Design and Performance of a Low Btu Fuel Rich-Quench-Lean Gas Turbine Combustor

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Introduction

General Electric Company is developing gas turbines and a high temperature desulfurization system for use in integrated gasification combined cycle (IGCC) power plants. High temperature desulfurization, or hot gas cleanup (HGCU), offers many advantages over conventional low temperature desulfurization processes, but does not reduce the relatively high concentrations of fuel bound nitrogen (FBN) that are typically found in low Btu fuel. When fuels containing bound nitrogen are burned in conventional gas turbine combustors, a significant portion of the FBN is converted to NO_x. Methods of reducing the NO_x emissions from IGCC power plants equipped with HGCU are needed.

Rich-quench-lean (RQL) combustion can decrease the conversion of FBN to NO_x because a large fraction of the FBN is converted into non-reactive N_2 in a fuel rich stage. Additional air, required for complete combustion, is added in a quench stage. A lean stage provides sufficient residence time for complete combustion.

Objectives

General Electric has developed and tested a rich-quench-lean gas turbine combustor for use with low Btu fuels containing FBN. The objective of this work has been to design an RQL combustor that has a lower conversion of FBN to NO_x than a conventional low Btu combustor and is suitable for use in a GE heavy duty gas turbine. Such a combustor must be of appropriate size and scale, configuration (can-annular), and capable of reaching "F" class firing conditions (combustor exit temperature = 2550°F).

Approach

The development of RQL2, a full scale (14" diameter, 10 lb/s total flow), rich-quench-lean gas turbine combustor is the culmination of a five year research and development effort. This effort began with testing of a small (2" diameter) perforated plate burner, using natural gas and natural gas/ammonia mixtures for fuel (Goebel and Feitelberg, 1992). The promising perforated plate burner tests were followed by the development of RQL1, a reduced scale (6" diameter, 0.75 lb/s total flow), rich-quench-lean combustor. RQL1 was tested using high temperature low Btu fuel produced by the pilot scale coal gasification and HGCU facility located at GE Corporate Research and Development in Schenectady, NY (Bowen *et al.*, 1995). At the optimum operating conditions, the conversion of NH_3 to NO_x in RQL1 was about 15%, or about a factor of 2 lower than expected from a conventional gas turbine combustor burning the same fuel. A detailed discussion of the RQL1 design and test results can be found in Bowen *et al*. (1995).

The approach taken to design RQL2 combustor was to build upon the prior RQL and low Btu combustor designs that were developed and tested at GE Corporate Research and Development (Bowen *et al.*, 1995). Several design features from the RQL1 combustor such as a converging rich stage geometry, a radially stratified quench section, and a backward facing step, were incorporated into the RQL2 design. Design features from conventional low Btu combustors were also used in the RQL2 design. The RQL2 combustor uses a fuel nozzle that was developed for conventional swirl stabilized diffusion flame low Btu combustors (Battista *et al.*, 1996) and the RQL2 combustor uses a filmed cooled lean stage liner which is similar to the liners used in conventional low Btu combustors. Additionally, the RQL2 combustor takes advantage of new gas turbine technology; for example, the RQL2 rich stage liner uses a new cooling scheme developed at GE Corporate Research and Development (Jackson *et al.*, 1996).

The general methodology used to design RQL2 is shown in Figure 1. The overall fuel/air ratio was determined by selecting the maximum combustor exit temperature, and by the decision to use pilot plant low Btu gas as the fuel (see Table 1). The goal of designing a combustor suitable for use in GE heavy duty gas turbines, which use multi-can combustors, dictated the overall dimensions of the RQL2 combustor. The distribution of the total available volume between the rich, quench, and lean stages was determined by combining: (1) a computational fluid dynamics (CFD) analysis, which predicted the overall flow field and the size and shape of the recirculation zones, and (2) chemical kinetic models, which related the rich stage residence time and temperature to the conversion of NH_3 to NO_x.

The separation of the the air supplies for the rich stage and quench/lean stage is a design feature carried over from RQL1. Dividing the total combustion air into two separate, independent-

Table 1: Typical Pilot Plant Low Btu Fuel Composition

Species	Mole Percent
CO	8.6
H_2	17.3
CH_4	2.7
N_2	30.1
CO_2	12.6
H_2O	28.0
Ar	0.3
NH_3	0.4
TOTAL	100.0

ly controlled streams is important from a research perspective, because this capability allows us to search for the optimum rich stage operating conditions. In addition, overall air management (e.g., air pressure drop) is simplified, because the rich stage cooling scheme can be designed almost independently of the quench/lean stage cooling scheme. This allowed much of the detailed design and modeling work for the rich stage to proceed independently of the quench/lean stage design.

Project Description

A schematic of the RQL2 combustor and test stand can be found in Figure 2. The 24" diameter pressure vessel containing the RQL2 combustor is divided into two separate chambers that are fed by independently controlled air supplies. The hot combustion gases flow through the RQL2 combustor, an impingement cooled transition piece, a sector from the film cooled first stage nozzle of a GE LM6000 gas turbine, and then exit into a water cooled exhaust duct. The burned gas is sampled with a water cooled probe located downstream of the LM6000 nozzle sector. The transition piece and all downstream components were used previously in tests of low Btu gas fuel nozzles (Bowen *et al.*, 1995).

