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Mixing of Multiple Jets With a Confined Subsonic Crossflow

Part III—The Effects of Air Preheat and Number of Orifices on Flow and Emissions in an RQL Mixing Section

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There are numerous prior references on a jet-in-crossflow (JIC). Because the references in previous JIC summaries are extensive, older reports and papers are not referenced in this report unless specific results are cited or relevant references are not included in the summaries. Secondary references are listed parenthetically only if 1) they are the same as, or similar to, the primary reference, or 2) they provide a backup reference. Our convention in listing previous reports is that if the secondary reference is the same as the primary reference we use “also”. We use “see also” if the earlier report is similar to the primary reference but there are differences in authors and/or minor differences in content, title, format, etc., or if the secondary reference is a back-up report.

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Summary

This study was motivated by a goal to understand the mixing and emissions in the Rich-burn/Quick-mix/Lean-burn (RQL) combustor scheme that has been proposed to minimize the formation of oxides of nitrogen (NO_x) in gas turbine combustors. The study reported herein was a reacting jet-in-crossflow experiment at atmospheric pressure. The jets were injected from the perimeter of a cylindrical duct through round-hole orifices into a fuel-rich mainstream flow. The number of orifices investigated in this study gave over- to optimum to under-penetrating jets at a jet-to-mainstream momentum-flux ratio of $J = 57$. The size of individual orifices was decreased as the number of orifices increased to maintain a constant total area; the jet-to-mainstream mass-flow ratio was constant at $MR = 2.5$. The experiments focused on the effects of the number of orifices and inlet air preheat and were conducted in a facility that provided the capability for independent variation of jet and main inlet air preheat temperature. The number of orifices was found to have a significant effect on mixing and the distributions of species, but very little effect on overall NO_x emissions, suggesting that an aerodynamically optimum mixer might not minimize NO_x emissions. Air preheat was found to have very little effect on mixing and the distributions of major species, but preheating both main and jet air did increase NO_x emissions significantly. Although the air jets injected in the quick-mix section of an RQL combustor may comprise over 70 percent of the total air flow, the overall NO_x emission levels were found to be more sensitive to main stream air preheat than to jet stream air preheat.

Nomenclature

A_J/A_M	jet-to-mainstream area ratio = $n((d/2)/(R))^2$
C	π*sqrt(2*J)/n; derived in reference 3
C_d	orifice discharge coefficient
d	round hole diameter
d_j	effective round hole diameter = (d)(sqrt (C_d))
DR	jet-to-mainstream density ratio, ρ_{jets}/ρ_{main}
J	jet-to-mainstream momentum-flux ratio = $(\rho V^2)_{jets}/(\rho U^2)_{main}$ $(MR)^2/DR/(C_d)^2/(A_J/A_M)^2$
MR	jet-to-mainstream mass-flow ratio = $(\rho VA_{total})_{jets}/(\rho UA_{can\ cross\text{-}section})_{main}$ $(DR)(V_J/U_M)(C_d)(A_J/A_M)$
n	number of round holes in quick-mix module
R	radius of the quick-mix module
r	radial distance from the module center
U	axial velocity

U_M unmixed mainstream velocity
V_J jet exit velocity
x downstream distance; $x = 0$ at leading edge of orifice
ϕ equivalence ratio = $(\text{fuel/air})_{\text{actual}}/(\text{fuel/air})_{\text{stoichiometric}}$

Introduction

Many control strategies intended to modify mixing and emissions in gas turbine combustors rely on jets in a crossflow of gas to mix fluids. One application of this technique is the mixer section in the Rich-burn/Quick-mix/Lean-burn (RQL) combustor that has been proposed to minimize the formation of oxides of nitrogen (NO_x) in gas turbine combustors. In an RQL, jets of air are typically introduced from the wall of the quick-mix section into a richer than stoichiometric mainstream flow resulting in a combination of mixing and reaction. The goal is to transition the mixture from an overall fuel-rich to an overall fuel-lean condition as quickly as possible to try to minimize NO_x formation in the mixing section by minimizing the time during which regions exist that consist of near stoichiometric species concentrations at high temperatures. Thus, the success of the RQL combustor strategy depends on the efficiency of the mixing section of the combustor.

Numerous jet in crossflow (JIC) studies, summarized in references 1 to 5 have yielded insight on flow field characteristics resulting from jet mixing. Most JIC research prior to 1970 contributed measures of centerplane parameters and jet shape for unconfined single jets. Many of the studies summarized in reference 1 were motivated by the engine exhaust aerodynamics of Vertical/Short Take-Off and Landing (V/STOL) aircraft. The summary in reference 2 focused on computational methods. The studies summarized in reference 3 were motivated by the dilution process in conventional gas turbine combustors and those summarized in reference 4 (for cylindrical ducts) and reference 5 (for opposed rows of jets in rectangular ducts) were motivated by the RQL.

Nothing was identified for a steady confined JIC in the studies summarized in references 3 to 5 that penetrated significantly farther or mixed faster than a single, round, unbounded jet. Thus, the penetration of the single unbounded jet should be considered as the maximum for confined JICs. Although the single jet is a key component in combustors and provides considerable insight, flows of direct interest to the combustor application are confined and the interaction between jets is a major factor in determining mixing performance.

Many of the studies summarized in references 4 and 5 sought to define conditions to optimize the mixing. Nonreacting experiments have been used to investigate the mixing of air jets into a cross stream. The primary emphasis of these studies (e.g., ref. 6), was directed at investigating the effects of varying the jet-to-crossflow momentum-flux ratio and the shape, orientation, and number of orifices. An optimization scheme, using a statistical approach, was subsequently applied in reference 7 to determine the orifice configurations that lead to optimal mixing in a cylindrical duct.

Tests on JIC mixing in reacting flows in a cylindrical duct have been reported in references 8 to 11. In many of these experiments the model gas turbine combustors contained two rows of holes for primary and dilution air mixing typical of conventional combustors, as opposed to a single row quick mixing scheme. These studies included varying operating conditions such as air preheat (ref. 8), fuel-air ratio (ref. 9), fuel injection (ref. 10), or the momentum of the primary jets (ref. 11). In reference 11 a geometric parameterization was pursued, but it was related to varying the axial positions of the rows of the primary and dilution jets rather than changing orifice configurations.

NO_x measurements in flametube RQL combustors have been reported in references 12 to 16. The investigation of the relation between mixing and NO_x emissions in reference 17 utilized the results of non-reacting experiments, and analytically superimposed the kinetics of NO_x production. (The studies reported in references 12 to 17 were actually conducted several years prior to their becoming publicly available.)

A journal article including results of measured NO_x emissions in a model RQL combustor with a single row of orifices was published in reference 18. Both inlet air streams were preheated to the same temperature and the operating pressure was varied. The crossflow was swirling; all tests were made using a 20 round hole orifice configuration; and emissions measurements were made with a ganged multiport probe at the exit of the model combustor, which was at an axial distance equal to more than ten duct radii downstream of the jet injection.

The authors of reference 18 identified two potential sources for the emission of NO_x in an RQL combustor. One source was the formation of prompt NO in the Rich-burn zone; the second source was the NO formation that could occur in the Quick-mix section as a result of the formation of thermal NO_x. It was suggested in reference 18 that mixing downstream of the rich zone was critical in an RQL and that the jet-to-mainstream momentum-flux and mass-flow ratios were important factors. The authors also concluded that optimal mixing would minimize NO_x.

