# Development of a Catalytic Combustor for Fuel Flexible Turbines

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## Abstract

Siemens has been working on a catalytic combustor for natural gas operation for several years using the Rich Catalytic Lean (RCL$^{TM}$) design. The design has been shown to produce low NOx emissions on natural gas operation. By operating the catalyst section fuel rich, the design shows considerable promise for robust operation over a wide range of fuel compositions including syngas. Under the sponsorship of the U. S. Department of Energy's National Energy Technology Laboratory, Siemens Westinghouse is conducting a three year program to develop an ultra low NOx, fuel flexible catalytic combustor for gas turbine application to Integrated Gasification Combined Cycle (IGCC) plants. Experimental validation of the rich catalytic design at full pressure and flow conditions are presented for natural gas operation and initial lightoff characteristics on syngas. The combustor basket design modifications necessary to extend the operation of this combustor to syngas fuels typical of IGCC are presented.

## Introduction

In recent years the rise in natural gas prices has brought renewed interest in alternative fuels. This has made the syngas fuel created from Integrated Gasification Combined Cycle (IGCC) plants an attractive option for gas turbine power plants. Current emission requirements are in effect which require reduction of NOx emissions from gas turbine power plants to the low single digit levels. Maintaining low emissions while operating with a wide variety of fuels presents a challenge to gas turbine combustion design. The lower emission requirements in effect in many states can only be meet with exhaust gas cleanup (SCR) or with catalytic combustion. Siemens Westinghouse has been investigating catalytic combustion for natural gas fuelled turbines over several years using the Rich Catalytic Lean (RCL) design. This design has shown the potential for low emission levels on natural gas fuel and to provide robust operation over a wide variety of fuel flows and compositions. Under contract for the U. S. Department of Energy, Siemens Westinghouse is developing a fuel flexible catalytic combustor using the RCL design for IGCC application using large industrial gas turbines such as the Siemens SGT6-5000F engine.

## Catalytic Combustor Design

For IGCC application it is essential that the combustor operate and achieve low emissions with both syngas and natural gas. Because of this the current catalytic combustor design developed for natural gas operation will be used as a basis for the IGCC low NOx combustor design. The application of the RCL catalytic combustion system to a typical large frome gas turbine engine is shown in Figure 1. The combustor basket for this application consists of six (6) catalytic modules surrounded by a central pilot. Both the pilot and the modules exit into the downstream burnout region. Some of the air flow entering the basket is diverted to the plot nozzle. The fuel flow to the catalyst section and the pilot nozzle are independently controlled. The pilot used in this application has a two stage design; one stage is diffusion the other is premixed. The pilot is necessary to provide stability to the downstream burnout region while operating at low loads. At base load the diffusion stage of the pilot will be shut off and the premix stage shut off or minimized. In this design no preburner is required; the catalyst is designed to become active at the compressor exit temperature. Experimental testing of the combustor at simulated low load conditions has shown that it is possible to stabilize the down stream burnout section of the combustor with the pilot at loads less than

50% even when the catalyst is not active. Based on this data the goal of the design is to obtain lightoff of the catalyst at or below 50% load on the SGT6-5000F engine.

