

DEVELOPMENT OF A SYSTEM FOR LEAN, PREVAPORIZED, PREMIXED COMBUSTION

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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.

The work presented in this paper describes the development of a low-nitrogen oxides (NO_x) LPP system for combustion of liquid fuels that 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 NO_x formation, of the liquid 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 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 carbon monoxide (CO) (Davis and Black, 2000). 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 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 (1978) 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 (Oumejjoud, et al., 2005). 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 designers still desire to use lean, premixed, prevaporized (LPP) combustion. Several approaches have been reported in the literature (Maier and Wittig, 1999; Imamura, et al., 2001; Ikezaki, et al., 2001; Lin, et al., 2004; Lee, et al., 1995; Michou, et al., 1999; Hoffmann, et al., 1998; Mansour, et al., 2001) to overcome flashback and autoignition in the premixers of LPP combustors. 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 multiport liquid fuel injection systems are employed for better fuel/air mixing (Lin, et al., 2004). 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 fuel vaporization and conditioning process (Roby, et al., 2006) 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.

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 gas turbine A 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 gas turbine A at atmospheric pressure, and for a gas turbine B and gas turbine C gas turbine at full pressure (Knodle, 1998).

The atmospheric pressure, swirl-stabilized burner coupled to the fuel vaporization system used for the experiments is shown in Figure 1. 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 (620°F) to 620°K (656°F).

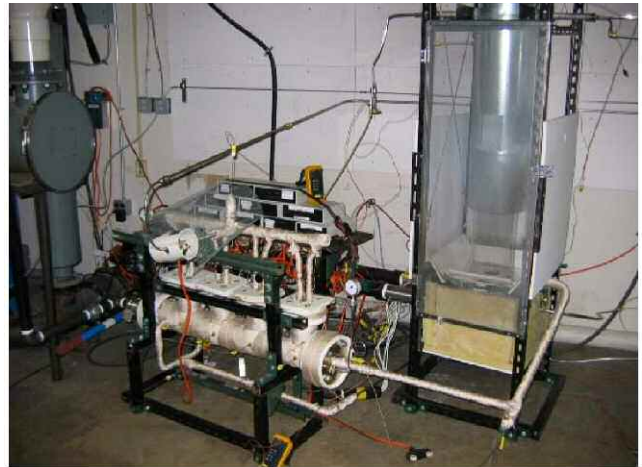


Figure 1. Laboratory Test Facility with Atmospheric Pressure, Swirl-Stabilized Burner Coupled to LPP Vaporizer System.

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 2.



Figure 2. 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 blowout 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 3 shows a representative atmospheric pressure flame structure for natural gas and for fuel oil #1 from a gas turbine A 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.

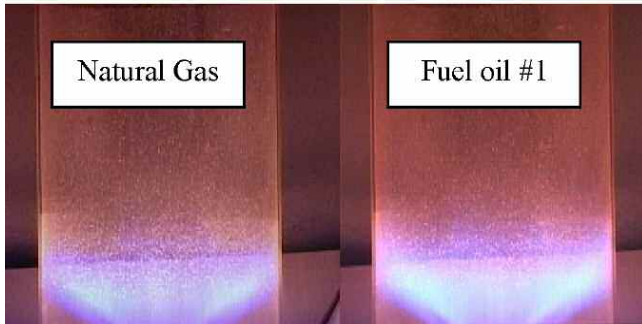


Figure 3. Comparison of Natural Gas and Fuel Oil #1 Flames at Atmospheric Pressure for Gas Turbine A Fuel Nozzle at Full Load Conditions.

Figures 4 and 5 show the results of atmospheric pressure testing of a single gas turbine fuel nozzle at gas turbine A 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 flashbacks 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.