Studies in references 19 and 20 reported results for reacting flow JIC experiments in a cylindrical duct at atmospheric pressure without inlet air preheat. A carbon balance technique similar to that in reference 21 was used in references 19 and 20 to obtain the equivalence ratio. Alternate methods for obtaining the local equivalence ratio in a reacting flow were investigated in reference 22. The effects of coupling between the mainstream and plenum flows in both cylindrical and annular ducts are presented in reference 23. A study of the effects of preheat and number of orifices at elevated pressure was the objective in reference 24. A spreadsheet for the mixing of multiple jets in a rectangular duct was developed and demonstrated in references 25 and 26.

The study in reference 27 extended the work reported in references 19 and 20 to address the effects on both mixing and emissions of varying inlet air preheat and varying the number of orifices with preheated inlet air. The experiments were conducted at atmospheric pressure in a facility that provided for independent variation of jet and main (crossflow) inlet air preheat temperature. Measurements were made at 16 radial and circumferential locations at a downstream distance equal to the radius of the mixer section. Results are reported in reference 27 for configurations with 8, 12, 14, and 22 round holes to give over- to optimum to under-penetrating jets at $J = 57$.

Representative results from reference 27 are presented in this report. The focus is on the effect of varying the number of orifices with both the jet and main air preheated to the same temperature and the effect of independently preheating the jet and main air for an “optimum” mixer. The influence of preheating each stream independently was assessed to provide additional insight into the NO_x formation in an RQL although in a practical combustor the air for both streams would emanate from the same plenum and the jet inlet air temperature would be different from the main inlet air temperature only if the air in either stream was used for another function prior to entering the combustion chamber.

Experiment

Facility

The experimental facility used in this study 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 was mixed with air upstream of the ignition point. Fuel-rich combustion was stabilized downstream of the quarl by a swirl-induced recirculation zone. To dissipate the swirl in the flow and to introduce a uniform nonswirling flow into the 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 mixing section was modular and included a cylindrical section through which the mainstream effluent passed, and to which jet air was supplied from a surrounding plenum. The plenum for the jet air was fed by four equally-spaced air ports located toward the base of the plenum. A high-temperature steel flow-straightening device installed in the plenum conditioned and equally distributed the jet air entering the mixing module.

The mixing modules were 280 mm (11 in.) in length with inner and outer 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 provided sealing between the module and the stainless steel mating surfaces to form the plenum for the air jets.

Recirculating heaters of 20 and 25 kW were utilized to supply the necessary preheat to the main and jet air lines respectively. The preheat temperatures were independently established and controlled.

Experimental Conditions

The flow and geometric conditions are presented in tables 1 and 2. The experiments were performed for a jet-to-mainstream momentum-flux ratio J of 57 and a mass-flow ratio MR of 2.5, both typical of RQL mixer conditions. The fuel-rich equivalence ratio and overall equivalence ratios (ϕ) were 1.66 and 0.45, respectively. The operating pressure for the system was one atmosphere. Operating conditions for the experimental parametric variations are noted in table 1.

As derived in reference 3, the optimum number of round holes in a cylindrical duct is $n = \pi(\mathrm{sqr}(2J))/2.5$. For a momentum-flux ratio J of 57, the optimal mixer would have 13.4 holes. Thus, two of the four mixing modules adopted in reference 27 were 12-hole and 14-hole configurations. In order to provide unambiguous over- and under-penetrating cases, 8-hole and 22-hole modules were included as well (table 2). The orifice diameters were varied between modules in order to maintain a constant total jet area of 1244 mm^2 (1.93 in.^{2}). In this study A_J/A_M = 25 percent, and as reported previously, the effective area was 18 percent (900 mm^2) so C_d = 0.72.

Measurements

For each module, species concentration measurements were obtained in a two-jet sector for a plane at x/R = 1 (plane 5 in figure 2(a)) where x/R was measured from the leading edge of the mixing module orifices. Note that $x/d = R/d$ for the data reported herein because $x = R$.

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

Area-weighting was calculated by dividing the sector at circular arcs that passed through radii midway between measurement radii, and this arc was then divided circumferentially at points midway between measurement locations. The area ratios from this calculation were applied as weighting factors to the individual measurements.

Species concentration measurements were 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 was analyzed by non-dispersed infrared (NDIR) analysis for CO and CO_2, paramagnetic analysis for O_2, flame ionization detection (FID) for total hydrocarbons, and chemiluminesence (CLD) for NO_x. Data are reported as measured and were not "corrected" for either the ambient humidity or the expected water content of the flow.

Probe Design

A double-jacked water-cooled stainless steel probe 762 mm (30 in.) in length was used to extract gas samples from the quick mixing section (fig. 3). The probe measured 8 mm in outer diameter and tapered to 3.2 mm at the tip. A 45° bend was made 25.4 mm (1 in.) from the tip. The probe design was influenced by the research in reference 7 that reported that a thermocouple probe with a 45° angled tip was best as it biased the mainstream and jet flows equally in the orifice region. The probe location was fixed and the rig was traversed to obtain the measurements. The plane of the angled probe tip was positioned such that the tip was pointed toward the center of the sector wall.

Measurement Uncertainty

The extractive emissions measurement protocol was conventional. The analyzers were standardized equipment which was checked frequently with span gases. Readings on the NO_x analyzer would be expected to be around 200 ppm for an aeroengine at cruise conditions and that number would be expected to vary about 5 to 10 ppm from the mean. CO_2 is typically around 7 percent with a data fluctuation between 1 and 1 1/2 percent. The mean of O_2 is around 12 percent or less. The variability of O_2 is usually less than for CO_2, as the O_2 reading is usually very steady. As for the relation between what exists in the flow and what is measured; this is a classical question, and they are assumed to be the same when standard procedures are followed.

A measure of the uncertainty of the data is given by analyzing the species measurements to determine the midplane and centerplane means and variances. In a perfect world, the 3 midplane measurements would be equal at a given radius and the 2 centerplane measurements would be equal, but they often aren't. Their variability is a measure of both spatial and species uncertainty in the measurements. The uncertainty values for NO_x, CO, CO_2, and O_2 using all 192 measurements were: NO_x = 4.39 ppm; CO = 1.77 percent, CO_2 = 1.96 percent; and O_2 = 3.30 percent, where the values given are two standard deviations from the appropriate local mean and are not area weighted.

Results and Discussion

This report focuses on (1) the effect of the number of orifices with both streams preheated and (2) the effect of air preheat for the 12 hole module to illustrate the trends observed. Note that the trends are much more important than absolute values and that it was shown in references 3 to 5 that trends were the same whether they came from CFD calculations, empirical model calculations, nonintrusive concentration measurements, or probe measurements. The flow and emissions data collected for all the different preheat conditions and modules tested are presented in reference 27.

Effect of Number of Orifices With Preheated Inlet Air

Measurements are reported in this section with both the main and jet air preheated for modules with 8, 12, 14, and 22 round holes. This gives over-, optimum, and under-penetrating jets at J = 57 to show the influence of the number of orifices on mixing and emissions. Previous studies in references 19 and 20 identified optimal mixing configurations in a reacting flow for round hole modules in the absence of inlet air preheat. The data presented in figures 4 to 7 are also for experimental conditions with J = 57 and MR = 2.5 but with both the main and jet air preheated to the same temperature as would probably be the case in a practical RQL combustor. Results are shown in reference 27 for other preheat conditions, but the trends in them are similar to those shown here.

Figure 4 reveals the similarity of the NO_x concentrations in the mid and wall regions for the several modules. The contour distributions in figure 5 also show that high NO_x concentrations were measured in the jet wakes for all modules. This suggests that a significant production of NO_x can occur downstream of the orifices in the region of the jet wakes. Note that there are substantial differences in the distribution of NO_x among the modules. The NO_x uncertainty value using the 64 measurements with both streams preheated was 5.72 ppm, where this value is two standard deviations from the appropriate local mean for each measurement and is not area weighted.

