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EXPERIMENTAL STUDY OF NO$_X$ FORMATION IN LEAN, PREMIXED, PREVAPORIZED COMBUSTION OF FUEL OILS AT ELEVATED PRESSURES

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ABSTRACT

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. However, none of the reported works in the literature has looked at altering fuel combustion characteristics in order to delay the onset of ignition in lean, premixed combustion systems.

The work presented in this paper describes the development of a patented low-NOx LPP system for combustion of liquid fuels which modifies the fuel rather than the combustion hardware in order to achieve LPP combustion. In the initial phase of the development, laboratory-scale experiments were performed to study the combustion characteristics, such as ignition delay time and NOx 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. Extended lean operation was observed for the liquid fuels as a result of the wider lean flammability range for these fuels compared with natural gas. Premature ignition of the LPP fuel was controlled by the level of inert gas in the vaporization process.

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 NOx 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 NOx and 20 ppm CO [1]. Water/steam injection has a dilution and cooling effect, lowering the combustion temperature and thus lowering NOx 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 NOx 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 NOx 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 NOx 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 especially 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 NOx levels produced by spray combustion, gas turbine designers still desire to use Lean, Premixed, Prevaporized (LPP) combustion. Several approaches have been reported in the literature [4–12] to overcome flashback and autoignition in the premixers of LPP combustors. These approaches attempt to achieve low NOx 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 (NOx 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 NOx emissions ascribed to fuel-bound nitrogen present in fuel oil #2. Also, tests showed that the LPP combustion system helps to reduce the NOx 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.

The initial phase of development of the LPP system described in this work involved laboratory-scale experiments to study combustion characteristics, such as ignition delay time and NOx formation, of the liquid fuels that are vaporized into gaseous form in the presence of nitrogen diluent. In the second phase of this program, the LPP system [13] was commissioned to perform large-scale pilot experiments on atmospheric pressure and high pressure test rigs. Fuel oil #1 and fuel #2 were chosen as typical liquid fuels for the tests. In this study, fuel oil #1 refers to commercially available kerosene, and fuel oil #2, known as diesel fuel #2, is similar to commercially available home heating oil. Also, for comparative study, experiments were performed with n-heptane, which is a widely studied liquid fuel. The chemical and physical specifications of the fuel oils are listed in Table 1. The chemical analysis shows that when compared to fuel oil #1, fuel oil #2 has a higher content of aromatics as well as fuel-bound nitrogen and sulfur.

		Fuel oil #1	Fuel oil #2
API gravity at 60 ^{o}F		45.7	37.6
Specific gravity at 60 ^{o}F		0.7985	0.8373
Visocity at 40 ^{o}C (cSt)		1.04	2.6
Molecualr Weight		150	182
Paraffins	vol%	83.6	79.3
Aromatics	vol%	15.7	19.8
Olefins	vol%	0.7	0.9
C	wt%	85.78	86.83
H	wt%	14.15	13.09
N	wt%	0.02	0.04
S	wt%	0.03	0.03
H/C Molar Ratio		1.91	1.85
Chemical Formulla		$C_{11}H_{21}$	$C_{13}H_{24}$

Table 1: Chemical and physical properties of fuel oil #1 and #2 used in the experiments.

EFFECT OF DILUENT ON IGNITION DELAY TIME

As discussed above, one of the causes of flashback in gas turbine combustors is the premature autoignition of the fuel in air during premixing. One way to avoid autoignition is to extend the induction period, known as the ignition delay time, of the fuel/air mixture, by reducing the formation of combustion radicals that are necessary for autoignition of the mixture at a given temperature. In hydrocarbon oxidation, during the induction period the diluent plays an important role as a third-body enhancer for recombination reactions and slows down the radical formation [14]. These effects, in turn, extend the induction period so that the ignition process will be delayed. Therefore, increasing the diluent fraction of the fuel/oxidant mixture will increase the ignition delay time. In the present work, the effect of diluents on ignition delay time was investigated for vaporized liquid fuels such as fuel oils and n-heptane.

