3.2.2.2

Catalytic Combustion in Large Frame Industrial Gas Turbines

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3.2.2.2-1 Introduction

Large frame gas turbine engines employ three different types of combustion systems: diffusion flame, lean premixed combustion and catalytic combustion. In diffusion flame combustors the fuel and air are injected separately into the combustion zone where they mix and react. Because of the nature of the design, these combustion systems tend to have flame temperatures that are typical of stoichiometric combustion and therefore produce high NOx emissions. Obtaining reasonable emissions from a diffusion flame combustion system generally requires the injection of diluents into the combustion section to lower the flame temperature, typically either water or steam. At current F-class firing temperatures these systems can produce NOx emissions in the range of 25 ppm NOx. In the lean premixed combustion system, the fuel and air are allowed to premix upstream of the flame zone. This results in a significantly lower flame temperature than the standard diffusion flame combustor resulting in lower NOx emissions without the need to inject water or steam. The limitation on low emissions from the lean premixed combustion systems is the combustion instabilities which occur as the lean flammability limit of the mixture is approached. These instabilities can lead to large pressure fluctuation in the combustion chamber. At F class temperatures the lean premixed combustion system can obtain NOx emissions in the range of 7-9 ppm. The catalytic combustion system shows promise to achieve lower emissions because the combustion instabilities at the lean flammability limit are no longer a limiting factor. Although catalytic combustion systems have not yet been employed in large industrial gas turbines, results from current development are encouraging and emissions in the range of 2-3 ppm are achievable.

3.2.2.2-2 Catalytic Combustion Design

The major development effort for catalytic combustion in large frame gas turbine engines was initiated as part of the DOE ATS program[1]. The goal of the ATS program was the development of a high–efficiency, high-firing temperature engine (>1700 K) with NOx emissions less than 10 ppm for lean premixed systems and 5 ppm for the catalytic system. On this program the basic design of the catalytic combustor for a large industrial gas turbine was developed. Since this program, considerable progress has been made on the design.

At the high firing temperatures of a typical gas turbine engine, it is not possible to design a pure catalytic approach where all of the fuel is reacted in the catalyst section. In the current design philosophy a hybrid catalytic two stage system is employed where the catalyst stage is followed with a homogeneous burnout region. Generally these systems will react 20-40% of the fuel in the catalytic stage. By reacting a portion of the fuel in the catalyst the stability of the flame in the homogeneous burnout zone is significantly improved. The hybrid catalytic combustion systems that have been investigated for large gas turbine engines are the lean catalytic lean burn (LCL) design and the rich catalytic lean burn (RCL) design.

Figure 1 shows the basic concept of the LCL design. In this design all of the fuel and air are premixed upstream and enter the catalyst section under fuel lean conditions. At the end of the catalyst section any fuel not reacted is burned out in a homogeneous reaction zone. To insure proper catalyst activity, this concept requires an inlet temperature of fuel air mixture to the catalyst of approximately 500 C. Since this temperature is higher than the compressor exit temperature of a typical gas turbine engine, a preburner will be necessary to achieve the desired catalyst inlet conditions. Operation of the catalyst in the lean region requires very close control of the air fuel ratio in the vicinity of the catalyst to avoid high reaction rates and excessive catalyst temperatures. The lean combustion concept has been pursued by Catalytica in their patented Xonon technology. This technology has been commercially operated on a small scale in the Kawasaki 1.5 MW engine. On large frame engines this technology has been studied by General Electric and Siemens Westinghouse.

Figure 2 shows a basic concept of the RCL design. In this design the inlet air flow to the catalyst is separated into two streams. A portion of the air is mixed with the fuel and reacts on the surface of the catalyst under fuel rich conditions. The remaining air is used to backside cool the catalyst. The two streams mix at the catalyst exit and then react and burnout in the homogeneous reaction zone. By operating the catalyst in the fuel rich region, the reaction rate is limited by the rate of diffusion of oxygen to the catalyst surface. Therefore this design is able to tolerate wider variations in air fuel ratio within the catalyst region than the LCL design. In this design the preburner is no longer required as the fuel and air react at compressor exit temperature typical of gas turbine engines. The choice of catalyst material is critical for this design in order to insure proper catalyst lightoff. Precision Combustion, Inc and Siemens Westinghouse have pursued the RCL combustion design[2].