It can be seen in figures 4 and 5 that the NO_x concentrations in the center region for the 8-hole module are significantly lower than for the other three modules. Since the 8-hole module is an over-penetrating case, NO_x concentrations near the centerline of the combustor were expected to be lower for this case. NO_x concentrations for the 8-hole module are very high in the jet wake region (fig. 5), probably as the large jets that are necessary in this case to maintain a constant total area produce a very significant wake.

For the nearly optimum mixers with 12 and 14 orifices, NO_x is high in both the wall region and near the center and lowest in the mid-span region. The prior results in references 19 and 20 identified the 12-hole module as the best mixer for J = 57.

Although the jets under-penetrate in the 22-hole case as expected, they do not under-penetrate enough to avoid a region of near-stoichiometric concentration at high temperature adjacent to the wall. The sector plots of figure 5, suggest that the NO_x levels are again highest in the wake of the jets.

The area-weighted average NO_x emission levels, shown in figure 6, are influenced mostly by the concentrations in the wall region. The area-weighted averages show that the various modules have remarkably similar overall NO_x emissions. The lowest area-weighted average NO_x (21.3 ppm) is only 14 percent lower than the highest (24.9 ppm). Jet penetration appears to have only a small impact on the area-weighted average NO_x concentration. The minimal sensitivity of overall NO_x to the number of orifices is a significant result, particularly if it is also observed at elevated pressure as is typical of combustors in gas turbine engines. This result suggests that an aerodynamically “optimum” mixer may not minimize NO_x.

The prior results in references 19 and 20 identified the 12-hole module as the best mixer for J = 57 and presumed that it would be most likely to produce the least NO_x. The results from the current study show that the 12-hole module produces the most overall NO_x at atmospheric pressure (see fig. 6) but while it is the highest, it is only slightly higher than the lowest average NO_x concentration.

Figures 7 present the distributions of CO (fig. 7(a)), CO_2 (fig. 7(b)), and O_2 (fig. 7(c)) for the four modules with jet and main air both preheated. Jet penetration and mixing are shown best by the O_2 distributions. The data for concentrations of the major species confirm that the number of orifices has a significant effect on the mixing distributions. The penetration of the jets for the 12 and 14 hole module cases is observed to be nearly “optimum” while the 8 and 22 hole modules result in over- and under-penetrating cases respectively as confirmed by the data in figures 7. Note that the highest concentrations of CO_2 are in the wall region for all the modules, and concentrations of CO are high in the center of the cylindrical duct for both the 14 and 22 hole modules, but the region of high CO is largest for the 22 hole module.

The overall NO_x values are given in the title of figure 5, and the measurement uncertainty and average values (not area weighted) of CO, CO_2, and O_2 for the 64 measurements with both streams preheated are included in the title of figures 7.

Effect of Preheat For an “Optimum” Mixer

The effect on the measured NO_x values of heating the inlet air for the 12 hole module is illustrated in figure 8. Three preheat conditions are shown. The first set of conditions is for no air preheat and provides a comparison to the results for the elevated inlet air preheat temperature conditions. The second set of conditions is for jet air preheat only (no main air preheat) and the third set of conditions has both the jet air and main air preheated to the same temperature as would probably be the case in a practical combustor. Figure 8 shows that preheating only the jet air results in relatively small increases in NO_x emissions compared to the case where both the main and jet air are preheated.

Figure 9 presents the corresponding NO_x sector plots. The condition in which both the main and jet air were preheated showed the largest NO_x increase for all the modules and shows the higher NO_x levels also seen in figure 8. This result confirms the expectation that the absolute value of NO_x emissions would increase with the inlet air preheated. Unlike the variation of the average NO_x for the 8, 12, 14, and 22 hole modules which are less that 2 standard deviations from their mean, the variations of the average NO_x for the preheat cases vary significantly from a low of 10.56 ppm for the case without preheat to a high of 26.47 ppm with both streams preheated. The NO_x measurement uncertainty and the mean using the 48 measurements with the 12 hole module for all three preheat conditions were 4.45 and 16.92 ppm respectively and are not area weighted. Again note that the uncertainty was calculated by averaging the variances from the local mean for each radius.

Area-weighted average NO_x concentrations at x/R = 1 are presented in figure 10 to show the effect of preheated air on overall NO_x emissions. This figure shows that preheating only the jet air increases the overall NO_x by only 20 percent from that obtained without preheat, whereas preheating both the main and jet air doubles the overall NO_x from that obtained with only the jet preheated.

The NO_x production in the fuel-rich zone was expected to be small compared to that produced in the mixing zone via the thermal (Zeldovich) mechanism, but figures 8 to 10 all show the dominating influence of the main air preheat on NO_x and the relatively small impact of preheating only the jet air. As the jet air is over 70 percent of the total air flow, the small effect of preheating the jets seems to be counter intuitive to the expectation that jet air preheat should be very important because high temperatures and near stoichiometric conditions may persist in the proximity of the jets and these are conditions that are important for NO_x production via the thermal mechanism..

Figures 11 present the concentrations of CO (fig. 11(a)), CO_2 (fig. 11(b)), and O_2 (fig, 11(c)), for the 12 round hole configuration for no preheat (left), jet air preheated (center), and both jet and main air preheated (right). Note that the emissions distributions are similar for species other than NO_x at all preheat conditions. The measurement uncertainty and the average values are given in the titles for figures 11. Unlike the average NO_x values which vary significantly with preheat, the mean values for CO, CO_2, and O_2 are all less than a standard deviation from their average. Similar results were observed and are shown in reference 27 for the other modules at these preheat conditions.

Conclusions

An experiment was performed to examine the effects of air preheat and the number of orifices on emissions in RQL combustor configurations. The facility that was used allowed the jet air preheat to be controlled independently from the main air preheat. Mixing modules (80 mm ID) with a varying number of round holes but the same total area (1244 mm^2) were evaluated while maintaining a constant jet-to-mainstream momentum-flux ratio (J = 57) and mass-flow ratio (MR = 2.5).

The results lead to the following conclusions

1. The number of orifices had a significant effect on mixing and the distributions of species. However, the overall NO_x data for a constant total orifice area at a fixed momentum-flux ratio was relatively insensitive to the number of jets on the perimeter of the quick mix section, suggesting that an aerodynamically “optimum” mixer may not lead to the minimization of overall NO_x emissions.
2. High concentrations of NO_x were observed in the wake of the jets near the wall for all modules probably because jet induced recirculation offers both high temperatures and lengthened residence times there.
3. Although the jet air comprised over 70 percent of the total airflow in the model RQL combustor and it was expected that higher jet air preheat temperature would contribute significantly to NO_x production, the impact of preheating jet air alone on NO_x emissions was small compared to preheating both main and jet air.
4. Air preheat was found to have very little effect on mixing and the distributions of major species, but preheating the mainstream air did increase NO_x emissions significantly.
5. Results from the current study (1) do not support the assumption that an optimal mixer would lead to the minimization of NO_x emissions, and (2) show that preheating both the mainstream and jet air has a significantly greater effect on NO_x emissions than preheating only the jet air.

