39th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit
20-23 July 2003, Huntsville, Alabama

AIAA 2003-4517

CONTROLLING COMBUSTION DYNAMICS IN A SWIRL COMBUSTOR VIA SPRAY OPTIMIZATION

M. Lal and M. Oljaca
MicroCoating Technologies, Inc.
5315 Peachtree Industrial Blvd.
Atlanta, GA 30341

E. Lubarsky, D. Shcherbik and S. Menon
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA 30332

B. Sekar
Wright Patterson AFB
Dayton, OH 45433

ABSTRACT

Experimental studies were performed to identify and characterize the influence of spray quality and operating parameter (air/fuel ratio) on combustion dynamics in a liquid-fueled turbulent swirl combustor. Heptane (C_7H_{16}) was used as liquid fuel. A novel electrically dissipative capillary injector, the Nanomiser® atomizer, was used to produce monodispersed spray allowing control over the mean droplet diameter independent of fuel or air flow rates. PDPA measurements indicate that this device is capable of generating droplets from 100 microns (coarse atomization) down to sub-micron range (ultra-fine atomization). Pressure oscillations and optical emissions from flame were used to characterize combustion dynamics. Significantly large variations of oscillatory pressure corresponding to variations in droplet properties were observed at different equivalence ratios. The existence of a range of droplet size that produces a minimum in oscillatory pressure amplitude was clearly exhibited. "Slow" control approach for suppressing combustion instabilities by changing spray properties was successfully demonstrated. Preliminary results on extension of similar approach for combustion dynamics control in a high pressure combustor is also briefly described.

INTRODUCTION

The design of a modern gas turbine combustor is increasingly dictated by low Lean Blowout (LBO) limits and short and uniformly mixed stable flame over a wide range of engine operating conditions, including rapid acceleration and deceleration. These combustion process characteristics including combustion efficiency and product emissions strongly depend on fuel type used and atomization quality[1]. Combustion instabilities are mainly driven by interactions between combustor acoustic and heat release oscillations, and may lead to premature wear or catastrophic failure. Passive means to avoid combustion instabilities include combustor geometry design, acoustic dampers and injection system design modification. These passive control methods require numerous design iterations, are very expensive and do not possibly cover the entire engine operating regime. Furthermore, these passive solutions were generally combustor specific and applicable over a limited range of operating conditions. Therefore, active control systems that can suppress combustion instabilities over a broader range of operating conditions and that can easily be incorporated into different engine designs are needed. Effective active control of combustion instabilities via modulation of fuel flow (simultaneous variation of liquid flux and droplet size) has been successfully demonstrated in model laboratory combustors[2,3]. These active control devices are very combursome and bulky and may not be suitable for airborne system[4].

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[5]. Even though the fuel is steadily injected, the acoustic pressure oscillations inside the combustor shape droplet trajectories and lifecycle. The phase relationship between acoustic oscillations and heat release from droplets could therefore either drive or dampen the instabilities[6]. The innovative Nanomiser® atomizer device was originally developed at MCT to produce ultra-fine atomization of chemical precursor solution for its flame based thin film coating applications. The quality of resulting thin film coating is primarily dictated by the quality of atomization. The Nanomiser® atomizer does not require any atomizing gas. It 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. Therefore, in a combustion system, oxidizer flow rate can be independently adjusted for proper equivalence ratio.

This paper highlights some salient features of the Nanomiser® liquid fuel atomizer and summarizes results of the influence of spray quality produced by this injector on controlling combustion dynamics in a liquid fueled swirl combustor. Brief description of on-going effort on using similar approach for combustion dynamics control in a high pressure combustor is also presented.

EXPERIMENTAL SETUP

The combustion system consisted of an atomizer, air distributor, a conical flame holder and a quartz tube open to atmosphere at downstream end. Quartz tubes (for optical access of the flame) of 42 mm diameter and various lengths to excite different acoustic frequencies were used as combustor. Liquid fuel, n-Heptane, pressurized up to 1200 psi was used to fuel the combustor through the Nanomiser® injector. A two-stage air-fuel mixing was employed. One-third of air was directly injected with swirl into the liquid spray and the remaining two-thirds were supplied in the flame region in an annular stream. The total air flow rate was fixed at 15 g/s and the equivalence ratio was altered by changing the fuel flow rate. Experiments were conducted at two equivalence ratios of 0.75 and 0.95. PDPA and Malvern droplet anemometers were used for cold flow spray characterization. An air cooled piezoelectric KISTLER pressure transducer was mounted close to flame holder to record time history of unsteady pressure oscillations. An optical system consisting of four photomultipliers, three beam splitters, a narrow band pass interference filter and appropriate combination of lenses and apertures was used for simultaneous measurement of OH* and C_2* chemiluminescence along the reacting flame zone. A kodak Ektapro Intensified Imager camera was used at controllable shutter speed of 4000 Hz in combination of a narrow band pass interference filter to obtain high speed images of the flame that described spatial and temporal characteristics of the combustion process. Figure 1 shows the schematics of the experimental facility.