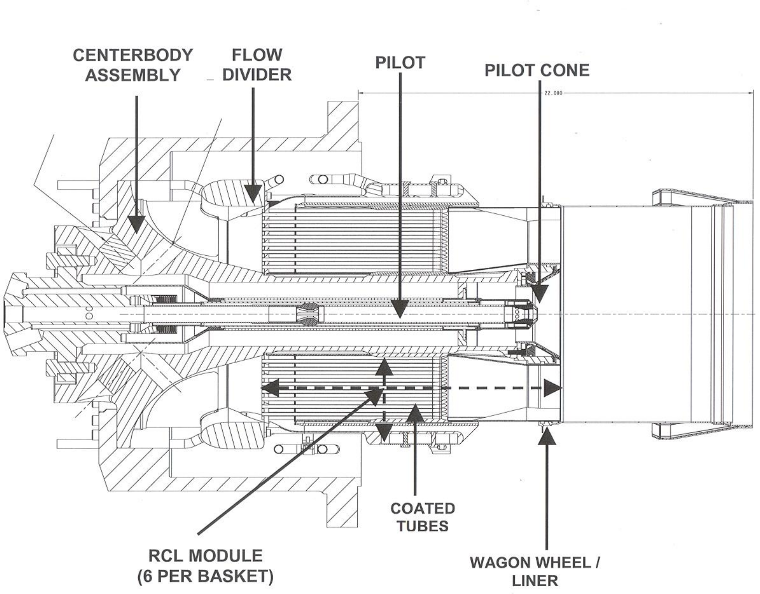

**Figure 1 Design of the Catalytic Combustor Basket**

The design of the catalytic combustion modules is shown in Figure 2. These modules consist of an array of tubes with catalytic coating on the outside diameter. The air entering the module is split into two streams. One stream mixes with the fuel and reacts on the outside surface of the tubes at an equivalence ratio of greater than the flammability limit of the mixture. The other stream flows inside of the tubes and is used to backside cool the catalyst. The fraction of the air that mixes with the fuel is called the split flow and is a critical parameter in the design of the catalytic reactor. This fraction is controlled by the component flow resistances and resulting pressure drops through the system. At the exit to the reactor, the two streams mix before entering the down stream burnout section of the reactor.

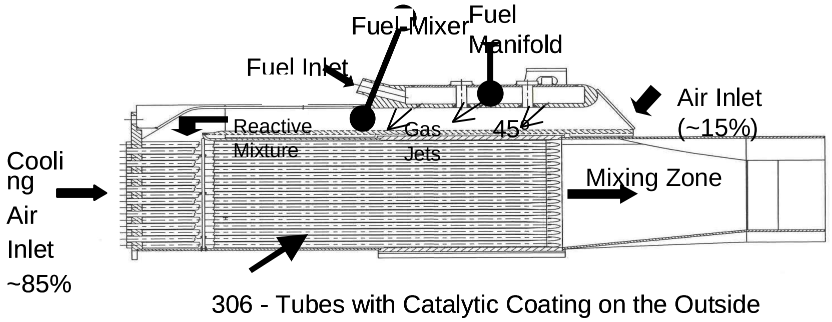

**Figure 2 Rich Catalytic Combustion Module**

## Natural Gas Test Results - Module

The design of the catalytic combustion system has been verified for natural gas operation through subscale module tests and full basket testing. Testing of a single catalytic module was performed at full pressure and flow rates for both the typical for current and older gas turbine engines. In the geometry of the module tests was set to simulate the fuel and air inlet flow conditions of the engine. The flow exiting the mixing region of the module was stabilized by the sudden expansion into a circular backside cooled liner. The emissions obtained during module testing are shown in Figure 3. All emission values were corrected to 15% O2. NOx emissions of less than 2 ppm and CO emissions of less than 10 ppm were obtained over a wide range of operating temperatures including those of the advanced gas turbine designs. Catalyst temperatures and module surface temperatures remained well below the design limits for all conditions tested. Combustion dynamic pressure fluctuations were not an issue at the temperature ranges of the test.