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TABLE 1.—OPERATING CONDITIONS

Parameter	Value
Momentum–flux Ratio, J	57
Mass-flow Ratio, MR	2.5
Discharge Coefficient, C_d	0.72
(Total jet area)/(cross-sectional area of duct), A_J/A_M	25%
Non-Preheated Inlet Air Temperature	22 °C (72 °F)
Jet Air Preheat Inlet Temperature	260 °C (500 °F)
Main Air Preheat Inlet Temperature	260 °C (500 °F)

TABLE 2.—ORIFICE CONFIGURATIONS

N	$d(mm)$	R/d
8	14.07	2.84
12	11.49	3.48
14	10.64	3.76
22	8.49	4.71

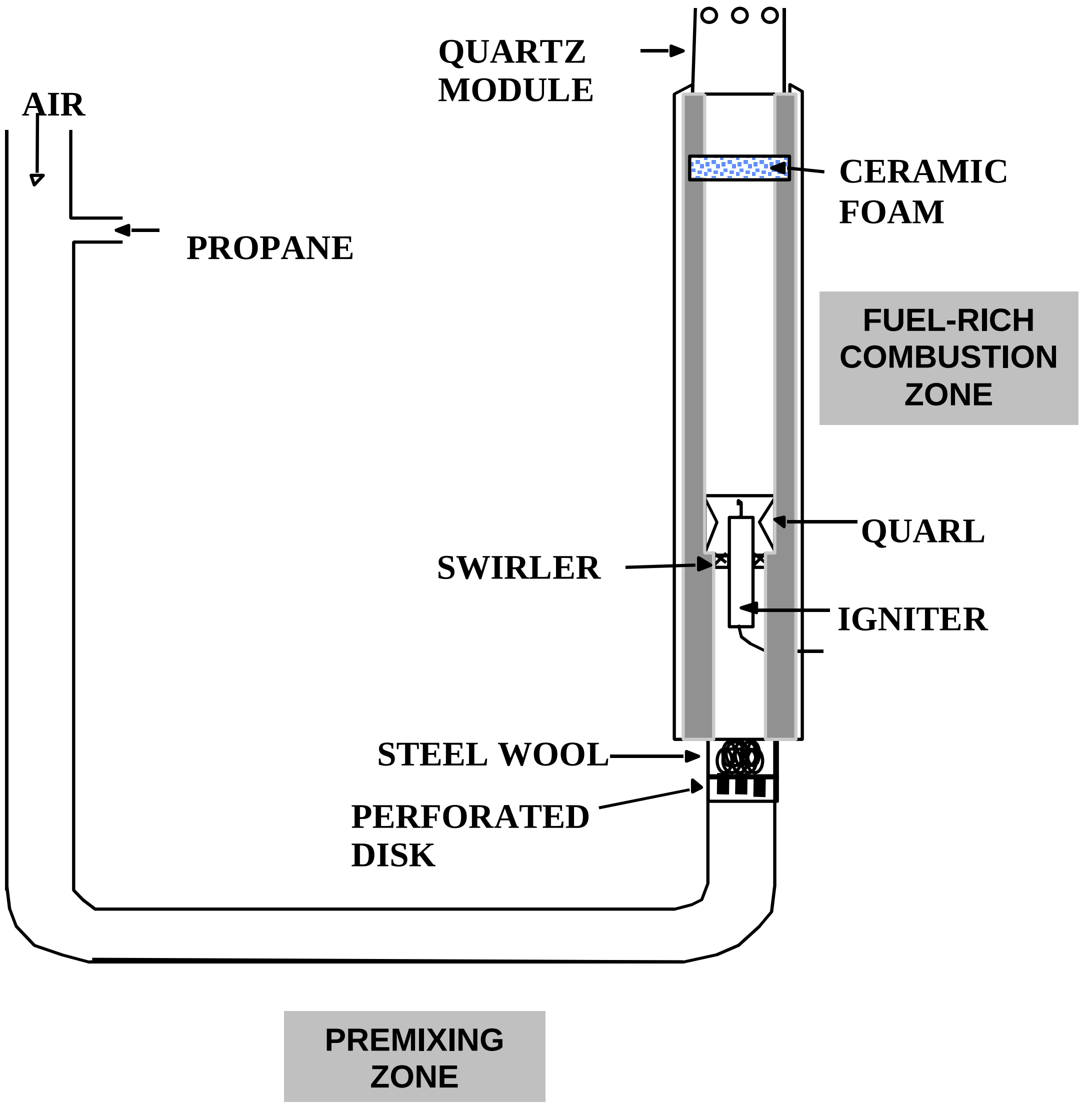
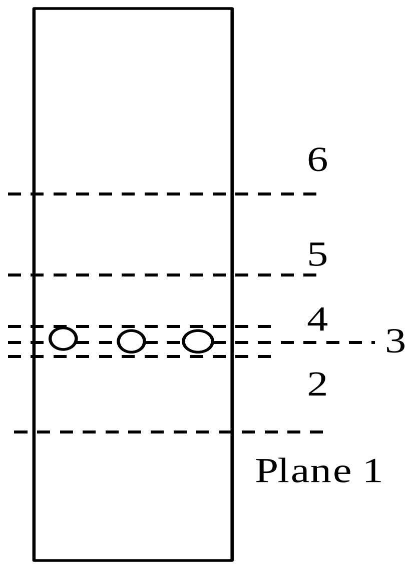
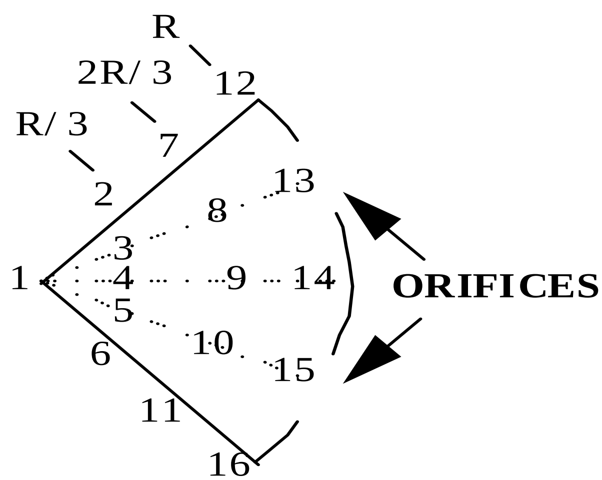


Figure 1.—Schematic of experimental rich product generator with quartz RQL module.



(a) Data plane locations



(b) Data point locations

Figure 2.—Measurement locations.

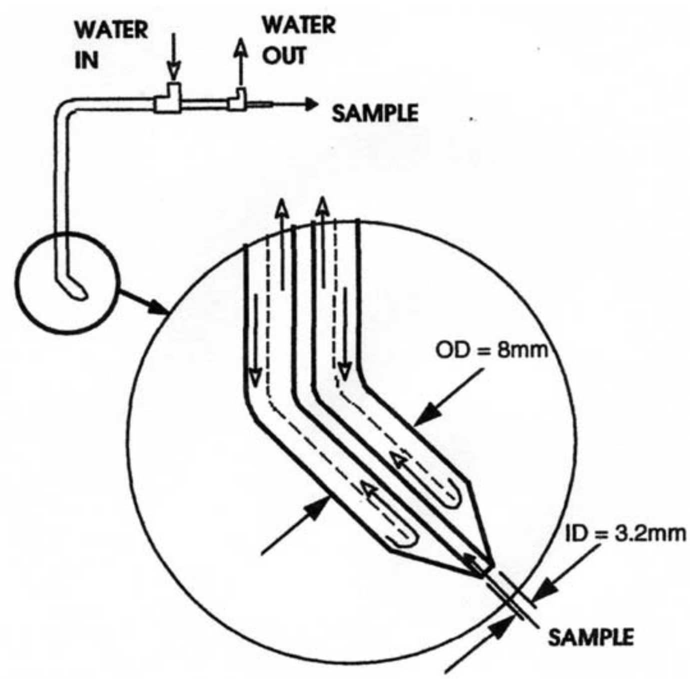


Figure 3.—Probe design.