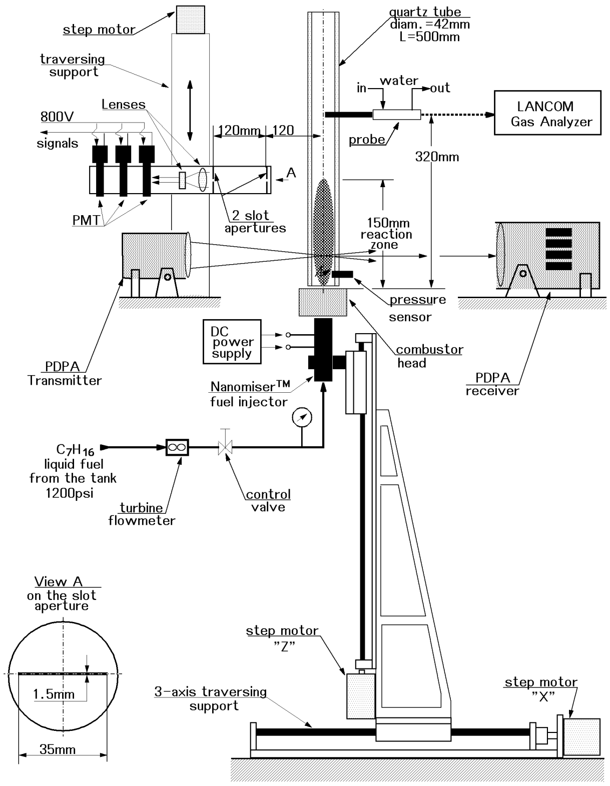

Figure 1. Schematic of test facility.

Liquid fuel delivery system consisted of pressurized vessel, solenoid valve, pressure gauge and a metering valve for flow rate adjustment. The fuel injector was specially designed to meet the flow and mounting requirements of the test facility. It was designed to flow 1 g/s at 500 psi. Since the atomization is not pressure based, different flow rate can be obtained by adjusting the fuel delivery pressure. Thus, the total air flow rate was fixed at 15 g/s and equivalence ratio was altered by adjusting fuel delivery pressure via metering valve.

RESULTS AND DISCUSSION

Salient Feature of the Nanomiser® Injector

The design and fabrication of prototype fuel injectors at MCT have mostly been dictated by customers' requirements. Nozzles have been built that flow little (3-10 mL/min) at high pressure (500 psi or more) to the ones that flow more (300 mL/min) at low pressure (70 psi or less). At the same time, injectors have been built to flow more than 1 L/min that is being successfully tested in a supercritical combustor. The most common feature among all these injectors is that none of them require any external atomizing fluid. Their designs are based on Nanomiser® technology that relies on bringing the fuel to a thermodynamically unstable state prior to injecting it through nozzle orifice. The nozzle orifice design promotes rapid breakup of liquid stream. A microprocessor based Nanomiser® controller operates on low DC voltage power supply and precisely controls the atomization process. It provides user with a dial to adjust spray quality that is modified by adjusting thermodynamic condition of fuel at nozzle orifice. Mean droplet size can be varied from 100 micron (coarse atomization) down to sub-micron (ultra-fine atomization). Droplets produced by the injector in ultra-fine atomization regime are very small even for heavy fuel like diesel and JP-8. Figure 2 shows onset of ultra-fine atomization of diesel fuel in a transparent, nitrogen-purged container at a flow rate of 300 mL/min with delivery pressure of 70 psi. The spray looks like a fog and droplets do not condense for at least 30 minutes after the injection is turned off.