A single low Btu gas fuel nozzle produces the swirl stabilized rich stage diffusion flame. This fuel nozzle, referred to as the N7B fuel nozzle, was originally designed for use in conventional low Btu fuel gas turbine combustors. Details of the development and testing of this fuel nozzle may be found elsewhere (Battista *et al.*, 1996; Bowen *et al.*, 1995).

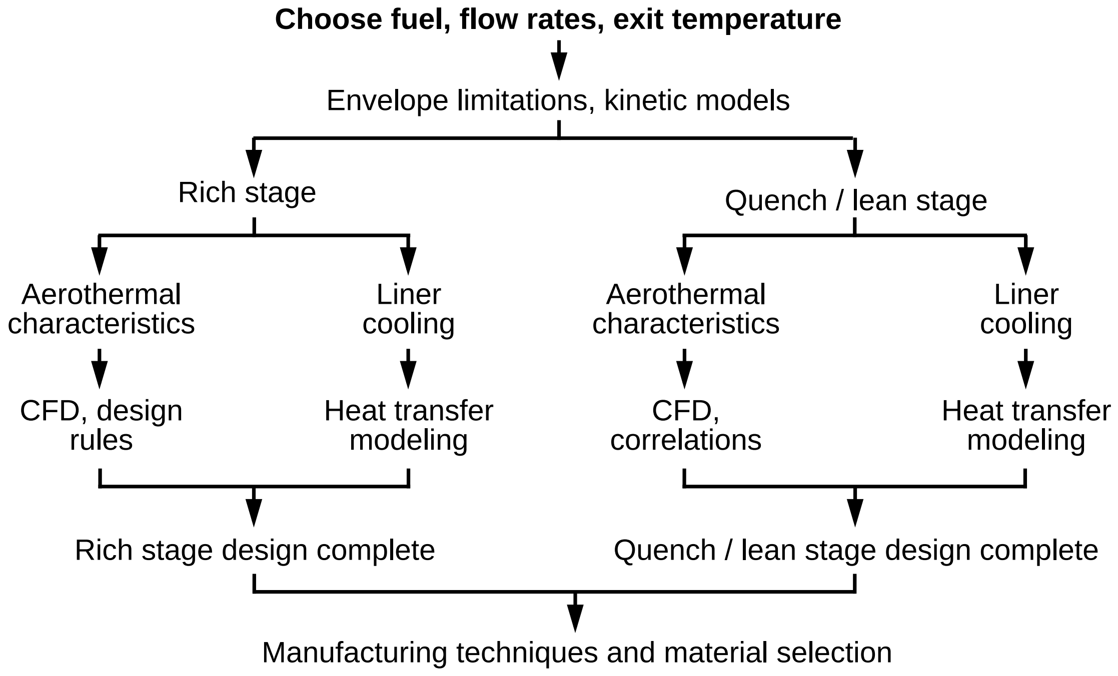

Figure 1: RQL2 design methodology.

The rich stage combustor liner consists of a 14" diameter cylindrical section followed by a conical section which reduces the diameter of the flow path from 14" to 7". Both the cylindrical and conical sections are approximately 13.5" long. Flow visualization tests and computational fluid dynamics (CFD) analysis have shown that the converging section is necessary to prevent the low pressure core of the swirling flow from drawing lean stage gases back upstream into the rich section. The converging section also provides a convenient method of reducing the flow area to a reasonable size for proper quenching.

Developing an adequate cooling scheme for the rich stage liner presented special challenges. The rich stage liner is relatively large, but relatively little air is available for cooling. Film cooling, one of the most effective methods of combustor liner cooling, is not desirable on the rich stage if NO_x emissions are to be minimized. For these reasons, the RQL2 rich stage combustor liner was fabricated with a novel double-walled structure developed at GE Corporate Research and Development. Internal cooling passages with narrow dimensions conduct cooling air circumferentially around the liner (see Figure 3). Air enters each rectangular cooling channel through an inlet hole and exits each channel through a slot which discharges into one of eight longitudinal collection tubes. The collection tubes, in turn, discharge into a plenum which supplies the air for the fuel nozzle and cap/cowl. The final design shown in Figure 3 was selected only after a detailed heat transfer analysis which used literature correlations for convective heat transfer, a finite element analysis code, and custom software tools. Haynes 230 was selected as the material for construction because of its superior properties at high temperatures.