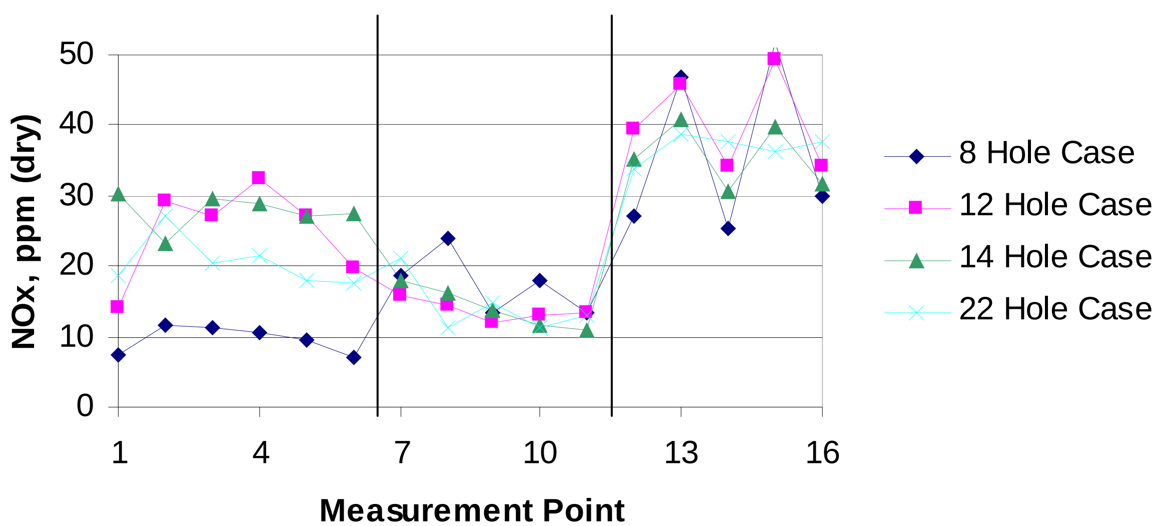


Figure 4.—Comparison of local NO_x data at x/R = 1 and J = 57 for modules with different numbers of round holes with both the main and jet air preheated.

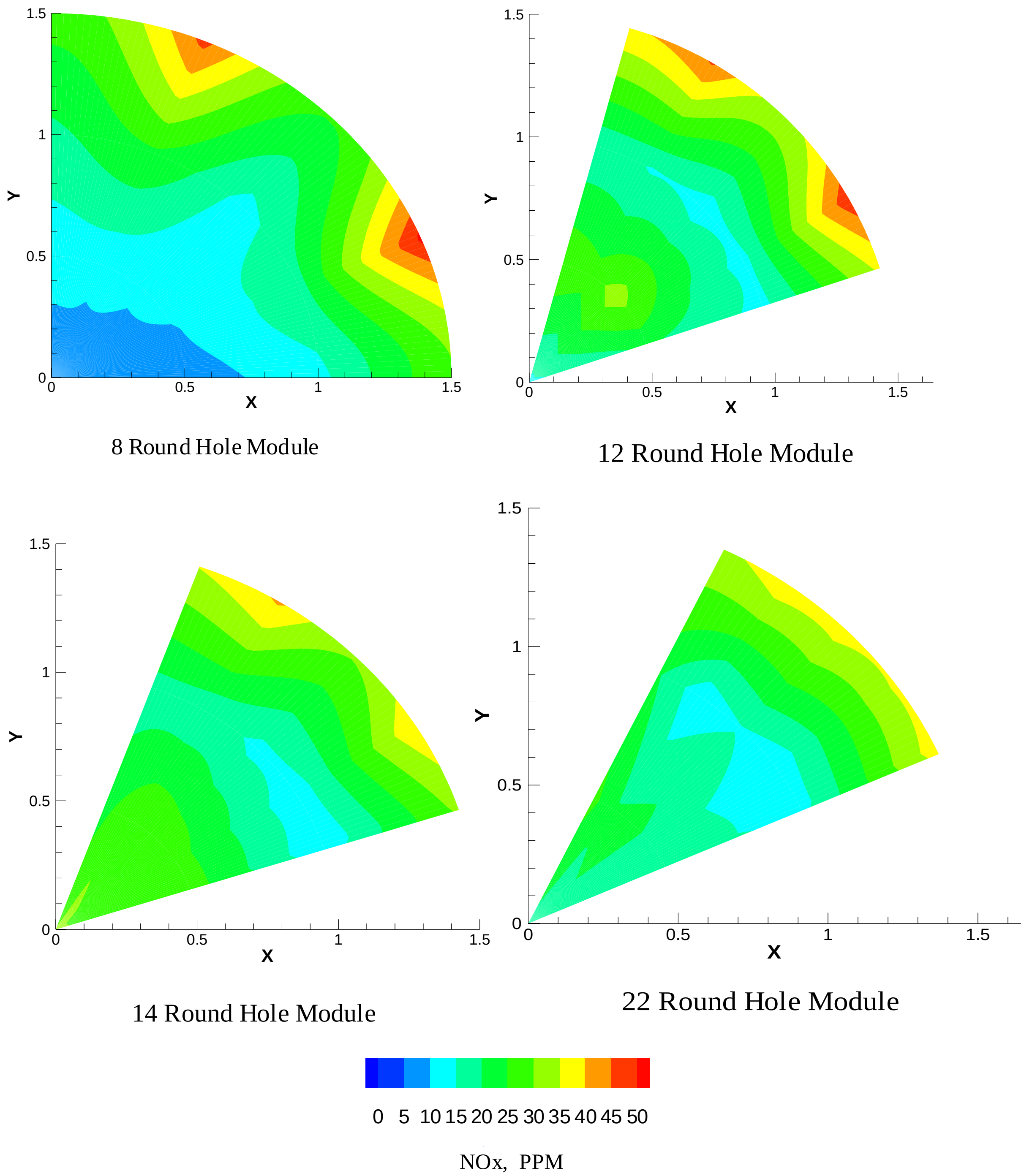


Figure 5.—NO_x distribution plots at x/R = 1 and J = 57 for modules with different number of round holes with both the main and jet air preheated; Measurement uncertainty (2σ) = 5.72 ppm; mean = 24.15 ppm.

Figure 6.—Area-weighted planar average NO_x emissions at x/R = 1 and J = 57 for modules with different number of round holes with both the main and jet air preheated.