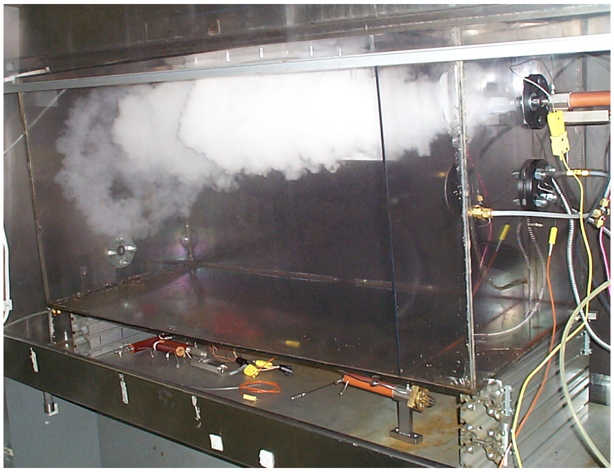

Figure 2. Ultra-fine atomization produced by Nanomiser® fuel injector.

Droplet size measurement for ultra-fine spray shown in Figure 2 was performed using Malvern laser fraunhofer. Figure 3 shows the particle size distribution obtained by Malvern instrument at a plane 2.5" from injector tip. Droplet size of 1 micron is the lower detection limit of the instrument and most of the droplets in the spray were of that size producing Sauter mean diameter of 0.69 micron. This indicates that the Nanomiser® injector is capable of producing ultra-fine atomization of heavy fuel like diesel even at high flow rates and low delivery pressure.

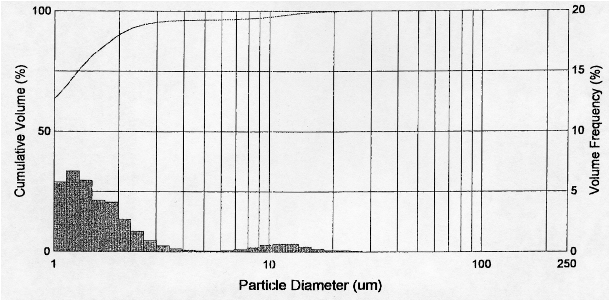

Figure 3. Droplet size distribution obtained by Malvern Instrument for ultra-fine spray shown in Figure 2.

Cold Flow Characterization

Cold flow experiments for Heptane fuel were performed using PDPA that, unlike Malvern particle sizer, allowed spray characterization at any point in the spray. Detailed spray characterizations were obtained at several points along three cross-sectional planes for two different flow rates and several different injector power settings. For cold flow experiments combustor elements (swirler, flame holder and quartz tube) were removed. Just bare injector was installed on the traverse. No assisting air blowing was provided. The closest vertical position to the injector tip where droplet size and velocity measurements were taken was 16 mm due to PDPA limitation on spray density.

Control of the spray properties was produced by variation of electric power supplied to the Nanomiser® fuel injector. To provide parameter for spray characterization, the actual injector power was normalized by the maximum power required to completely vaporize the supplied fuel.

The following paragraphs summarize the results of cold flow spray characterization. Across any cross-sectional plane of spray, larger droplets were observed near the centerline and droplet diameter decreased towards spray periphery. Central larger droplets also had higher velocities as compared to smaller peripheral droplets. Increasing injector power produced smaller and faster moving droplets. Moreover, increasing injector power produced nearly uniform droplet size distribution along the entire cross-sectional plane indicating mono-dispersed spray. Increasing injector power also increased cone angle of spray. Figure 4 indicates that the mean droplet size monotonically decreases with increasing injector power. It is important to note from

Figure 4 that size of droplets produced by Nanomiser® fuel injector does not depend on fuel flow rate. Furthermore, AMD (D_{10}) and SMD (D_{32}) approach each other as injector power is increased, indicating formation of mono-dispersed spray.

Mean and RMS velocity increase monotonically as the injector power is increased. The mean droplet velocity in the center of the spray is more than 50 m/s at a distance of 1 inch (2.54 cm) away from the injector tip. It is important to note that droplets initially accelerate and then decelerate as they move away from injector tip. The overall droplet size decreases with axial distance away from injector tip. This may be due to droplet evaporation as they move away from injector. At same injector power, the overall droplet size increases with increasing flow rate indicating that higher injector power is needed at higher flow rate in order to obtain similar level of atomization.

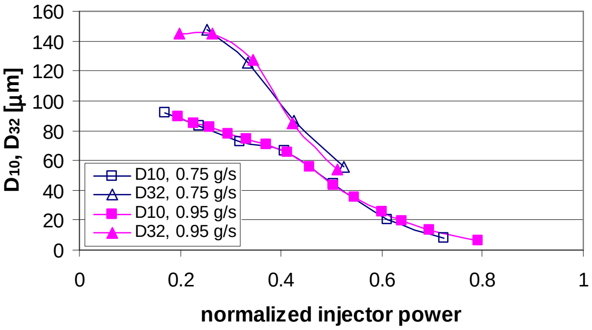

Figure 4. Mean diameter variation as a function of normalized injector power measured for m_f = 0.75 and 0.95 g/s.

