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ACTIVE CONTROL OF INSTABILITIES AND EMISSIONS IN HIGH-PRESSURE COMBUSTOR USING NANOMISER® FUEL INJECTOR

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ABSTRACT

This paper describes the operation of the Nanomiser® liquid fuel injector in a harsh environment of a high pressure combustor that exhibits severe instabilities (up to 40% of the mean pressure level) in the frequency range of 380-450Hz. These frequencies correspond to the fundamental acoustic modes of the combustor and these instabilities were observed during operation on both gas and liquid fuels (natural gas and n-heptane – C_7H_{16}). Frequency and amplitude of pressure oscillations in the combustor were found to be independent on the type of fuel. A Nanomiser® liquid fuel atomizer that requires no atomizing gas was used to produce mono-dispersed spray allowing control over the mean droplet diameter. Earlier PDPA (Phased Doppler Particle Anemometer) measurements performed in a similar device indicate that these atomizers are capable of generating droplets from 100 micron (coarse atomization) down to sub-micron range (ultra-fine atomization). The preliminary results of influence of degree of atomization on the oscillating pressure amplitude and on the NO_x and CO emissions in the combustion products were investigated only at few injector power settings. Experiments were performed only at coarse, intermediate and no atomization settings. These limited preliminary data do not provide enough information to create trends for dependence of the pressure amplitude and emissions upon the quality of atomization of the liquid fuel produced by the Nanomiser® fuel injector. Characteristics of instability (frequency and amplitude) were found to be the same at all three investigated atomization settings. For fuel-lean operation ($\varphi<0.6$), CO emissions reduce from 10-15 ppm for no atomization to close to zero ppm for intermediate atomization of fuel. On the other hand level of NO_x emissions was slightly higher for coarse atomization (20-30ppm) as compared to 15 ppm for no atomization of fuel at lean operating conditions. Detailed studies of effects of atomization qualities on instabilities and emissions are warranted under various operating conditions.

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INTRODUCTION

To date, combustion instabilities have hindered the development of numerous propulsion systems (e.g., rocket motors, gas turbines, ramjets, and afterburners) and power generating gas turbines. These instabilities are driven by "internal" feedback-like interactions between acoustic mode and combustion process heat release oscillations. Their presence shortens components life time and may, on occasion, produce catastrophic combustion system failure[1,2].

Traditionally, engineers have employed passive approaches to prevent the onset of combustion instabilities. These generally attempted to increase the damping of the unstable modes and/or decrease the driving of the instability by the combustion process. The former involved, e.g., nozzle modifications to increase acoustic energy transmission from the combustor to the environment or the addition of acoustic liners that damped the instability and modified the acoustic properties of the combustor. On the other hand, decreasing the driving by oscillatory combustion processes involved weakening (or elimination) of the coupling between the oscillatory combustion process and the combustor acoustic modes. This was accomplished by, e.g., modifications of the reactants feed systems, reactants injection location and elimination of surfaces that shed vortices. Another approach involved changing the acoustic properties of the combustor by, e.g., the addition of baffles to prevent the excitation of acoustic modes that could couple with the oscillatory combustion process[3]. Historically, development of such passive solutions proved to be time consuming and very costly. Furthermore, these passive solutions were generally combustor specific and applicable over a limited range of operating conditions. Consequently, there has been increased interest in recent years in the developing active control systems (ACS)[4] that could effectively damp combustion instabilities over wide ranges of operating conditions and used in different combustors with little or no modifications. The mechanisms of liquid fuel atomization and droplet evaporation are of fundamental importance of gas turbine combustion system. Droplet sizes and velocities produced by the atomizer play a significant role in driving and damping combustion instabilities. This is because the time delay between the injection and when a given droplet burns and releases its energy depends upon its initial size and velocity. Each droplet experiences chronologically different environments of heat and mass transfer rates and drag forces in the acoustic field inside the combustor. This effect has been advantageously exploited to demonstrate suppression of combustion instabilities in an atmospheric pressure swirl combustor merely by spray quality optimization. The existence of a range of droplet size distribution that produced a saddle point in oscillatory pressure amplitude was clearly identified[5].

This paper describes preliminary results of similar approach to controlling combustion instabilities by spray quality optimization in a high pressure combustor facility. A Nanomiser® liquid fuel atomizer that requires no atomizing gas was used to produce mono-dispersed spray allowing control over the mean droplet diameter. Initial experiments were performed only at coarse, intermediate and no atomization settings. Since only a certain range of droplet size may produce a minimum in oscillatory pressure amplitude, extended experiments are needed to sweep a broader range of droplet sizes at a fixed equivalence ratio to quantify the effects of atomization quality on suppression of combustion instabilities. Preliminary results on CO and NOx emissions are also described.