The ignition delay time experiments were performed in an atmospheric pressure flow reactor, which consists of a

premixing section and a plug-flow test section. The fuel was vaporized to gaseous form in a preheated nitrogen environment before being mixed with air in the premixing section, which is located at the entrance to the reactor. Figure 1 shows the cross-sectional view of the premixing section. The premixing section opens into the plug-flow test section via an expanding duct in order to prevent the separation of flows at the entrance of the test section. The test section is a 52" x 2" alumina tube placed inside a furnace with three independently controlled zone heaters.
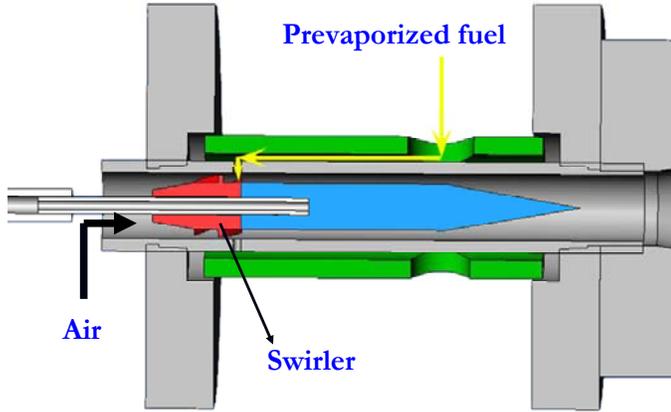
Figure 1: Schematic of the premixing section of the flow reactor used for ignition delay time measurements

One of the difficulties of any flow reactor experiment is mixing the fuel and oxidant quickly at the entrance to the reactor [15, 16]. In this work, the rapid mixing of the vaporized fuel with air was achieved by using a swirler followed by an expanding duct which opened into the test section. A photo-multiplier coupled with a narrow band filter (centered at 430 nm) was placed at the end of the test section to detect CH* emissions. The time between the injection of fuel vapor into the mixing section and the detection of the CH* emission signal was designated as the ignition delay time. The plug-flow test section was maintained at a constant initial reactor temperature. The flow reactor premixer temperature was maintained at 600 K in order to simulate the conditions in a gas turbine premixer. A detailed description of the flow reactor facility can be found in a previous publication [17].

Figure 2 shows the ignition delay time as a function of O_2 mole% in the inlet stream for n-heptane at 823 K and 900 K. The equivalence ratio of the fuel/oxidant mixture was maintained at stoichiometric conditions. The experimental measurements are compared with ignition delay time model predictions using the detailed kinetics mechanism of Curran et al. [18]. As can be seen in the figure, the effect of diluent on ignition delay time increases with decreasing inlet temperature. For example, for the n-heptane measurements shown in Figure 2, the ignition delay time is proportional to $[x_{O2}]^{-0.80}$ at 900 K and to $[x_{O2}]^{-2.2}$ at 823 K, where $[x_{O2}]$ refers to the mole% of O_2 in the inlet stream to the test section of the flow reactor.
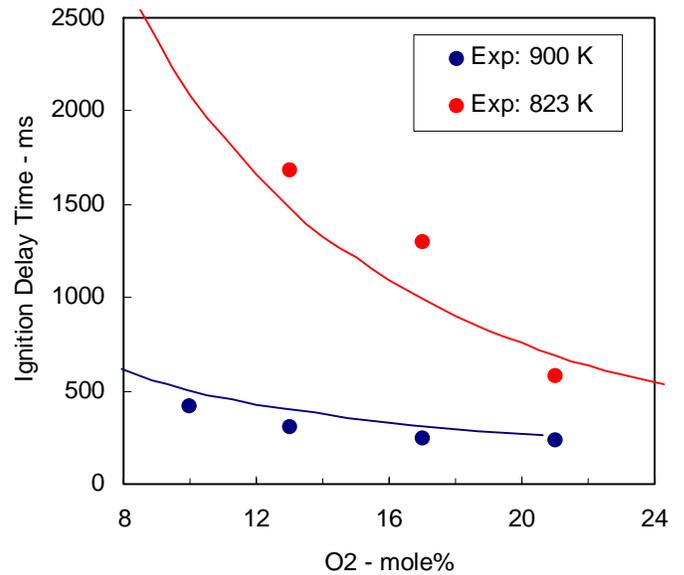

Figure 2: Atmospheric pressure ignition delay time measurements of stoichiometric n-heptane/O_2/N_2 mixture as a function of inlet O_2 composition. Key: symbols – experimental data; lines – ignition delay time model predictions using Curran et al. [18] detailed kinetic model.

