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Fuel Flexibility for Dry Low Emission Gas Turbines – Cleanly Burning Biofuels, Coal Liquids and Petroleum Fuels

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Dry low Emissions (DLE) systems employing lean, premixed combustion have been successfully used with natural gas in combustion turbines to meet stringent emissions standards. However, the burning of liquid fuels in DLE systems is still a challenging task due to the complexities of fuel vaporization and air premixing. Lean, Premixed, Prevaporized (LPP) combustion has always provided the promise of obtaining low pollutant emissions while burning liquid fuels such as kerosene and fuel oil. Because of the short ignition delay times of these fuels at elevated temperatures, the autoignition of vaporized higher hydrocarbons typical of most practical liquid fuels has proven difficult to overcome when burning in lean, premixed mode. To avoid this autoignition problem, developers of LPP combustion systems have focused mainly on designing premixers and combustors that permit rapid mixing and combustion of fuels before spontaneous ignition of the fuel can occur.

The work presented in this paper briefly describes the development of a patented low- NO_x LPP system for combustion of liquid fuels and presents some applications for this technology. In the initial phase of the development, laboratory-scale experiments were performed to study the combustion characteristics, such as ignition delay time and NO_x formation, of the liquids fuels that were vaporized into gaseous form in the presence of nitrogen diluent. In phase two, an LPP combustion system was commissioned to perform pilot-scale tests on commercial turbine combustor hardware. These pilot-scale tests were conducted at typical compressor discharge temperatures and at both atmospheric and high pressures.

In this study, vaporization of the liquid fuel in an inert environment has been shown to be a viable method for delaying autoignition and for generating a gaseous fuel stream with characteristics similar to natural gas. Tests conducted in both atmospheric and high pressure combustor rigs utilizing swirl-stabilized burners designed for natural gas demonstrated operation similar to that obtained when burning natural gas. Emissions levels were similar for both the LPP fuels (fuel oil #1 and #2) and natural gas, with any differences ascribed to the fuel-bound nitrogen present in the liquid fuels. Since the same combustor hardware can be used for both natural gas and LPP fuels, the operator has the flexibility to utilize a variety of fuels at a given site, without suffering any penalties in emissions.

Introduction

Traditionally, spray diffusion combustors have been employed in gas turbines that operate on liquid fuels such as fuel oil #1 and fuel oil #2. However, this diffusion mode of operation tends to produce unacceptable levels of NO_x emissions. The current technology for burning liquid fuels in gas turbines is to use water and/or steam injection with conventional diffusion burners. Emissions levels for a typical "state of the art" gas turbine, such as a GE 7FA burning fuel oil #2 in diffusion mode with water/steam injection, are 42 ppm NO_x and 20 ppm CO [1]. Water/steam injection has a dilution and cooling effect, lowering the combustion temperature and thus lowering NO_x emissions. But at the same time, water/steam injection is likely to increase CO emissions as a result of local quenching effects. Thus, the "wet" diffusion type of combustion system for liquid fuels must trade off NO_x emissions for CO emissions.

In recent years, stringent emissions standards have made lean, premixed combustion more desirable in power generation and industrial applications than ever before, since this combustion mode provides low NO_x and low CO emissions without water addition. Lean, premixed combustion of natural gas avoids the problems associated with diffusion combustion and water addition. Thus, lean, premixed combustion is the foundation for modern Dry Low Emissions (DLE) gas turbine combustion systems. When operated on natural gas, DLE combustion systems provide NO_x and CO emissions of 25 ppm or less with no water addition. However, these systems cannot currently operate in premixed mode on liquid fuels because of autoignition and flashback within the premixing section.

Plee and Mellor [2] characterized autoignition of the fuel/air mixture in the premixer as an important factor that causes flashback in practical combustion devices. Autoignition of the fuel/air mixture occurs before the main combustion zone, when the ignition delay time of the fuel/air mixture is shorter than the mean residence time of the fuel in the premixer. Autoignition preferentially occurs with the higher-order hydrocarbon fuels, such as fuel oils, which have shorter ignition delay times compared to natural gas [3]. The short ignition delay times of vaporized higher hydrocarbons have proven difficult to overcome when burning in lean, premixed mode.

Nevertheless, in order to overcome high NO_x levels produced by spray combustion, gas turbine users still desire to use Lean, Premixed, Prevaporized (LPP) combustion. Several approaches have been reported in the literature to overcome flashback and autoignition in the premixers of LPP combustors [4–12]. These approaches attempt to achieve low NO_x emissions by designing premixers and combustors that permit rapid mixing and combustion before spontaneous ignition of the fuel can occur. In most of the work reported on LPP combustion systems in the literature, the fuel is sprayed directly into the premixer so that the liquid fuel droplets vaporize and mix with air at lean conditions. Typically, swirlers with multi-port liquid fuel injection systems are employed for better fuel/air mixing [7]. However, unlike these attempts to alter hardware, there has been no reported work on altering fuel combustion characteristics in order to delay the onset of ignition in lean, premixed combustion systems.