The rich stage cooling structure was formed by first rolling the conical and cylindrical inner shells and then machining the shallow cooling channels into these shells. Bosses were welded longitudinally along the shells to provide enough material to weld the collection tubes and outer

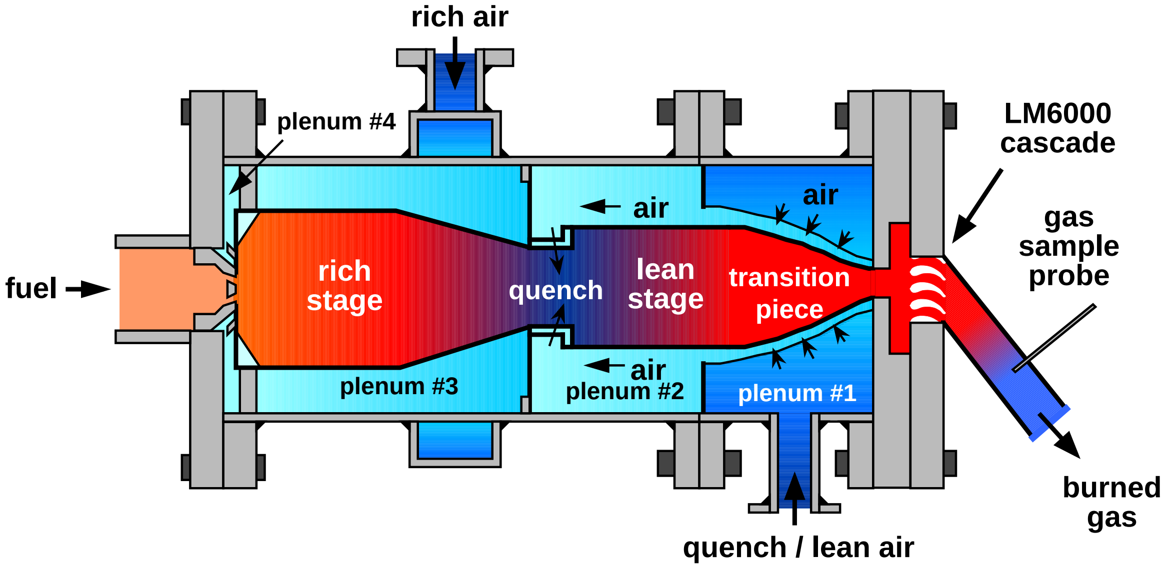

Figure 2: RQL2 combustor and test stand.

skin segments to the inner shell. The skin segments, with pre-drilled inlet air holes, were then welded to the bosses. The outer skin segments were bonded to the ribs of the inner shell using a laser spot welding technique. Finally, the cylindrical and conical sections were welded together and the collection tubes were welded in place using manual gas tungsten arc welds. Additional details of the manufacturing methods can be found in Jackson *et al*. (1996).

The quench section consists of a 7" diameter cylindrical section, approximately 4.3" long, and a backward facing step at the entrance to the lean section. The quench/lean stage air enters the combustor through quench air holes located at the downstream end of the cylindrical section. Rapid quenching is achieved with quench air holes of different sizes, referred to here as a "radially stratified quench". Larger holes create larger jets with greater momentum and which penetrate fur-