Figure 3 compares the ignition delay time of both vaporized fuel oils with n-heptane as a function of O_2 mole% at the inlet to the flow reactor at 900 K. Both fuel oil #1 and fuel oil #2 show longer ignition delay times than those of n-heptane due to the presence of aromatic hydrocarbons in the fuel oils. Fuel oil #1 shows a similar O_2 dependency on ignition delay time as that of n-heptane. However, the effect of O_2 on ignition delay time is higher for fuel oil #2 compared to n-heptane. For example, for the ignition delay time measurements shown in Figure 3, the n-heptane ignition delay time is proportional to $[x_{O2}]^{-0.8}$, while the fuel oil #2 ignition delay time is proportional to $[x_{O2}]^{-1.0}$, where $[x_{O2}]$ refers to the mole% of O_2 in the inlet stream to the test section of the flow reactor.
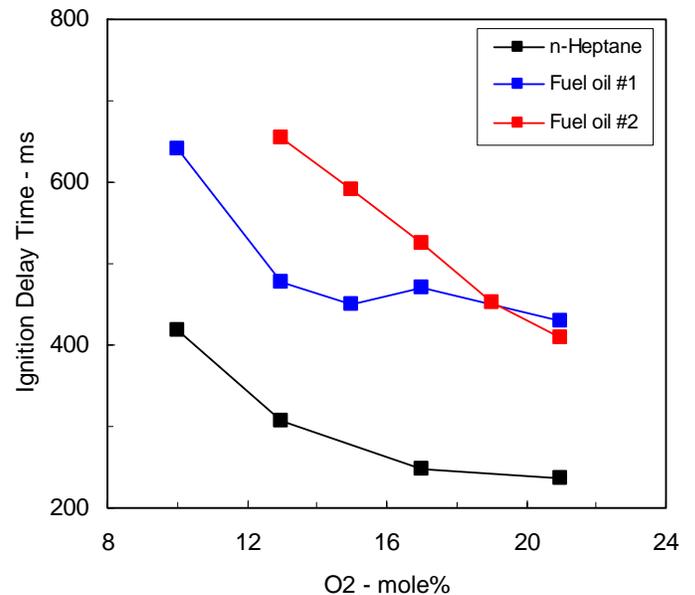

Figure 3: Comparison of ignition delay time measurements of n-heptane, fuel oil #1, and fuel oil #2 as function of inlet O_2 composition at 900 K inlet temperature, 1 atm pressure and 1.0 equivalence ratio.

3

EFFECT OF PRESSURE ON NO$_X$ FORMATION

In the LPP system design, the liquid fuel is vaporized in an inert environment to create a gaseous fuel. This gaseous fuel is then premixed with air and burned in a manner similar to lean, premixed natural gas combustion. However, fuel oil even as a gaseous fuel is expected to produce slightly higher NOx than natural gas fuel, as most fuel oils contain fuel-bound nitrogen. In this work, a series of experiments was performed over a range of pressures up to 10 atmospheres in a bench-scale, high pressure swirl burner to investigate the NOx production from the fuel oils when supplied as vaporized liquid fuels in an inert environment. To compare the formation of NOx with the vaporized fuel oils, experiments were also performed with natural gas.

The bench-scale LPP combustion system consists of a swirl-stabilized burner where a radially injected gaseous fuel stream is mixed with primary air before the fuel/air mixture reaches the burner surface. A cut-away view of the high pressure swirl burner is shown in Figure 4. A stand-alone vaporizing system for liquid fuels is directly connected to the fuel port of the swirler to supply the liquid fuel in gaseous form. Nitrogen was used as the diluent for vaporization. The burner was placed in a pressure vessel with a jacket cooling system along the wall. The pressure was varied from 1 atm to 10 atm. The air flow was varied from 1 g/s to 10 g/s with an input power of approximately 1 kW to 15 kW, respectively, for natural gas fuel. A water-cooled sample probe was placed just above the flame zone to draw exhaust gas samples into analyzers to measure CO, CO_2 and NOx emissions. Measurements of CO and CO_2 were obtained using nondispersive infrared ray absorption (NDIR) analyzers, while NOx was measured using chemiluminescence detection method.
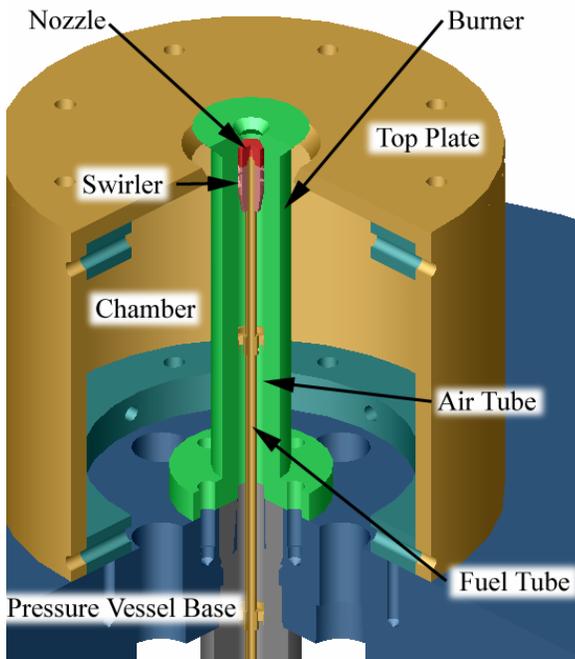

Figure 4: Cut-away view of the bench-scale, high pressure swirl burner used to investigate NOx emissions from the LPP combustion.

