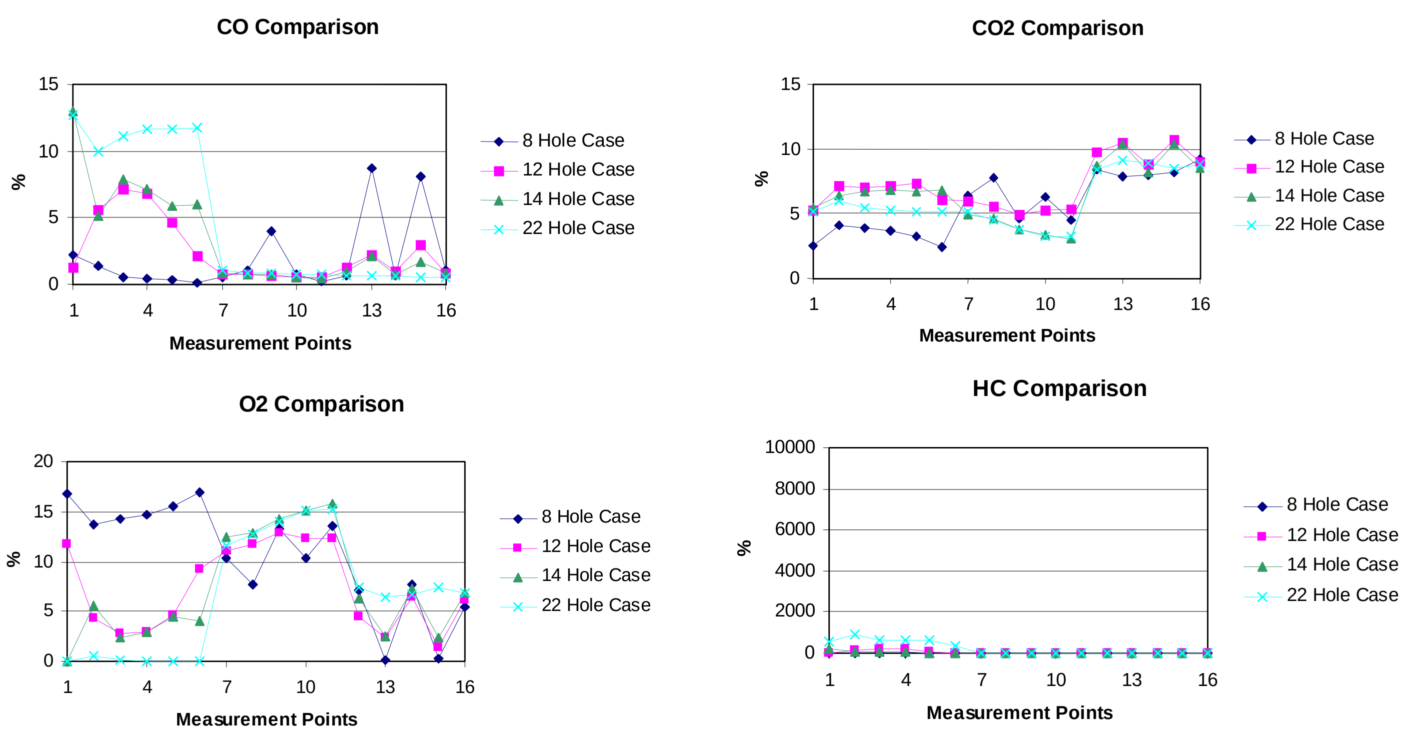
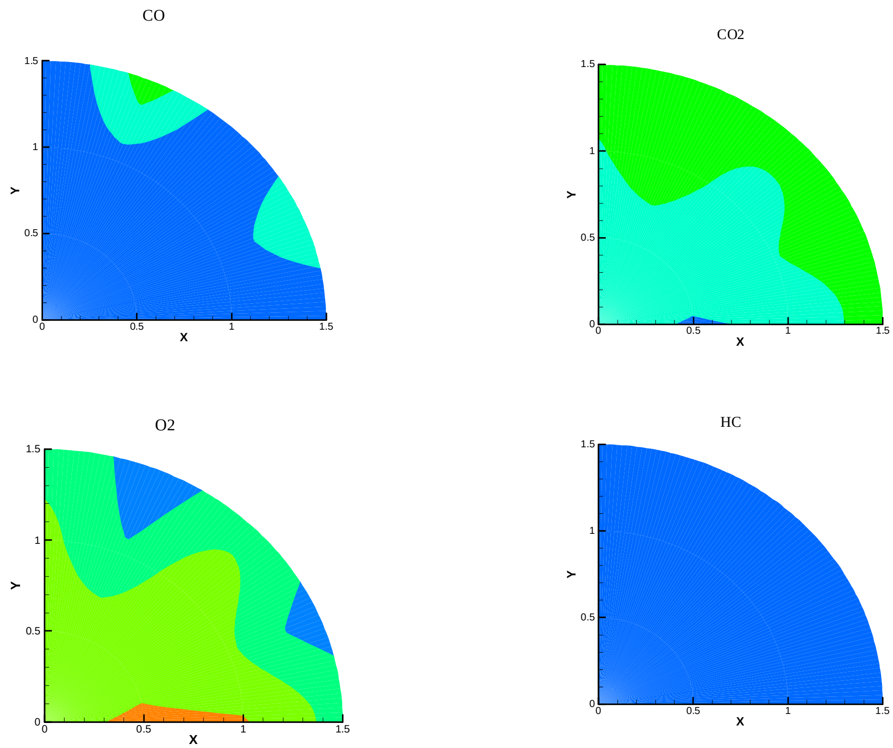
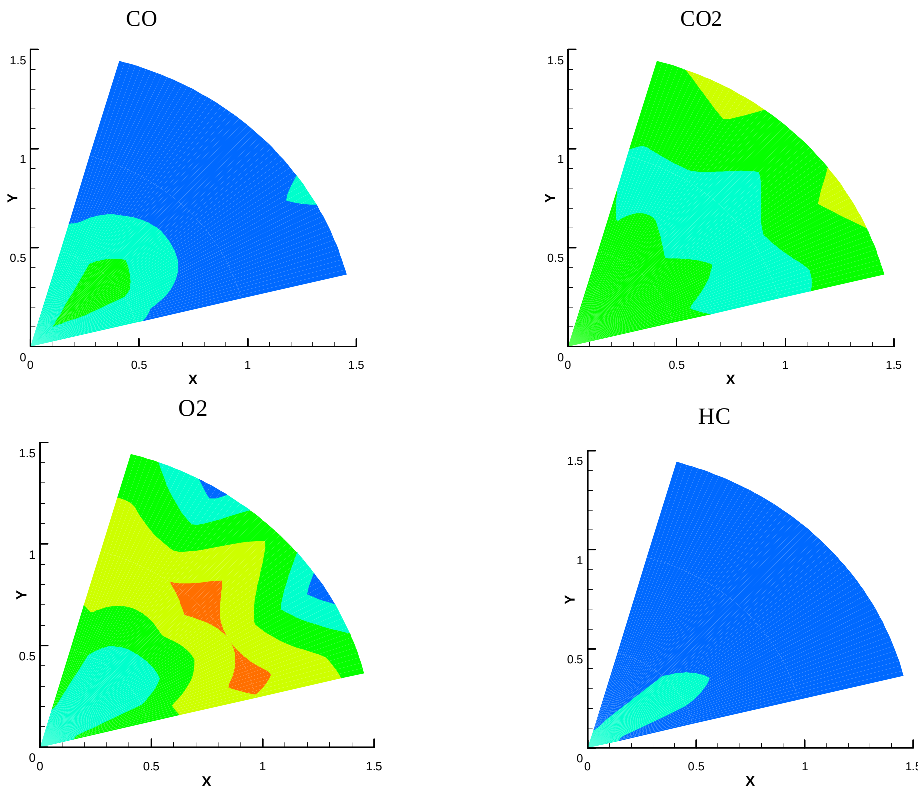