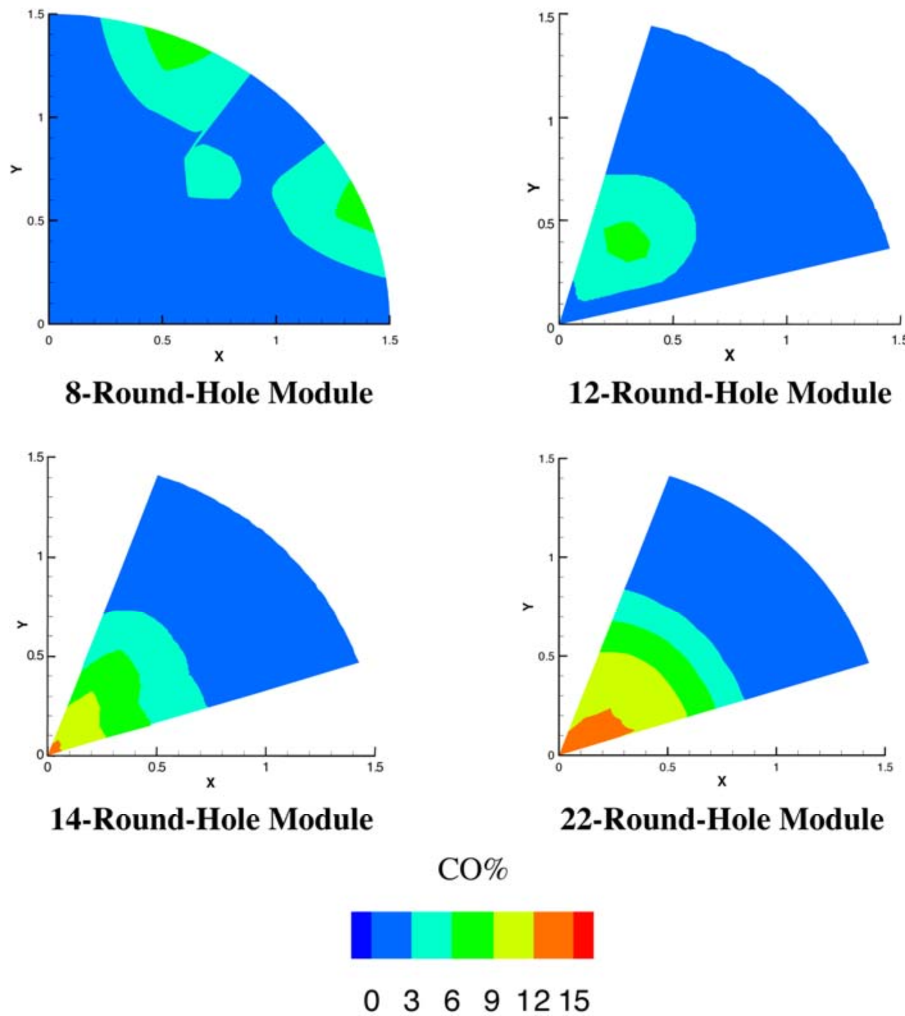


Figure 7(a).—CO distribution plots at x/R = 1 and J = 57 for modules with different number of round holes with both the main and jet air preheated. Measurement uncertainty (2σ) = 1.98 percent; mean = 2.91 percent.

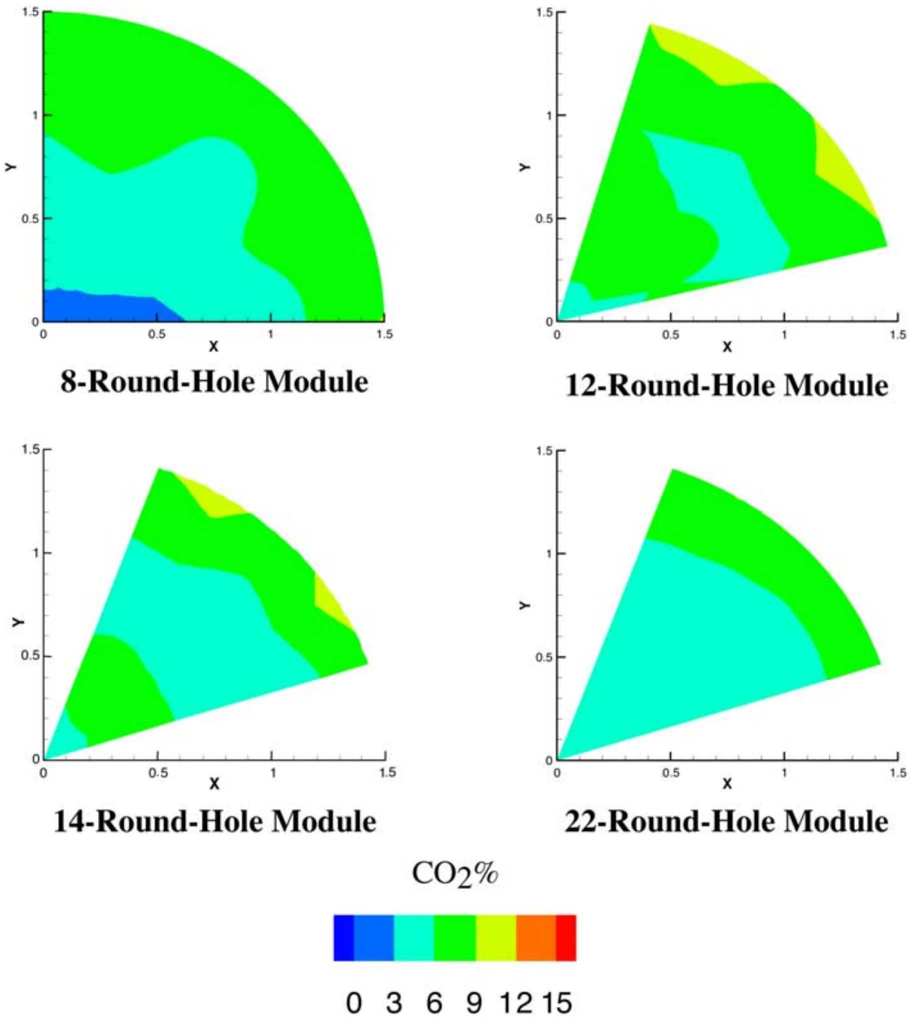


Figure 7(b).—CO_2 distribution plots at x/R = 1 and J = 57 for modules with different number of round holes with both the main and jet air preheated. Measurement uncertainty (2σ) = 1.15 percent; mean = 6.39 percent.

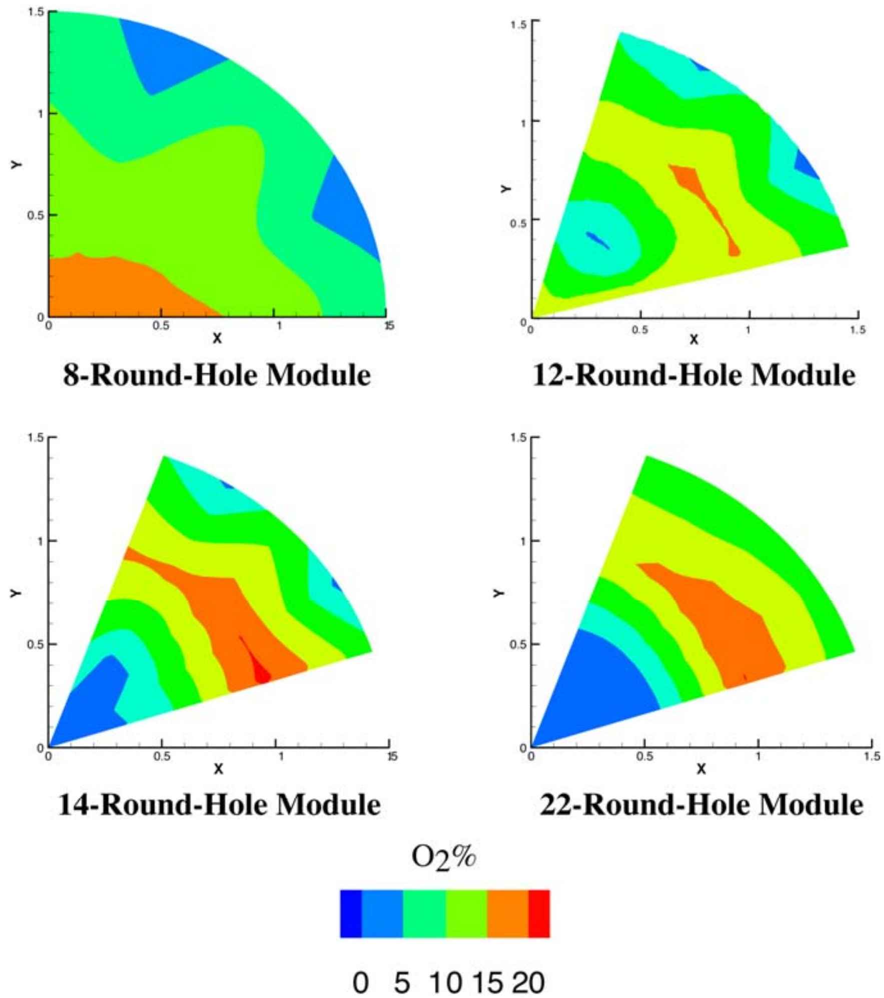


Figure 7(c).—O_2 distribution plots at x/R = 1 and J = 57 for modules with different number of round holes with both the main and jet air preheated. Measurement uncertainty (2σ) = 3.13 percent; mean = 7.96 percent (Concluded).