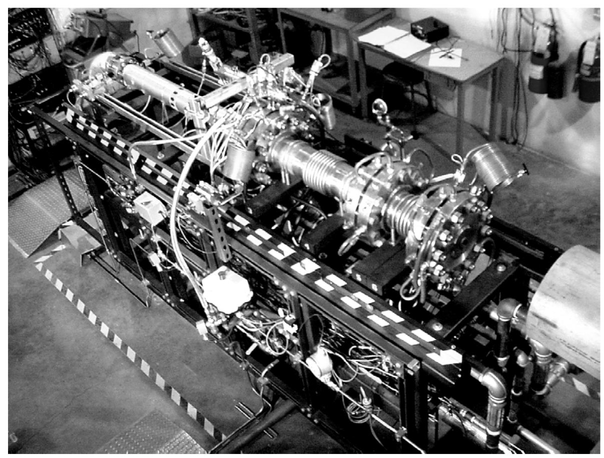


Figure 1. A general view on the experimental facility.

EXPERIMENTAL SETUP

A photograph of the developed experimental facility that was used in the reported study is shown in Figure 1. This facility was developed to study active combustion control under operating conditions that simulate those encountered in practical power generating gas turbine combustors. It consists of a high-pressure combustor, air and fuel supply systems, and an ignition system. Furthermore, this test facility possesses extensive capabilities for measuring air and fuel flow rates, dynamic pressures, NO_x and CO emissions and steady temperatures. It is remotely controlled during testing.