Experiments were performed to investigate the effect of diluent on NOx formation by varying the N$_2$ to fuel molar ratio in the vaporizer in a range from 2 to 10. During the experiments, nitrogen was preheated to 573 K (300°C) to vaporize the liquid fuel in the vaporizer. Figure 5 shows the NOx and CO measurements as a function of diluent to fuel molar ratio for fuel oil #2 at 5 atm and at an equivalence ratio of 0.6. In Figure 5, CO and NOx measurements show that the diluent N$_2$ to fuel molar ratio does not have any significant effect on CO and NOx emissions above a ratio of 4.
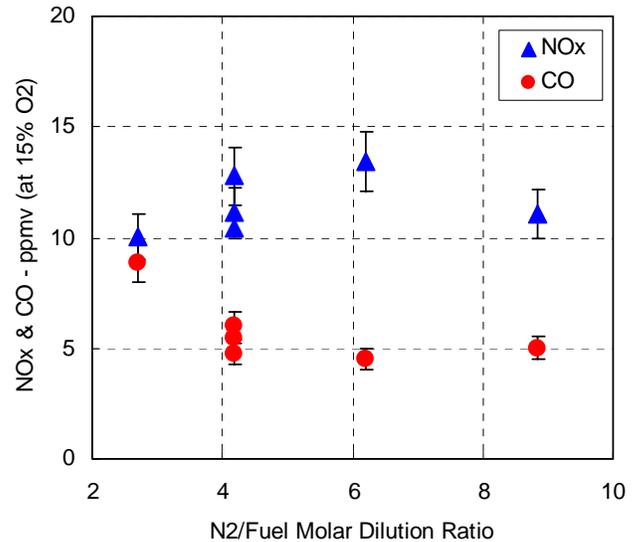

Figure 5: The effect of N2 to fuel dilution ratio on NOx and CO for fuel oil #2 at 5 atm and 0.6 equivalence ratio.

Figure 6 shows NOx measurements as a function of equivalence ratio for methane, fuel oil #1, and fuel oil #2 at several pressures. Due to the presence of fuel-bound nitrogen, the fuel oils produce higher NOx than methane. For methane, the NOx measurements increased from 2 ppm to 5 ppm when the equivalence ratio was increased from 0.55 to 0.75 at 2 atm. For fuel oil #2, the NOx increased from 5 ppm to 18 ppm when the equivalence ratio was changed from 0.5 to 0.7 at 8 atm. Fuel oil #1 and fuel oil #2 have 0.02 wt% and 0.04 wt% fuel-bound nitrogen, respectively, as listed in Table 1. Thus, potentially, the fuel-bound nitrogen can produce approximately 4 ppm and 10 ppm of NOx, respectively, for fuel oil #1 and fuel oil #2 at 0.6 equivalence ratio, assuming that all the fuel-bound nitrogen atoms are converted to NOx. At an equivalence ratio of 0.6, methane produced approximately 2 ppm NOx at 5 atm, as shown in Figure 6. The measured NOx emissions for fuel oil #1 and fuel oil #2 were 6 ppm and 10 ppm, respectively, at the same conditions. Thus, the difference in NOx between the methane and fuel oils can entirely be accounted for by the NOx that comes from the fuel-bound nitrogen.

The effects of pressure and equivalence ratio on NOx formation for fuel oil #2 are presented in Figure 7. The results are also compared with those of methane. The effect of pressure on NOx formation shows a similar trend for fuel oil #2 as for methane. When the equivalence ratio was increased from 0.5 to 0.7, the formation of NOx was increased by a multiple of approximately 2 for fuel oil #2, independent of pressure. Three factors contribute to the increase in NOx for