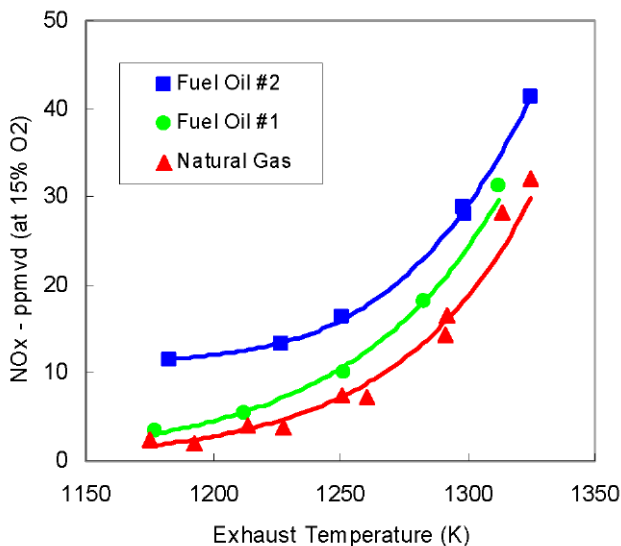


Figure 4. Comparison of Nox Emissions Measurements for Fuel Oil #2, Fuel Oil #1, and Natural Gas as a Function of Measured Exhaust Gas Temperature for a Single Fuel Nozzle at Gas Turbine A Full Load Conditions (100 Percent). Combustion Air Temperature was 613°K (644°F), Combustor Pressure was 1 ATM, and Fuel Dilution was 6:1 (Molar Basis).

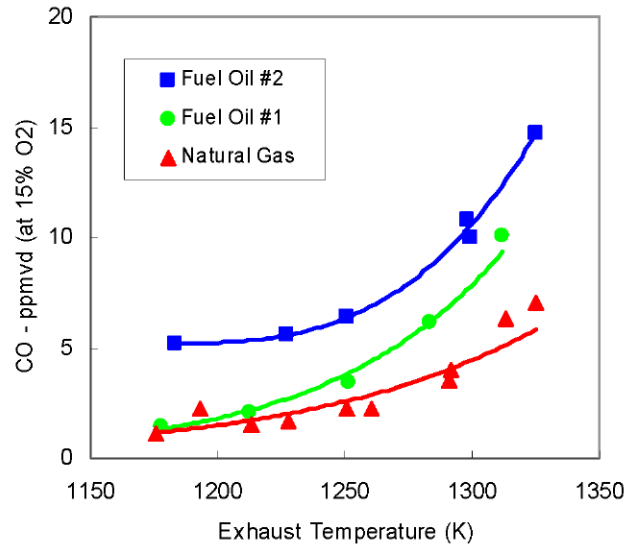


Figure 5. Comparison of CO Emissions Measurements for Fuel Oil #2, Fuel Oil #1, and Natural Gas as a Function of Measured Exhaust Gas Temperature for a Single Fuel Nozzle at Gas Turbine A Full Load Conditions (100 Percent). Combustion Air Temperature was 613°K (644°F), Combustor Pressure was 1 ATM, and 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 2 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 6 shows NOx and CO emissions at full load conditions for both natural gas and fuel oil #2.

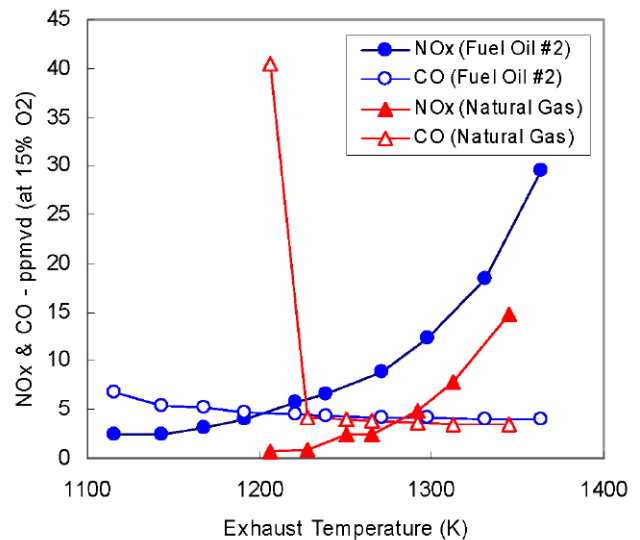


Figure 6. Comparison of Nox and CO Emissions Measurements for Fuel Oil #2 and Natural Gas as a Function of Measured Exhaust Gas Temperature for a Single Fuel Nozzle at Gas Turbine B Full Load Conditions (100 Percent). Combustion Air Temperature was 648°K (707°F), Combustor Pressure was 12.6 ATM, and 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 are 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 6 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 6 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 7 shows comparable NO_x and CO emissions for both gas turbine B and C single nozzle full load conditions. The data indicate that similar emissions are achieved, even though the gas turbine C full load conditions are at higher temperature and pressure than the gas turbine B 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.

