THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS
345 E. 47th St., New York, N.Y. 10017

98-GT-287

THE ULTIMATE NOx SOLUTION FOR GAS TURBINES

J. Charles Solt
csolt@mv.catalytica-inc.com

Catalytica Combustion Systems Inc.
www.catalytica-inc.com

ABSTRACT

Since the introduction of emission standards for gas turbines in the late '70s and early '80s, the gas turbine industry has responded with a variety of combustion and cleanup alternatives that have improved emissions. While the emissions were being reduced, the cost of control, and the negative environmental impacts were often significant.

Thanks to a technological breakthrough, catalytic combustion has now been achieved, and can fulfill the promise of low cost NOx elimination without the high cost of SCR or the operational problems associated with Lean Pre-Mix.

NOx Formation

NOx is composed of oxygen and nitrogen, so the air entering the engine, consisting of 21% oxygen and 79% nitrogen, contains all the ingredients necessary to produce this pollutant. The only additional factor that is required is a temperature high enough to cause oxygen and nitrogen to combine (see Fig 1). Turbine manufacturers try to prevent the formation of NOx primarily by reducing the peak flame temperature below the range in which NOx is formed.

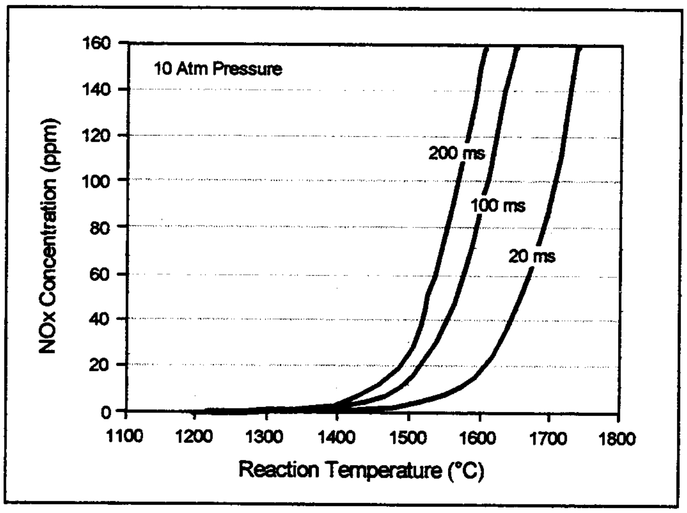

Figure 1. NOx Formation as a function of Time and Temperature

Diffusion Flame Combustion

Before the concern about NOx emissions arose, gas turbine manufacturers primarily aimed at building a rugged, long-life combustor with a good temperature distribution, reliable light-off, and which would not flame out under transient load conditions. To achieve these design goals it was helpful to burn the fuel under conditions that were very close to stoichiometric, that is, conditions where there is just enough oxygen to burn all of the fuel. Under

Presented at the International Gas Turbine & Aeroengine Congress & Exhibition
Stockholm, Sweden — June 2–June 5, 1998

stoichiometric conditions, the fuel burns at the highest possible temperature in the primary combustion zone, so these conditions produce large amounts of NOx.

Dry Control

Following the introduction of NOx control requirements, turbine manufacturers examined the possibility of operating away from high-temperature stoichiometric conditions. Operating under lean conditions, where there is more air in the primary combustion zone than is necessary to burn all the fuel, lowers the peak temperature and reduces NOx formation. This was referred to as "dry control", and usually resulted in a NOx reduction of only 10-20%.

Wet Controls

The turbine manufacturers next developed wet controls. These controls inject water or steam into the primary combustion zone along with the fuel. The water or steam serves as a diluent that reduces peak flame temperature and hence NOx formation. The advantage of water is that it requires only about half as much water as does steam to obtain a given amount of NOx reduction. Consequently, water introduces fewer contaminants than does steam, assuming the water and steam are of the same quality. Both water and steam increase the power output because there is more mass flow through the engine, but they also increase the maintenance costs. Water injection also greatly increases the fuel consumption for a given amount of power. Steam injection reduces fuel consumption. However, if there is another use for steam at the facility, fuel will be required to replace the steam injected, so both water and steam injection significantly increase the overall fuel requirements. Applications of these technologies can result in a substantial increase (>50 ppm) in CO and UHC.

Lean Premixed Technology

Turbine manufacturers then developed processes that use air as a diluent rather than water or steam. Manufacturers achieved this by premixing the fuel and air before they enter the combustor. This type of process is called *lean premix combustion*. Lean premix combustion processes developed by gas turbine manufacturers have a variety of names, including the Dry-Low NOx (DLN) process of General Electric, the Dry-Low Emissions (DLE) process of Rolls-Royce and the SoLoNOx process of Solar Turbines.