Combustor Dynamics Characterization

Since the Nanomiser® fuel injector does not require any atomizing gas supply, it was possible to obtain full map of combustor dynamics at both equivalence ratios of ϕ=0.75 and ϕ=0.95 with varying injector power (spray quality). These equivalence ratios corresponded to the cold flow experiments of m_f = 0.75 g/s and 0.95 g/s, respectively. Air flow rate was m_{air} = 15 g/sec in all the runs. For each equivalence ratio, flow rate of n-heptane was kept constant. Spray quality was controlled by varying the injector power. This power was then converted to AMD (D_{10}) (obtained by cold flow characterization of the injector) to present the map of combustor dynamics. Amplitude of oscillatory combustor pressure was plotted with respect to AMD (D_{10}) to generate the map. This map is shown in Figure 5 for both equivalence ratios.

Combustion instabilities were exhibited at both equivalence ratios of 0.75 and 0.95. Similar trends for combustor dynamics were exhibited for both equivalence ratios. The RMS pressure level of the combustor had a distinctive minimum at a certain droplet size value. Increasing or decreasing injector input power around the operating point corresponding to minimum pressure oscillation causes an increase in pressure oscillation. For both equivalence ratios, the existence of a certain range of droplet sizes that produce a saddle point in oscillatory pressure amplitude was clearly exhibited. Minimum (suppressed) value of the RMS pressure amplitude was 25 ~ 30 % of the unstable pressure amplitude for both equivalence ratios. Spectral analyses of time histories of oscillatory pressures in the combustor indicate that the primary frequency of oscillation corresponded to the first resonant longitudinal mode of the quarter-wavelength for both unstable and suppressed operating conditions.

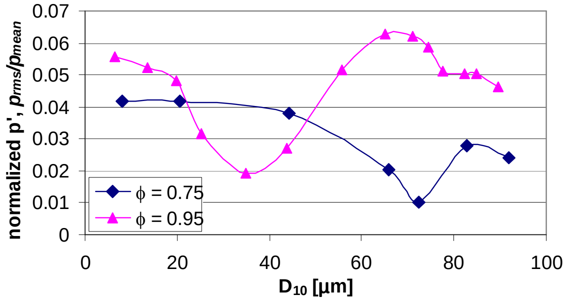

Figure 5. A map of combustor dynamics as a function of mean droplet diameter at two different equivalence ratios

Combustion Dynamics Control

A "slow" control approach was adopted to demonstrate combustion dynamics control. To demonstrate effectiveness of active "slow" control, combustor was operated at equivalence ratio of 0.75 and the injector power was adjusted until the instability was suppressed. The peak-to-peak pressure amplitude was measured to be 0.7 psi at characteristic frequency of 350 Hz corresponding to a quarter wave acoustic mode of 610 mm long quartz tube. Then, the equivalence ratio was increased by increasing the fuel flow rate without increasing air flow rate and injector power. As soon as the equivalence ratio was changed to 0.95, the combustor became unstable instantaneously and peak-to-peak pressure oscillation amplitude jumped to 3 psi corresponding to more than 20% of the mean combustor pressure. At this point, the injector input power was manually adjusted to alter the droplet size and stabilize combustor resulting in a reduction of peak-to-peak pressure amplitude to 0.9 psi. Strong pressure oscillations in the investigated liquid fueled combustor were suppressed only by variation of the injector power that, in turn, varied the spray quality. Similar experiment with 500 mm tube reduced peak-to-peak pressure amplitude from 17% to 2.5%, and that with 390 mm tube reduced it from 10% to less than 1%. This proof of concept demonstration can be upgraded to “fast” active control of combustion dynamics, with an observer constantly monitoring the instability and a controller adjusting injector power in real time to suppress the instabilities.

High Pressure Facility

Successful demonstration of combustion dynamics control in atmospheric pressure turbulent swirl combustor provided motivation to test Nanomiser® fuel injector in a high pressure combustor at Georgia Tech where violent pressure oscillations of up to 40% of mean pressure has been recorded. The test facility is shown in Figure 6 and is described in detail elsewhere[7].