In this study, vaporization of the liquid fuel in an inert environment has been shown to be a technically viable approach for LPP combustion. As described in this paper, a patented fuel vaporization and conditioning process [13] was developed and tested to achieve low emissions (NO_x and CO) comparable to those of natural gas while operating on liquid fuels, without water or steam addition. In this approach, liquid fuel is vaporized in an inert environment to create a fuel vapor/inert gas mixture, LPP gas, with combustion properties similar to those of natural gas. Premature autoignition of the LPP gas was controlled by the level of inert gas in the vaporization process. Tests conducted in both atmospheric and high pressure test rigs utilizing typical swirl-stabilized burners (designed for natural gas) found operation similar to that achieved when burning natural gas. Emissions levels were similar for both the LPP gas fuels (fuel oil #1 and #2) and natural gas, with any differences in NO_x emissions ascribed to fuel-bound nitrogen present in fuel oil #2. Also, tests showed that the LPP combustion system helps to reduce the NO_x emissions by facilitating stable combustion even at very lean conditions when using liquid fuels. Extended lean operation was found for the liquid fuels due to the wider lean flammability range for these fuels compared with natural gas. An added advantage of the fuel vaporization and conditioning process is the ability to achieve fuel-interchangeability of a natural gas-fired combustor with liquid fuels. This was described in much greater detail in a recent paper [14].

SINGLE GAS TURBINE BURNER TESTING

Combustion tests of the LPP Combustion System were performed on actual turbine hardware at both atmospheric and high pressure conditions. A Solar Turbines Centaur 50 gas turbine fuel nozzle was used for all real hardware tests [15]. This natural gas nozzle was used for the vaporized liquid fuel (LPP gas) tests without any modifications. Tests were conducted at single nozzle, full load conditions for a Centaur 50 at atmospheric pressure, and for a Taurus 60 and Taurus 70 gas turbine at full pressure.

The atmospheric pressure, swirl-stabilized burner was coupled to the fuel vaporization system used for the experiments. This laboratory test facility was able to supply up to 0.6 kg/s flow rate of air for the atmospheric pressure tests and included a quartz combustion liner to view the flame. Atmospheric pressure tests were performed with combustion air at typical gas turbine compressor discharge temperatures of 600 K to 620 K. The elevated pressure tests were conducted on a full temperature, full pressure combustor test stand capable of supplying combustor air at typical compressor discharge temperatures and pressures. During these high pressure gas turbine burner tests, the liquid fuel was supplied in gaseous form from the LPP liquid fuel vaporizer skid shown in Figure 1.

Figure 1: LPP liquid fuel vaporizer skid used for gas turbine burner testing at elevated pressures.

The testing involved a study of emissions and combustion characteristics, such as flame stability and lean blow-out limits. Both the atmospheric pressure and high pressure tests were performed at typical compressor discharge temperatures. For the high pressure tests, typical compressor discharge pressures were also used. Figure 2 shows a representative atmospheric pressure flame structure for natural gas and for fuel oil #1 from a Centaur 50 fuel nozzle at full load conditions. As can be seen in the figure, the LPP flame with fuel oil #1 exhibits a very similar flame structure and color to that of the natural gas flame.

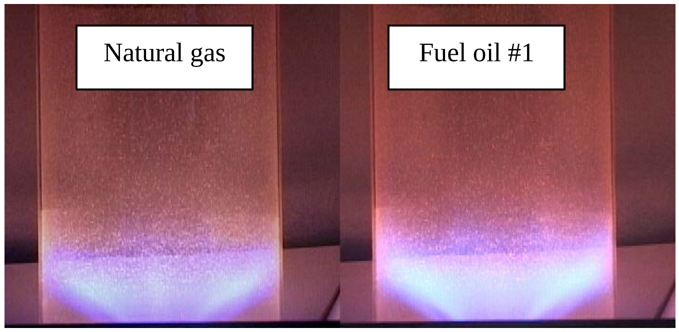

Figure 2: Comparison of natural gas and fuel oil #1 flames at atmospheric pressure for Centaur 50 fuel nozzle at full load conditions.

Figures 3 and 4 show the results of atmospheric pressure testing of a single gas turbine fuel nozzle at Centaur 50 full load conditions for three fuels. Prevaporized fuel oil #1 and fuel oil #2 run as LPP gas both show low NO_x and CO emissions comparable to those of DLE combustion systems fired on natural gas. The figures show that these low NO_x and low CO emissions are achieved simultaneously. As discussed earlier, the primary difference between natural gas and LPP gas NO_x emissions can be attributed to the fuel-bound nitrogen present in the fuel oils. Also, during the testing, no flash backs were observed at any of the test conditions when operating on the fuel oils using the LPP system, and a stable flame was easily maintained when switching fuels from natural gas to LPP gas and back again.