Most industrial gas turbine manufacturers have programs to develop lean premix combustion systems. Most of the commercially available systems are guaranteed to reduce NOx emissions to a level in the range of 25-42 ppm, depending on the manufacturer and the particular turbine model. A few manufacturers have guaranteed lower emission levels, but some of these manufacturers are experiencing problems with combustion noise and combustor deterioration. Applications of these technologies can result in a substantial increase (>50 ppm) in CO and UHC.

SCR

Another approach to controlling NOx is to remove the NOx from the turbine exhaust. A number of technologies are available to remove NOx from exhaust streams. The first of these technologies to be developed was Selective Non-Catalytic Reduction (SNCR), which is the basis of a proprietary Exxon process called Thermal DeNOx. In this process ammonia is injected into the combustion products at a temperature of about 900°C (1650°F) and the NOx reacts with the ammonia producing nitrogen and water. However, this process is not applicable to gas turbines because the required temperature of 900°C (1650°F) occurs in the middle of the expansion section, so it is not possible to achieve good mixing with the injected ammonia. Fuel Tech has developed a similar SNCR process, called NOxOut, based on urea rather than ammonia. Although this process operates at lower temperatures than the Exxon process, it still requires too high a temperature to be applicable to gas turbines.

Another technology for removing NOx from exhaust is Non-Selective Catalytic Reduction (NSCR), which has been used successfully for a number of years with reciprocating engines (piston engines). However, this technology requires operating under rich, rather than lean conditions, which is not possible for gas turbine systems.

A third technology is Selective Catalytic Reduction (SCR). In SCR, the NOx reacts with an injected reducing agent, usually ammonia, on the surface of a catalyst. The required temperature is much lower than for SNCR processes, such as Thermal DeNOx or NOxOut, so SCR processes have been used successfully with gas turbines for several years. SCR typically produces a reduction of 80% in the level of NOx entering the catalytic unit. The operating temperature of an SCR unit is usually too low to allow the turbine exhaust to be injected directly into the unit. Instead the exhaust first enters a heat recovery device, such as a boiler, with the SCR unit placed in the middle of the device. This is a very common arrangement in gas turbines with heat recovery equipment and should certainly be addressed in permit applications for gas turbines.

SCR is a relatively expensive control technology, so it may not be cost-effective if the economic impact is evaluated on an incremental basis. However, if the economic impact is evaluated on a total basis, with SCR combined with water injection, for example, then SCR may appear to be cost-effective. The economic impact of SCR combined with one of the dry low NOx technologies is essentially the same on a total or incremental basis, since the starting point is the level of NOx produced by the turbine using the dry low NOx technology.

The lower the level of emissions from the gas turbine the less cost effective SCR technology will be. With a control technology that reduces NOx to extremely low levels, SCR will never be economically viable and applicants will not be forced to use this technology. For this reason it is often worthwhile to consider control technology that reduces NOx to very low levels.

Catalytic Combustion

Catalytic combustion has also been investigated for a number of years as a means of controlling NOx in gas turbines. An advantage of catalytic combustion is that it is flameless combustion, as the fuel and air react on a catalytic surface. There has been a major breakthrough in catalytic combustion recently, the XONON Flameless Combustion™ control technology, developed by Catalytica Combustion Systems Incorporated (CCSI), achieves 3 ppm NOx with CO and UHC < 10 ppm.

This catalytic combustion technology, which is the result of several key inventions, is a breakthrough in providing ultra-low emissions for both current and future gas turbine engines. This technology is the "ultimate" step in pollution prevention for gas turbines.

Over the last five years, CCSI has developed a proprietary catalytic combustion system. This system is now in commercial demonstration.

The catalytic combustion system, which is completely contained within the combustor of the gas turbine, is a new way to carry out combustion that prevents the formation of NOx while achieving low CO and UHC levels.

The success of the system results from a two stage combustion process in which about half of the fuel is combusted within the catalyst module, and the remainder burns homogeneously downstream of the catalyst. This process is flameless, and typically produces less than 1 ppm of NOx. Depending on the temperature of the air leaving the compressor (or recuperator), a pre-burner may be required to achieve the temperature required for the catalytic reaction. Where a pre-burner is used, most of the NOx (usually less than 3 ppm) is formed in the pre-burner.

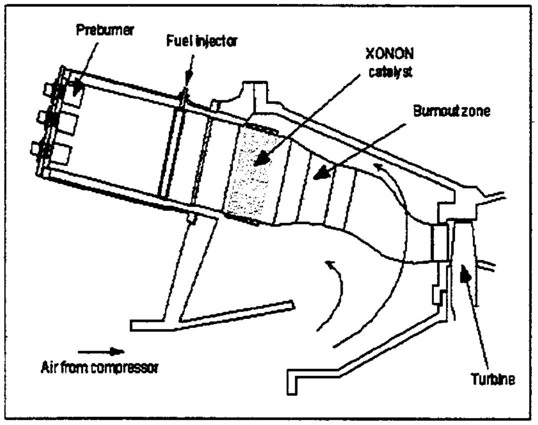

Figure 2. Catalytic Combustor System

There are two proprietary features of the system that allow it to succeed where other attempts have failed.