fuel oils as the equivalence ratio is increased: (1) the amount of fuel-bound nitrogen available for NOx conversion is also increased; (2) the increase in flame temperature creates more thermal-NOx formation; (3) the prompt-NOx contribution increases as the availability of CH-like radicals increases as the mixture gets richer. The last two factors also contribute to the increase in NOx for methane as the equivalence ratio is increased, as shown in Figure 6. The difference in NOx between methane and fuel oil #2 is equivalent to the NOx produced by the fuel-bound nitrogen.
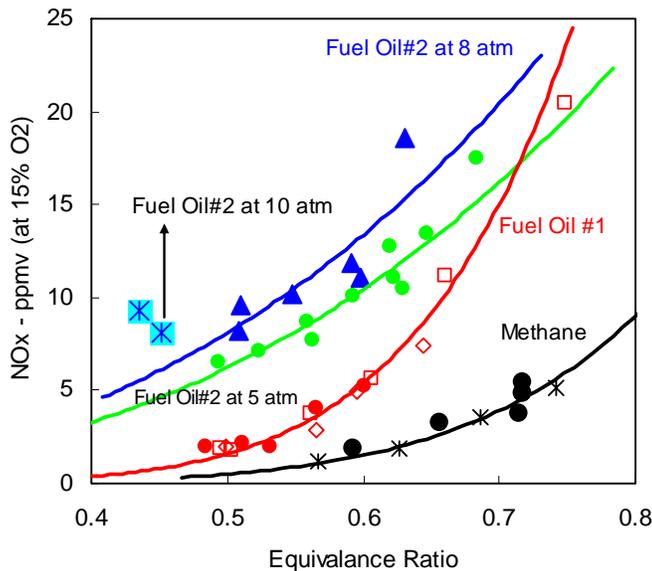
Figure 6: Comparison of NOx measurements for methane and fuel oil #1 and #2 as a function of equivalence ratio at varying pressures. Key: black – methane at 2 atm (*) and 5 atm (•) pressures; red – Fuel oil #1 at 3 atm (◊), 4 atm (□) and 5 atm (•) pressures; Green (•) – Fuel oil #2 at 5 atm; Blue (▲) – Fuel Oil #2 at 8 atm. The lines indicate the trends. Fuel to N_2 molar dilution was 1 to 5.
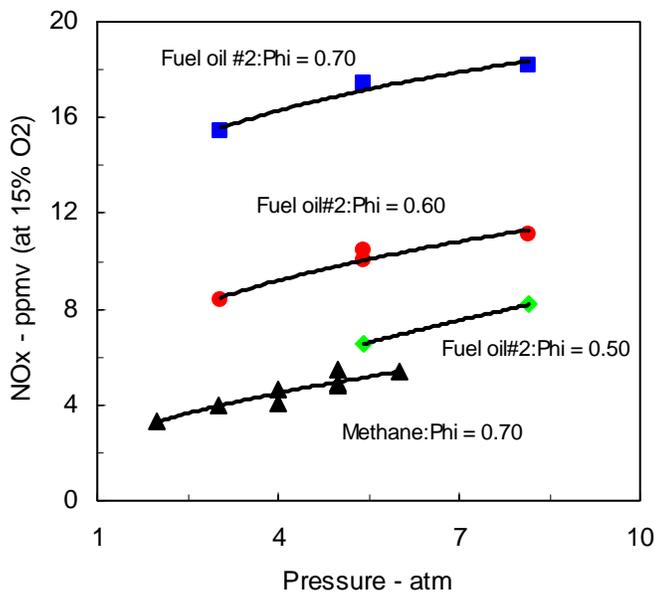

Figure 7: Comparison of NOx measurements for methane and fuel oil #2 as a function of pressure. Fuel to N_2 molar dilution was 1 to 5.

From the chemical composition analysis shown in Table 1, the contribution of fuel-bound nitrogen to the NOx would be 12 ppm for fuel oil #2 at 0.7 equivalence ratio. In Figure 7, the measured NOx for fuel oil #2 at 0.7 equivalence ratio is approximately equal to the NOx produced by methane plus 12 ppm fuel-NOx. These results indicate an apparent quantitative conversion of fuel-bound nitrogen to NOx at these lean conditions.

The results given in Figure 7 show that NOx formation in methane and fuel oil #2 exhibits a slight positive dependence on pressure. The effect of pressure on NOx emissions during lean, premixed combustion is influenced by many factors [19–23]: degree of fuel-air mixing, equivalence ratio, residence time, and inlet temperature. Leonard and Stegmaier [19], Steele et al. [20], and Bhargava et al. [21] studied the influence of pressure on NOx formation in lean, premixed systems, but reached differing conclusions. Leonard and Stegmaier [19] concluded that NOx emissions are independent of pressure for a perfectly premixed system with a flame temperature in the range from 1700 K to 1900 K. Lean, premixed combustion experiments of Bhargava et al. [21], performed from 7 atm and 27 atm, showed that the pressure effect on NOx is negligible up to 0.50 equivalence ratio. However, equivalence ratios larger than 0.5 showed a positive pressure dependence on NOx. Bhargava et al. [21] indicated that equivalence ratio and absolute pressure are also important factors that determine the effect of pressure on NOx. Conversely, Steele et al. [20], who performed high pressure jet-stirred reactor experiments from 1 atm to 7 atm, reported a slightly negative pressure dependence on NOx. The results of Steele et al. may be due to the absence of a significant plug-flow residence time in the downstream of the jet-stirred reactor used in their experiments. Thus, based on the experimental data [19, 21] reported in the literature and the experimental results discussed in this paper, it can be concluded that NOx formation in a gas turbine combustor is independent of pressure or has a slight positive pressure dependence at very lean conditions. However, NOx emissions will increase with pressure for higher equivalence ratio mixtures.