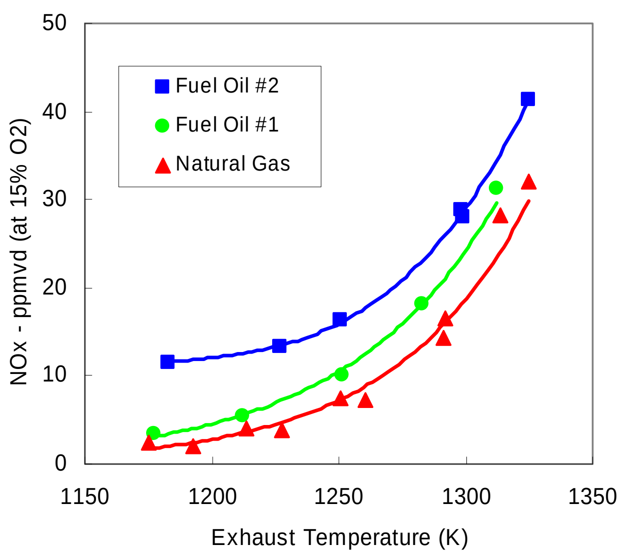

Figure 3: Comparison of NOx emissions measurements for fuel oil #2, fuel oil #1, and natural gas as a function of measured exhaust gas temperature for a single fuel nozzle at Centaur 50 full load conditions (100%). Combustion air temperature was 613 K, combustor pressure was 1 atm, and fuel dilution was 6:1 (molar basis).

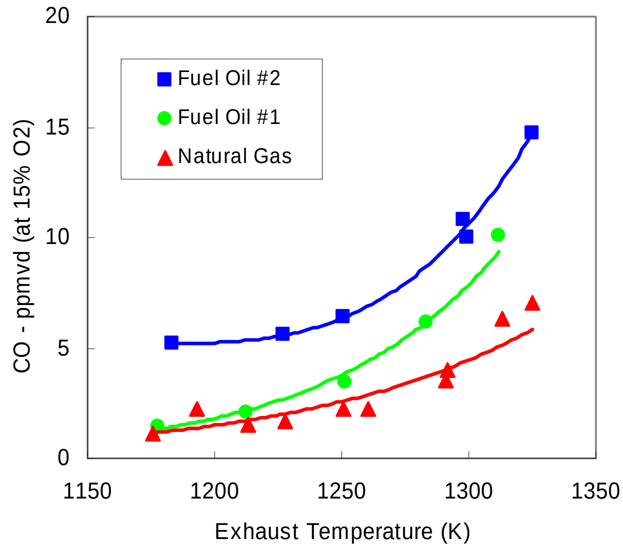

Figure 4: Comparison of CO emissions measurements for fuel oil #2, fuel oil #1, and natural gas as a function of measured exhaust gas temperature for a single fuel nozzle at Centaur 50 full load conditions (100%). Combustion air temperature was 613 K, combustor pressure was 1 atm, and fuel dilution was 6:1 (molar basis).

Actual turbine hardware tests were conducted using a high pressure facility capable of testing a single gas turbine fuel nozzle at full compressor discharge temperature and pressure. The LPP liquid vaporizer shown in Figure 1 was used to supply the liquid fuels in gaseous form. The same fuel nozzle used for natural gas testing was also used for liquid fuel testing on LPP gas without any modifications. Figure 5 shows NO_x and CO emissions at full load conditions for both natural gas and fuel oil #2.

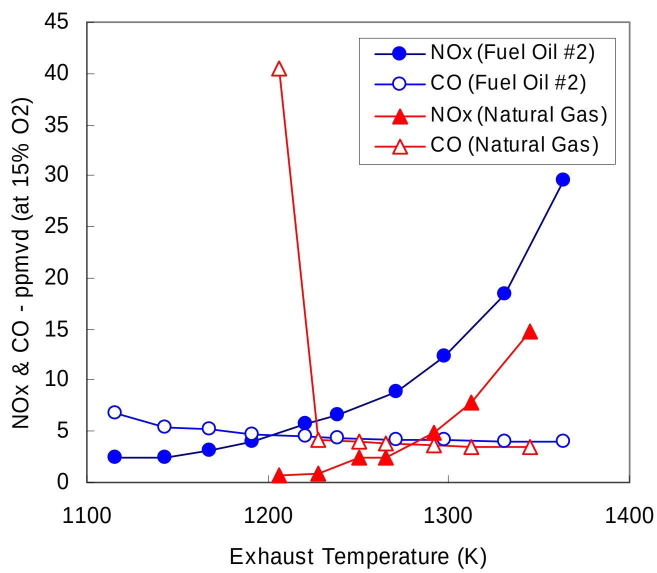

Figure 5: Comparison of NOx & CO emissions measurements for fuel oil #2 and natural gas as a function of measured exhaust gas temperature for a single fuel nozzle at Taurus 60 full load

conditions (100%). Combustion air temperature was 648 K, combustor pressure was 12.6 atm, and fuel dilution was 5:1 (molar basis).

During the testing, emissions and dynamics data were taken over a range of lean equivalence ratios from approximately 0.75 to the lean blow-off (LBO) limit. However, the emissions data is plotted against measured exhaust gas temperature in order to provide a common temperature reference. The lowest temperature data points shown in Figure 6 reflect the experimentally observed LBO limit. Figure 5 shows that fuel oil #2 LPP gas has an extended LBO limit compared to natural gas and thus can achieve NO_x emissions nearly as low as natural gas despite the fuel-bound nitrogen.