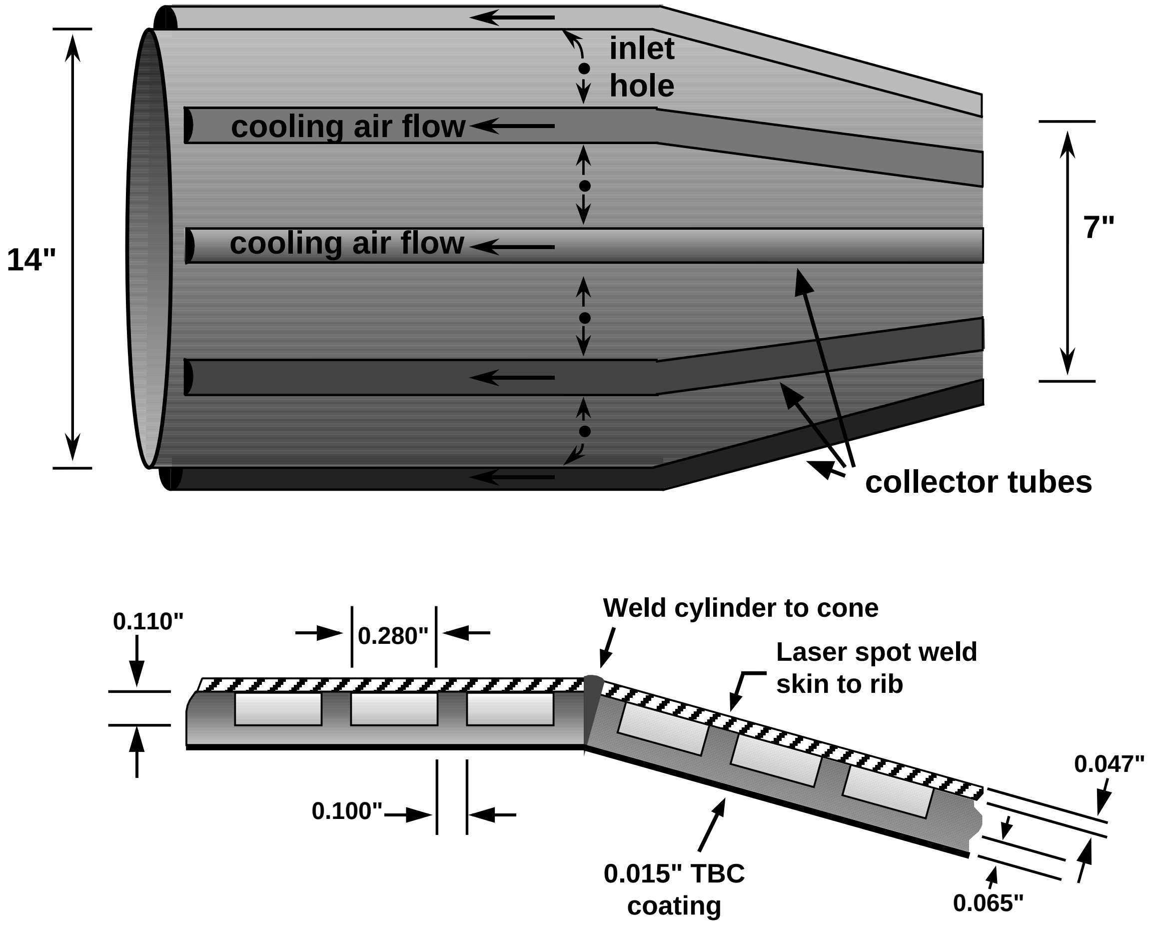

Figure 3: Double-walled rich stage combustor liner. **Top:** General arrangement of inlet cooling holes and collector tubes, with direction of air flow indicated. For clarity, the inlet holes are shown for only one circumferential cooling channel. **Bottom:** Liner wall cross-section in the region of the junction between the cylindrical and conical sections, showing the dimensions of the internal cooling channels.

ther into the hot gas flow. Smaller holes create smaller jets which do not penetrate to the centerline of the combustor. The quench/lean air entering through the smaller holes mixes with the flow closest to the wall, while the quench/lean air entering through the larger holes mixes primarily with the flow near the centerline of the combustor. The quench holes were sized using standard correlations for jets penetrating into a cross flow (Lefebvre, 1983). Both the cylindrical section and backward facing step are impingement cooled.

The lean section was fabricated from the aft portion of a modified MS6000 liner, and is approximately 10.5" in diameter and 14.5" long. The MS6000 film cooling holes were reduced in diameter and all of the mixing and dilution air holes were eliminated. The design goal was for 70% of the quench/lean air to enter the combustor through the quench holes, with the remaining 30% entering through the lean stage film cooling holes. To reduce cooling air leakage, a modified MS6000 combustor hula seal is used to seal the interface between the lean section and the transition piece.

Using flow sleeves, baffles, and seals, the region inside of the pressure vessels was divided up into four plenums (see Figure 2). The quench/lean stage air is fed into plenum #1, and from this plenum the air flows through an impingement sleeve to cool the transition piece. After cooling the transition piece all of the air from this plenum flows into plenum #2, which feeds the quench holes and the lean stage liner film cooling holes. Similarly, the air for the rich stage is feed into plenum #3, flows through the double-walled rich stage combustor liner and into plenum #4, which supplies air to the fuel nozzle and cap/cowl.

Results

The first pilot plant test of RQL2 (designated as Test 9 for programmatic reasons) was conducted during March 1996. RQL2 test conditions are listed in Table 2. Due to limitations of the HGCU system, the low Btu fuel flow rate was limited to 1.5 lb/s, rather than the gasifier capacity

	Rich Stage/Lean Stage Air Flow Rate Ratio		
	20/80	30/70	40/60
Low Btu Fuel Temperature	680 °F	680°F	640°F
Low Btu Fuel Flow Rate	0.8 – 1.5 lb/s	0.7 – 1.3 lb/s	0.5 – 1.3 lb/s
Rich Stage Air Temperature	680°F	690°F	700°F
Rich Stage Air Flow Rate	0.85 lb/s	1.1 lb/s	1.4 lb/s
Lean Stage Air Temperature	740°F	740°F	710°F
Lean Stage Air Flow Rate	3.3 lb/s	2.6 lb/s	2.1 lb/s

Table 2: RQL2 test conditions. Combustor chamber pressure = 10 atm ±10% for all air splits.

of 2.2 lb/s. Although the HGCU system accepts low Btu gas at about 1000°F, the relatively low fuel flow rates and heat losses from the piping combined to produce relatively low fuel temperatures at the combustor inlet (see Table 2). The reduction in fuel flow rate and temperature necessitated corresponding reductions in the air flow rate to achieve the target combustor exit temperature.

RQL2 was fired for more than 96 hours during Test 9. During this time several series of tests were conducted with the total combustion air divided into varying fractions between the rich and quench/lean stages. In a typical series, both the total air flow rate and the fractional distribution of the combustion air between the rich and quench/lean stages were held constant. The fuel flow rate was then adjusted in steps to vary the combustor exit temperature from about 1600°F to more than 2550°F. During this process, which typically required several hours to complete, continuous measurements were made of NO_x, CO, CO_2, and O_2 concentrations in the exhaust gas. An analyzer failure early in Test 9 prevented measurements of unburned hydrocarbon emissions.