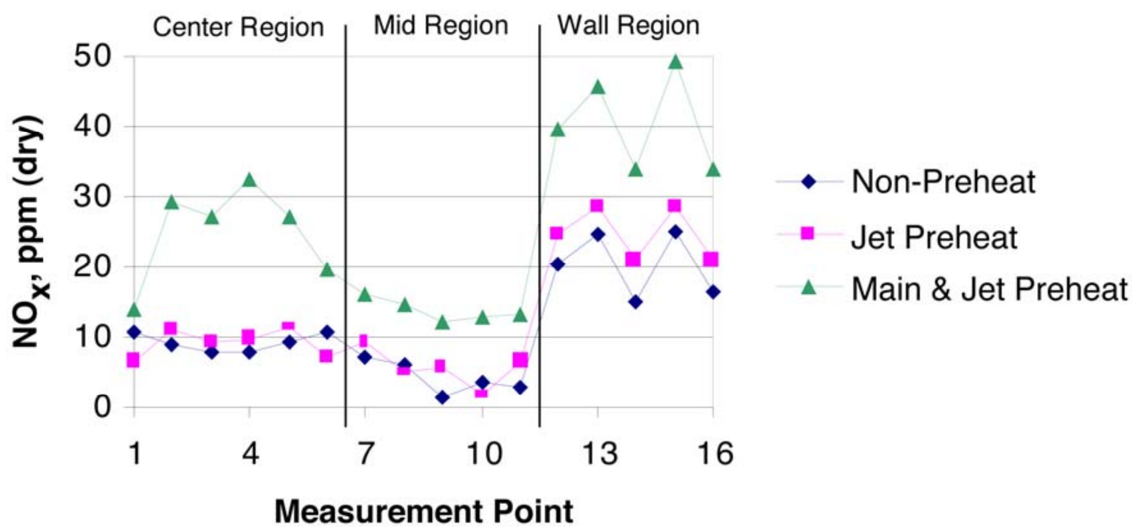


Figure 8.—Comparison of local NO_x data at x/R = 1 and J = 57 for the 12 round hole module with different air streams preheated.

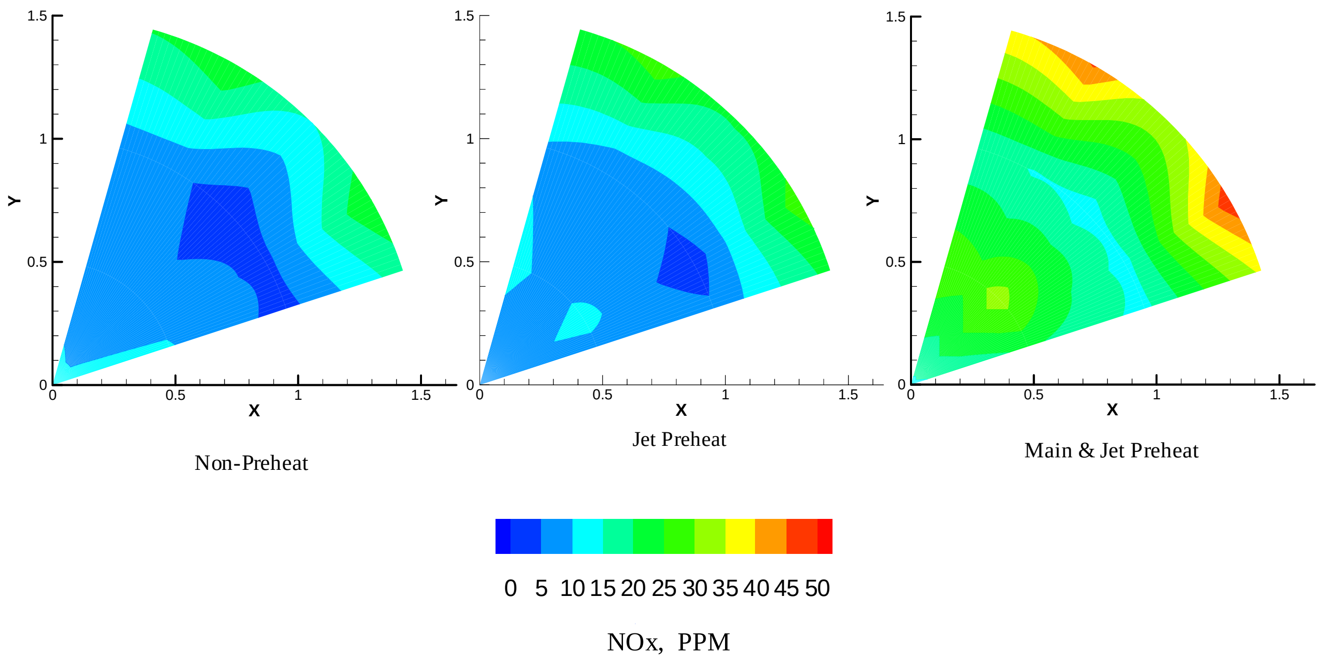


Figure 9.—NO_x distribution plots at x/R = 1 and J = 57 for the 12 round hole module with different air streams preheated. Measurement uncertainty (2σ) = 4.45 ppm; mean = 16.92 ppm.

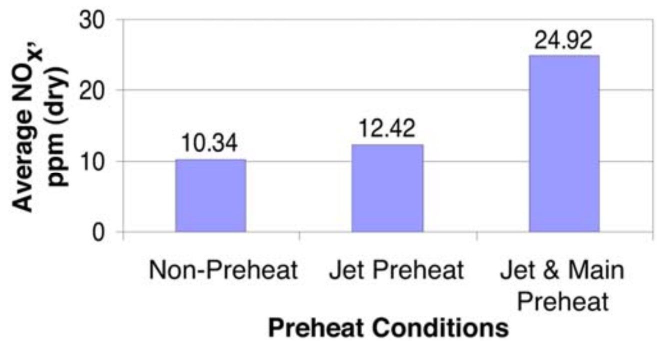


Figure 10.—Effect of air preheat on area-weighted NO_x data at *x*/*R* = 1 and *J* = 57 for the 12 round-hole module with different air streams preheated.