PILOT-SCALE TESTING

The next stage of development of the LPP system involved pilot-scale testing to study emissions and combustion characteristics, such as flame stability and lean blow-out (LBO) limits, on realistic turbine hardware. A scaled-up version of the lean, premixed, swirl-stabilized burner used for the high pressure bench- scale tests was designed, built, and tested. The design of this scaled-up burner is similar to that found in modern DLE gas turbine combustion systems [1, 24–27]. The atmospheric pressure, swirl-stabilized burner coupled to the fuel vaporization system used for the experiments is shown in Figure 8. This large-scale test facility was able to supply up to 0.6 kg/s flow rate of air for the atmospheric pressure tests.
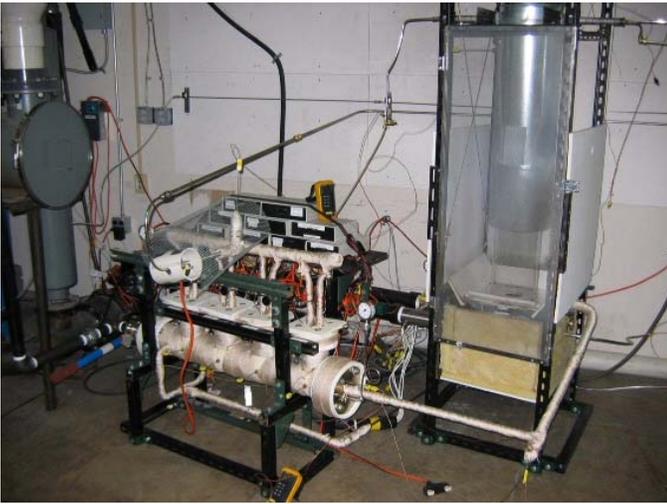
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Figure 8: Large-scale atmospheric pressure, swirl-stabilized burner coupled with LPP vaporizer system.

Atmospheric pressure tests were performed with combustion air at typical gas turbine compressor discharge temperatures of 600 K to 620 K. Figure 9 shows NOx emissions data obtained in the atmospheric pressure, swirl-stabilized burner for methane, fuel oil #1, and fuel oil #2. Figure 9 also compares the natural gas NOx measurements of Leonard and Stegmaier [19], as well as the NOx data at 2 atm and 5 atm of pressure obtained in the high pressure swirl burner described in Figure 6. The experimental data of Leonard and Stegmaier [19] was measured between 1 atm and 30 atm. The NOx measurements shown in Figure 9 for fuel oil #2 are approximately the same as those observed in the high pressure swirl burner experiments. The same figure also shows that fuel oil #1 produced relatively lower NOx, while natural gas gave higher NOx when compared with the high pressure burner results.
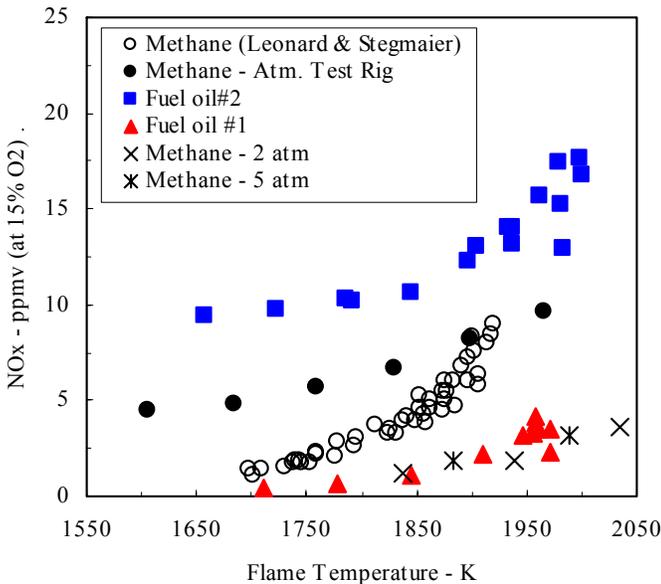

Figure 9: NOx data obtained in the atmospheric pressure test rig for methane, fuel oil #1, and fuel oil #2. The data is compared with the methane data of Leonard and Stegmaier [19] as well as the NOx data obtained in the high pressure swirl burner described in Figure 6 at 2 atm and 5 atm.

SINGLE GAS TURBINE BURNER TESTING

The next step in the pilot-scale testing was to perform combustion tests 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. 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, a Taurus 60, and a Taurus 70 gas turbine [27]. Figure 10 shows the LPP liquid fuel vaporizer skid used for the elevated pressure tests. During the gas turbine burner tests, the liquid fuel was supplied in gaseous form from the vaporizer skid shown in Figure 10.