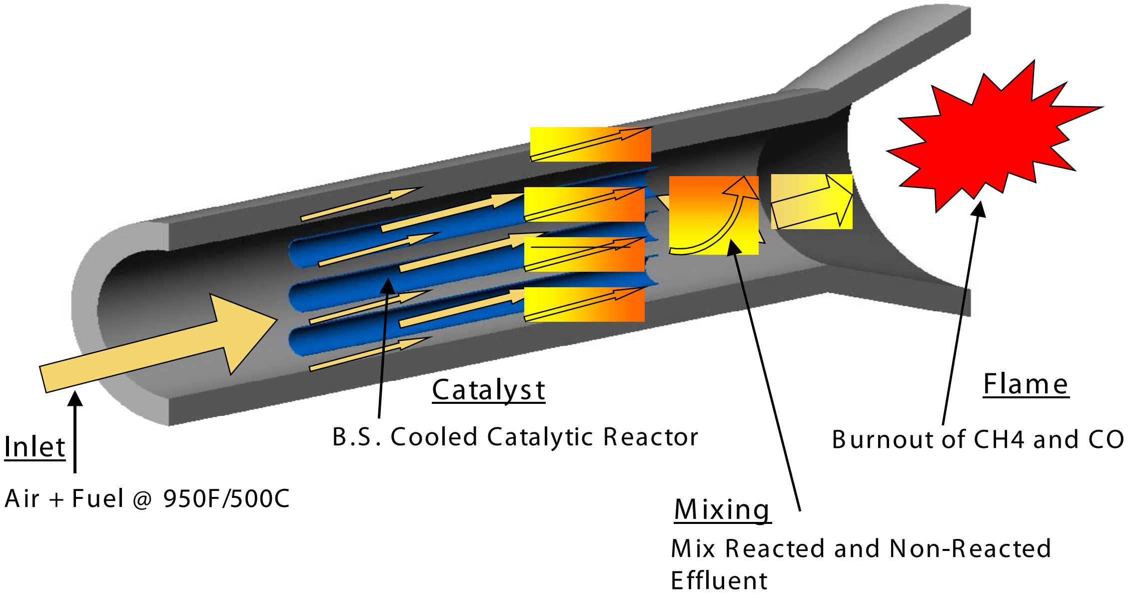

Fig. 1. LCL Combustion System

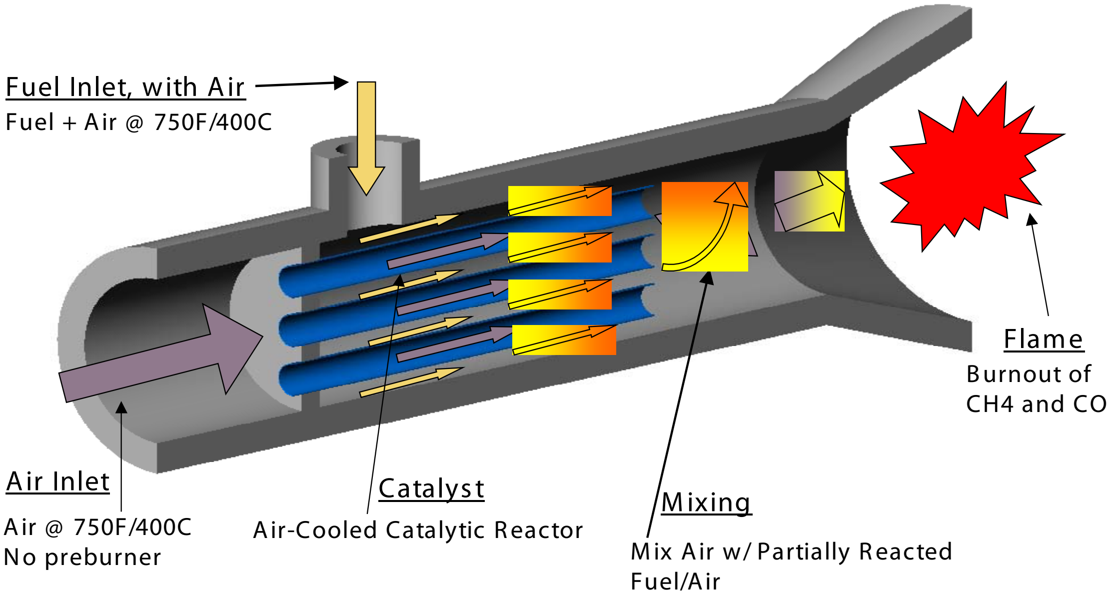

Fig. 2. RCL Combustion System

3.2.2.2-3 Rich Catalytic Combustion Applied to Large Gas Turbine Engines

As part of the ATS program, Siemens Westinghouse performed an evaluation of both the RCL and LCL systems. Based on subscale module testing of both technologies, it was clear that either design could meet the emission targets of the catalytic program. The RCL design was chosen for two main reasons. By eliminating the pre-burner, the design was much more compact and could be easily fit into the existing envelope of the current gas turbine combustor without major modification to the casing. Also because of the operation in the rich region the design was much more tolerant of variations in both air and fuel flow. Over firing tests were performed on both designs and the RCL design was able to survive a severe over fuel transient without damage. This was not the case for the LCL design. Under the ATS program, the basic design of the RCL catalytic module was developed and the conceptual design of catalytic basket was developed. This design was continued for application to the lower firing temperature SGT6-3000E engine. Full scale basket testing was performed on this design at both E-class and F-class firing temperatures.