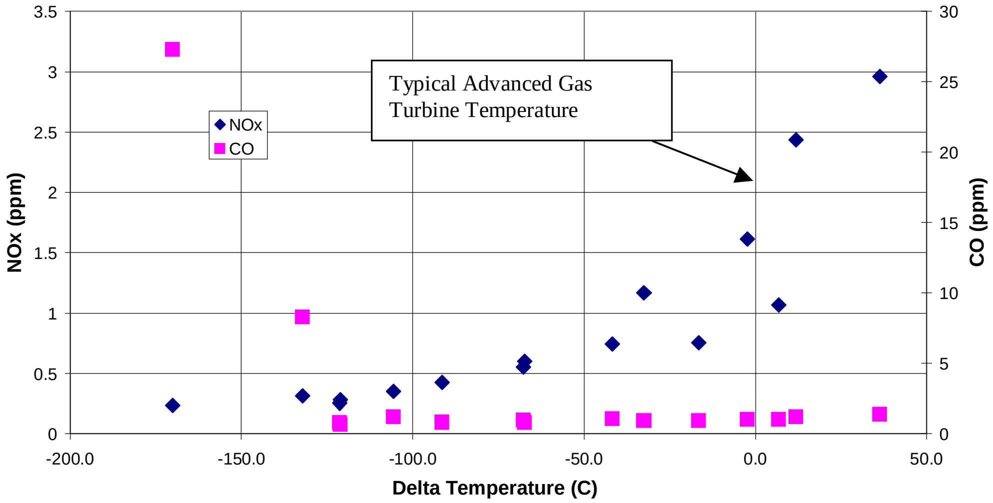

**Figure 3 Full Scale Catalytic Module Test Results**

## Natural Gas Testing Results – Full Basket

Full scale basket testing was performed on the catalytic basket design in the Siemens test facility located at ENEL in Italy. This facility duplicates the engine geometry and is capable of simulating full pressure and flow conditions for both the newest high pressure, high firing temperature engines and the older engine designs. The instrumented basket used for testing is shown in Figure 4. The full scale basket results confirmed that with the addition of the pilot, the basket could be loaded from startup to baseload and maintain stable operation throughout the load range. Catalyst light off was repeatably obtained at temperatures between 300 and 330 C. Emissions results from the full scale basket tests are presented in Figure 5. All emission values are corrected to 15% O2. The results are presented as a function of the air fuel ratio to the head end of the catalytic basket. The addition of the pilot resulted in a slight increase in NOx emissions over the module test results. In addition, because of the shorter residence time in the engine, as compared to the module test rig, modifications to the burnout zone were necessary to maintain acceptable CO emissions when operating at the lower firing temperatures typical of older gas turbine engines. It was necessary to add dilution air to the transition of these engines in order to increase the operating temperature of the combustor to achieve acceptable CO burnout. It is interesting to note that the NOx emissions at the higher firing temperature of the advanced gas turbine designs were comparable to those of the older engines. This is because the higher firing temperature provided additional stability to the catalytic burnout region enabling these engines to run at a significantly lower pilot fraction. Based on these tests emissions in the range of 3 ppm NOx and 10 ppm CO are achievable in both new and older engines with the present design.

**Figure 4 Catalytic Combustor Basket for the Siemens Engine**

During normal operation the basket and module metal temperatures remained within limits. To verify the robust nature of the rich catalytic design, an over firing test was performed by increasing the fuel flow to the combustor. Even through transition temperatures were 200 C above the operating temperature limit, the catalyst tube temperatures remained within limits throughout the entire test and no damage to the catalyst was observed.