Figure 5 also shows that the crossover point between NO_x and CO emissions extends to lower temperatures (and therefore lower equivalence ratios) for fuel oil #2 LPP gas as compared to natural gas. As can be seen from the figure, fuel oil #2 LPP gas showed increased flame stability and an extended LBO limit at lower temperatures (equivalence ratio) compared to natural gas.

Figure 6 shows comparable NO_x and CO emissions for both Taurus 60 and Taurus 70 single nozzle full load conditions. The data indicate that similar emissions are achieved, even though the Taurus 70 full load conditions are at higher temperature and pressure than the Taurus 60 operating conditions. Finally, as was observed in the atmospheric pressure tests, these high pressure tests also demonstrate that stable burner operation was easily maintained when switching fuels from natural gas to LPP gas and back again.

The significance of the data shown in Figure 6 is that liquid fuels such as fuel oil #2 LPP gas are able to achieve low NO_x emissions levels similar to natural gas. For an exhaust temperature (firing temperature) of 1318 K, Figure 6 shows NO_x and CO emissions for natural gas to be 9 ppm and 3.5 ppm, respectively. The comparable fuel oil #2 LPP gas emissions at the same exhaust temperature are 16 ppm for NO_x and 4.0 ppm for CO. Because the LPP gas fuel characteristics are similar to those of natural gas, Fuel oil #2 LPP gas is capable of being used in modern DLE gas turbine combustion systems without changes to the burner hardware while achieving much lower NO_x and CO emissions than fuel oils burned in conventional spray flames with water addition.

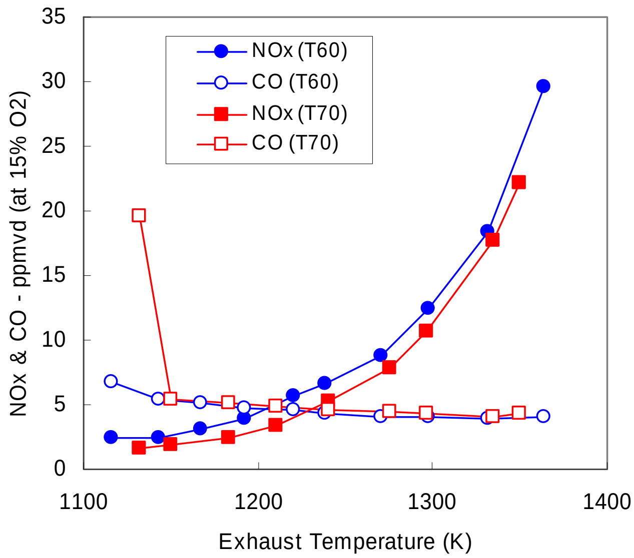

Figure 6: Comparison of NOx & CO emissions measurements for fuel oil #2 as a function of measured exhaust gas temperature for a single fuel nozzle at Taurus 60 (T60) and Taurus 70 (T70) full load conditions (100%). Combustion air temperatures were 648 K (T60) and 706 K (T70), combustor pressures were 12.6 atm (T60) and 16.2 atm (T70), and fuel dilution was 5:1 (molar basis).

BIODIESEL FUEL TESTING

Additional testing of the LPP Combustion System was performed in an atmospheric pressure combustor rig using B100 biodiesel. Two types of biodiesel were used for testing, one based on palm oil (palm methyl ester, (PME)) and the other based on soy oil (soy methyl ester (SME)). For this testing, the Solar Turbines Centaur 50 natural gas nozzle was used with no modifications to the burner hardware. Again, combustor inlet temperatures were maintained at typical compressor discharge temperatures of 600 K to 630 K. Figure 7 shows a photograph of the biodiesel flame viewed through the quartz combustor liner. A comparison of Figure 7 with the flame images for natural gas and fuel oil #1 presented in Figure 2 shows that the biodiesel burned as a lean, premixed LPP Gas also produces a clean, light blue flame similar to natural gas and fuel oil.

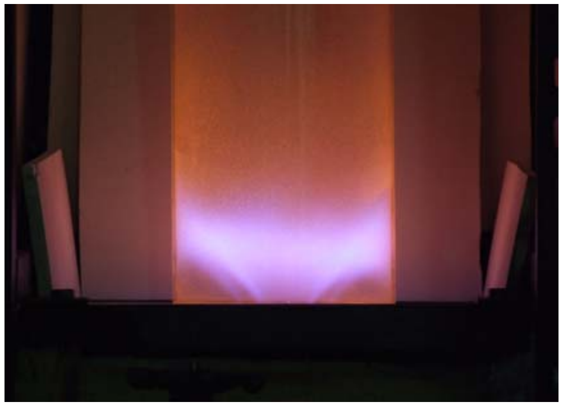

Figure 7: Soy-based biodiesel flame at atmospheric pressure for Centaur 50 fuel nozzle at full load conditions.