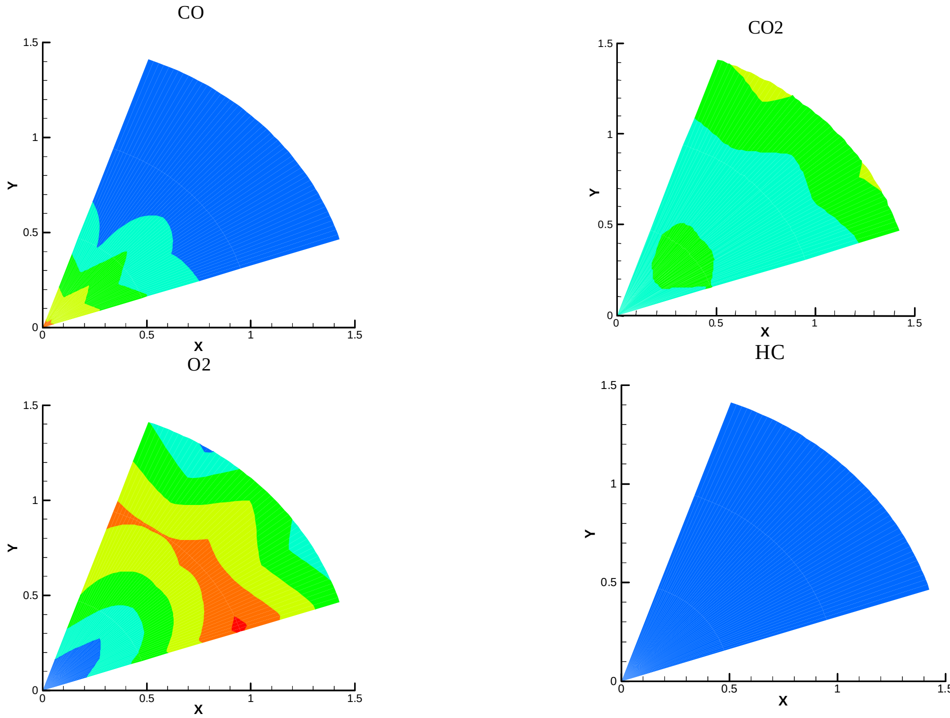
Figure 9. Species Concentrations for Main & Jet Air Preheat



