Ultra Low NOx Catalytic Combustion for IGCC Power Plants

Phase II Final Technical Report

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Abstract

In order to meet DOE's goals of developing low-emissions coal-based power systems, PCI has further developed and adapted it’s Rich-Catalytic Lean-burn (RCL®) catalytic reactor to a combustion system operating on syngas as a fuel. The technology offers ultra-low emissions without the cost of exhaust after-treatment, with high efficiency (avoidance of after-treatment losses and reduced diluent requirements), and with catalytically stabilized combustion which extends the lower Btu limit for syngas operation.

Tests were performed in PCI's sub-scale high-pressure (10 atm) test rig, using a two-stage (catalytic then gas-phase) combustion process for syngas fuel. In this process, the first stage consists of a fuel-rich mixture reacting on a catalyst with final and excess combustion air used to cool the catalyst. The second stage is a gas-phase combustor, where the air used for cooling the catalyst mixes with the catalytic reactor effluent to provide for final gas-phase burnout and dilution to fuel-lean combustion products.

During testing, operating with a simulated Tampa Electric's Polk Power Station syngas, the NOx emissions program goal of less than 0.03 lbs/MMBtu (6 ppm at 15% O_2) was met. NOx emissions were generally near 0.01 lbs/MMBtu (2 ppm at 15% O_2) (PCI’s target) over a range on engine firing temperatures. In addition, low emissions were shown for alternative fuels including high hydrogen content refinery fuel gas and low BTU content Blast Furnace Gas (BFG). For the refinery fuel gas increased resistance to combustor flashback was achieved through preferential consumption of hydrogen in the catalytic bed. In the case of BFG, stable combustion for fuels as low as 88 BTU/ft^3 was established and maintained without the need for using co-firing. This was achieved based on the upstream catalytic reaction delivering a hotter (and thus more reactive) product to the flame zone. The PCI catalytic reactor was also shown to be active in ammonia reduction in fuel allowing potential reductions in the burner NOx production.

These reductions of NOx emissions and expanded alternative fuel capability make the rich catalytic combustor uniquely situated to provide reductions in capital costs through elimination of requirements for SCR, operating costs through reduction in need for NOx abating dilution, SCR operating costs, and need for co-firing fuels allowing use of lower value but more available fuels, and efficiency of an engine through reduction in dilution flows.

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Executive Summary

This Final Report describes the results obtained for catalytic combustion of syngas fuel, under PCI's contract with DOE. The technology uses the fuel flexibility of PCI's Rich-Catalytic Lean-burn (RCL®) catalytic reactor in a combustion system for syngas fuel.

The program is directed toward DOE's goals of developing low-emissions coal-based power systems. Specifically, the technology targets meeting DOE's Vision 21 target of NOx emissions < 0.01 lbs/MMBtu (< 3 ppm at 15% O_2) for coal-derived fuels. The technology offers these low emissions without the cost of exhaust after-treatment, with high efficiency (avoidance of after-treatment losses, and reduced diluent requirements), and with catalytically stabilized combustion which extends the lower Btu limit for syngas operation.

Tests were performed in PCI's sub-scale high-pressure (10 atm) test rig, using two-stage (catalytic to gas-phase) combustion process for syngas fuel. In this process, the first stage is a Rich-Catalytic Lean-burn (RCL®) catalytic reactor, wherein a fuel-rich mixture contacts the catalyst and reacts while final and excess combustion air cools the catalyst. The second stage is a gas-phase combustor, wherein the catalyst cooling air mixes with the catalytic reactor effluent to provide for final gas-phase burnout and dilution to fuel-lean combustion products.

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Nomenclature

BFG	Blast Furnace Gas
FTIR	Fournier Transform Infra-Red Spectroscopy
GC	Gas Chromatograph
IGCC	Integrated Gasification Combined Cycle
LBO	Lean Blow-Out
LHV	Lower Heating Value
NOx	Oxides of Nitrogen
PCI	Precision Combustion, Inc.
RCL®	Rich Catalytic Lean-burn
SCR	Selective Catalytic Reduction
SOP	Standard Operating Procedure
UHC	Unburned Hydrocarbons

Introduction

Under the present program, Precision Combustion, Inc. (PCI) tested a new method of catalytically combusting syngas fuels for ultra low emissions, achieving a milestone goal of achieving NOx emissions below 0.03 lbs/MMBtu with the potential for achieving emissions as low as 0.01 lbs/MMBtu (equivalent to < 3 ppm NOx at 15% excess oxygen). In addition, the combustor was used to produce low emissions with alternate fuels including refinery fuel and the low-BTU blast furnace gas. For all fuel types, the combustor produced a robust, stable flame.

Currently, NOx emissions from conventional coal-fired power plants vary widely, from about 0.4 to 2.0 lbs/MMBtu depending on burner type. Low-NOx coal burners can reduce these emissions by about half, but ultra-low NOx emissions, to compete with natural gas fired turbines, requires alternative combustion means or aftertreatment.

One promising approach for emission reduction is coal gasification, followed by combustion of the resulting syngas within a gas turbine engine. IGCC power plants have been proven to achieve high efficiency with reasonably low emissions, including NOx emissions guarantees of less than 25 ppmv (at 15% O2), corresponding to about 0.1 lbs/MMBtu. However, further reduction in NOx emissions, typically by dilution of the fuel with inert gases, faces barriers in terms of flame stability and impact on overall cycle efficiency.