Figure 8 shows a comparison of NO_x results obtained for biodiesel with those of natural gas and fuel oil #1 and fuel oil #2. As can be seen in the Figure, the biodiesel emissions are similar to those obtained from natural gas and fuel oil #1 and slightly lower than the NO_x emissions obtained from fuel oil #2. This result is to be expected since the biodiesel contains no significant fuel-bound nitrogen. Fuel bound nitrogen levels in the biodiesel fuels tested ranged from 2.1 to 4.1 ppm by weight. For reference, the fuel bound nitrogen level for the fuel oil #2 tested was 0.04 by weight (400 ppm by weight).

Figure 9 shows a similar comparison of CO results obtained for biodiesel with those of natural gas and fuel oil #1 and fuel oil #2. This Figure shows that the biodiesel also produces very low CO emissions when burned premixed using the LPP Combustion System. Unlike some combustions systems where NO_x and CO emissions must be traded-off with each other, the LPP Combustion technology simultaneously achieves both low NO_x and CO emissions when burning liquid fuels.

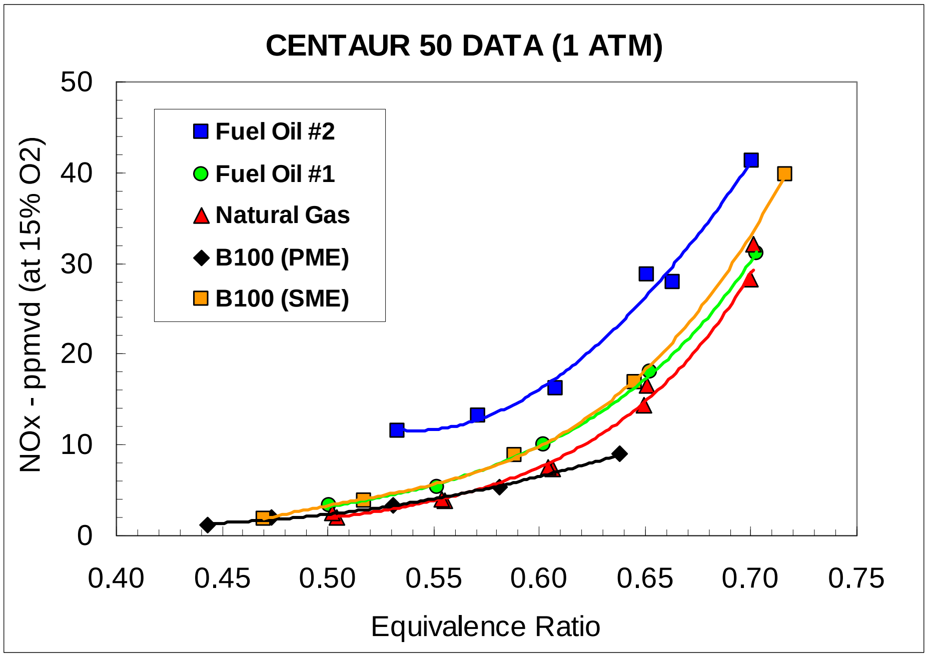

Figure 8. NOx emissions measurements for fuel oil #2, fuel oil #1, natural gas and biodiesel as a function of measured equivalence ratio for a single fuel nozzle at Centaur 50 full load conditions (100%). Combustion air temperature was 625 K, combustor pressure was 1 atm and fuel dilution was 5:1 (molar basis).