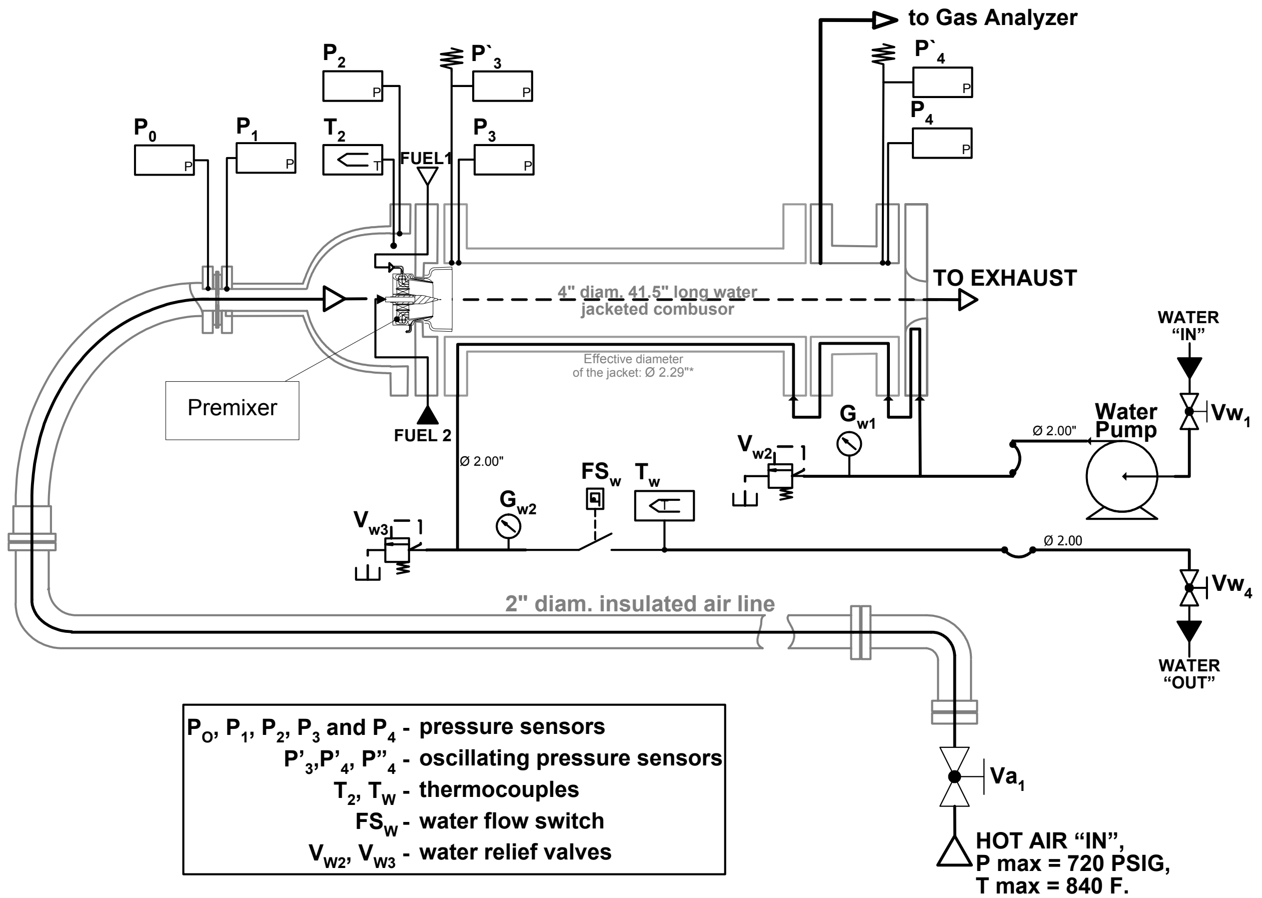


Figure 2. A schematic of the combustor and its air supply system.

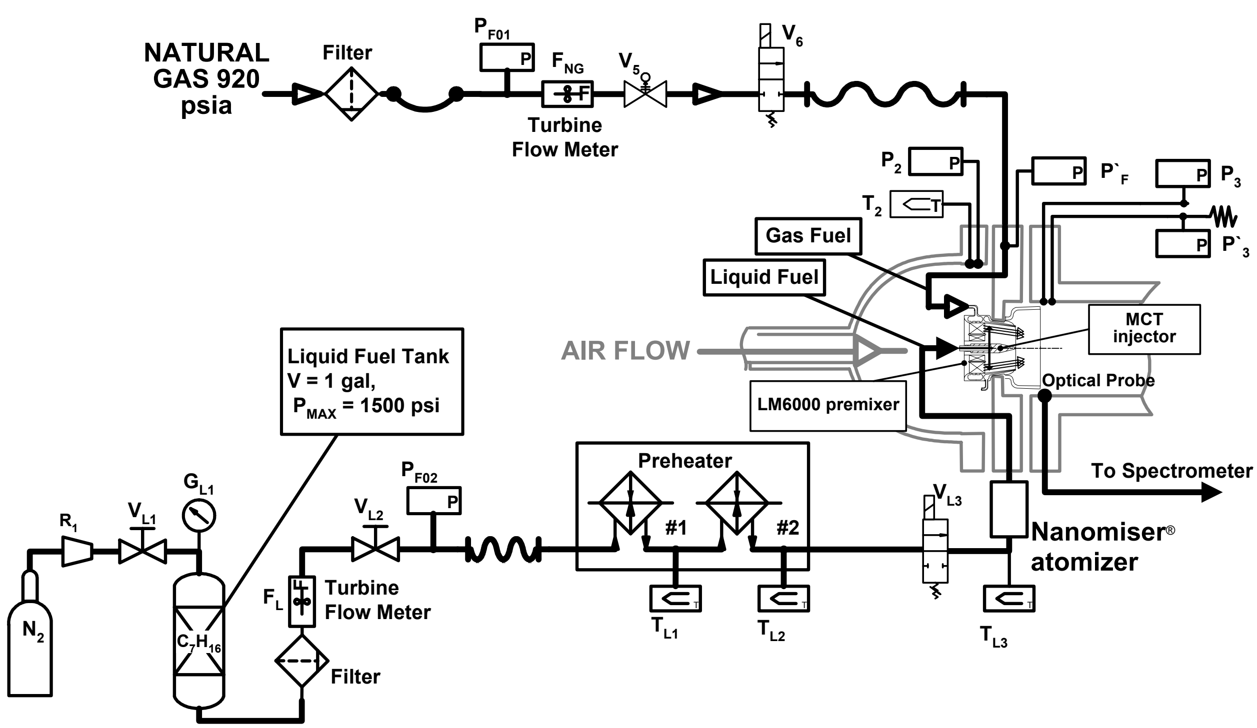


Figure 3. A schematic of the fuel supply system.