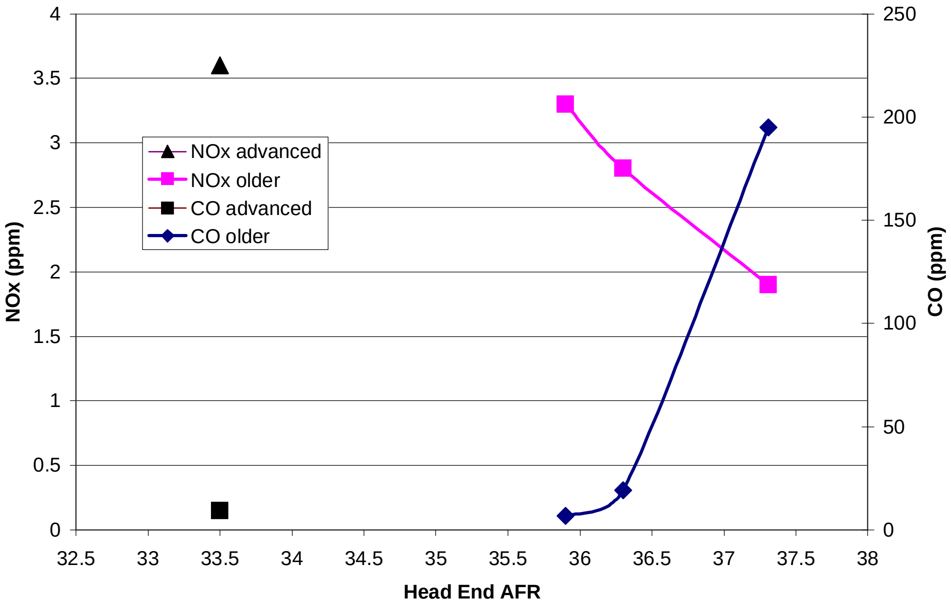

**Figure 5 Full Scale Catalytic Basket Test Results**

## Catalytic Coating Syngas Testing

Catalyst development has focused on traditional precious metal catalysts (Pt, Pd, Rh) in a ceramic based matrix coated onto a metal tube made from an oxidation resistant alloy. Screening tests have been performed on catalyst coatings in a single tube reactor facility at Casselberry, Florida. The single tube reactor is designed to simulate the gas conditions (pressure, temperature, velocity) on the catalyst and cooling air side of the tube encountered during engine operation. With the single tube rig the cooling air and rich combustion air can be independently controlled enabling a study of the effects of the air split on lightoff. Typical lightoff data obtained form the rig is shown in Figure 6 for both natural gas and syngas fuels. The syngas fuel was supplied from bottled gases mixed to the expected composition at the gasifier outlet as shown in Table 1. The experimental results showed that light off temperatures on natural gas were always higher for natural gas than for syngas. This indicates that a coating which can produce acceptable lightoff on natural gas will perform even better on syngas. With the best available current coatings, light off for natural gas is between 300-330 C for natural gas and 260-280 C for syngas. Two different coating were identified which met these requirements. Even coating which had high lightoff on natural gas (400 C) were able to lightoff on syngas at temperatures below 300 C. From Figure 6 it is evident that light off of the entire tube is almost instantaneous for natural gas. On syngas the light off is slower with one section of the tube lighting first and the temperature rise spreading to the hole tube within 3-4 seconds.

Once a coating has demonstrated acceptable lightoff in the single tube rig durability testing is performed. Coating adhesion, sintering and catalyst agglomeration will be evaluated through thermal cycling and long term durability testing. The thermal cycling tests are performed in a furnace at three different temperatures. Long term durability studies will be performed using the single tube rig and in a subscale test rig.