- The catalyst module incorporates a chemical thermostat that acts to limit the catalyst temperature even at relatively high fuel/air ratios, so that the gas temperature within the catalyst can be significantly below the turbine inlet temperature. This feature provides long catalyst module life and the ability to use the same technology for a variety of gas turbine inlet temperatures ranging from 825°C (1515°F) to 1500°C (2730°F).
- The catalyst module is composed of several sections, each designed to perform a specific function and achieve a specific operating temperature. This provides maximum flexibility, allowing engineers to design the optimum system for a specific gas turbine.

With the catalytic combustion system, the combustor can produce the very high outlet gas temperatures required for modern gas turbines, but the catalyst operates at a relatively low temperature. This allows the use of a metal substrate which provides good durability for the overall combustor system.

In both the catalytic combustion system and lean premix combustors fuel and air are premixed to minimize the peak combustion temperature. However, in the lean premix combustor the fuel-air mixture has a much higher combustion temperature than in the catalytic combustion system as a conventional flame must be generated and sustained at the very high gas velocities present in the lean premix combustor. The higher combustion temperature results in higher levels of NOx. If more air is mixed into the fuel in a lean premix system to further reduce the NOx level, the flame becomes unstable and combustor noise and vibration become problems.

In the catalytic combustion system the fuel-air mixture is very dilute; in fact, the mixture is so dilute that it would not support a conventional flame. Nevertheless the catalyst module can combust this fuel-air mixture without a flame. In addition, the catalyst is designed to combust only a portion of the fuel, providing the ability to control the gas outlet temperature from the catalyst module to a temperature that allows the use of a metal substrate for the catalyst. Downstream of the catalyst the remaining fuel combusts in a flameless homogeneous reaction that produces almost no NOx.

With extensive development, lean pre-mix combustion systems have only achieved NOx levels of about 25 ppm or, in a few cases, 15 ppm. With only a few years of development, full scale tests at turbine operating conditions for a variety of turbines, the catalytic combustion system has already demonstrated NOx levels of less than 5 ppm and is expected to achieve levels of 2-3 ppm in commercial operation. Figure 3 shows the applicability of the catalytic combustion system over a wide range of combustor outlet temperatures, including advanced turbine designs. Even at combustor outlet gas temperatures of 1500°C (2730°F), envisioned for the next generation of turbines, the NOx level is only 2 ppm.

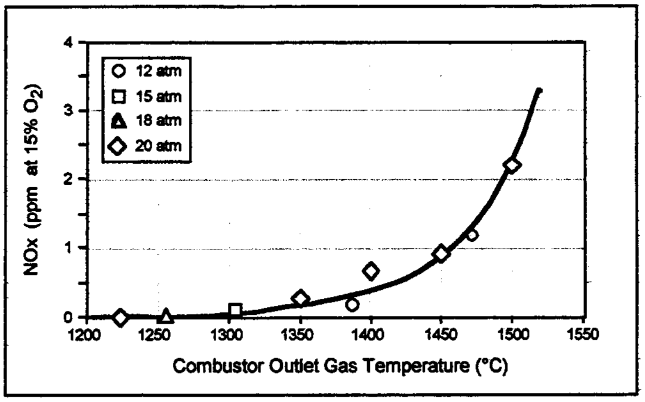

Figure 3. NOx emissions from a catalytic combustion system

Testing

Testing continues on the at CCSI to determine parameters such as catalyst performance, operating range, durability, susceptibility to contamination, etc. In addition, full scale testing at actual turbine operating conditions has been completed at both Solar and GE on single cans in the turbine companies testing facilities. Both of these tests demonstrated compliance with the goals, and showed NOx emissions of less than 3 ppm and CO and UHC below 10 ppm.

The catalytic combustion system has now completed a 1000 hour test in an actual industrial gas turbine engine (KHI M1A-13). The catalyst module showed no deterioration. The testing was performed in a test cell using a dynamometer as load. The test included over 250 start cycles, and numerous load changes. Testing again demonstrated the ability of the catalytic combustion system to achieve less than 3 ppm NOx while holding CO and UHC below 10 ppm.

Next Phase, will include field testing to demonstrate durability and operation under actual field conditions. Several sites under consideration, and the testing should be underway by the time the ASME Gas Turbine Conference starts in June of '98.

Conclusion

CCSI is now designing commercial combustion systems that will be in operation in late 1998. They have announced a joint program with GE to make the technology available for retrofit on existing units, and are working with several gas turbine OEMs to make it available on new products.