High-Pressure Combustor and Air Supply System.
A schematic of the combustor with its air supply system is shown in Figure 2. Air is supplied to the combustor through a 2 inch (50.8mm) diameter, 59 inch (1270mm) long air intake pipe (between sections "1"-"2"), whose diameter increases to 6 inches (152.4mm) as it approaches the combustor (section "2"). This end of the air supply is connected to the "dome" flange, which incorporates the fuel pre-mixer. The combustor inlet flange (section "3") is connected to the "dome" flange. The combustor's diameter and length are 4 inches (102mm) and 41.5 inches (1054mm), respectively. The combustion products leave the combustor through a choked exhaust nozzle whose throat diameter equals 0.866 inch (22mm). The exhaust nozzle and combustor are water-cooled. A booster pump increases the circulating water pressure to ~50 psi (0.345Mpa) at the cooling water jacket entrance. The temperature of the cooling water was generally around 150^0F (65^0C) at the outlet of the cooling jacket. The air supply lines were thermally insulated using high-temperature calcium silicate panels and aluminum jacketing. The high pressure air was initially stored in 14 high-pressure 2500psi (17.24Mpa) cylinders. From there, the air could pass through an air-heater or flow directly into the high-pressure test cell that housed the experiment. In the reported experiments, a control system was used to maintain the air pressure and temperature at P_0=260psia (~1.8Mpa) and 230-284°F (110-140°C), respectively, at the inlet to the test cell. At these air pressure and temperature, the air flow rate and pressure in the combustor were in the m_{air}=0.57-0.66 lbm/s (0.26-0.3kg/s) and P_3=105-110psia (0.71-0.75Mpa) ranges, respectively.

Fuel Supply System.

A schematic of the fuel system is shown in Figure 3. Liquid fuel and natural gas (NG) can be supplied to the separate injection orifices. Liquid fuel (n-Heptane C_7H_{16}) was stored in a one-gallon high pressure vessel, which was pressurized from the N_2 cylinder up to 1800 psi. Liquid fuel flow rate was measured using <OMEGA 9504> micro-turbine flow meter. Liquid fuel supply system incorporated a system for fuel preheating. It consisted of a solenoid valve, a Nanomiser® atomizer and injector orifices as shown in Figure 4.

Natural gas was supplied from three high-pressure 3500 psi (24.13Mpa) cylinders and a control system was used to maintain the fuel pressure at P_{F0}=900psi (6.12Mpa) at the inlet to the test cell. The test facility metering units were used to maintain the fuel flow rate to the combustor in the m_{fuel} =0.070-0.092 lbm/s (38-42g/s) range. The electrically actuated metering valve (<WORCESTER CONTROLS ¼"-4" CPT 44>) was incorporated into the control loop with a FTB-900 series turbine flow meter equipped with FLSC-62 loop powered 4-20 mA <OMEGA> transmitter and a set point controller on the operator's console. The fuel supply system was designed to supply two separate fuel lines. In the current study, all the natural gas (NG) fuel was supplied to the orifices in the LM 6000 pre-mixer blades through a single line.

Fuel Injection Module.
The fuel was injected into the moving air stream through ten orifices. In this design, the fuel injection orifices were located near the base of the outer swirling blades and the fuel was injected radially outward towards the outer diameter of the air-flow passage. The Nanomiser® atomizer brings the fuel to thermodynamically unstable condition. The atomization controllability and droplet size are critically dependent on the thermodynamic state of the liquid and geometry of the injection nozzle. The Nanomiser® injection nozzle geometry promotes the control of atomization and allows rapid disintegration of liquid stream. By adjusting thermodynamic conditions at the nozzle exit, a wide range of spray quality (droplet size and velocity, cone angle and penetration length) can be achieved without any air/oxidizer supply. Figure 5 shows the controllability of atomization. Therefore, in a combustion application, oxidizer flow rate can be independently adjusted for proper equivalence ratio.

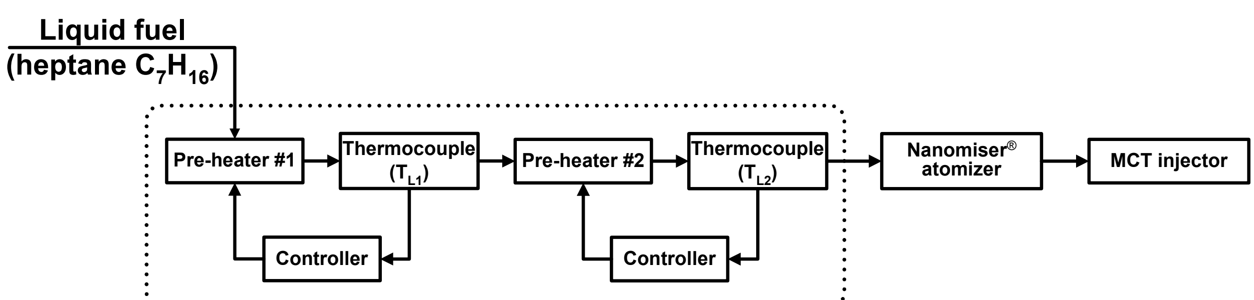


Figure 4. A block diagram of the liquid fuel heating control for high-pressure combustion tests.