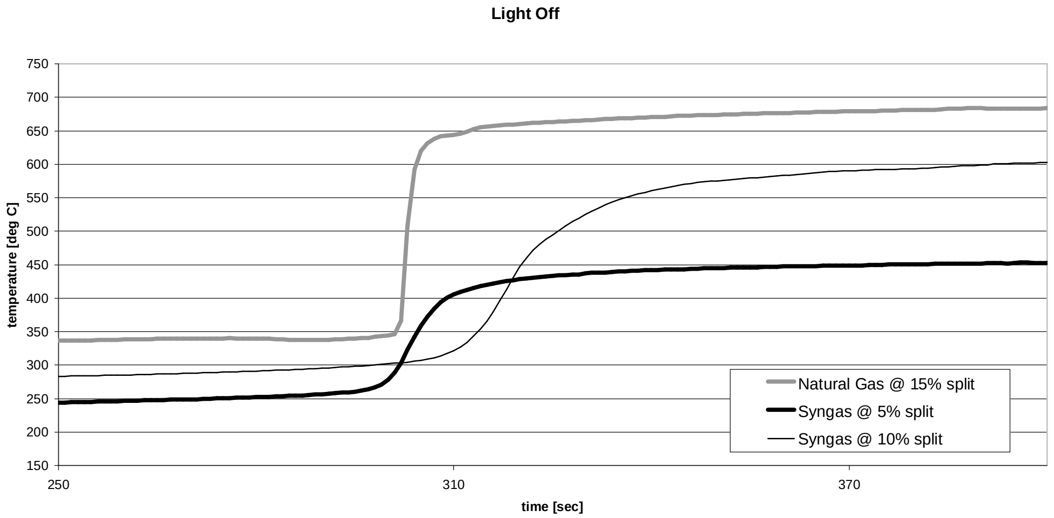

**Figure 6 Catalyst Lightoff Data**

| | Volume % |
|---|---|
| CH4 | 7.4 |
| CO2 | 7.9 |
| CO | 59.8 |
| H2 | 24.0 |
| N2 | 0.9 |

**Table 1 Syngas Composition**

## Modeling Results – Natural Gas and Syngas

Operation of a catalytic combustor on syngas presents several technical challenges. Because of the much lower heating value of the syngas, as compared to natural gas, the fuel flows to the combustor are larger for the same flame temperature. This difference in fuel flow rates generally will require separate injection ports for syngas and natural gas. The high hydrogen content of the syngas results in increased flammability limits and flame speeds, increasing the possibility of flashback. For conceptual design studies of the fuel flexible catalytic combustor a numerical model of the catalytic reactor was developed. This model calculates the fuel-air, coolant and tube metal temperatures as a function of position along the length of the catalytic reactor. This model represents the homogeneous and heterogeneous reaction rates, diffusion to and from the catalyst surface, convective heat transfer to reactive mixture and coolant along with heat conduction through the tube wall. The surface reaction kinetics were obtained from simplification of the mechanism of Hickman and Schmidt. Gas phase kinetics were modeled with the GRI mechanism. Heat and mass transfer rates were calculated from standard textbook correlations. The model also calculates the pressure drops between the two flow paths. By equalizing the pressure drops it is possible to determine the flow split between the reaction and cooling air for a given geometry. This flow split is critical to the performance of the catalytic reactor.