Figure 4 shows NO_x emissions measured during Test 9 with 20% of the combustion air sent to the rich stage and 80% of the combustion air sent to the lean stage. Figures 5 and 6 show measured NO_x emissions with air splits of 30% rich/70% lean and 40% rich/60% lean, respectively. The conversion of NH_3 to NO_x is also shown in Figures 4 through 6. Conversion was calcu-

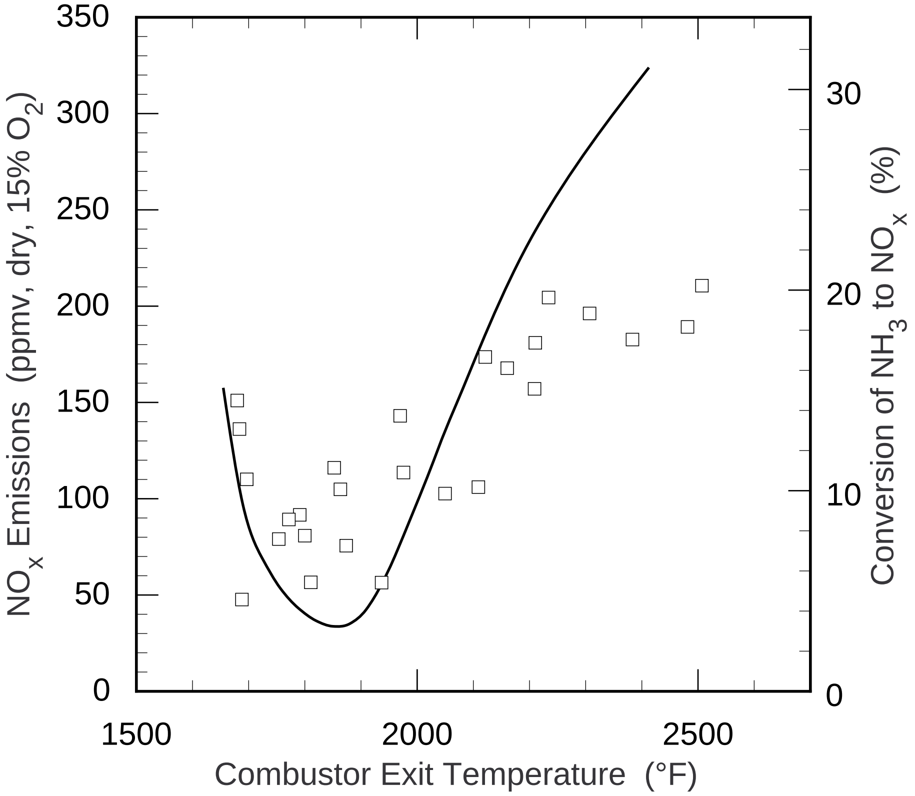

Figure 4: RQL2 NO_x emissions at a 20/80 rich/lean air split. The solid line represents the SLICER model predictions.

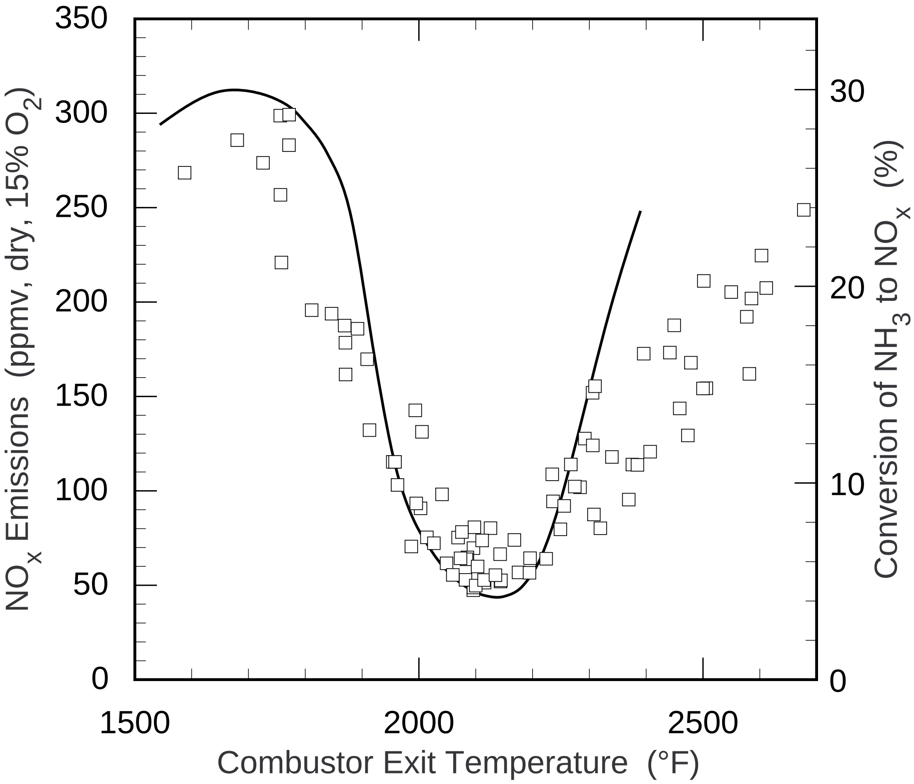

Figure 5: RQL2 NO_x emissions at a 30/70 rich/lean air split. The solid line represents the SLICER model predictions.