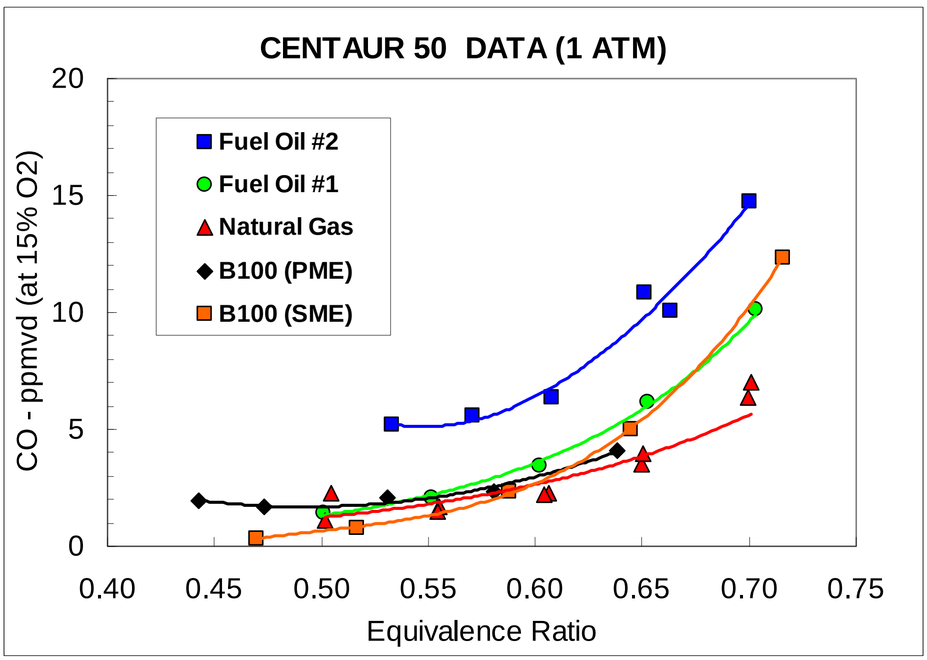

Figure 9. CO emissions measurements for fuel oil #2, fuel oil #1, natural gas and biodiesel as a function of measured equivalence ratio for a single fuel nozzle at Centaur 50 full load conditions (100%). Combustion air temperature was 625 K, combustor pressure was 1 atm and fuel dilution was 5:1 (molar basis).

These results demonstrate that the LPP Combustion System is capable of burning biodiesel, a renewable fuel, in a gas turbine combustor with NO_x and CO emissions similar to those obtained from operation on natural gas. These results were obtained using a commercial DLE gas turbine nozzle designed for lean, premixed combustion of natural gas with no modifications to the nozzle hardware. Thus, using the LPP Combustion System, a DLE gas turbine can achieve extremely low NO_x and CO emissions and produce no "net" greenhouse gases when burning biodiesel.

FISCHER-TROPSCH FUEL TESTING

Additional testing of the LPP Combustion System was performed in an atmospheric pressure combustor rig using synthetic JP-8 fuel (called S-8) created using the Fischer-Tropsch process from natural gas. Studies have shown that fuels resulting from the Fischer-Tropsch process have the same characteristics and are chemically identical even though they may have been created from different feedstock such as natural gas, biomass or coal [16].

For this testing, the Solar Turbines Centaur 50 natural gas nozzle was again used with no modifications to the burner hardware. Combustor inlet temperatures were maintained at typical compressor discharge temperatures of 600 K to 630 K. The S-8 fuel burned as a lean, premixed LPP Gas also produces a clean, light blue flame similar to natural gas and fuel oil shown in Figure 2.

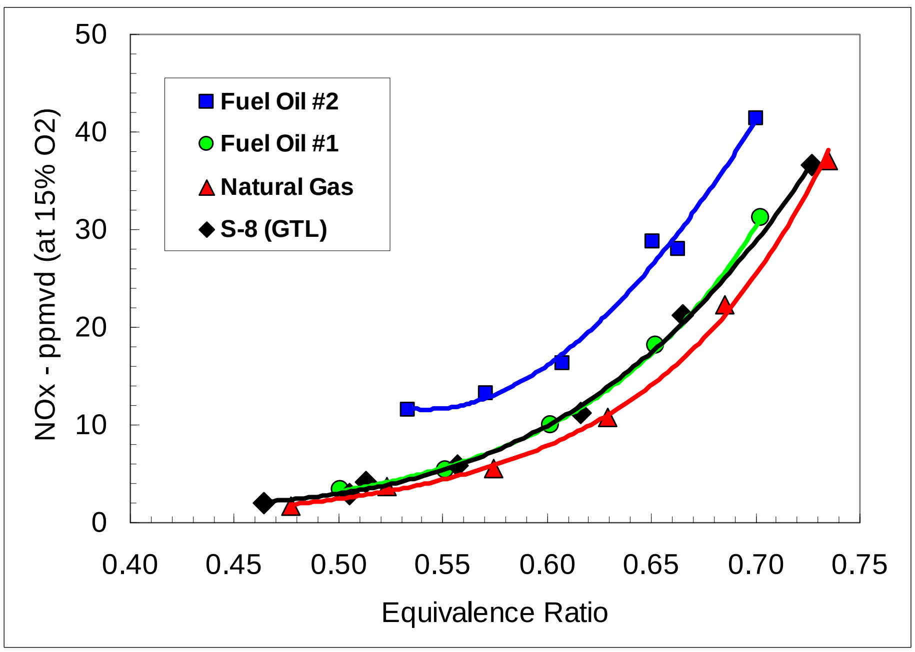

Figure 10: Comparison of NOx emissions measurements for fuel oil #2, fuel oil #1, synthetic JP-8 (S-8) and natural gas as a function of equivalence ratio for a single fuel nozzle at Centaur 50 full load conditions (100%). Combustion air temperature was 627 K, combustor pressure was 1 atm, and fuel dilution was 5:1 (molar basis).