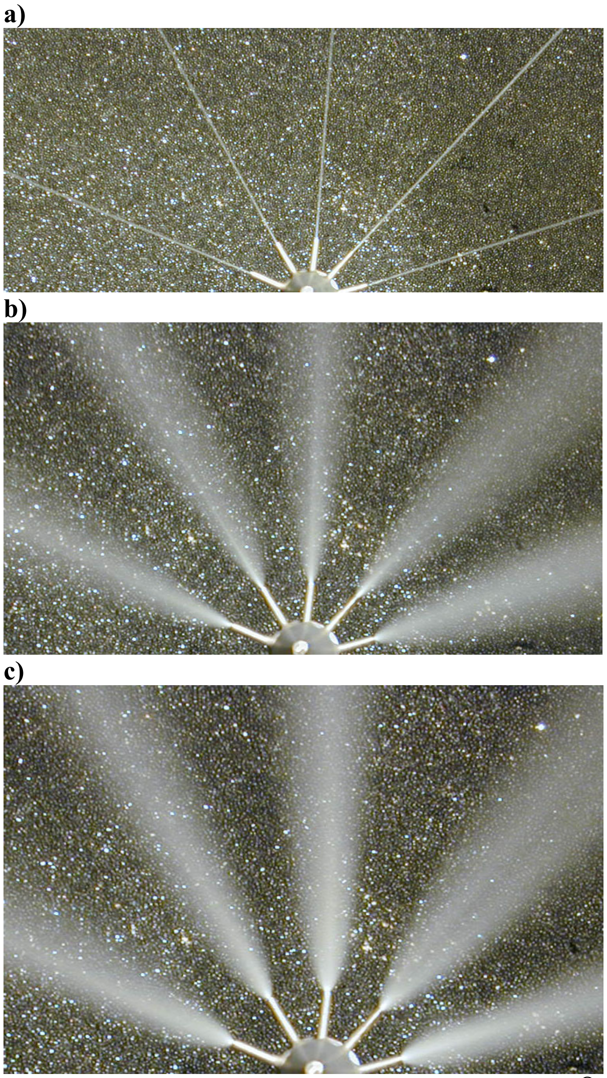


Figure 5.Atomization controllability using Nanomiser® fuel injector. (a) no atomization, (b) coarse atomization and (c) fine atomization.

Dynamic Pressure Measurements.

Piezoelectric pressure transducers <KISTLER 211B2> together with the multi-channel coupler (i.e., KISTLER 5124A1) were used to measure the dynamic pressures in the combustor, in the fuel supply. Five transducers in the combustor were installed on “semi-infinite tubes” at a distance of 9’’ (230mm) from the combustor wall, to provide a flat frequency response and protect the transducers from overheating. These transducers are shown in Figure 2. They have designations $P'_{1\text{-}4}$ (subscript numbers stand for cross-section designation). In the section “3” three transducers were installed to indicate possible onset of the tangential or azimuthal spinning mode. They have designations P'_{31}, P'_{32} and P'_{33} (see also schematic on the Figure 3

Following a procedure recommended by the transducers manufacturer the electronic circuits that were used to convert the electrical signals supplied by the pressure transducers into pressure had been calibrated before the tests. The calibration procedure consisted of relating the voltage measured by the transducers to pressure amplitudes using “certificates of calibration” provided by the transducers manufacturer.

In addition to the electronic calibration, sensitivity of the measuring channels was periodically proved by acoustic calibration. For this purpose, transducers, which were previously exposed to the severe experimental conditions, were installed in the cavity of the actuation valve together with the new transducer of the same type, which was used only for this procedure. Then strong periodic pressure oscillations up to 50psi p-p amplitude at the frequency about 400Hz were generated in the valve cavity and all the sensors outputs were recorded simultaneously. Decision about the further use of the tested transducer was taken on the basis of comparison of the measured signals. Of course such a procedure cannot replace factory calibration or “on site” calibration by the calibrated acoustic source. It was undertaken because the strong calibrated acoustic source, which generates pressure oscillations with the amplitude close to those measured during combustor tests at the frequency of instability was not available. Nevertheless, this periodic verification of the sensors sensitivity assured the researcher of validity of the sensors and their equal sensitivity.