Catalytic combustion is known to improve flame stability, and can also reduce NOx emissions without excessive use of diluent, thus maintaining cycle efficiency. Therefore, PCI proposed, under this program, to further develop and test its fuel-flexible rich catalytic combustion system with syngas fuels, to demonstrate the feasibility of achieving ultra-low NOx emissions in IGCC power plants.

PCI's catalytic combustion system is especially well suited for syngas fuels, since it is designed to operate robustly and with constant performance using a wide range of fuels. PCI, with DOE and gas turbine manufacturer support, developed this advanced catalytic combustor technology to offer ultra-low emissions (NOx < 3 ppm) and efficient catalytic combustion initially for natural-gas-fired gas turbines. Originally developed under a DOE SBIR program, the technology offers simultaneous improvements in emissions, efficiency, fuel flexibility and component life and is now moving toward natural-gas-fired gas turbine field trial. The technology has retrofit potential and has been demonstrated to be operable with multiple fuels (natural gas, pre-vaporized diesel, gasoline). Natural gas fired combustor module tests, performed under large frame gas turbine conditions, have demonstrated the robustness of the technology, as well as stable combustion with NOx emissions as low as 2 ppm at 15% O_2 and low combustion dynamics, in a package sufficiently compact to fit into existing large frame machine combustor volumes.

Since the reactor is fuel rich, it is oxygen limited and, as a result, greatly independent of the fuel used. This unique feature makes a RCL® reactor a good candidate for use in systems required to be fuel-flexible (operates on multiple fuel sources with the fuel in use depending on variables as current availability, cost, or some other constraint) or on systems in which the fuel is inherently variable. This oxygen limitation is also of benefit for mitigation of flashback in the combustor through providing a barrier between fuel air premixer and downstream flame. These benefits would be of use, in particular, for engines running on syngas, high hydrogen content fuels such as refinery fuel gas or pure hydrogen, and reduced energy content fuels such digester gases and blast furnace gas (BFG).

Tests of syngas, refinery fuel gas, and BFG were performed in PCI's sub-scale high-pressure (10 atm) test rig, using a two-stage (catalytic then gas-phase) combustion process for syngas fuel. In this process, the first stage consists of a fuel-rich mixture reacting on a catalyst with final and excess combustion air used to cool the catalyst. The second stage is a gas-phase combustor, where the air used for cooling the catalyst mixes with the catalytic reactor effluent to provide for final gas-phase burnout and dilution to fuel-lean combustion products

This report describes the successful results of the program. In summary, the PCI catalytic reactor showed stable and low emissions performance with a variety of fuels including syngas, refinery fuel gas, and blast furnace gas. Stable combustion with low single digit NOx was demonstrated at 10 atm for a variety of fuels for gas turbine applications. Also, for fuels contaminated with ammonia, the presence of the catalyst before the flame front resulted in a reduction in NOx produced by the combustor, through reduction of the concentration of ammonia reaching the combustor flame.

Background

For the combustion of natural gas, PCI has developed and performed engine demonstrations of a Rich-Catalytic Lean-burn (RCL$^{®}$) combustion system capable of delivering NOx emissions lower than 2.0 ppm. The RCL$^{®}$ system is based on the concept of stabilizing combustion with catalytically-reacted fuel and air having a temperature below the instantaneous autoignition temperature (Smith et al., 2005). PCI’s RCL$^{®}$ system is shown schematically in Figure 1. As shown, the combustion air stream is split into two parts upstream of the catalyst. One part is mixed with all or the majority of the fuel and contacted with the catalyst, while the second part of air is used to backside cool the catalyst. The cooling air stream can also carry a small amount of fuel with flashback controlled by maintaining the fuel concentration below the flammability limit. At the exit of the reactor, the catalyzed fuel/air stream and the cooling flow are rapidly mixed to produce a fuel-lean, reactive mixture prior to final combustion.

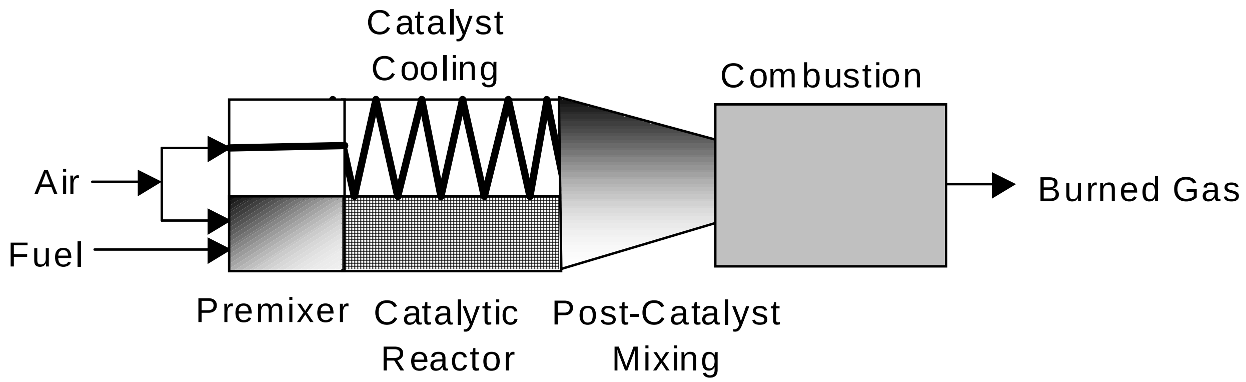

Figure 1. Schematic of Rich-Catalytic Lean-burn (RCL®) Combustion System

With the RCL® approach, the fuel-rich mixture contacting the catalyst has insufficient oxygen (e.g. oxygen limited) to completely oxidize all of the fuel. The limited availability of oxygen limits the extent of catalyst-stage reaction. Thus, the catalyst-stage operating temperature is kept to a safe level regardless of fuel-type.