Figure 10: 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 11 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.
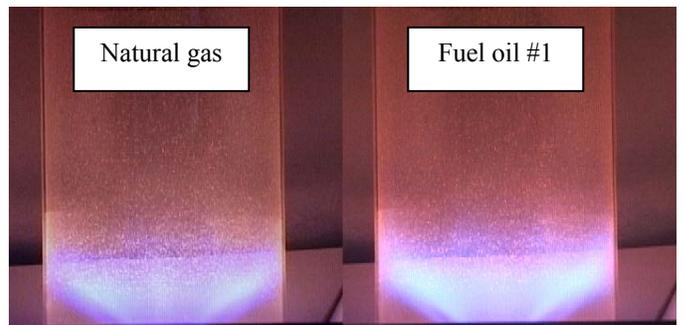

Figure 11: Comparison of natural gas and fuel oil #1 flames at atmospheric pressure for Centaur 50 fuel nozzle at full load conditions.

Figures 12 and 13 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 NOx and CO emissions comparable to those of DLE combustion systems fired on natural gas. The figures show that these low NOx and low CO emissions are achieved simultaneously. As discussed earlier, the primary difference between natural gas and LPP gas NOx 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.
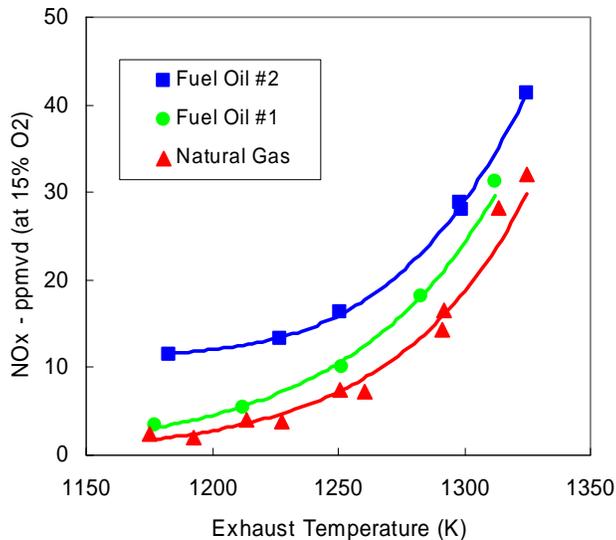

Figure 12: Comparison of NOx emissions measurements for fuel oil #2, fuel oil #1, and natural gas as a function of measured exhaust gas temperature for a single fuel nozzle at Centaur 50 full load conditions (100%). Combustion air temperature was 613 K, combustor pressure was 1 atm, and fuel dilution was 6:1 (molar basis).
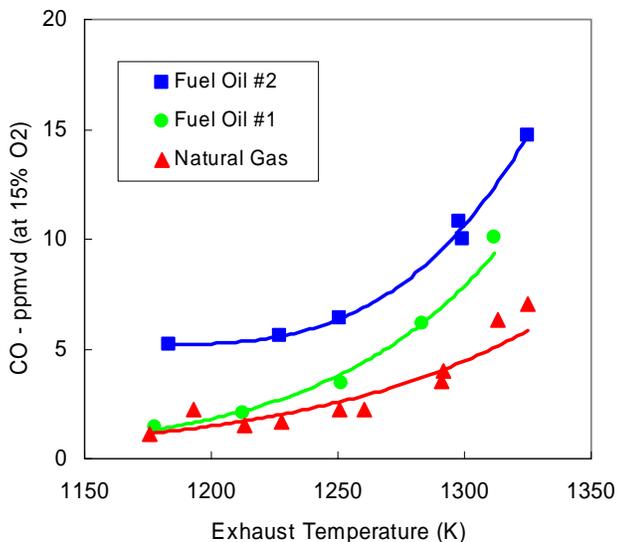