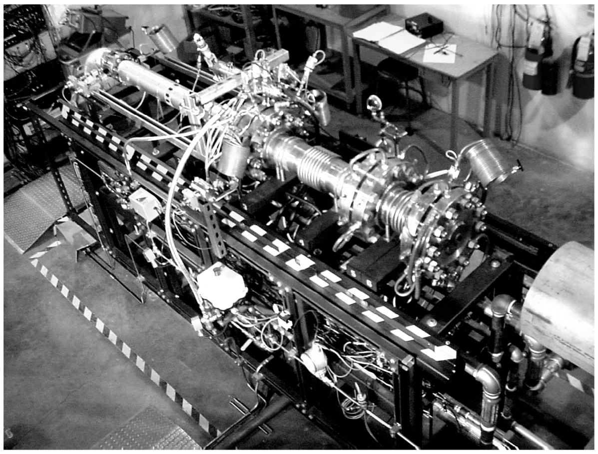

Figure 6. The high pressure facility.

This combustor houses an industrial (GE LM6000) premixer and is designed to burn natural gas at a nominal flow rate of 50 g/s that is introduced into the combustor via outer swirler blades and central injector. In order to operate this combustor on liquid fuel, a Nanomiser® fuel injector was designed and built and a liquid fuel delivery system similar to the one used in atmospheric pressure combustor was built and installed. As a first step, it was proposed to replace central gas injector with liquid fuel injector. Heptane was again selected as liquid fuel and central gas injector was replaced with Nanomiser® fuel injector. This injector was designed for nominal flow rate of 10 g/s. The pressure drop across the injector was designed to be high (1000 psi) in order to decouple flow modulation due to pressure oscillations inside the combustor. The injector was designed to have ten orifices corresponding to ten blades in the premixer swirler. These orifices were designed to inject fuel at the base of the outer swirler for enhanced mixing with gushing air stream. Figure 7 shows this injector producing coarse and fine atomization of Heptane fuel. This injector also demonstrated similar type of controllability of spray quality as was demonstrated by the injector for atmospheric pressure combustor. Detailed cold flow spray characterization has not been performed due to safety hazard.

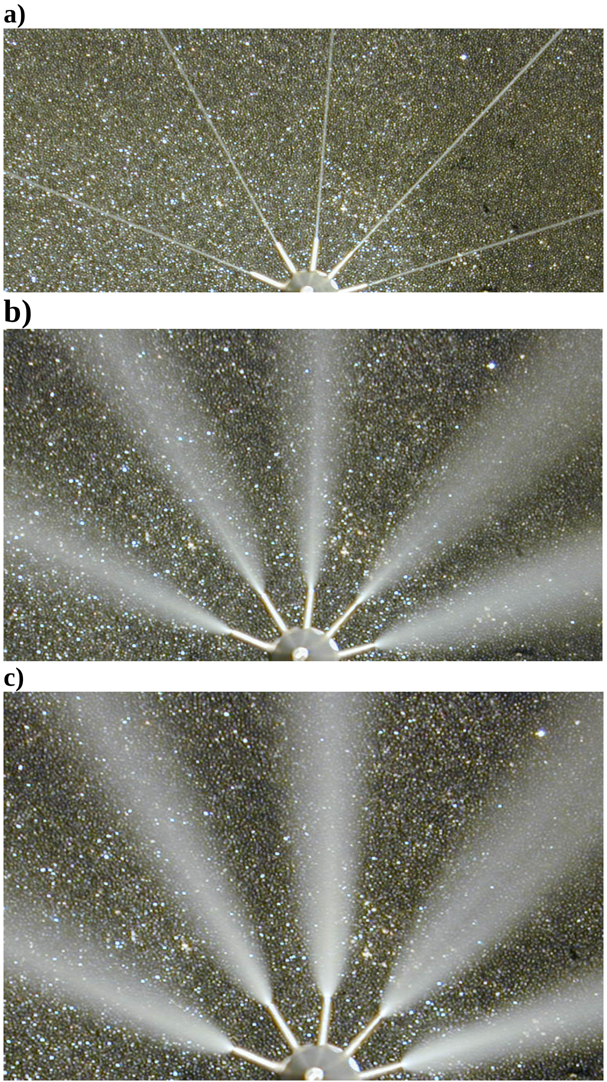

Figure 6.Atomization controllability using Nanomiser® fuel injector. (a) no atomization, (b) coarse atomization and (c) fine atomization.