During the initial development phase of the RCL design, testing was performed on the subscale module level. The full scale combustor basket was divided into 6 individual subscale modules each of which was designed to operate at 1/6 of the total combustor basket flow. The basic design of the RCL catalytic module is shown in figure 3. In this design the catalyst is composed of tubes with catalytic coating on the outside surface. These tubes are brazed to a plate on the upstream end and flared on the down stream end. A portion of the inlet air (~15%) enters the fuel mixing chamber where fuel is injected and allowed to mix before entering the catalyst region. This rich fuel air mixture flows along the outside of the tubes and is allowed to react on the catalyst surface. The remaining air enters the inside of the tubes and provides backside cooling for the catalyst surface. Both streams are allowed to mix down stream of the catalyst zone before they enter the homogeneous reaction zone. The ratio of air flow between the reacting fuel region and the cooling air is determined by pressure drops between the two flow paths. For a given design the fuel split is fixed. Figure 4 shows the catalytic module design used for testing.

Catalytic module testing was performed at full engine conditions for both the STG-6-3000E and the STG-6-5000F engines. Module testing confirmed that emissions could be maintained at less than 2 ppm NOx and 10 ppm

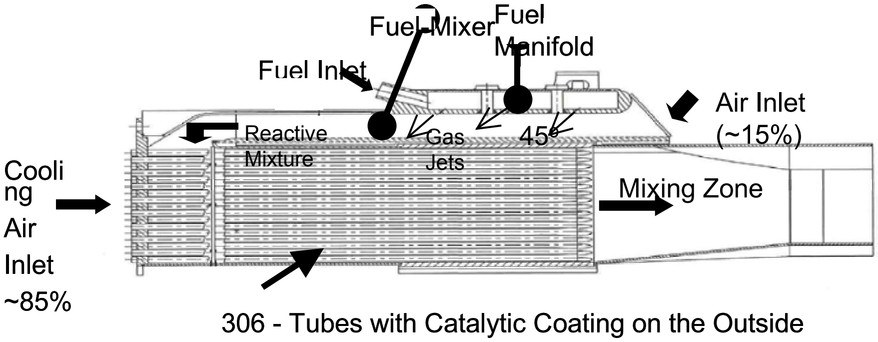

Fig. 3. Rich Catalytic Module Design

Fig. 4. Rich Catalytic Module Design

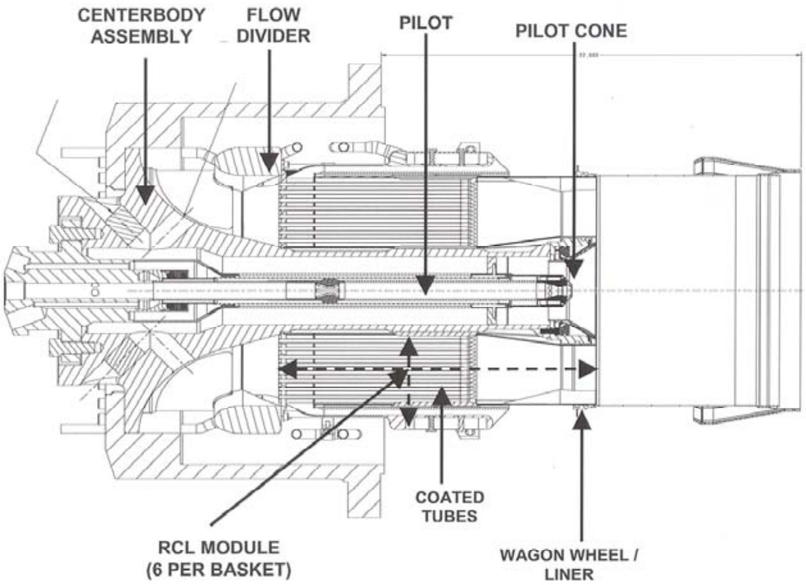

Fig. 5. Catalytic Combustor for the Siemens SGT6-5000F Engine

CO for a wide range of conditions including both the E and F class engines. Throughout all conditions the catalyst and metal temperatures remained within limits.