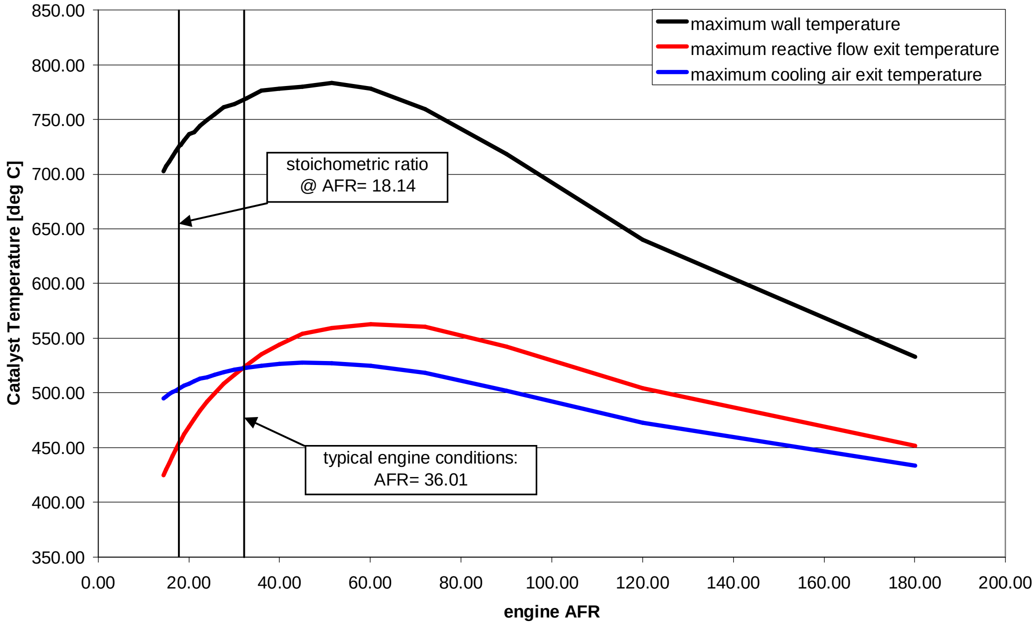

**Figure 7 Calculated Reacting Gas and Catalyst Temperatures for Typical Gas Turbine Engine**

Figure 7 shows the effect of the engine air fuel ratio on the maximum gas and tube temperatures in the catalytic reactor under typical gas turbine conditions while operating on natural gas with 16% of the air in the reaction section. For this calculation 16% of the total air to the module enters the fuel manifold and is mixed with the fuel flow to react on the catalyst surface. Because the catalyst operates in the rich region, increasing the fuel flow actually reduces the reaction and the catalyst temperatures. This is due to the fact that the reaction is limited by the rate of diffusion of oxygen to the surface when the reactor is operating in the rich region. One interesting observation from this analysis is the operation of the catalyst when the fuel flow is reduced. As the fuel flow is reduced, the equivalence ratio in the catalyst would be reduced and eventually the catalyst section would no longer be operating fuel rich. As expected, the catalyst surface tube temperature increases as the AFR is initially increased. There is, however, a maximum temperature of the catalyst metal surface which is below the catalyst surface design temperature limit of 900 C. Although the percentage of fuel conversion continues to increase with the increase in AFR the total amount of fuel in the reactor is decreasing.

Figure 8 shows the percentage of fuel and oxygen converted in the reactor. From this figure it can be seen that the reaction is limited by oxygen diffusion in the fuel rich region and by methane diffusion in the fuel lean region. These results are significant because they confirm the durability advantages of the rich catalytic approach. A properly designed reactor will not overheat at any operating condition.

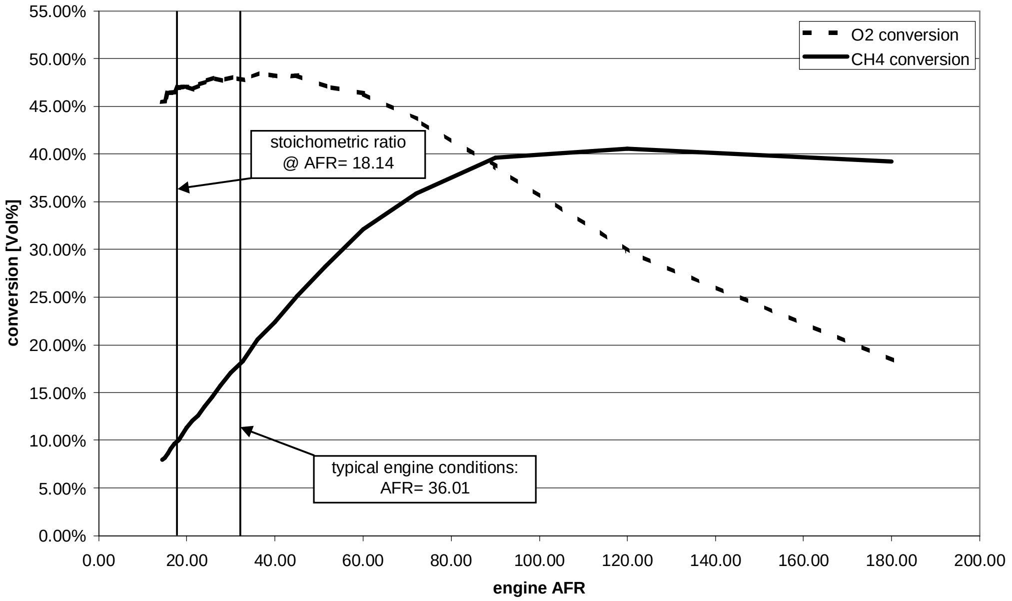

**Figure 8 Calculated Fuel and Oxygen Conversion for a Typical Gas Turbine Engine**

Figures 9 and 10 show the calculated maximum reactor gas and tube temperatures as a function of the fuel split for natural gas and syngas. Figure 9 compares the model temperature calculations with the experimental results for the module tests which were conducted with a split flow of 14%. The model slightly under predicts the fuel conversion and therefore the reactor temperatures. In order to take full advantage of the catalyst, it is necessary to maximize the split flow while maintaining the catalyst surface temperature below the 900 C limit. Later module designs have been developed to operate at higher air splits.