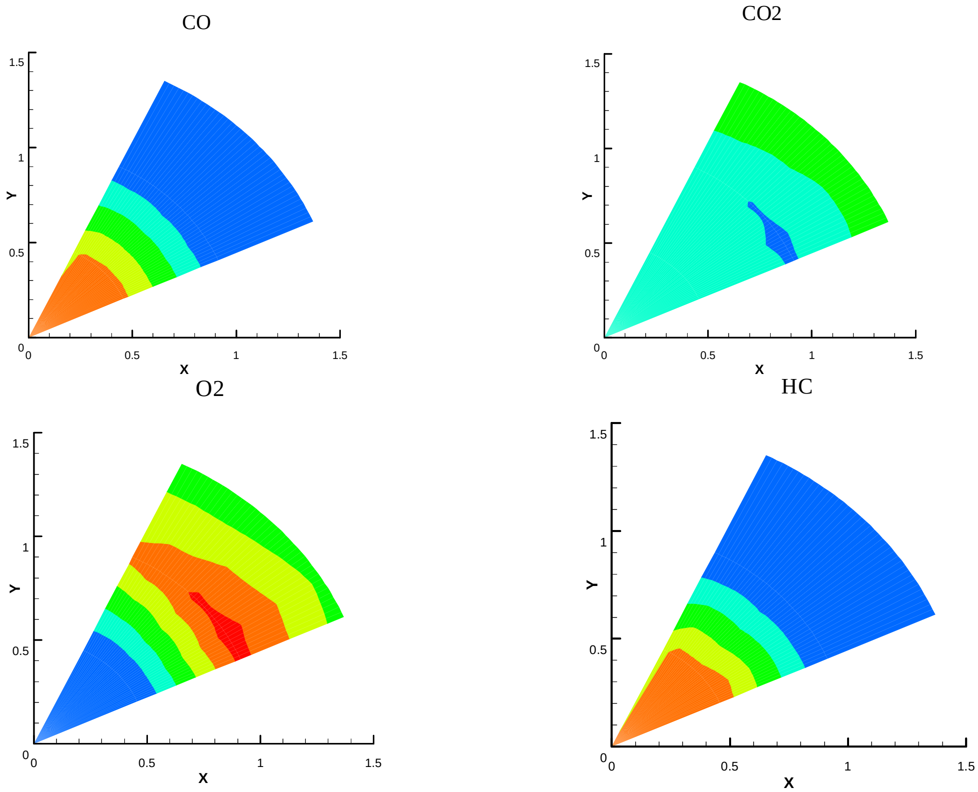
8 Round Hole Module



12 Round Hole Module

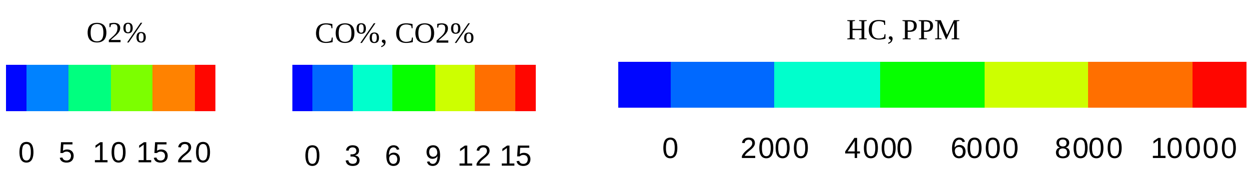


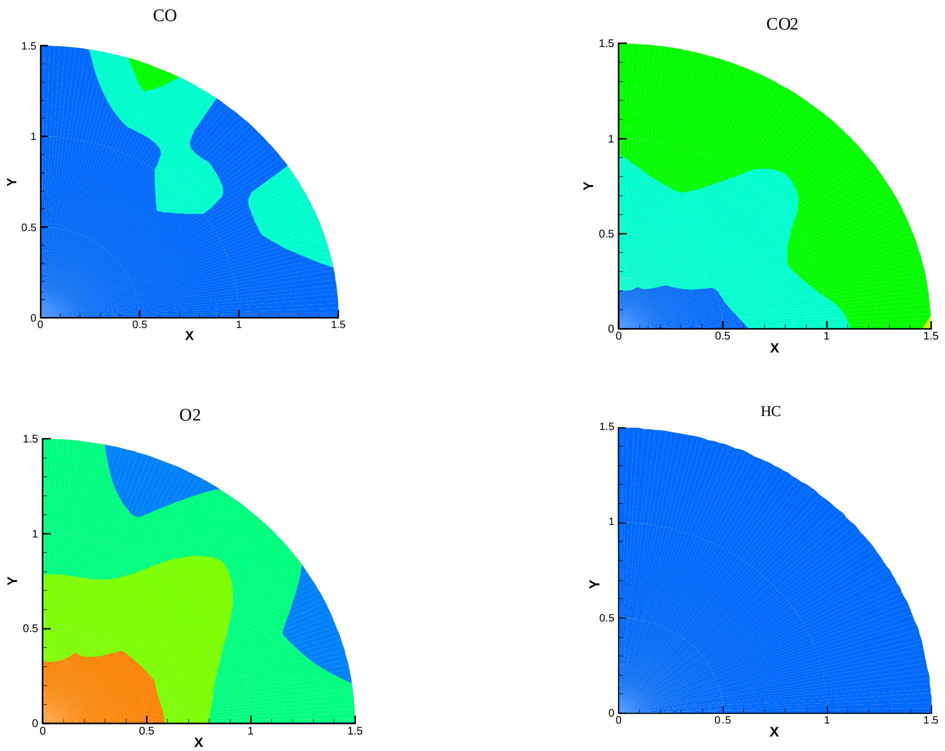
14 Round Hole Module



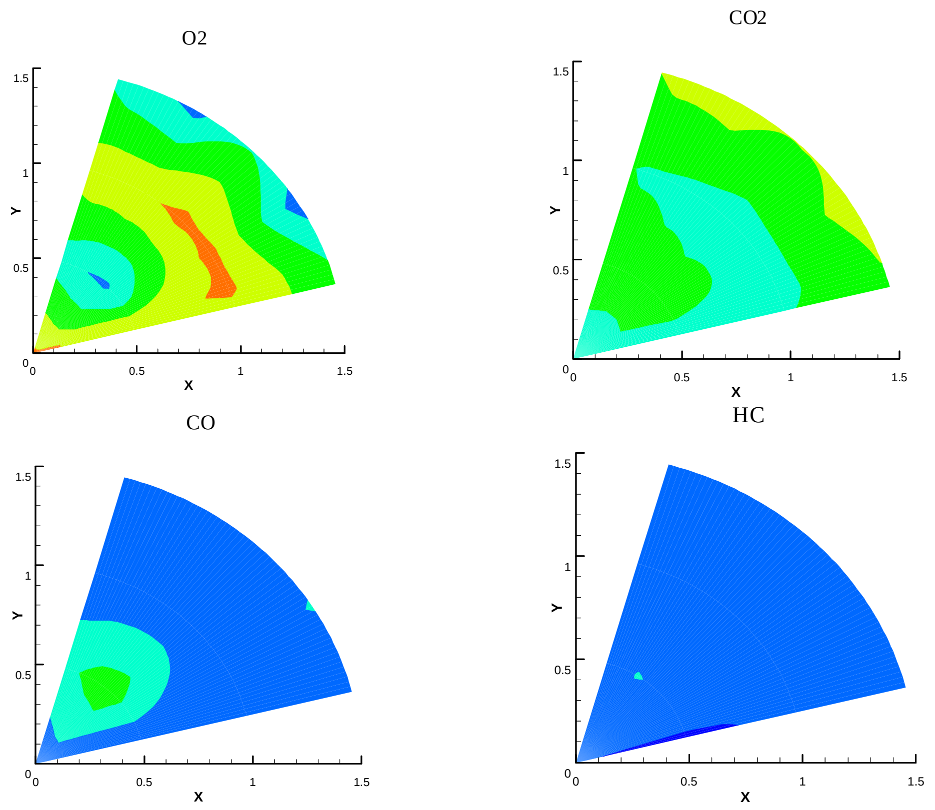
22 Round Hole Module

Figure 10. Species Concentration Distribution Plots for Non-Preheated Air

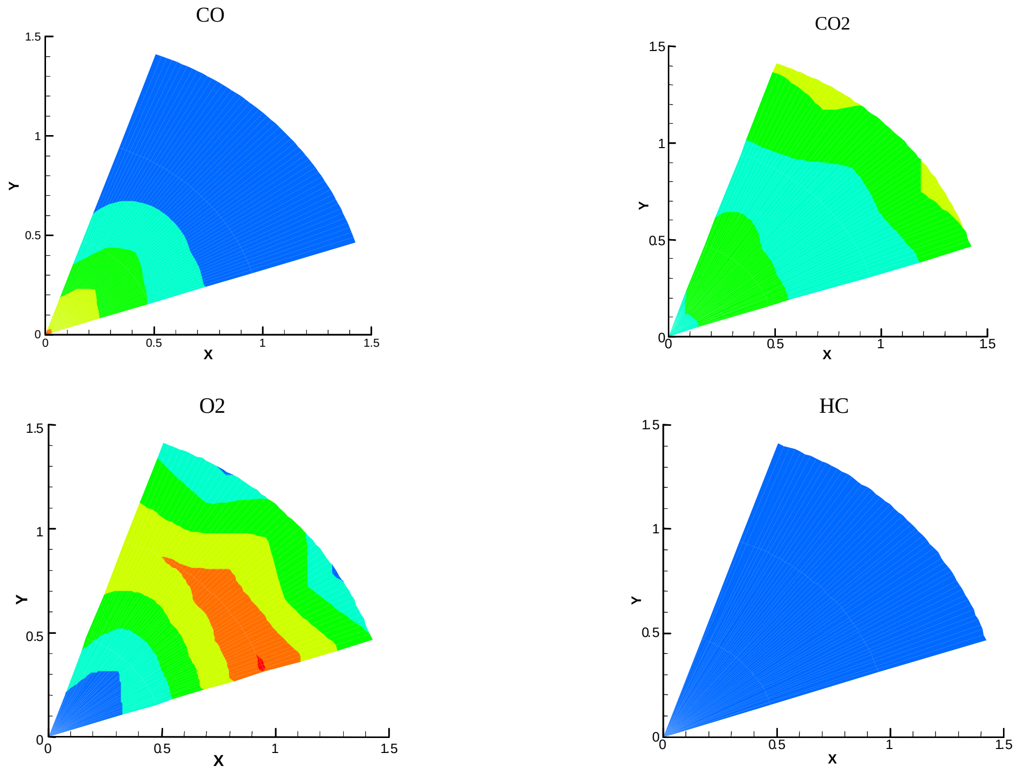




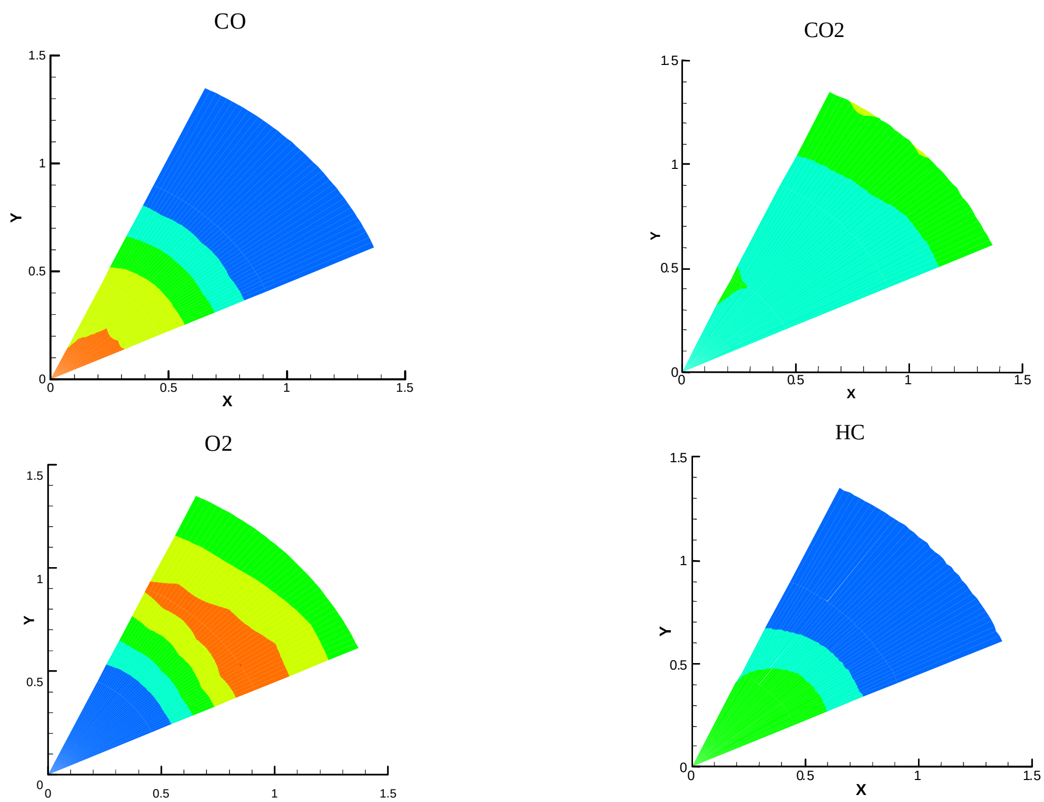
8 Round Hole Module



12 Round Hole Module

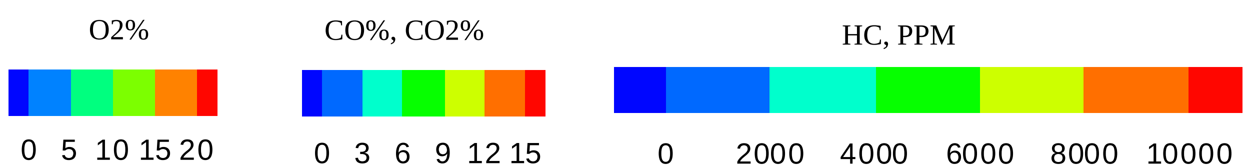


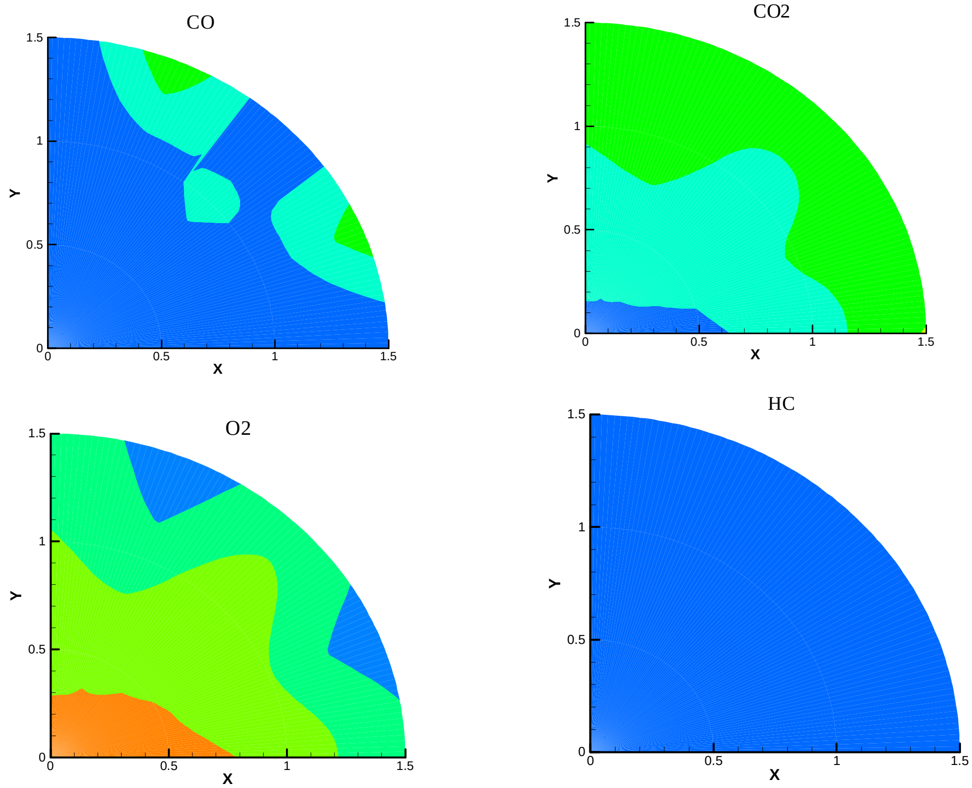
14 Round Hole Module



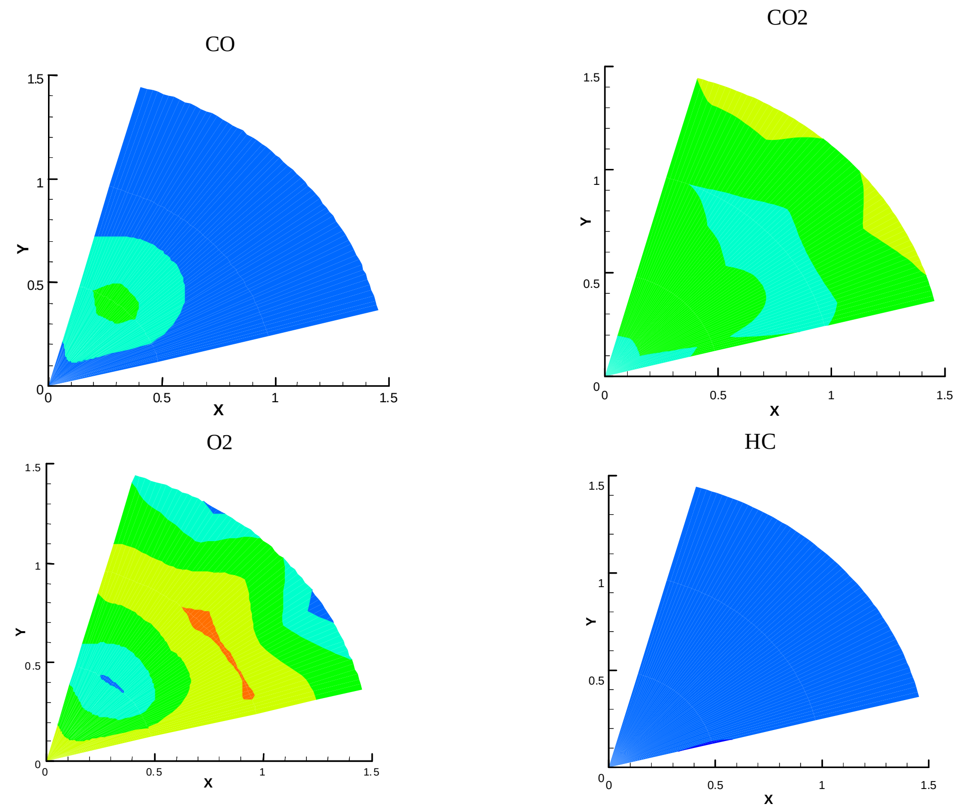
22 Round Hole Module

Figure 11. Species Concentration Distribution Plots for Jet Preheated Air