Fuel-rich operation of the catalyst also provides significant catalyst advantages, including wide choice of catalyst type (many catalysts are active under fuel-rich conditions), improved catalyst durability (non-oxidizing environment), and low catalyst lightoff and operating temperatures.

The RCL® system has been successfully tested in both rig and engine tests for natural gas fuel. Results from work with Solar Turbines, Incorporated (Karim et al., 2003; Smith et al., 2005) showed NOx emissions as low as 1 ppm were achievable in rig tests, while the engine tests showed NOx emissions around 2 ppm, both with CO below 10 ppm. The engine test also demonstrated excellent RCL® reactor operability through the entire range of engine operating conditions, including transient events such as start-up, shutdown, and load shifting.

In addition to testing with natural gas, the RCL® combustion system has been tested at subscale with other fuels. This testing at PCI has demonstrated multi-fuel operation of the catalytic reactor, followed by ultra-low NOx lean-premixed combustion downstream of the catalyst for multiple fuels, including simulated low BTU fuel, gasoline, and vaporized diesel fuels [Smith, et al., 2006].

The results of this developmental testing and the inherent behavior of rich catalytic combustion make the RCL® combustion system an ideal candidate for further expansion and application for low emission syngas/hydrogen/lo-BTU fuelled gas turbine applications. The following sections discuss the results of subscale testing to verify low emission performance of rich catalytic combustion with these fuels.

Technical Results

The present concept is easily scalable and can be enlarged and integrated for gas turbine power generation applications. For this reason, all the operating conditions such as inlet temperatures, relative mass flow rates of fuel and air, and combustor flame temperatures were chosen to closely match typical engine operating conditions. An exception would be reactor pressure which was rig limited.

A sub-scale catalytic reactor for 10 atm high-pressure testing with syngas fuel was fabricated at PCI, and is shown prior to final assembly in the photograph in Figure 2. The reactor housing is the long piece shown and flow is from the top-right to bottom-left of the photograph. During assembly, an injector for syngas fuel is fitted at the upstream end of the reactor where fuel and air mix to provide a fuel-rich fuel/air mixture to the catalyst. The large flange-like piece shown in the photograph contains the fuel plenum and the syngas fuel is delivered through the needle-like injectors surrounding the central hole as shown. The reactor is fitted with a variety of instruments including: thermocouples to measure catalyst and housing temperatures, flush-static pressure ports to measure reactor pressures, and gas sample extraction ports to measure gas composition entering and exiting the reactor by means of a gas chromatograph (GC). These instrumentation lines are coiled and visible in the photograph.

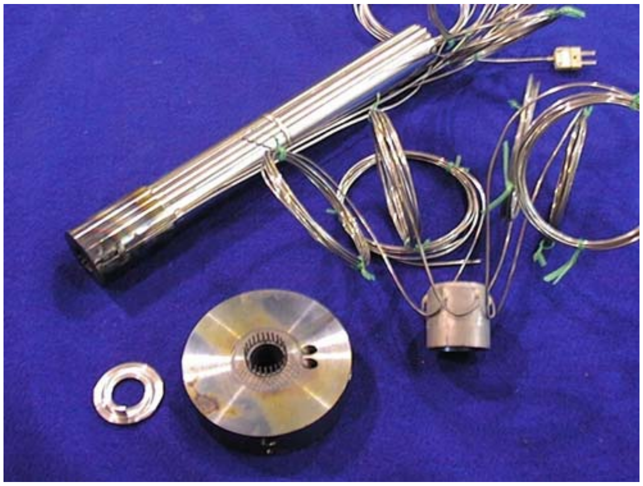

Figure 2. Photograph of Sub-scale Catalytic Reactor for Syngas Combustion.

For high-pressure testing, the catalytic reactor of Figure 2 is inserted into the combustion test rig shown in Figure 3. Flow is from right to left, and the reactor is inserted at the right hand side of Figure 3. Two independently controllable air supplies are provided (both heated and at high pressure); the larger air supply (entering from the right in Figure 3) provides catalyst cooling air, which becomes primary zone combustion air in the gas-phase combustor, and the smaller air supply (entering from the vertical pipe at the top-right of Figure 3) provides air to the fuel-rich fuel/air mixture. For operation with syngas fuel, two heaters are also provided (but not shown in this photograph); one heater heats N_2 diluent just before it is mixed with fuel, and the second heater heats all other fuel components and CO_2. These heaters ideally bring the fuel temperature to 300 C which is typical of actual syngas temperatures provided to gas turbine engines.

Downstream of the reactor, the catalytically reacted gases and the catalyst cooling air burn in the high-pressure 'combustor burnout section' labeled in Figure 3. This is where the reactor products and cooling air leaves the 0.6-inch reactor, mix, and complete the burnout of fuel within a 2-inch ID ceramic combustor liner, giving about a 10:1 dump ratio on an area basis. The combustor burnout section is instrumented with 6 S-type thermocouples to measure flame temperatures and 6 gas sample extraction ports located axially along the combustor liner at 3-inch increments. A hydrogen torch is used to ignite gas-phase combustion. This torch remains on during rig stabilization (to ensure safe burnout of all fuel prior to the rig exhaust), but is turned off when the combustor flame becomes self sustaining and prior to obtaining steady-state data.