A full scale combustor basket was designed using 6 catalytic modules surrounded by a central pilot[3]. Figure 5 shows the combustor configuration envisioned for use in the Siemens gas turbine engine. The pilot is necessary to insure stable operation of the combustor basket at low loads. The goal of the design is to minimize or completely shut off the fuel flow to the pilot at baseload conditions. Although the pilot contributes to NOx emissions, this can be minimized by replacing the standard diffusion pilot design with a premixed pilot. Based on this concept, a full scale basket was fabricated and tested at the Siemens full pressure single basket test facility in Italy. This facility duplicates the geometry and flow conditions (pressure, temperature, air and fuel flow) of a single basket as installed in a Siemens gas turbine engine. Data was obtained for a range of firing temperatures encompassing the SGT-6-3000E and the SGT-6-5000F engines. The basket used for these tests is shown in figure 6.

As expected, the emissions for the full basket tests were slightly higher than those of the module tests due to the pilot. For the SGT-6-3000E engine it was necessary to add dilution air to raise the combustor temperature in order to achieve proper CO burnout. At these conditions the catalytic combustion system was able to produce emissions of 3.3 ppm NOx and 7 ppm CO. When the temperature was increased to SGT-6-5000F conditions, the improved stability at higher temperatures enabled the combustor to run at a significantly lower pilot fraction. The resulting NOx and CO emissions were nearly the same as for the lower firing temperature conditions, 3.6 ppm NOx and 9 ppm CO. Basket and catalyst metal temperatures and combustor pressure oscillations were well below the design limits during the test. As part of this test program, an overfiring test was performed, with no damage to the catalytic module components.

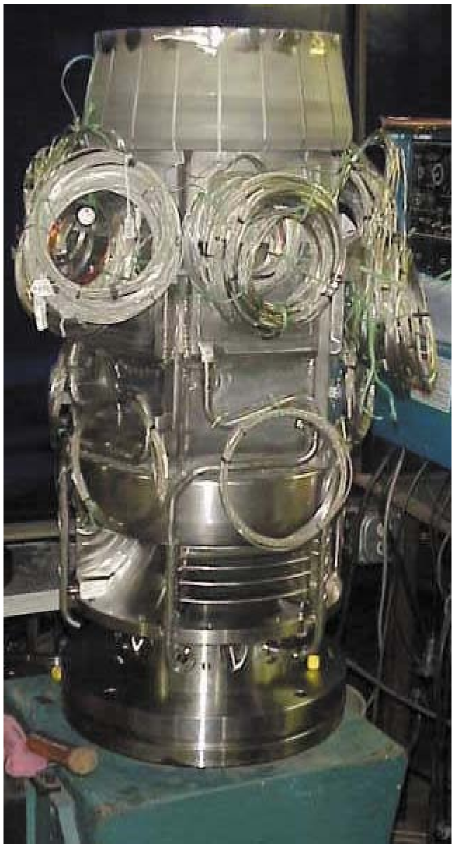

Fig. 6. Full Scale Catalytic Combustor

3.2.2.2-4 Conclusions

The rich catalytic combustion approach has been designed for application to the Siemens SGT-6-3000E and STG-6-5000F engine. Rig testing has shown that the design is capable of emissions in the range of 2 –3 ppm at SGT-6-5000F temperatures. This design has been shown to be robust with respect to variation in air and fuel flow. Additional work is underway to reduce the emissions. Current development on the RCL concept is focused on the fuel flexibility aspects of the design and the application to syngas and hydrogen fuels.

3.2.2.2-5 Notes

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1. D.B Fant,G.S. Jackson, H. Karim, D.M. Newburry, P. Dutta, K.O. Smith, and R.W. Dibble, “Status of Catalytic Combustion R&D for the Department of Energy Advanced Turbine Systems Program,” *ASME Journal of Enginering for Gas Turbines and Power*, (2000): 293-300.

2. L. Smith, et al, US Patent No. 6,174,159, “Method and Apparatus for a Catalytic Firebox Reactor,” 1999; W.C. Pfefferle, L. Smith, M.J. Castaldi, US Patent No. 6,358,040, “Method and Apparatus for a Fuel Rich Catalytic Reactor,” 2000.

3. D.M. Newburry, US Patent No. 6,415,608, “Piloted Rich-Catalytic Lean-Burn Hybrid Combustor,” 2000.

BIOGRAPHY

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Dr Laster has a Ph.D. in Mechanical Engineering from Purdue University with a specialty in the area of combustion. He taught combustion and heat transfer at Texas A&M University. He has 12 years industrial experience in the gas turbine field at Siemens Westinghouse. He has been involved in the design of dry low NOx combustors and catalytic combustion systems. He has been involved in several projects related to alternatuve fuels for gas turbine systems.