lated using the measured fuel NH_3 concentration of 4600 ppmv, and by assuming non-FBN NO_x formation (e.g., thermal NO_x) was negligible. This is a reasonable assumption for the very low heating value pilot plant fuel (higher heating value = 110 Btu/SCF).

As expected from models and previous RQL1 results, NO_x emissions were a strong function of the air split between the rich and lean stages, as well as the rich stage equivalence ratio (i.e., the combustor exit temperature). With the air split held constant, a distinct minimum in NO_x emissions was observed at the optimum rich stage equivalence ratio. With an air split of 40% rich/60% lean, the minimum in NO_x emissions occurred at a combustor exit temperature of about 2400°F. With a 30/70 rich/lean air split, the minimum in NO_x occurred at a combustor exit temperature of about 2100°F. With a 20/80 air split, the minimum in NO_x occurred at about 1800°F. For all three air splits, the minimum occurred at a rich stage equivalence ratio of about $\varphi_{rich} = 1.25$.

At the optimum rich stage equivalence ratio, NO_x emissions were about 50 ppmv (on a dry, 15% O_2 basis). With 4600 ppmv NH_3 in the fuel, this corresponds to a conversion of NH_3 to NO_x of about 5%. At the optimum conditions, RQL2 NO_x emissions were more than a factor of 3 lower than expected from a conventional diffusion flame combustor burning the same fuel. For example, in previous pilot plant tests using a GE MS6001B combustor, the conversion of

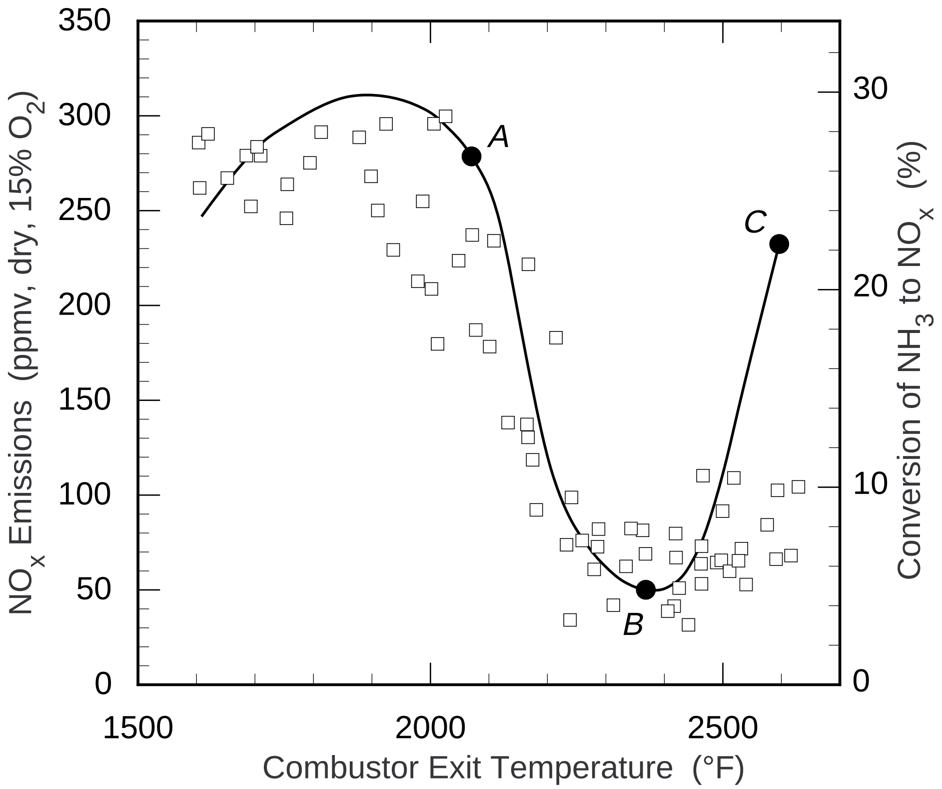

Figure 6: RQL2 NO_x emissions at a 40/60 rich/lean air split. The solid line represents the SLICER model predictions. Model points labeled "*A*", "*B*", and "*C*" correspond to rich stage equivalence ratios of 0.9, 1.25, and 1.6, respectively.

NH_3 to NO_x ranged from 20 to 80%, depending upon the combustor exit temperature (Battista *et al*., 1996). As conditions were shifted away from the optimum, RQL2 NO_x emissions gradually increased until they were comparable to a standard combustor.