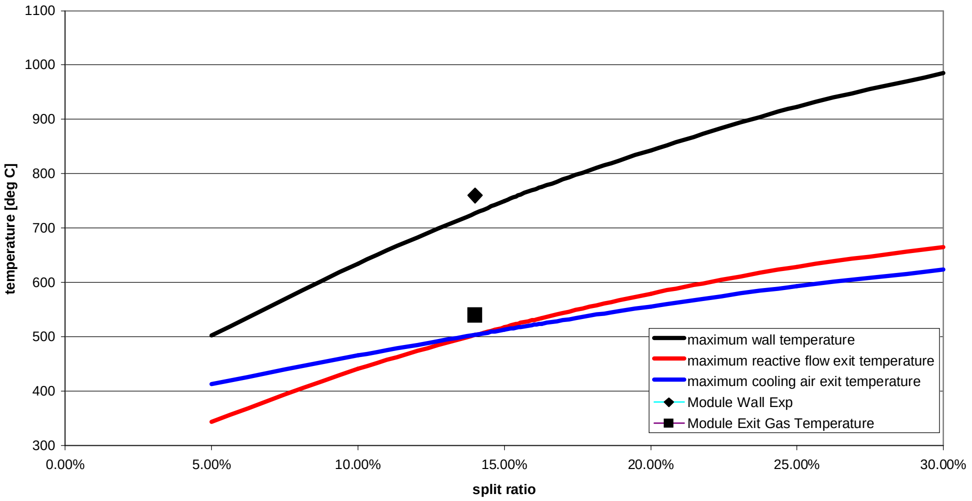

**Figure 9 Reactor Temperatures on Natural Gas for a Typical Gas Turbine**

Figure 10 shows the same temperature plot for syngas fuel. The model shows that syngas is reactive on the catalyst surface and that stable operation of the reactor can be maintained at the anticipated syngas flows of a typical IGCC application. Looking at the figures the optimal flow split for the syngas would be different than natural gas. At a given split the syngas temperatures are higher. This present a challenge in the design of a fuel flexible gas turbine combustor which has acceptable performance on both fuels.