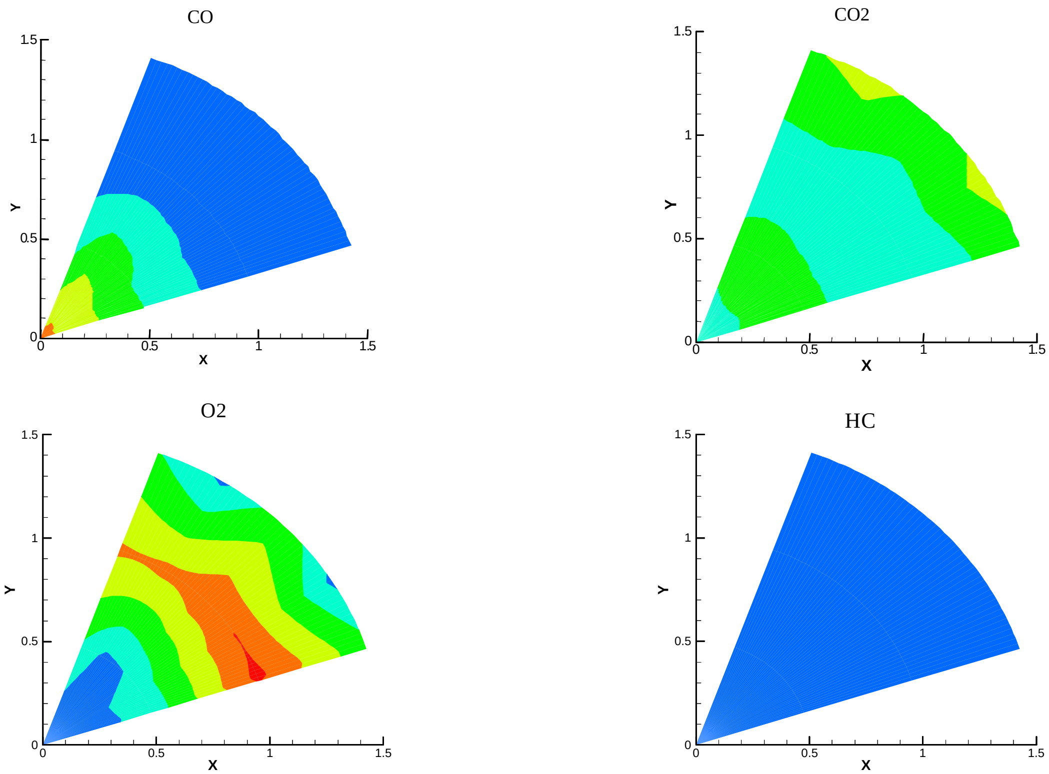




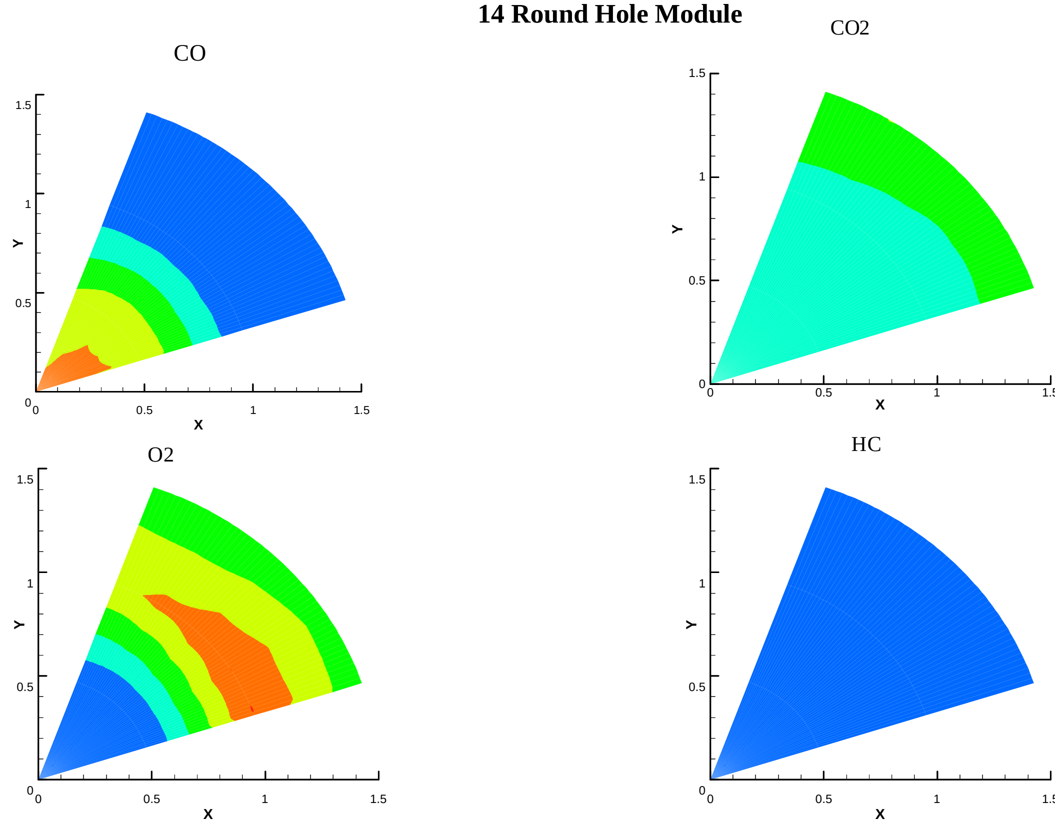
8 Round Hole Module



12 Round Hole Module

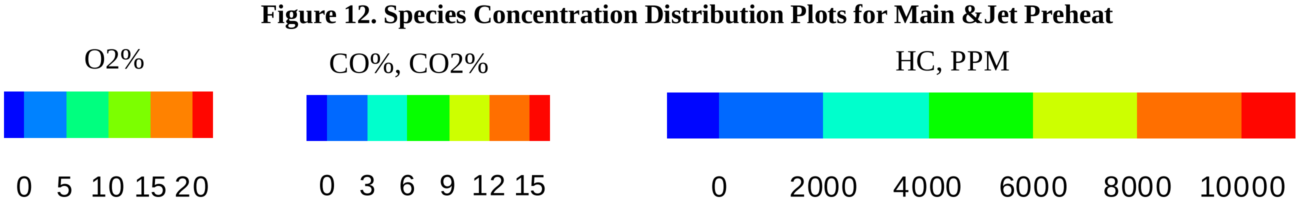


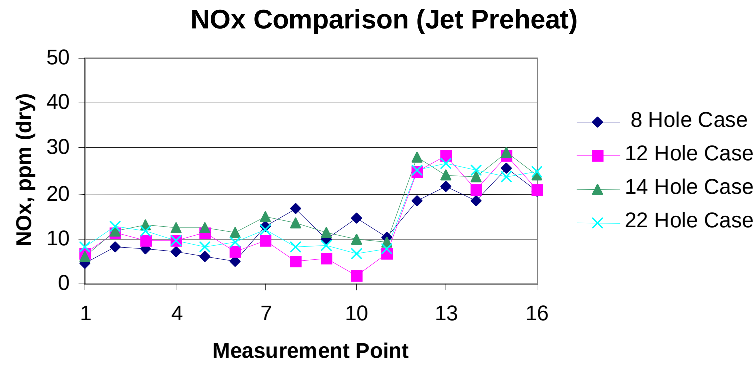
14 Round Hole Module



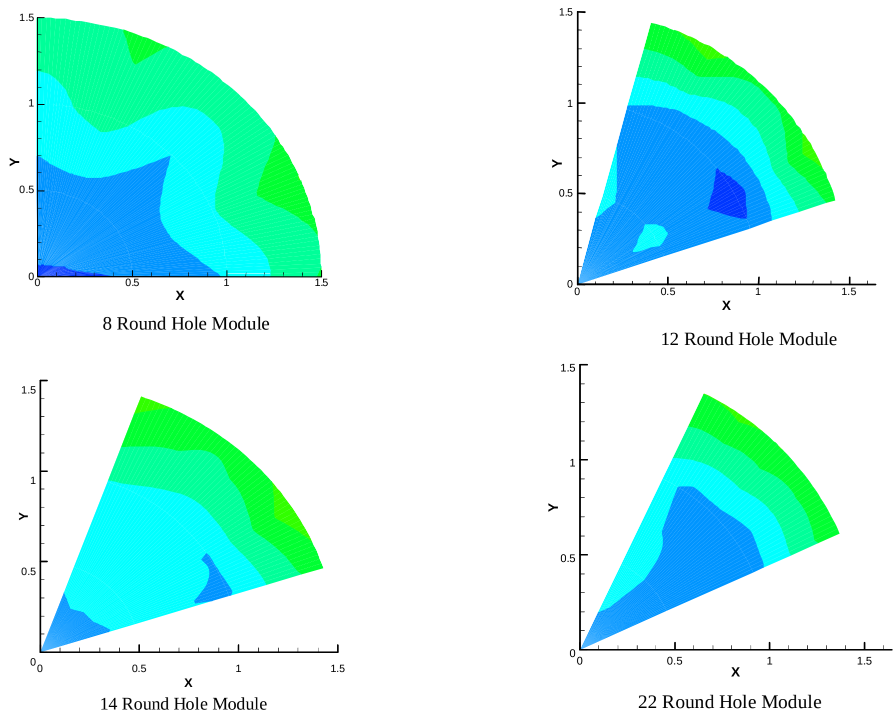
22 Round Hole Module

Figure 12. Species Concentration Distribution Plots for Main &Jet Preheat

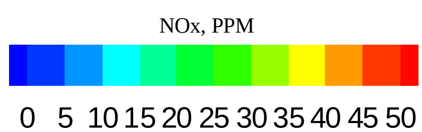


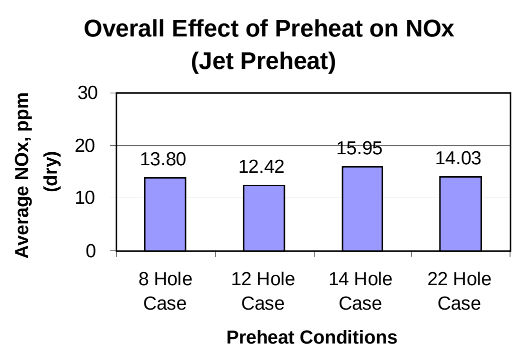


Measured Data



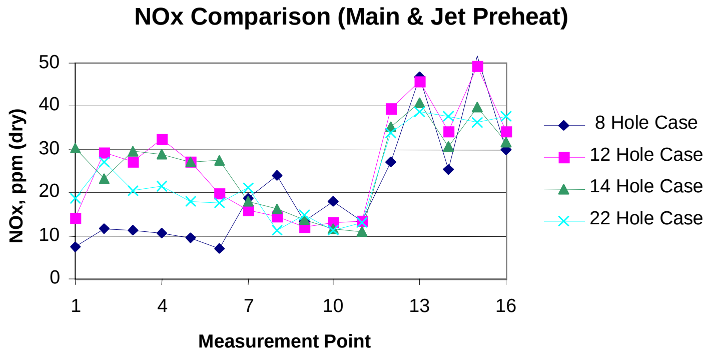
Distribution Plots



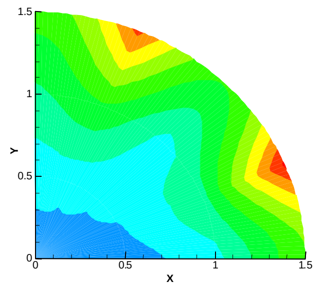


Area Weighted Planar Averages

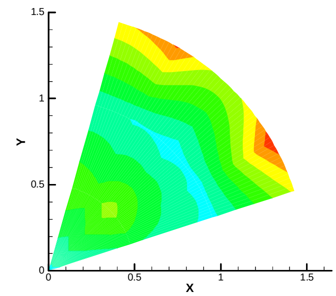
Figure 13. NO_X Comparison for Jet Air Preheat