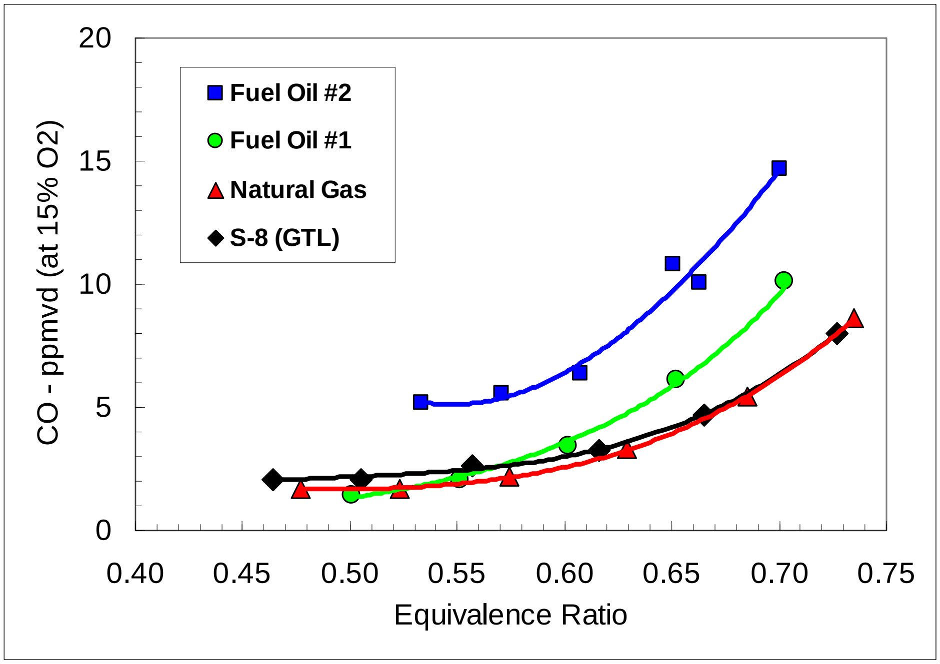

Figure 11: Comparison of CO emissions measurements for fuel oil #2, fuel oil #1, synthetic JP-8 (S-8) and natural gas as a function of measured exhaust gas temperature for a single fuel nozzle at Centaur 50 full load conditions (100%). Combustion air temperature was 627 K, combustor pressure was 1 atm, and fuel dilution was 5:1 (molar basis).

Figure 10 shows a comparison of NO_x emissions obtained for S-8 with those of natural gas and fuel oil #1 and fuel oil #2. As can be seen in the Figure, the S-8 emissions are similar to those obtained from natural gas and fuel oil #1 and significantly lower than the NO_x emissions obtained from fuel oil #2 containing fuel bound nitrogen. The low NO_x emissions were to be expected since the S-8 contains no fuel-bound nitrogen. Figure 11 shows a similar comparison of CO emissions obtained for S-8 with those of natural gas and the fuel oil #1 and fuel oil #2. This Figure shows that the S-8 also produces very low CO emissions when burned lean, premixed and prevaporized using the LPP Combustion System.

These results demonstrate that the LPP Combustion System is capable of burning a Fischer-Tropsch fuel, in this case S-8, in a DLE gas turbine combustor with NO_x and CO emissions similar to those obtained from operation on natural gas. These results were obtained using a commercial gas turbine nozzle designed for lean, premixed combustion of natural gas with no modifications to the nozzle hardware. Similar results are expected for any Fischer-Tropsch fuel, including naphtha, diesel or heating oils derived from a variety of feedstocks.

Discussion

The emissions and operational characteristics of the Lean, Premixed, Prevaporized combustion technology results described in this paper represent a new and clean way of burning a wide range of liquid fuels. The LPP technology focuses on changing the characteristics of the fuel rather than trying to change the combustion hardware. Since the LPP Combustion system utilizes burners designed for natural gas, no changes to the DLE gas turbine combustor hardware was required. The LPP Combustion system provides the capability to cleanly burn liquid fuels and achieve natural gas level emissions without the need for post combustion pollution control equipment.

The LPP technology demonstrated that natural gas level emissions can be obtained for a wide range of fuels including fuel oil #1, fuel oil #2, biodiesel and S-8 (synthetic JP-8). Figure 12 shows the full load NO_x performance for a range of fuels using LPP Combustion technology compared to both natural gas performance and the fuel oil #2 diffusion "spray" flame benchmark with water addition. Similar emissions to that of natural gas can be obtained for fuel oil #2 with the small difference in NO_x emissions (about 6 ppmv @ 15% O2) attributable to fuel bound nitrogen.