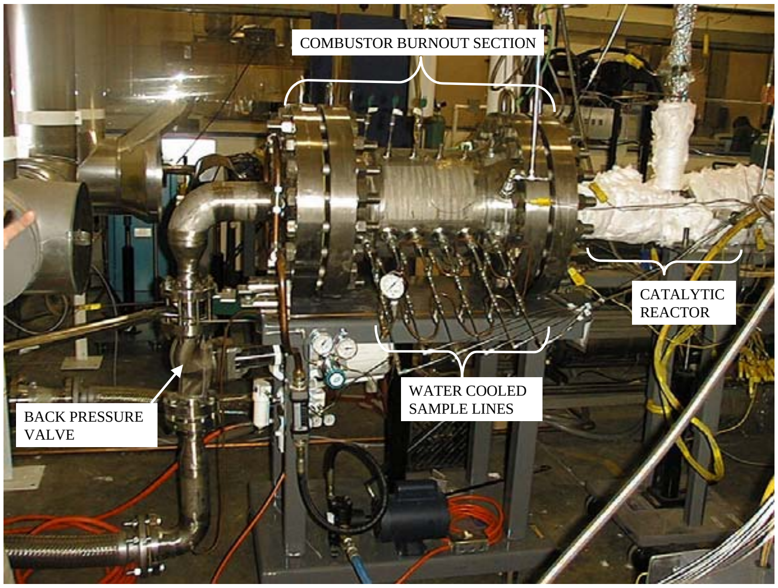

Figure 3. Photograph of PCI's 10 atm Sub-scale Combustor Rig for Syngas Combustion.

High-pressure air is supplied to the rig from compressors, which can deliver 0.12 pps air at about 145 psia into the rig. At this flow rate, the rig inlet air can be heated to 932 F (500 C). Fuel and diluent are supplied from bottles or Dewar flasks at high pressure, and are pressure regulated to the proper delivery pressure to the rig. All flows (air, fuel, and diluent) are metered with electronic mass flow controllers. Each fuel component is separately metered and then mixed with the other components. For the current tests, five fuel components were introduced: H_2, CO, CH_4, CO_2, and N_2.

Operating Conditions and Startup Procedures

Tests were conducted at 10 atm, 750 F (400 C) combustor inlet temperature for air and 570 F (300 C) for fuel, and operating conditions were determined from references to simulate an F-class gas turbine operating on syngas. Note that all emissions reported in ppm are corrected to 15% excess oxygen, dry.

Startup was best accomplished by bringing the reactor to fuel-rich conditions using methane fuel, with some diluent addition to ensure proper mixing. This is similar to actual syngas gas turbine operation. Due to the operation in the fuel rich regime inherent to the present concept, transitioning the fuel from methane to syngas occurs smoothly. When necessary, a small amount of H_2 was temporarily added to the methane to light off the reactor. Once the catalyst and combustor were lit and the rig was thermally stable, syngas fuel flow was ramped up while methane fuel flow was ramped down, holding catalyst equivalence ratio approximately constant. This startup procedure was economical and safe: it minimized the use of high-volumes of costly laboratory syngas fuel blend, and also avoided use of excessive amounts of H_2 during transient and ignition events, where there was a concern that unburned H_2 might enter the exhaust stack and create an explosion hazard. This procedure would be similar to syngas combustor startup in actual engine applications.

RCL® Reactor Syngas Testing

Results from this study demonstrate the feasibility of using an RCL® reactor for syngas combustion to obtain ultra-low emissions in the downstream combustor. The current practice of nitrogen injection for NOx control reduces the effective heating value of the fuel and negatively impacts cycle efficiency. Using the rich catalytic system of the present concept, the inherent low emissions of the combustor reduce the need for excessive and costly diluents, increasing cost effectiveness of the reactor.

Fuel Composition

The baseline syngas fuel composition was derived from data gathered from the open literature. For the high pressure sub-scale tests, "baseline" operating conditions were based on the typical fuel from the IGCC plant at Tampa Electric's Polk Power Station. The Tampa Polk plant operates with syngas generated from a Texaco oxygen-blown coal gasifier feeding a GE 107FA combined cycle system. The final syngas formula used for baseline testing is tabulated in Table 1. Parametric tests were conducted by keeping the H_2/CO ratio constant while varying the Btu content (diluent content).

Table 1. Simplified Baseline Syngas Composition used for High-Pressure Tests.

H_2 (%)	CO (%)	CO_2 (%)	N_2 (%)	LHV (Btu/ft^3)
20	20	10	50	117

Preliminary Testing at Atmospheric Pressure

Syngas fuel tests were performed at atmospheric pressure using a variant of the RCL® two-stage (catalytic/gas phase) combustion process originally developed for natural gas. These preliminary tests were intended to provide some initial experience in syngas fuel operation, and in catalyst and combustor behavior using syngas fuels. The results were used to help guide reactor design and test planning for the subsequent high-pressure tests.

Thus, the following atmospheric pressure test objectives were established to facilitate successful high pressure (10 atm) testing:

1. Characterize RCL® catalyst lightoff and extinction temperature for syngas fuel.
2. Characterize RCL® catalyst operating temperature and reactor fuel conversion.
3. Obtain preliminary NOx and CO emissions.
4. Establish a Standard Operating Procedure (SOP) for rig operation using syngas fuel (e.g. startup, catalyst lightoff, etc.).

Testing and Results. Although the equivalence ratio was varied during atmospheric testing, the syngas blend remained fixed (consistent H_2/CO ratio). Emissions measurements were obtained over a range of conditions, as tabulated in Table 2. Overall equivalence ratio was measured at the emissions probe, downstream of the catalyst and near the exit of the gas-phase combustor. In general, the low emissions measured show that at atmospheric pressure, NOx emissions less than 3 ppm (0.015 lbs/MMBtu NOx) were easily achieved for equivalence ratios as high as 0.53 corresponding to a combustor adiabatic flame temperature of 1450 C (2642 F).