Figure 13: Comparison of CO emissions measurements for fuel oil #2, fuel oil #1, and natural gas as a function of measured exhaust gas temperature for a single fuel nozzle at Centaur 50 full load conditions (100%). Combustion air temperature was 613 K, combustor pressure was 1 atm, and fuel dilution 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 10 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 14 shows NOx and CO emissions at full load conditions for both natural gas and fuel oil #2.
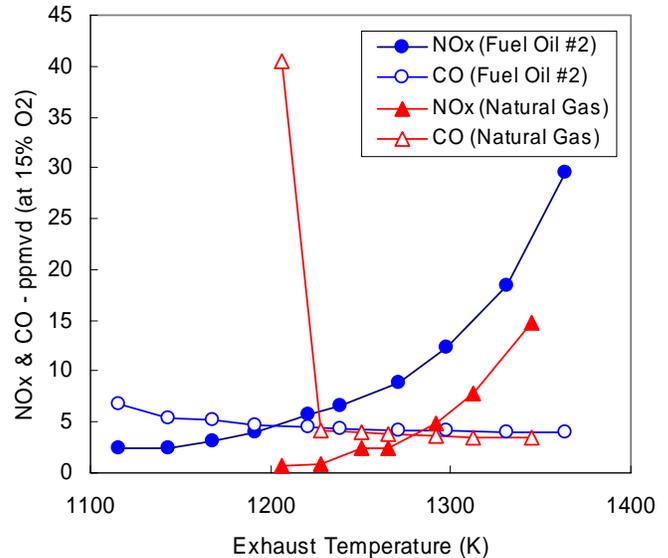

Figure 14: Comparison of NOx & CO emissions measurements for fuel oil #2 and natural gas as a function of measured exhaust gas temperature for a single fuel nozzle at Taurus 60 full load conditions (100%). Combustion air temperature was 648 K, combustor pressure was 12.6 atm, and fuel dilution was 5:1 (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 14 reflect the experimentally observed LBO limit. Figure 14 shows that fuel oil #2 LPP gas has an extended LBO limit compared to natural gas and thus can achieve NOx emissions nearly as low as natural gas despite the fuel-bound nitrogen.

Figure 14 also shows that the crossover point between NOx 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 15 shows comparable NOx 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.
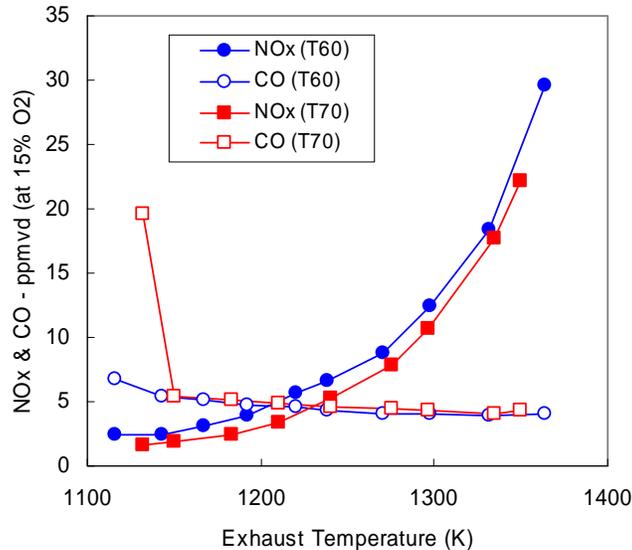

Figure 15: Comparison of NOx & CO emissions measurements for fuel oil #2 as a function of measured exhaust gas temperature for a single fuel nozzle at Taurus 60 (T60) and Taurus 70 (T70) full load conditions (100%). Combustion air temperatures were 648 K (T60) and 706 K (T70), combustor pressures were 12.6 atm (T60) and 16.2 atm (T70), and fuel dilution was 5:1 (molar basis).

The significance of the data shown in Figure 14 is that liquid fuels such as fuel oil #2 LPP gas are able to achieve low NOx emissions levels similar to natural gas. For an exhaust temperature (firing temperature) of 1318 K, Figure 14 shows NOx 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 NOx 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 NOx and CO emissions than fuel oils burned in conventional spray flames with water addition.

CONCLUSIONS

This paper described the development of and results from a patented low-NOx 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 diluent. The effect of nitrogen diluent on ignition delay time was measured in a laboratory-scale flow reactor. The experimental results show that diluent nitrogen increased the ignition delay time at typical air/fuel premixing conditions in gas turbines. Also, high pressure, swirl-stabilized burner experiments were performed to study NOx formation using the LPP combustion system. The fuel oils in gaseous form were premixed with air and burned to achieve very low NOx emissions comparable to those of natural gas in a lean, premixed combustion system. The difference in NOx between methane and the fuel oils was attributed to the conversion of fuel-bound nitrogen into NOx.

Finally, the test program demonstrated that the LPP combustion system described in this paper was able to produce low NOx and low CO emissions without autoignition and flashback. These results were achieved at compressor discharge temperatures and pressures using actual full-scale turbine hardware designed for natural gas operation without any modifications to the combustor hardware. The test data show that at equivalent exhaust (firing) temperatures, NOx emissions for natural gas and fuel oil #2 LPP gas were 9 ppm and 16 ppm, respectively. CO emissions were 3.5 ppm and 4.0 ppm, respectively. Because the LPP gas fuel characteristics are similar to 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 single digit NOx and CO emissions levels.

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