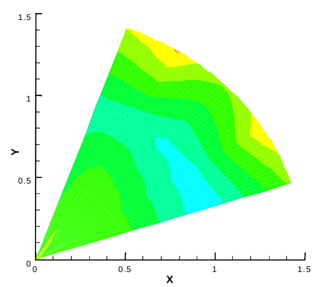
Measured Data



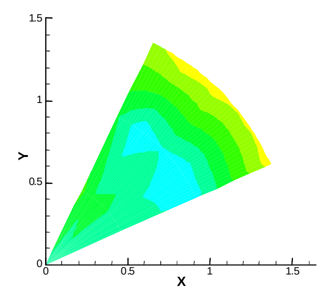
8 Round Hole Module



12 Round Hole Module



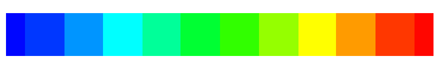
14 Round Hole

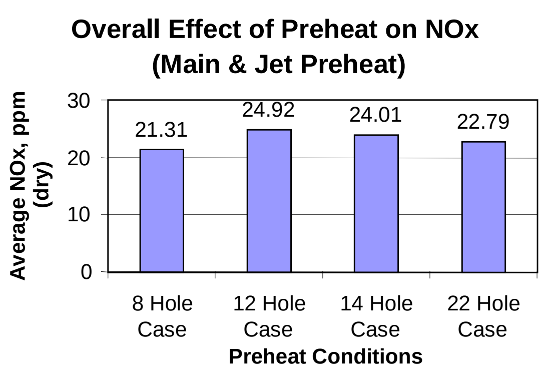


22 Round Hole

Distribution Plots

NOx, PPM





Area weighted Planar Averages
Figure 14 NO_X Comparison for Main &Jet Air Preheat

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)

2. REPORT DATE
September 1999

3. REPORT TYPE AND DATES COVERED
Technical Memorandum

4. TITLE AND SUBTITLE
The Effect of Air Preheat at Atmospheric Pressure on the Formation of NO_x in the Quick-Mix Section of an Axially Staged Combustor

5. FUNDING NUMBERS
WU–537–02–20–00
NCC3–412