From the atmospheric tests, many observations were made and were useful during high pressure testing. For fuel-rich conditions, syngas lightoff temperature was about 356 F (180 C), while extinction temperature was < 176 F (< 80 C). Catalyst operating temperature and axial profile were similar to those obtained using methane fuel.

Table 2. Summary of Emissions Measurements at Atmospheric Pressure.

Adiabatic Flame Temperature (°C / °F)	Overall Equivalence Ratio	CO (ppm)	NOx (ppm)
1450 / 2642	0.53	1.5	2.6
1412 / 2573	0.50	0.8	2.4
1300 / 2372	0.45	0.8	1.9
1274 / 2325	0.40	1.4	1.5

Testing at High Pressure (10 atm)

Objectives. The primary goal of the sub-scale high-pressure tests was to evaluate emissions performance of the RCL® combustion system with syngas fuel. Thus, the primary objectives listed below relate to performance of the downstream combustor during operation on syngas fuel:

1. Characterize combustor emissions (NOx, CO, and UHC) and lean blowout (LBO) at engine baseline conditions. Vary fuel flow to establish low-emissions turndown range, characterized be low NOx and CO emissions, for engine applications. Use baseline syngas fuel composition, baseline reactor configuration (fixed percentage of air to fuel-rich fuel/air mixture), and baseline (base load) inlet air conditions (constant pressure, air flow, and temperature).
2. Characterize combustor performance (emissions and LBO) for non-baseline syngas fuel compositions. In particular, keep constant H_2/CO

ratio but vary Btu content. For each fuel composition tested, vary fuel flow to establish low-emissions turndown range. This provides performance data for low Btu fuel applications such as BFG.

Emissions Performance. Emissions measurements reported were obtained from the gas sample port located 15 inches downstream of the injector, corresponding to 50 ms residence time. This represents the maximum residence time expected in a low-emissions gas turbine combustor, and therefore also represents the maximum expected NOx emissions for a given operating condition.

All measurements were made with a combustor inlet air temperature of 750 F (400 C) and a syngas fuel temperature of 570 F (300 C). Adiabatic flame temperatures were calculated based on fuel/air ratio as measured by the emissions analyzers (i.e. from gas samples extracted at the 15-inch gas sample probe location).

Figure 4 plots measured NOx and CO emissions as a function of adiabatic flame temperature at 10 atm pressure for the “baseline” syngas composition of 20% H_2, 20% CO, 10% CO_2, and 50% N_2, giving a LHV of 117 Btu/ft^3. With this fuel composition, NOx emissions were 2 ppm (0.01 lbs/MMBtu) at the 2550 F (1399 C) flame temperature data point corresponding to the baseline IGCC combustor firing temperature and representing operation at 100% load.

As the fuel/air ratio was decreased, CO emissions remained near zero for flame temperatures greater than about 2250 F (1232 C), permitting a 300 F (149 C) turndown in flame temperature from the 2550 F (1399 C) baseline point, allowing ultra low emissions operation over a wide range of engine loads. These results – CO near zero, and NOx equal to or less than 2 ppm (0.01 lbs/MMBtu) for full load and below – easily met the emissions goal. This demonstrates the potential of the use of rich catalytic systems to achieve ultra-low NOx from syngas power generation with reduced diluent requirements.

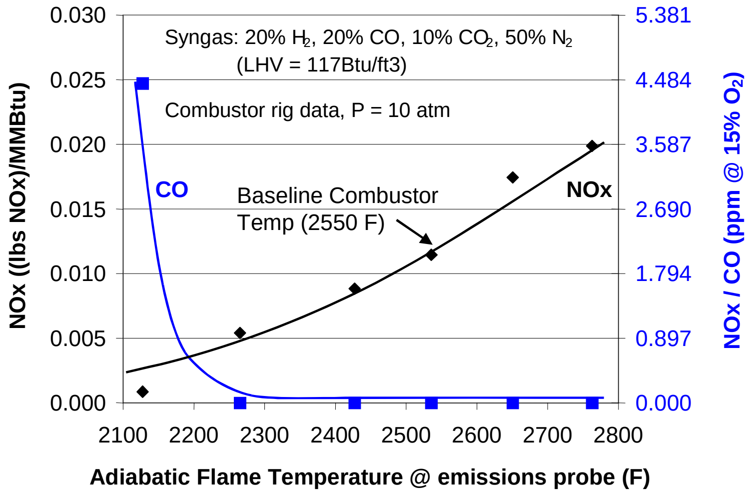

Figure 4. Measured NOx and CO Emissions as a Function of Flame Temperature at the Emissions Probe Demonstrating the Benefit of the Rich Catalytic Concept Combustor for achieving Ultra-low NOx using Syngas Fuels

In another parametric test, the heating value of the diluted syngas fuel was reduced to determine operability. NOx emissions are shown in Figure 5. It is important to note that the right-hand vertical axis in Figure 5 (NOx values in ppm) is only applicable to the baseline syngas composition, as marked. For the fuel composition with a lower heating value, NOx emissions in ppm are slightly lower than shown (for the 88 Btu/ft^3 fuel, 0.011 lbs/MMBtu is equivalent to 1.6 ppm at 15% O_2).