RQL2 NO_x emissions measured during Test 9 were modeled with SLICER, a set of custom software modules for modeling sequentially linked ideal chemical reactor networks. SLICER models are assembled from these custom software modules and the Chemkin II package of programs and subroutines (Glarborg *et al*., 1986; Lutz *et al*., 1988; Kee *et al*., 1989). In the SLICER model of RQL2, the rich stage was represented as an equivolume perfectly stirred reactor (PSR) and a plug flow reactor (PFR) in series. The SLICER model combines the flow exiting the rich stage PFR with the quench/lean stage air in a second PSR, which feeds a second PFR. Inputs to the SLICER model include the measured combustion chamber pressure, rich and quench/lean air flow rates, air temperature, fuel composition, fuel flow rate, and fuel temperature. The chemical kinetic mechanism included more than 50 species and 250 elementary reaction steps (Michaud *et al*., 1992).

Results from the SLICER modeling are indicated by the solid lines in Figures 4, 5, and 6. The SLICER representation of RQL2 both qualitatively and quantitatively matches the NO_x emissions measurements. The SLICER predictions are insensitive to the relative sizes of the rich stage PSR and PFR. At high rich stage equivalence ratios the SLICER NO_x emissions are slightly sensitive to the relative size of the quench/lean PSR and PFR. Increasing the quench PSR volume tends to decrease model NO_x emissions at high φ_{rich}.

The key chemical reactions that govern NH_3 destruction and NO_x formation in RQL2 can be identified using the SLICER model and by performing a reaction path analysis (RPA) on individual reactors. For example, consider the chemical reactions within the rich stage PSR at a 40/60 air split. Near the optimal rich stage equivalence ratio (designated by point "*B*" in Figure 6), a major route for NH_3 destruction is

$$NH_3 \rightarrow NH_2 \rightarrow NH \rightarrow N \rightarrow N_2$$

where reaction partners have been omitted for brevity. Key reactions in this NH_3 destruction pathway are

$$NH + H \rightarrow N + H_2 \qquad \text{(R1)}$$

and

$$N + NO \rightarrow N_2 + O \qquad \text{(R2)}$$

R1 is a simple abstraction reaction, while R2 is the reverse of one of the well-known thermal NO_x formation reactions. Comparing reaction rates at point "*A*" ($\varphi_{\mathrm{rich}} = 0.9$) to point "*B*" ($\varphi_{\mathrm{rich}} = 1.25$) shows that when the rich stage PSR is too lean, the molar flux of N atoms through the forward direction of R1 slows down by a factor of four, mainly due to a nine fold reduction in the H atom concentration. This reduces N atom concentrations by a factor of twelve. As a consequence, N_2 formation (and NO destruction) through R2 slows down at point *A* relative to point *B*. The gas leaving the rich stage PSR at point *B* contains only 55 ppmv NO_x (on a dry, 15% O_2 basis), and some of this NO_x will be destroyed in the rich stage PFR. In contrast, the gas leaving the rich stage PSR at point *A* contains 278 ppm NO_x (on a dry, 15% O_2 basis), and none of this NO_x will be destroyed in the rich stage PFR.

When the rich stage PSR is too fuel rich (point "*C*" in Figure 6, $\varphi_{\mathrm{rich}} = 1.6$), a different reaction becomes important. Reaction R3

$$NH_3 + H \rightarrow NH_2 + H_2 \qquad \text{(R3)}$$

is a **source** of NH_2 at point *B*, but is an NH_2 **sink** at point *C*. The rich stage PSR NH_2 concentration at point *C* is more than 5 times the NH_2 concentration at point *B*, causing R3 to proceed in the reverse direction and **make** NH_3 rather than **destroy** NH_3. The NH_3 concentration in the rich stage PSR at point *C* is 39 times greater than at point *B*. With NH_3 destruction dramatically slowed in the rich stage, a relatively large amount of NH_3 survives until the quench stage, where a significant fraction is converted into NO_x. Overall, the reaction path analysis of the RQL2 SLICER model yields similar insights and conclusions as the RPA of the RQL1 kinetic model.

Measured CO emissions are shown in Figures 7, 8, and 9 for the same air splits shown in Figures 4, 5, and 6, respectively. CO emissions were between 5 and 30 ppmv (dry, 15% O_2) under all conditions, indicating the quench stage design provided adequate mixing, and the short lean stage provided sufficient residence time to complete combustion. Overall, CO emissions were lowest when the air split was closest to the design value (the 40/60 air split) and tended to increase as the air split was adjusted away from the design value (the 30/70 and 20/80 air splits).