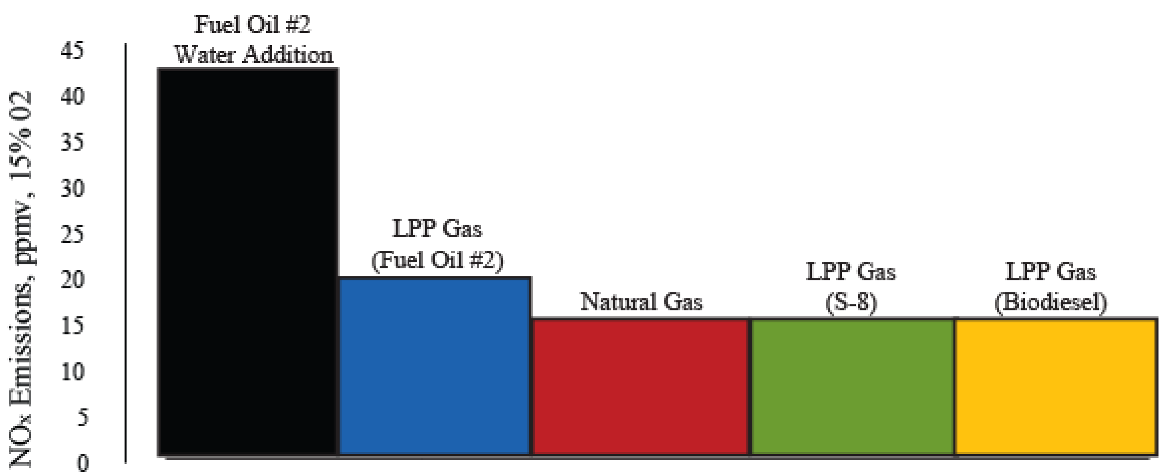

Figure 12: Comparison of NO_x emission benchmark (42 ppmv) for liquid fuel oil #2 with NOx emission performance for fuel oil #2, biodiesel, synthetic JP-8 (S-8) and natural gas for a single fuel nozzle at Centaur 50 full load operating conditions (100%).

The big benefit of burning biodiesel is that the carbon emissions are considered to be "neutral" or "net zero" [17,18]. Conventional application of biofuels to gas turbines for the generation of renewable energy encounters the same emissions limitations on NO_x and CO as conventional petroleum fuels [19,20]. Water or steam addition is required in spray diffusion burners to achieved the "state of the art" benchmark level of 42 ppmv NO_x @15% O2. Figure 12 shows that the LPP Combustion technology offers a significant improvement over the 42 ppm NO_x level for liquid fuel operation and that natural gas level emissions can be achieved with liquid fuels. Burning biodiesel using the LPP Combustion technology achieves both natural gas level emissions and no "net" carbon emissions and thus represents the cleanest use of renewable fuels for power generation.

The results of burning S-8 and achieving natural gas level emissions is significant as it demonstrates the clean nature of Fischer-Tropsch fuels and the low emissions achievable using the LPP Combustion technology. The S-8 used for this test represents a surrogate for coal derived and biomass derived liquids. There is significant interest in utilizing coal derived liquids and biomass derived liquids today and into the future as fuels for transportation and power generation [21,22, 28]. Coal will continue to play and important role in the worlds energy needs for decades to come [26,29]. On possible route to "clean coal" is through the burning of coal derived liquids using LPP Combustion technology in high efficiency gas turbines.

The Fischer-Tropsch process has been used to make a variety of liquid fuels from coal and biomass feedstock and has been in commercial use around the world for many years [23,24,25]. The range of fuels typically produced include diesel, jet-A, JP-8 (S-8) and naphtha. Naphtha is a low value byproduct stream resulting from the Fischer-Tropsch process and occurs in significant quantities (20 to 44% of total output) [30,31]. Using LPP Combustion technology, this low value naphtha stream can be converted into high value steam and electricity while achieving natural gas level emissions. Using the naphtha for power generation leaves the "premium" fuels (Jet-A, S-8 & diesel) for transportation applications. With CO_2 sequestration during the coal to liquids process, burning naphtha in a high efficiency combined cycle gas turbine can produce power below the current California emission performance standard of 1,100 lbs CO_2/MW-hr [27].

Conclusions

This paper described the results from a patented low emission Lean, Premixed, Prevaporized (LPP) combustion system [13] for liquid fuels. In the LPP combustion system, liquid fuels were vaporized into gaseous form in an inert environment using nitrogen as the diluent. Results showed that diluent nitrogen increased the ignition delay time at typical air/fuel premixing conditions in gas turbines. Test performed with the LPP combustion system on a wide range of liquid fuels were able to produce low NO_x and CO emissions without autoignition and flashback. Increased flame stability and an extended lean blow-off limit were observed for the prevaporized liquid fuels compared to natural gas.

The fuels in gaseous form were burned in actual commercial DLE gas turbine combustor hardware designed for natural gas operation. No modifications to the combustor hardware were made to accommodate the vaporized liquid fuels. Low NO_x and CO emissions comparable to natural gas were achieved for all liquid fuels tested. The difference in NO_x between natural gas and fuel oil #2 was attributed to the conversion of fuel-bound nitrogen into NO_x. NO_x and CO emissions for biodiesel and the Fischer-Tropsch fuel S-8 were the same as natural gas. Low NO_x emissions for these fuels was expected as biodiesel has very little fuel bound nitrogen and the Fischer-Tropsch fuel S-8 has no fuel bound nitrogen.

The LPP Combustion system provides the capability for tremendous fuel flexibility and low emission not previously attainable in modern DLE gas turbines with liquid fuels. Natural gas level emissions have been demonstrated for conventional petroleum fuels (fuel oil #1 and fuel oil #2), renewable fuels (soy and palm oil based biodiesel) and Fischer-Tropsch fuels (S-8). The LPP Combustion technology provides fuel flexibility between natural gas and conventional petroleum fuels, enables the cleanest use of renewable fuels and provides a "clean coal" alternative when burning coal derived liquids in high efficiency combined cycle gas turbines.

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