Optical Monitoring of the Combustion Dynamics

Chemiluminescence measurements were used to monitor combustion dynamics. Fiber-optic probe was installed in the combustor through the flange (see section 3 on the Figure 3) in such a way that fiber termination was flat to the combustor wall. It penetrated the wall ½ inch (12.5mm) downstream the combustor’s heat shield. At this position probe was oriented towards the position of the maximum heat release inside the combustor. Site view angle of the fiber was 10° (at the level of half maximum intensity), thus it was also indicative to the movement of the heat release maximum out of its site view. Fiber–optic probe was connected to the <PERKIN-ELMER 650S> spectrometer, whose wavelength was centered at 430nm to sense CH* radical chemiluminescense from the flame.

NO_x and CO Emissions

Combustion product emission data was obtained by LANCOM series II gas analyzer. An air-cooled sampling probe was positioned 30” (762 mm) downstream of the pre-mixer and used to continuously transport gas products to the analyzer, which was installed in the control room. This system can measure the concentrations of CO, NO_x, and O_2.

RESULTS AND DISCUSSION

To determine the performances of the investigated Nanomiser® liquid fuel injector, combustor's dynamics and emissions were studied at its relatively low power (25%) using natural gas fuel (NG) or liquid n-Heptane. At these operating conditions, the combustor exhibited the same instabilities as observed at full power but at relatively lower amplitudes. This allowed us to conduct controllability tests operating at relatively low flow rates of the liquid fuel near the design point of the Nanomiser® fuel injector. Tests on the liquid fuel were conducted in the absence and presence of atomization control of the fuel supplied to the injection orifices.

Investigation of Combustor's Dynamics.

Since the investigated combustor was developed to study active control of combustion instabilities, it was designed to be unstable. This was accomplished by maximizing the extent of highly reflective surfaces (i.e., walls) that don't absorb sound and the use of a "short" nozzle that practically consisted of an orifice in a wall. Consequently, this combustor exhibited extremely high amplitude, longitudinal, instabilities over its entire range of operating conditions. Typical dependence of the combustor's pressure oscillations upon the equivalence ratio is presented in Figure 6. Figure 6-a shows that at the investigated operating conditions ($p_{comb.}$=100-110psi, air temperature t_{air}=110-140^{0}C) combustor reveals only fundamental acoustic mode (on both liquid and natural gas fuels), whose frequency varies between 380Hz and 450Hz due to the temperature of the products at different equivalence ratios between φ=0.48 and φ=1.1. Combustor demonstrated unstable behavior in the entire range of investigated equivalence ratios. At the same time the amplitude of instability strongly depends on the equivalence ratio, at which combustor is operated. In the lean operating range instability with the oscillating pressure level (i.e., p-p oscillating pressure amplitude divided by the mean pressure) of nearly 30%. Maximum of pressure amplitude of almost 40% was observed at the equivalence ratio φ=0.68. At relatively rich operating conditions φ>0.90 oscillating pressure amplitude did not exceed 16% of the mean combustor pressure.

The time dependence and spectra of oscillations in the combustor at different equivalence ratios and types of fuel in Figure 6 are shown in Figure 7 where the same number describes the corresponding conditions in each figure. It shows that very similar type of instabilities was observed on both natural gas and liquid fuel. Pressure oscillations are very regular and shape of the signal reflects strong non-linearity of the oscillations. Signal of the optical sensor is highly modulated (almost 100%) and generally follows signal of the pressure sensor. It demonstrates much stronger amplitude dependence upon the equivalence ratio than pressure sensor, especially in the range of equivalence ratio 0.7<φ<1.1, which possibly reflects shifting of the reaction zone out of the optical probe site view.