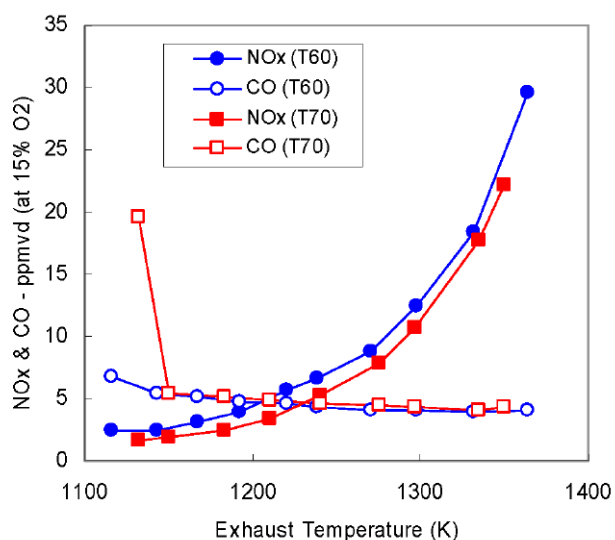


Figure 7. Comparison of Nox and CO Emissions Measurements for Fuel Oil #2 as a Function of Measured Exhaust Gas Temperature for a Single Fuel Nozzle at Gas Turbine B (T60) and Gas Turbine C (T70) Full Load Conditions (100 Percent). Combustion Air Temperatures were 648°K (707°F) (T60) and 706°K (812°F) (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 7 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 (1913°F), Figure 7 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.

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 (Lifshitz, 2001). 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 8 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 inch × 2 inch alumina tube placed inside a furnace with three independently controlled zone heaters.

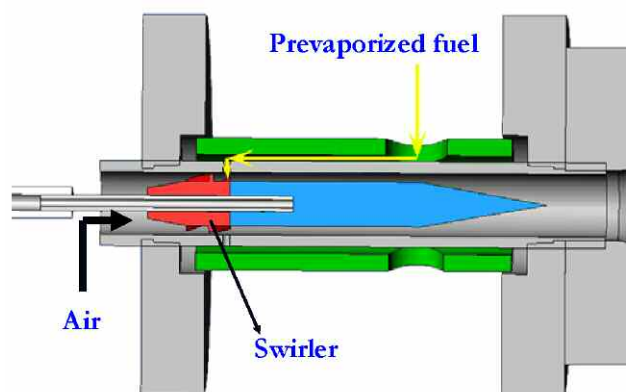


Figure 8. Schematic of the Premixing Section of the Flow Reactor Used for Ignition Delay Time Measurements.

One of the difficulties of any flow reactor experiment is mixing the fuel and oxidant quickly at the entrance to the reactor (Yetter, et al., 1991; Gokulakrishnan, et al., 2003). In this work, the rapid mixing of the vaporized fuel with air was achieved by using a swirler followed by an expanding duct that 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 carbon-hydrogen* (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 pre-mixer temperature was maintained at 600°K (620°F) in order to simulate the conditions in a gas turbine pre-mixer. A detailed description of the flow reactor facility can be found in a previous publication (Gokulakrishnan, et al., 2006).

Figure 9 shows the ignition delay time as a function of O₂ mole% in the inlet stream for n-heptane at 823°K (1022°F) and 900°K (1160°F). 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. (1998). 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 $(x_{O_2})^{-0.80}$ at 900°K (1160°F) and to $(x_{O_2})^{-2.2}$ at 823°K (1022°F), where (x_{O_2}) refers to the mole% of O₂ in the inlet stream to the test section of the flow reactor.