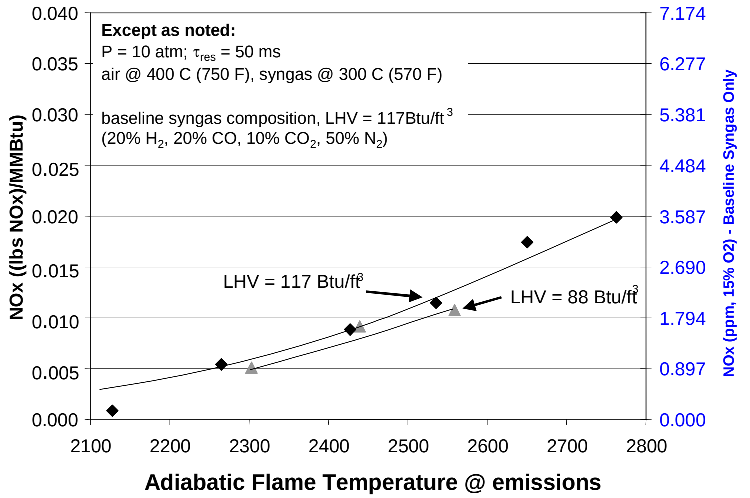

Figure 5. Measured NOx Emissions for Two Different Syngas Compositions having LHVs of 88 and 117 Btu/ft^3.

It is worth noting that, as shown in Figure 5, catalytic combustion allows stable operation with low emissions for the low Btu syngas case (88 Btu/ft^3) even at flame temperatures as low as 2300 F (1260 C). CO emissions were less than 5 ppm in all cases, and were near zero for flame temperatures greater than 2200 F (1204 C). The fuel compositions for the data shown in Figure 5 are listed in Table 3. Stable operation with low-Btu has been achieved primarily through heating of the fuel air mixture by partial reaction of the upstream rich fuel/air mixture. This heating increases downstream stability through enhancement of the reaction rates of the downstream flame. In addition, insensitivity of the fuel rich reactor concept to heating value variation is demonstrated.

Table 3. Syngas Compositions for Data shown in Figure 5, Arranged by Heating Value.

H_2 (%)	CO (%)	CO_2 (%)	N_2 (%)	LHV (Btu/ft^3)
15	15	10	60	88
20	20	10	50	117

RCL® Reactor Testing Using Alternate Fuels

In addition to syngas experiments, tests were performed to observe RCL® reactor performance with other low heating value and high-hydrogen fuels. Two additional fuels that were tested were blast furnace gas and refinery fuel gas, both of importance for power generation applications.

Blast Furnace Gas

Rich catalytic combustion of an 82 Btu/ft^3 blast furnace gas was tested using the same sub-scale high-pressure combustion rig as that of the syngas. For these tests the simulated blast furnace gas (23% CO, 22% CO_2, 1.4% H_2, 0.6% CH_4, and 53% N_2) entered the reactor after being heated to about 446 F (230 C). Combustion air (including catalyst-bound or catalyst-side air) entered the reactor at about 662 F (350 C). Stable combustion can not be easily achieved for a fuel at this low heating value without co-firing with a more reactive fuel such as natural gas or diesel. For locations where either is not available or too costly, a rich catalytic system will provide required stability for the flame through the mechanism of the use of catalytically enhanced pre-reaction heating the fuel air mixture (and greatly increasing its reactivity) before it enters the flame zone. Results show that combustion of this gas is extremely stable following fuel-rich catalytic reaction, even at adiabatic flame temperatures as low as 2250 F (1232 C).

The high diluent fraction of the fuel means that high fuel-lean equivalence ratios are needed in the combustor burnout zone to achieve a desired flame temperature for the turbine, i.e. the stoichiometric flame temperature for this blast furnace gas is only about 2700 F (1482 C) for the inlet temperatures tested. Tests were performed over a range of adiabatic flame temperatures in the combustor burnout section, from about 2250 to 2500 F (1232 to 1371 C).

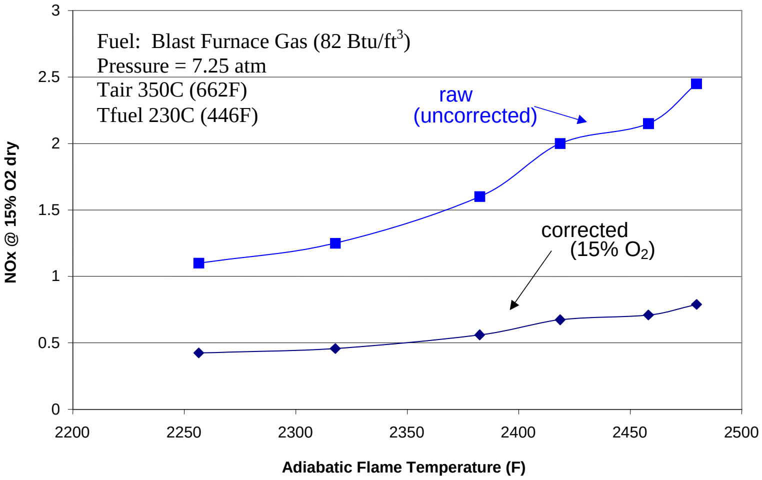

Figure 6: NOx Emissions, Uncorrected and Corrected to 15% O_2, with Variation of Flame Temperature with Blast Furnace Gas Showing High Turndown and Ultra-low Emissions with a Stable Downstream Flame

For blast furnace gas operation, ultra-low emission levels were achieved for all conditions tested. NOx emissions for blast furnace gas operation are plotted in Figure 6, as measured by sample extraction from a cooled probe located 15 inches downstream of the catalyst exit. For all conditions tested, NOx emissions were measured below 2.5 ppm on a raw basis (uncorrected) and below 1 ppm corrected to 15% O_2 dry. CO emissions were near zero (< 1 ppm) for all conditions shown. In general, NOx emissions were ultra-low as a result of the low blast furnace gas flame temperatures.