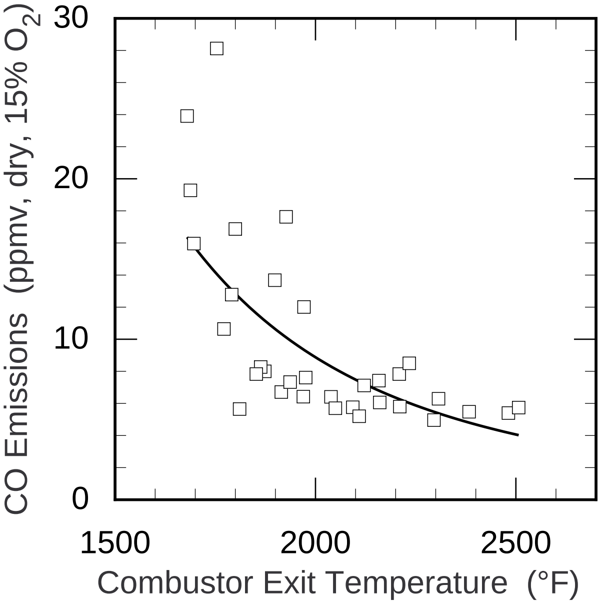

Figure 7: RQL2 CO emissions at a 20/80 rich/lean air split. The solid line shown in Figures 7 through 9 is a best-fit through the measurements, not a model prediction.

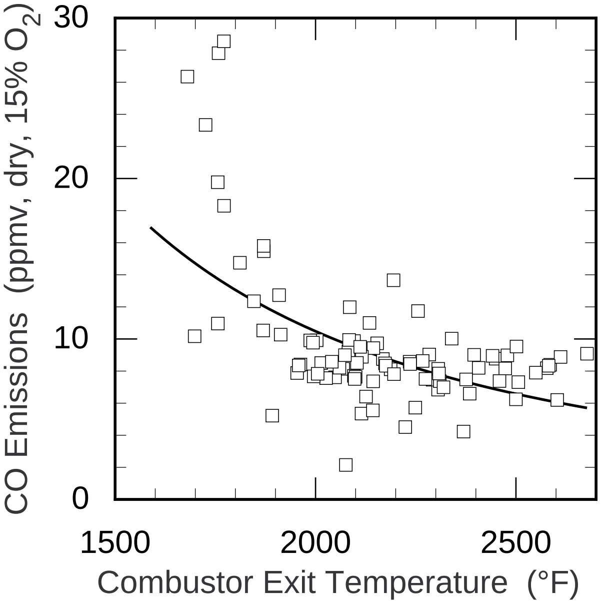

Figure 8: RQL2 CO emissions at a 30/70 rich/lean air split.

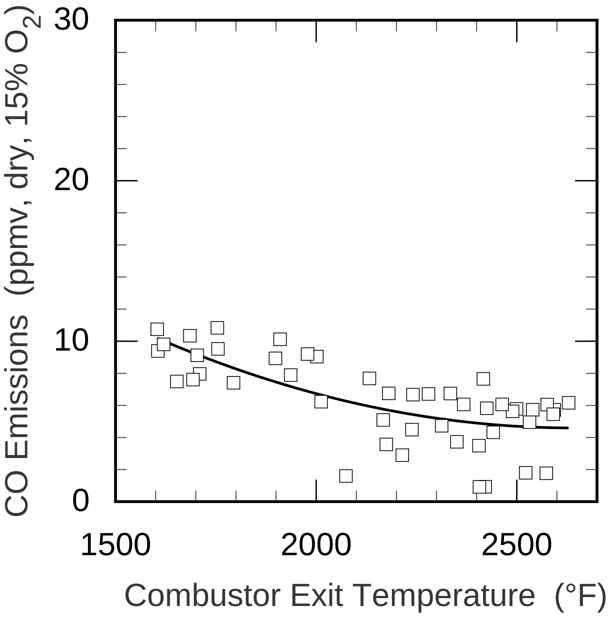

Figure 9: RQL2 CO emissions at a 40/60 rich/lean air split.

Applications

The RQL2 combustor has demonstrated the potential for low NO_x emissions from IGCC power plants equipped with HGCU. Combustor modifications (such as RQL2) are almost always a less expensive method of NO_x reduction than flue gas treatment. The concepts generated in the design and development of RQL2, as well as the improved understanding of rich-lean combustion, may be applied in future low Btu fueled gas turbines. RQL2 concepts may also be incorporated into low NO_x combustors for natural gas and liquid fuel turbines.

Future Activities

The SLICER model and reaction path analysis described above serve several useful purposes. First, RPA identifies the elementary chemical reactions which are most important in the conversion of NH_3 to NO_x in a rich-quench-lean combustor. Research aimed at improving chemical kinetic models of RQL combustion should focus on these key chemical reactions. Second, the RPA indicates that HCN does not play a significant role in the NH_3 destruction chemistry, as has been proposed in the literature. This further suggests that the fuel methane concentration should have little impact on the overall conversion of NH_3 to NO_x. Finally, the excellent agreement between the SLICER model and the Test 9 measurements over a wide range of combustor exit temperatures and air splits suggests that the model can be used to perform "what-if" calculations. Because the model has been validated against experimental data, variations in the fuel composition (including NH_3 content), fuel temperature, and rich stage residence time can all be considered computationally. This type of numerical study may be the part of future work.

Acknowledgements

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