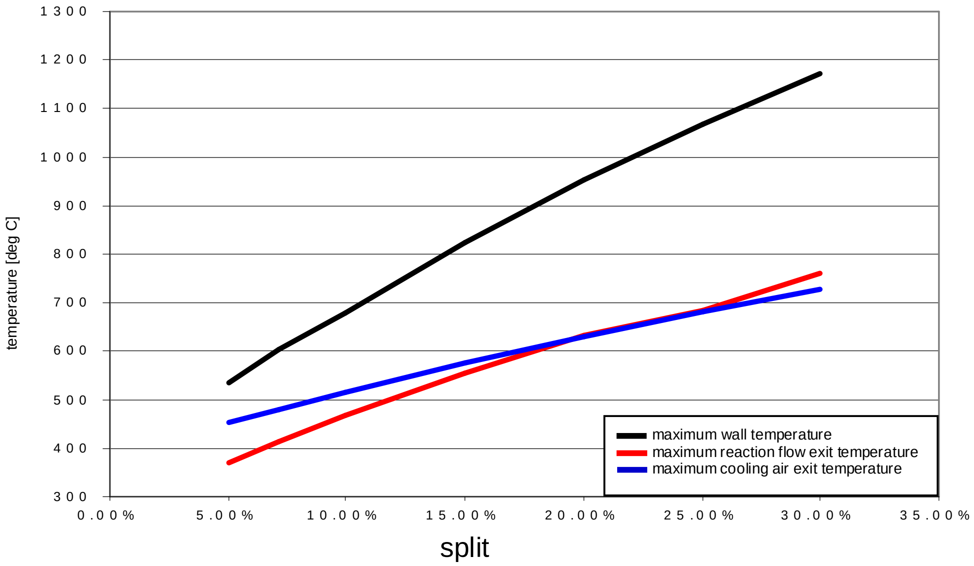

**Figure 10 Reactor Temperatures for Syngas for a Typical Gas Turbine**

Because the air split between the fuel rich section and the cooling air is controlled by component flow resistances through the flow paths, it is difficult to design a reactor which can achieve optimal operation for both syngas and natural gas. The high fuel flow through the catalytic module during syngas operation causes a high pressure drop through the reacting flow path and therefore reduces the air split during syngas operation. Although the engine can operate successfully with a lower air split to the fuel region, the performance of the system can be improved if the air split flow is increased. To maintain optimal reactor performance on both natural gas and syngas, several potential design configurations were investigated. These configurations can be grouped into three types as listed in Table 2.

In the first configuration the catalytic reactor is optimized for natural gas and some of the syngas fuel is diverted from the catalyst section using additional fuel staging. By diverting fuel flow during syngas operation the pressure drop through the fuel rich path will be reduced, resulting in an increase in the split flow. Two options were studied for diverting the syngas fuel. The first option is to preferentially inject roughly 20% of the syngas along with some of the nitrogen produced in the air separation unit (ASU) at a point upstream of the entrance to the cooling tubes. This option would increase the air split by forcing some of the fuel flow through the cooling air flow path while also reducing the flow though the reacting mixture pathway. The amount of fuel injected in this manner would be limited to insure that the mixture on the cooling air side of the catalytic reactor is always below the flammability limits. A second option would be to inject roughly 25% of the syngas directly into the burnout zone. This would again increase the split air because the total flow through the rich fuel air path would be reduced. These two staging options could also be combined to obtain the maximum amount of split air and therefore maximize the conversion.

The second configuration would be to keep all of the fuel in the module and find a way to increase the air supply pressure to the fuel manifold. By increasing the air pressure only to the fuel manifold it is possible to maintain a higher air split flow during syngas operation. One means of increasing the air pressure in the manifold is to use the syngas fuel to drive an air eductor connected to the fuel manifold. The disadvantage of this configuration would be the requirement of a higher syngas pressure to drive the eductor.

The third configuration involves redesigning the reactor to get the optimal air split during syngas operation. If the reactor is optimized for syngas, the air split through the catalyst section would be too high for natural gas operation, resulting in excessive catalyst surface temperatures. To maintain safe operation on natural gas fuel, it would be necessary to add a valve restricting the air to the split region during natural gas operation. Preliminary modeling has shown that all of these configurations can be made to work for a fuel flexible catalytic combustor. The next phase of the project is to perform a more detailed analysis of each configuration and downselect the final combustor design.

**Table 2 – Summary of Catalytic Combustor Design Options for IGCC**

| Concept Approach | Syngas Operation | Natural Gas Operation |
|---|---|---|
| No change to the current catalytic module design. Bypass the catalyst section with some fuel during syngas operation. | Options include staging or bypassing syngas and nitrogen to increase fuel conversion on the reactant side. | No impact |
| No change to the current catalytic module design. Increase air flow through the reaction side using an eductor. | Syngas air split can be optimized but will require higher syngas pressure to drive the eductor | No impact |
| Modify current catalytic module for syngas. | Can be optimized for syngas conversion. | Requires device to control air split during natural gas operation |

## Conclusions

The rich catalytic design has shown the potential for ultra low NOx emissions and robust operation while operating on natural gas fuel. Modeling of the combustion system has shown that this design can also be applied to syngas. Catalytic coatings have been identified which will produce acceptable lightoff characteristics on both syngas and natural gas. Several options have been identified for optimal operation on both fuels. Additional work will be necessary to down select the final design for the fuel flexible coatings have been identified which have acceptable performance, lightoff and conversion, for both fuels.