Refinery Fuel Gas

Testing of RCL® reactor combustion of refinery fuel gas was also conducted using the same hardware configuration as previous tests for syngas and blast furnace gas. Results showed NOx emissions below 3 ppm for flame temperatures below 2800 F (1538 C).

For the refinery fuel gas tests, the simulated refinery fuel gas comprised 30% H_2 and 70% CH_4, and entered the reactor without passing through a fuel heater. However, some fuel heat was obtained from hot combustor rig components so that the fuel plenum gas temperature measured about 347 F (175 C). Combustion air entered the reactor at about 734 F (390 C).

Tests were performed over a range of adiabatic flame temperatures, from about 2400 to 3000 F (1316 to 1649 C) in the combustor burnout section, and at a pressure of 10 atm. NOx and CO emissions were measured at each condition, as well as O_2 and CO_2. GC measurements indicated that the rich catalytic system preferentially oxidized the hydrogen in the fuel and therefore a primarily natural gas mixture exited the reactor to be reacted in the downstream flame front. This gives the benefit of having a more uniform (the reactor will filter out potential changes in hydrogen content) and predictable flame (significant reductions of the hydrogen contribution to flame speed and potential autoignition events) in the downstream combustor.

NOx emissions for the RCL® reactor combustion of refinery fuel gas are plotted in Figure 7, as measured by the downstream emission probe. NOx emissions were measured below 3 ppm for flame temperatures less than about 2800 F (1538 C) indicating lean premixed combustion in a downstream flame zone. The majority of the H2 in the fuel was converted in the reactor leaving only methane to burn as a low emissions premixed flame without flashback. CO emissions were less than about 1 ppm for all conditions shown. This shows the validity of the use of the more stable and controllable rich catalytic concept combustor for achievement of ultra-low emissions with high hydrogen fuels such as refinery fuel gas.

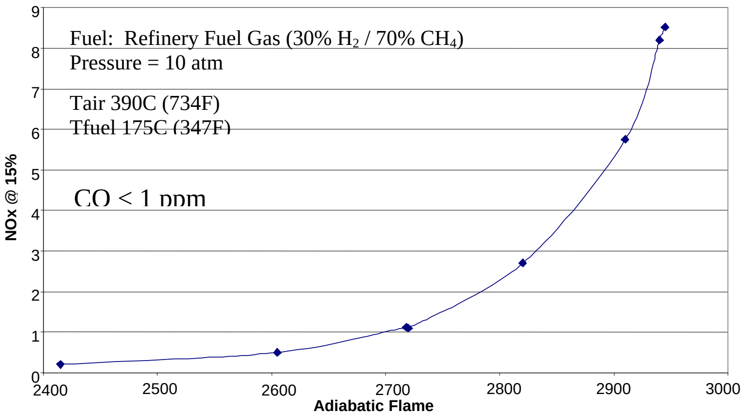

Figure 7: NOx Emissions, Corrected to 15% O_2, as a Function of Flame Temperature for Refinery Fuel Gas (30% H_2 and 70% CH_4) Low NOx Values Indicate Flame is Lean Premixed Stabilized Downstream of Reactor

RCL® Reactor and Ammonia Tests

A common trace species in syngas is ammonia formed from conversion of the fuel-bound nitrogen present in the coal to nitrogen/hydrogen compounds. Ammonia, when present in a fuel, has been found to dramatically increase production of NOx emissions, primarily through the Fenimore mechanism. In the rich catalytic stage of the PCI reactor concept, the catalyst may promote the breakdown of the ammonia molecule (NH_3) to N_2 and H_2 and thus reduce the contribution of the ammonia to production of NOx by the combustor flame zone. Thus, the effect of the presence of ammonia in diluted hydrogen fuel on NOx generation in the PCI reactor was determined.

Test Conditions

The reactor setup was the same as was used for previous testing. The ammonia concentration was measured at different points in the fuel rich catalytic reactor and combustor through the use of a FTIR probe. Also GC data for conversion in the reactor and emissions data from the combustor were taken. Operation on ammonia doped fuel was compared to data for pure H_2/N_2 fuel, in particular for emissions.

Testing was performed at a system pressure of 10 atm, with air and fuel preheating to 400C (750 F) and 200C (390F) respectively. The combustor was operated over a range of burner exit temperatures through variation of the overall equivalence ratio.

In order to more easily see the effects of catalyst on ammonia present in the fuel, the fuel was spiked with a relatively high level of ammonia, around 65 ppm by volume. Ammonia was added to the fuel stream by injecting nitrogen containing 227 ppm NH_3. The injection rate was varied to keep total ammonia concentration in the fuel constant. For this testing, the fuel consisted of a mixture of 42% H_2 and 58% N_2.

Results

Figure 8 shows measured ammonia concentration at the inlet and exit (before mixing with cooling air) of the rich catalytic reactor as a function of combustor exit temperature. The increase in ammonia concentration with flame temperature observed in the premixer is due to the reactor operating more fuel rich at increased flame temperatures. Since ammonia in the fuel is held constant at 65 ppm, there will proportionally be more ammonia with increase in fuel richness. At the catalytic reactor exit, ammonia concentration is lower than the catalytic inlet indicating that some NH_3 is converted to other species over the catalyst. In addition, at higher flame temperatures (where mixtures in the reactor are more fuel rich), there is a greater reduction of ammonia within the reactor bed. After reaction with the catalyst, when mixed with cooling air, a mixture concentration of about 4 ppm of ammonia passes to the combustor flame. Without reaction, a mixture of about 6 ppm would pass to the flame.