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

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

8. PERFORMING ORGANIZATION REPORT NUMBER
E–11872

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—1999-209431

11. SUPPLEMENTARY NOTES
M.A. Vardakas, M.Y. Leong, J. Brouwer, and G.S. Samuelsen, UCI Combustion Laboratory, University of California at Irvine, Irvine, California, 92697–3550 (work funded under Cooperative Agreement NCC3–412), and J.D. Holdeman, NASA Glenn Research Center. Responsible person, J.D. Holdeman, organization code 5830, (216) 433–5846.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Category: 07 Distribution: Nonstandard

This publication is available from the NASA Center for AeroSpace Information, (301) 621–0390.

12b. DISTRIBUTION CODE

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

The Rich-burn/Quick–mix/Lean-burn (RQL) combustor concept has been proposed to minimize the formation of nitrogen oxides (NO_x) in gas turbine systems. The success of this combustor strategy is dependent upon the efficiency of the mixing section bridging the fuel-rich and fuel-lean stages. Note that although these results were obtained from an experiment designed to study an RQL mixer, the link between mixing and NO_x signatures is considerably broader than this application, in that the need to understand this link exists in most advanced combustors. The experiment reported herein was designed to study the effects of inlet air temperature on NO_x formation in a mixing section. The results indicate that NO_x emission is increased for all preheated cases compared to non-preheated cases. When comparing the various mixing modules, the affect of jet penetration is important, as this determines where NO_x concentrations peak, and affects overall NO_x production. Although jet air comprises 70 percent of the total airflow, the impact that jet air preheat has on overall NO_x emissions is small compared to preheating both main and jet air flow.

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

15. NUMBER OF PAGES
29

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	