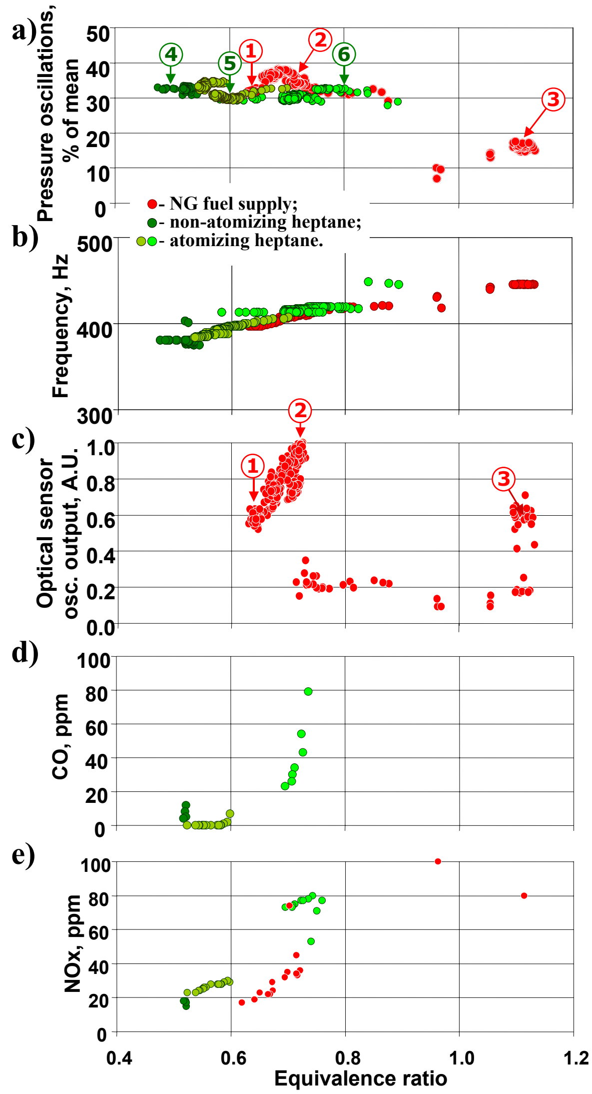


Figure 6. Dependence of combustion dynamics and emissions upon the equivalence ratio.

a) normalized pressure amplitude;
b) frequency of oscillations;
c) optical sensor oscillatory output;
d) CO emissions;
e) NOx emissions.

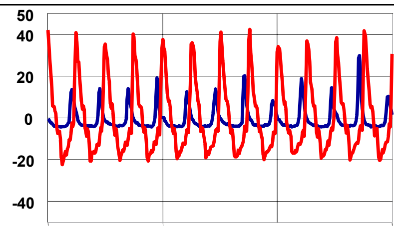
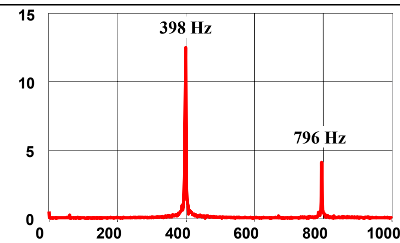
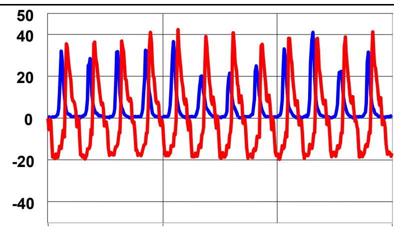
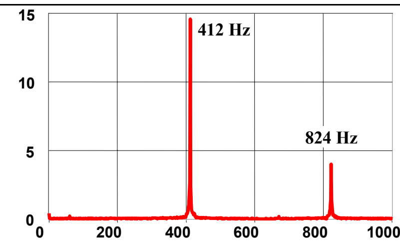
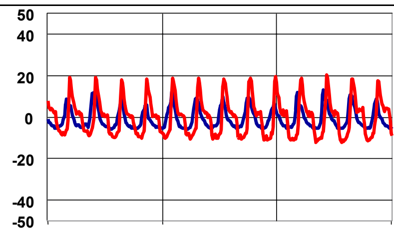
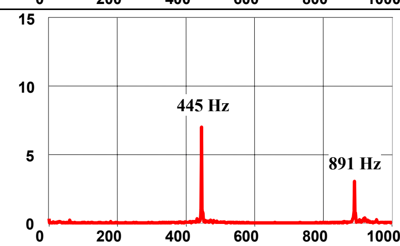
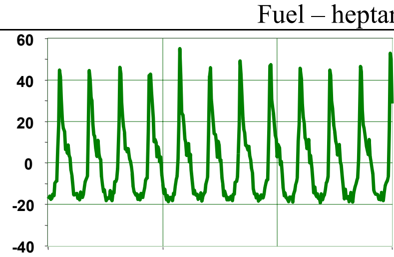
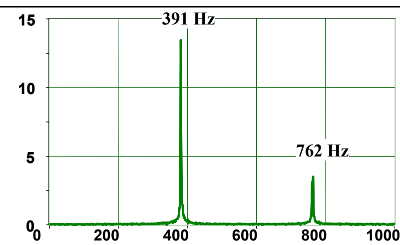
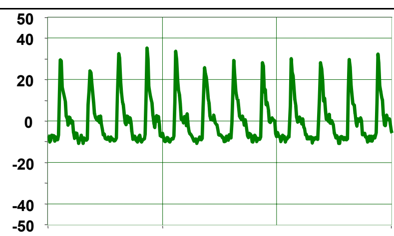
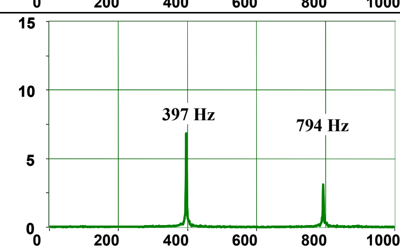
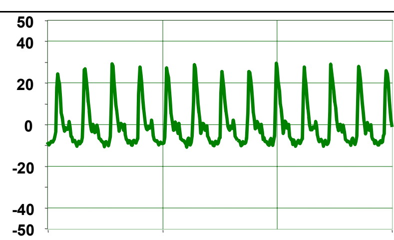
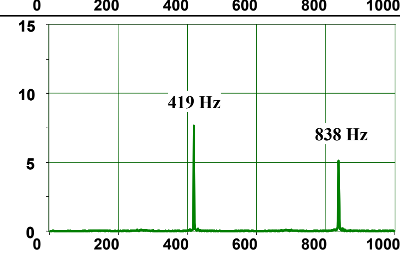
Point# φ	Time histories, psi (time interval τ = 0.03sec)	Combustor pressure spectra, psirms
Fuel – natural gas		
1 φ = 0.64		
2 φ = 0.71		
3 φ = 1.1		
Fuel – heptane C_7H_{16}		
4 φ = 0.50		
5 φ = 0.60		
6 φ = 0.80		