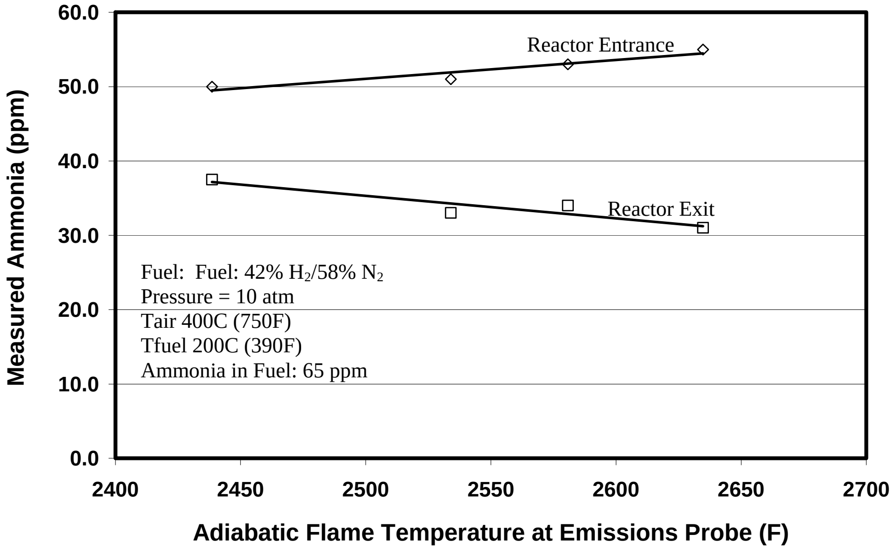

Figure 8: Reduction of Ammonia using RCL® Reactor for High Ammonia Concentration

The NOx emissions from the combustor are plotted and compared with no ammonia present in the fuel in Figure 9. The Figure shows NOx emissions with the standard fuel with no ammonia doping, NOx emissions of the RCL® combustor with 65 ppm of ammonia addition, and an estimate of the NOx emissions assuming no catalytic conversion of NH_3 using a proportional calculation method. As expected, the addition of ammonia to the fuel results in a large increase in NOx emissions. However, the increase in NOx in the RCL® combustor is significantly reduced compared to what it is estimated without catalytic reaction. This proves the usefulness of the rich catalytic concept for abatement of increases in NOx emissions due to ammonia contamination in the fuel. Applied to an engine, this would increase efficiency and reduce operating and capital costs of an engine, through reduction in required fuel dilution, fuel cleaning, or use of SCR for NOx clean-up.

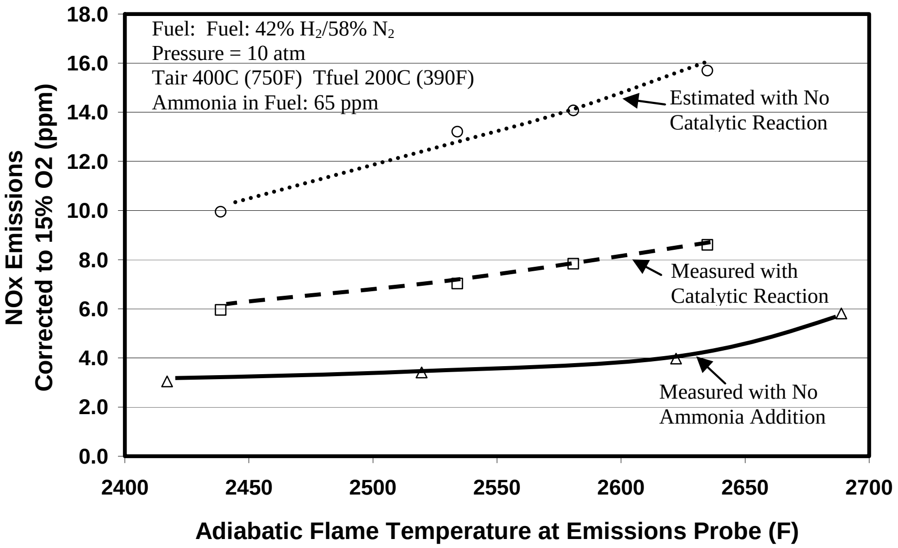

Figure 9: Reduction in NOx through Use of RCL® Reactor in High Ammonia Fuel

Conclusions

Successful operation of the RCL® combustion system was demonstrated at 10 atm for syngas fuel simulating operation of Tampa Electric's IGCC plant. NOx emissions were measured in the range of 0.01 lbs/MMBtu (< 3 ppm at 15% O_2) with potential for further reductions available.

In addition to the syngas fuel tests, further tests were conducted with alternate fuels with low heating values and/or high hydrogen content. The two types of alternate fuels tested were blast furnace gas and refinery fuel gas. Both fuels performed well, with good flame stability for blast furnace gas with NOx levels below 2.5 ppm and refinery fuel gas with NOx levels below 3 ppm.

Ammonia present as a contaminant in the syngas was shown to be converted to other species on the catalyst. This will lead to lower emissions of NOx from a combustor operating on such a fuel.

The reductions of emissions of NOx and increase in the capability to operate on alternative fuels (such as BFG and refinery gases) will reduce requirements for NOx abatement such as increased dilution and/or SCR gas treatments. This will lead to decreases in capital/operating costs and increase engine efficiency.

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