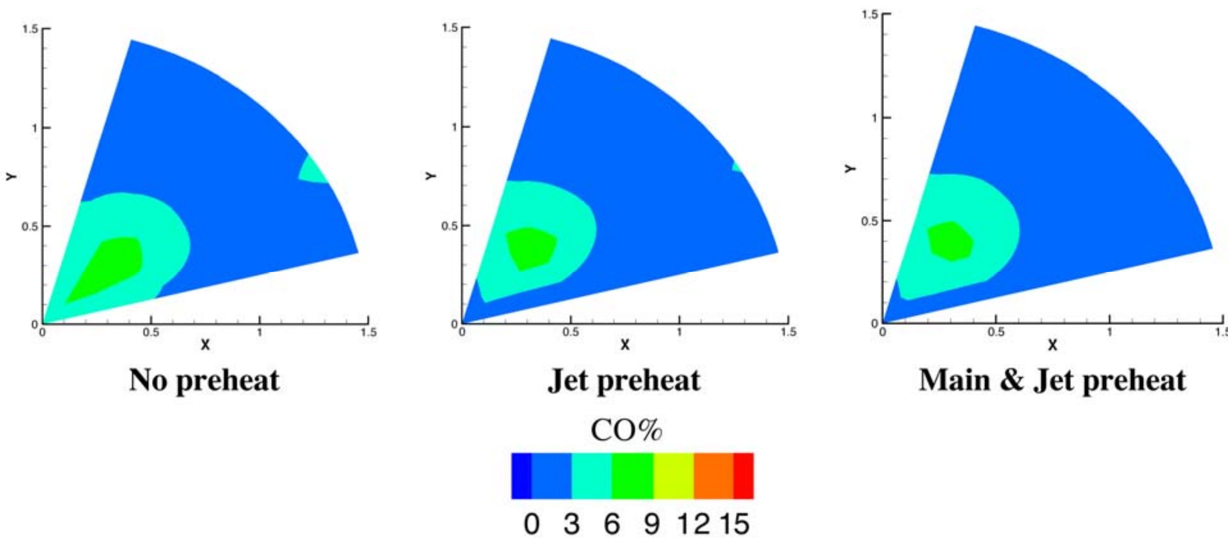


Figure 11(a).—CO distribution plots at *x*/*R* = 1 and *J* = 57 for the 12 round hole module with different air streams preheated. Measurement uncertainty (2σ) = 2.37 percent; mean = 2.63 percent.

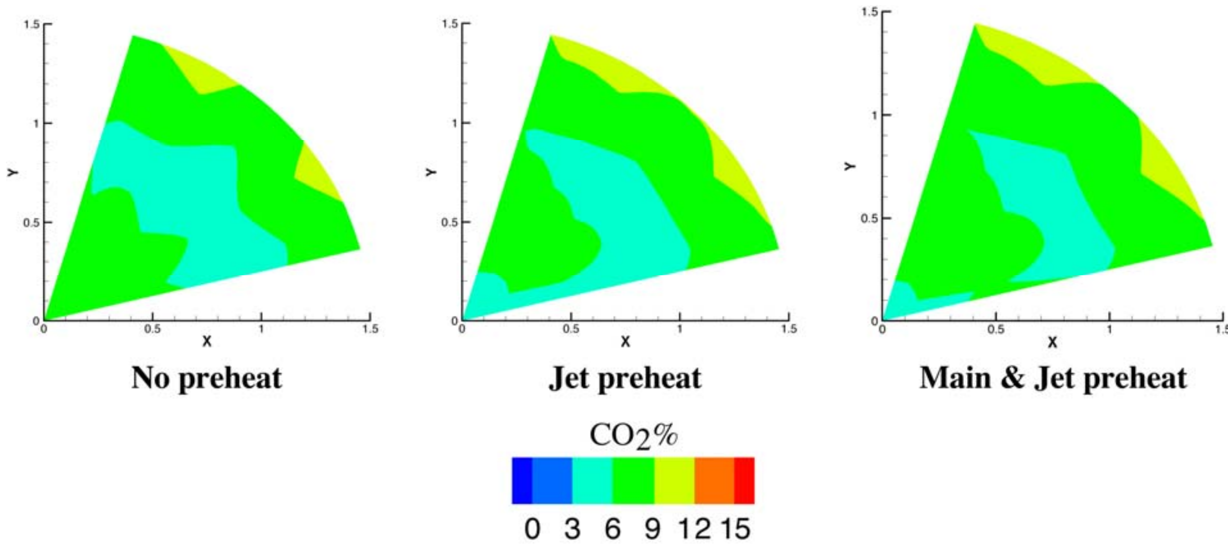


Figure 11(b).—CO_2 distribution plots at x/R = 1 and J = 57 for the 12 round hole module with different air streams preheated. Measurement uncertainty (2σ) = 2.73 percent; mean = 7.24 percent.

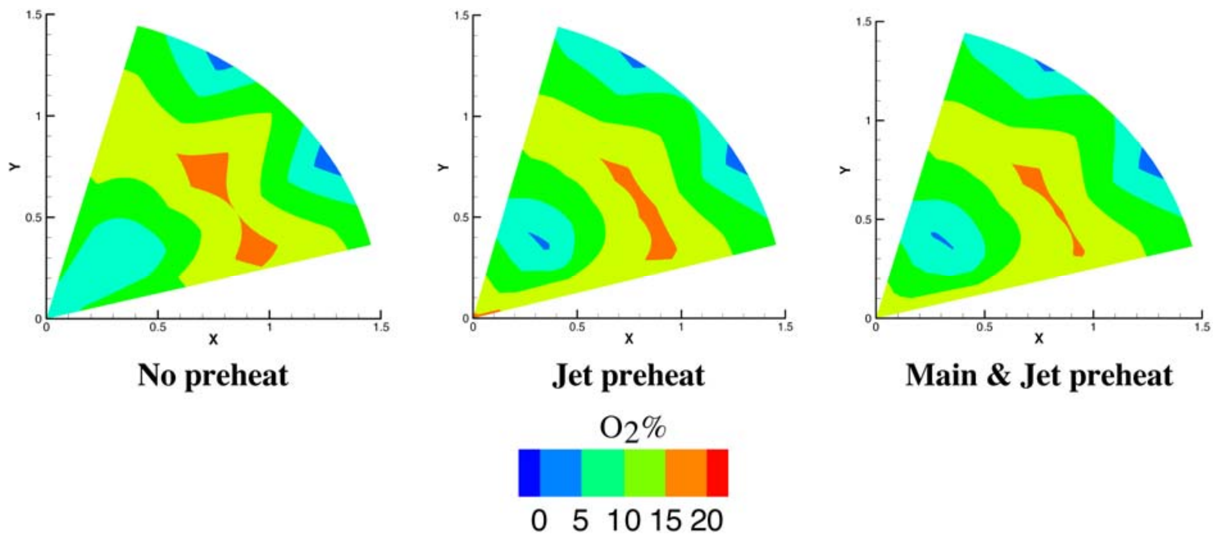


Figure 11(c).—O_2 distribution plots at x/R = 1 and J = 57 for the 12 round hole module with different air streams preheated. Measurement uncertainty (2σ) = 3.33 percent; mean = 7.46 percent (Concluded).

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13. SUPPLEMENTARY NOTES

14. ABSTRACT
This study was motivated by a goal to understand the mixing and emissions in the Rich-burn/Quick-mix/Lean-burn (RQL) combustor scheme that has been proposed to minimize the formation of oxides of nitrogen (NOx) in gas turbine combustors. The study reported herein was a reacting jet-in-crossflow experiment at atmospheric pressure. The jets were injected from the perimeter of a cylindrical duct through round-hole orifices into a fuel-rich mainstream flow. The number of orifices investigated in this study gave over- to optimum to under-penetrating jets at a jet-to-mainstream momentum-flux ratio of $J = 57$. The size of individual orifices was decreased as the number of orifices increased to maintain a constant total area; the jet-to-mainstream mass-flow ratio was constant at $MR = 2.5$. The experiments focused on the effects of the number of orifices and inlet air preheat and were conducted in a facility that provided the capability for independent variation of jet and main inlet air preheat temperature. The number of orifices was found to have a significant effect on mixing and the distributions of species, but very little effect on overall NOx emissions, suggesting that an aerodynamically optimum mixer might not minimize NOx emissions. Air preheat was found to have very little effect on mixing and the distributions of major species, but preheating both main and jet air did increase NOx emissions significantly. Although the air jets injected in the quick-mix section of an RQL combustor may comprise over 70 percent of the total air flow, the overall NOx emission levels were found to be more sensitive to main stream air preheat than to jet stream air preheat.

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

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