The combustor was successfully operated on liquid fuel using Nanomiser® fuel injector at reduced power level corresponding to 10 g/s of Heptane fuel. Limited run time due to 1-gallon capacity of fuel tank has thus far hindered any prolonged continuous testing even at reduced power level. This is an on-going effort and so far only couple of injector power settings have been tested for recording combustion dynamics. It is noteworthy to mention as a preliminary result that the nature of combustion dynamics exhibited by liquid fuel is very similar to the one exhibited by natural gas under similar operating conditions (e.g., fuel flow rate, equivalence ratio, power level, etc.). This indicates proper design and operation of the Nanomiser® fuel injector in high pressure facility. Pressure inside combustor is nonlinear as shown in Figure 7 for a typical fuel-lean operating condition.

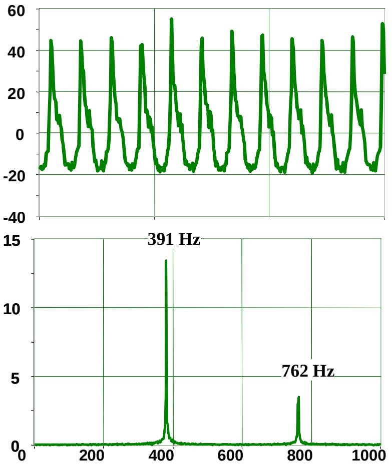

Figure 7. Typical pressure oscillations time history (psi) and spectra for operation on heptane at $\phi=0.50$.

For future testing in high pressure facility, a pump will be used allowing extended continuous testing in order to obtain full mapping of combustor dynamics and exhaust emissions. Once combustor dynamics maps are obtained with respect to spray quality at different equivalence ratios, controllability of instabilities can be demonstrated.

CONCLUSIONS

This paper describes a novel method for active control of combustion instabilities via spray quality optimization. Results obtained in an atmospheric pressure turbulent swirl combustor indicate that strong pressure oscillations in the combustor can be suppressed merely by optimizing spray qualities. The "slow" control of combustion instabilities was demonstrated by manually optimizing the spray quality. This concept can be integrated into a fast feedback control that constantly monitors the onset of instabilities and consequentially adjusts the spray qualities in real time to suppress them. On-going effort on applying this approach of active control of combustion dynamics via spray quality optimization in a high pressure liquid fueled combustor is currently underway.

ACKNOWLEDGMENT

This work is supported by Air Force grant F33615-01-2-2105 (contract monitor Dr. Balu Sekar) under the Dual Use of Science and Technology program.

REFERENCES

[1] Lefebvre, H., "Fuel Effects on Gas Turbine Combustion – Ignition, Stability and Combustion Efficiency," *ASME J. ENG. Gas Turbines and Power*, vol. 107, pp. 24-37, 1985.

[2] Kappei, F., Lee, J.-Y., Johnson, C. E., Lubarsky, E., Neumeier, Y. and Zinn, B. T., "Investigation of Oscillatory Combustion Process in Actively Controlled Liquid Fuel Combustor," AIAA 2000-3348, *36th AIAA/ASME/SAE/ASEE Joint Propulsion Conference*, Huntsville, AL, July 2000.

[3] Heising, R., Lubarsky, E., Neumeier, Y., Neumaier, M. and Zinn, B. T., "Experimental Characterization of an Oscillating Liquid Fuel Spray Combustion for Suppression of Combustion Instabilities." AIAA 2000-1024, *38th Aerospace Science Meeting & Exhibit*, Reno, NV, Jan 2000.

[4] Johnson, C. E., Neumeier, Y., Lubarsky, E., Lee, J.-Y., Neumaier, M. and Zinn, B. T., "Suppression of Combustion Instabilities in a Liquid Fuel Combustor Using a Fast Adaptive Control Algorithm,' AIAA 2000-0476, *38th Aerospace Science Meeting & Exhibit*, Reno, NV, Jan 2000.

[5] Crocco, L. and Cheng, S. I., *Theory of Combustion Instability in Liquid Propellant Rocket Engines*, Butterworth Scientific Publication, London, 1956.

[6] Duvvur, A., Chiang, C. H. and Sirignano, W. A., "Oscillatory Fuel Droplet Vaporization: Driving Mechanism for Combustion Instability," *J. Propul. Power*, Vol. 12(2), pp. 358-365, 1996.

[7] Neumeier, Y., Cohen, J., Shcherbik, D., Lubarsky, E., Zinn, B.T., and McManus, K., "Suppression of Combustion Instabilities in Gaseous Fuel Combustor Using Fast Adaptive Control Algorithm. Part 1: Controllability Tests", AIAA 2002-4076, *38th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*, Indianapolis, IN, July 2002.