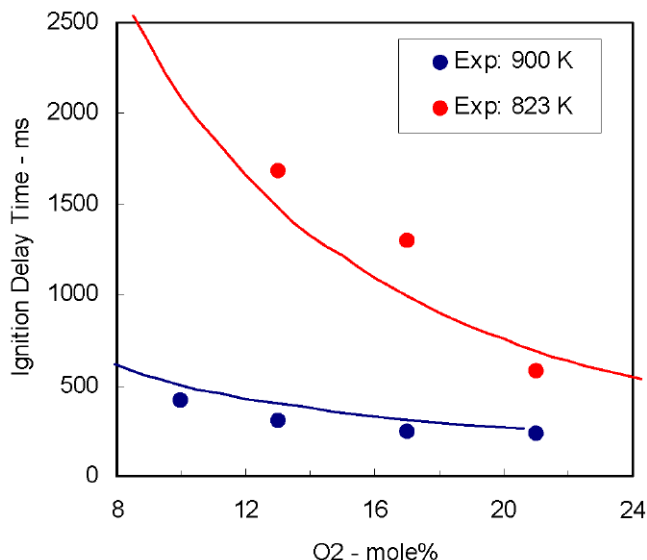


Figure 9. Atmospheric Pressure Ignition Delay Time Measurements of Stoichiometric *n*-Heptane/O₂/N₂ Mixture as a Function of Inlet O₂ Composition. (Key: symbols—experimental data; lines—ignition delay time model predictions using Curran, et al. [1998], detailed kinetic model.)

Figure 10 compares the ignition delay time of both vaporized fuel oils with *n*-heptane as a function of O₂ mole% at the inlet to the flow reactor at 900°K (1160°F). 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 O₂ dependency on ignition delay time as that of *n*-heptane. However, the effect of O₂ 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 $(x_{O_2})^{-0.8}$, while the fuel oil #2 ignition delay time is proportional to $(x_{O_2})^{-1.0}$, where (x_{O_2}) refers to the mole% of O₂ in the inlet stream to the test section of the flow reactor.

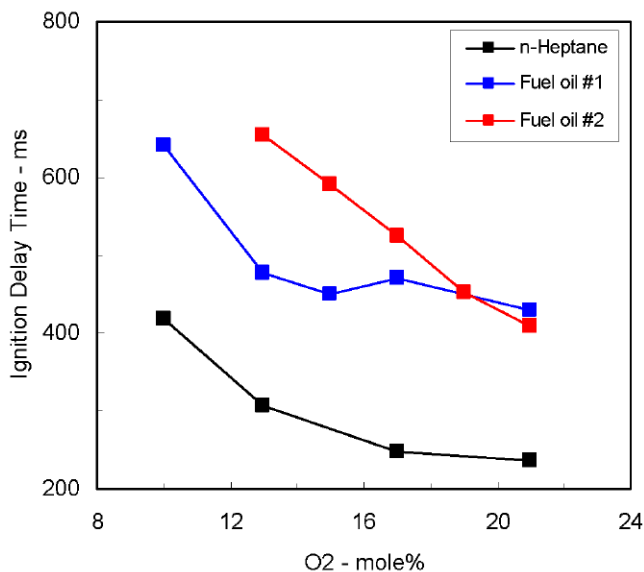


Figure 10. Comparison of Ignition Delay Time Measurements of *n*-Heptane, Fuel Oil #1, and Fuel Oil #2 as Function of Inlet O₂ Composition at 900 K Inlet Temperature, 1 ATM Pressure and 1.0 Equivalence Ratio.

CONCLUSIONS

This paper described the development of and results from a low-NO_x lean, premixed, prevaporized combustion system (Roby, et al., 2006) 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 NO_x formation using the LPP combustion system. The fuel oils in gaseous form were premixed with air and burned to achieve very low NO_x emissions comparable to those of natural gas in a lean, premixed combustion system. The difference in NO_x between methane and the fuel oils was attributed to the conversion of fuel-bound nitrogen into NO_x.

Finally, the test program demonstrated that the LPP combustion system described in this paper was able to produce low NO_x 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, NO_x 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 NO_x and CO emissions levels.

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