Figure 7. Pressure and optical output time histories and pressure spectra at different equivalence ratios and types of fuel.

Pressure spectra reveals very strong spike at the frequency of the fundamental acoustic mode and at its sub-harmonics. Frequency and amplitude of pressure oscillations in the combustor was found to be independent on the type of fuel (heptane or NG).

CONCLUDING REMARKS:

- This study demonstrated satisfactory operation of the Nanomiser® liquid fuel injector in a harsh environment of the high pressure combustor, that experienced severe instabilities (up to 40% of the mean pressure level) in the frequency range of 380-450Hz. This fundamental acoustic mode, whose frequency depends on the temperature of products and position of the reaction zone, was observed during operation on both gas and liquid fuels (natural gas and n-heptane –C_7H_{16}). Frequency and amplitude of pressure oscillations in the combustor was found to be independent on the type of fuel (heptane or NG). This fact indicates proper design of the Nanomiser® liquid fuel injector as it provides fuel to air mixing similar to the one achieved on the original LM6000 GE premixer.

- The preliminary results of influence of degree of atomization on the oscillating pressure amplitude and on the NO_x and CO emissions in the combustion products were investigated only at few injector power settings. Experiments were performed only at coarse, intermediate and no atomization settings. These limited preliminary data do not provide enough information to create trends for dependence of the pressure amplitude and emissions upon the quality of atomization of the liquid fuel produced by the Nanomiser® fuel injector. Characteristics of instability (frequency and amplitude) were found to be the same at all three investigated atomization settings. For fuel-lean operation ($\varphi<0.6$), CO emissions reduce from 10-15 ppm for no atomization to close to zero ppm for intermediate atomization of fuel. On the other hand level of NO_x emissions was slightly higher for coarse atomization (20-30ppm) as compared to 15 ppm for no atomization of fuel at lean operating conditions.

- It was found that parameters of the liquid fuel supply system significantly limited experimental capabilities. Especially:

    1. Run time in one test was limited to less then 3 minutes because high pressure vessel (1 gallon) was used for fuel supply. This time interval is not long enough for reliable NOx and CO measurements as well as for application of different levels of atomization) in one test run.
    2. Powerful in-line electric pre-heater in combination with the compact heater was used for control temperature of the fuel supplied to the Nanomiser®. Temperature of the fuel was monitored only at the heater output. This design resulted in high local temperatures of the inner walls of the fuel pre-heater. Cooking of n-heptane led to the clogging of the Nanomiser®.
    3. Nanomiser® design investigated in this study was able to supply maximum 10g/s fuel flow rate to the combustor, whose operating range is 40-50g/s. This resulted in limitation of the combustor power output and limited range of operating conditions, at which effect of atomization could be investigated.

In future testing of the Nanomiser® liquid fuel injector a new fuel supply and temperature control system will be used. High pressure fuel supply will be provided by a pump from the low pressure preheated fuel tank. Tight temperature control will be conducted using compact heater. This new system will provide better capabilities for investigation of instability and emissions control using Nanomiser® liquid fuel injector.

ACKNOWLEDGMENTS

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