DEVELOPMENT OF AN INDUSTRIAL SCALE COMBUSTION TEST AND RESEARCH FACILITY FOR ALTERNATIVE FUELS AND FUEL FLEXIBILITY DEMONSTRATION

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Abstract

Depleting resources of conventional fossil fuels, energy security and increased environmental awareness of the adverse impact of green-house emissions have all led energy and the environment to be critical areas of concern. As a result, the gas turbine engine industry is focused on developing environmentally benign engines capable of converting a variety of fuels to useful work or power. As major gas turbine manufacturers continue to develop alternative fuel systems for engines, there is a clear and pressing requirement for technology demonstration environments that enable the development of combustion systems and support the entire development process starting from research to test and evaluation to certification.

The Gas Turbine Laboratory of the Institute for Aerospace Research at the National Research Council Canada has been a major partner in the development of gas turbine combustion technologies for a number of Canadian and international companies for more than fifty years. The laboratory has recently launched a major gas turbine fuel flexibility initiative called, Alternative Fuels Facility for Research and Development. The purpose of the paper is to describe the industrial scale test and research facility developed under this program.

1 Motivation and Objectives of the Program

Although gas turbine combustor technologies have matured considerably over the last sixty years, they need to continuously evolve to meet the ever-changing needs of industry and society. Depleting resources of conventional fossil fuels, energy security and increased awareness of the adverse impact of energy production on the environment have all led energy and the environment to be critical areas of concern for the public and for the governments [1, 2]. Consequently, the gas turbine engine industry is shifting the focus from strictly pollutant reduction to developing environmentally friendly engines, capable of converting a variety of fuels to useful work or power [3]. The current focus is towards the development of novel technologies and strategies to reduce pollutant emissions for all types of gas turbines; and more importantly in an era of diminishing hydrocarbon fuel reserves, to impart a multi-fuel capability to gas turbine engines, within the framework of existing technologies [4].

There are however, major technical challenges including understanding of combusting alternative fuels, concept validation, certification and standardization that need to be resolved before these truly “green” and “omnivorous” gas turbines and systems can be introduced [5]. For example, engines burning synthetic fuels, derived via Fischer-Tropsch (FT) process, have issues related to lubrication and fuel system elastomer leakage. Similarly, key challenges in using pure biofuels are the tendency of these fuels to freeze at normal operating cruise temperatures and poor thermal stability at high temperatures.

As major gas turbine manufacturers continue to develop alternative fuel systems for engines, there is a clear and pressing requirement for technology demonstration environments that enable the development of combustion systems and support the entire development process starting from research to test and evaluation to certification.

The Gas Turbine Laboratory (GTL) of the Institute for Aerospace Research at the National Research Council Canada has been a major partner in the development of gas turbine combustion technologies for a number of Canadian and international companies for more than fifty years. GTL has recently launched a major gas turbine fuel flexibility initiative with a capital investment of $18.7M. The program called **A**lternative **F**uels **F**acility f**o**r **R**esearch and **D**evelopment" (AFFORD) [6] builds on the existing capability that allows technology demonstration of combustors, fuel systems and full engines. Due to unique competencies of the facility, the overall data set generated will be of vital importance and value to various stakeholders in gas turbine industry with interest in the application and use of alternative fuels towards energy security and climate change objectives.

The purpose of the paper is to describe the industrial scale test and research facility developed under this program.

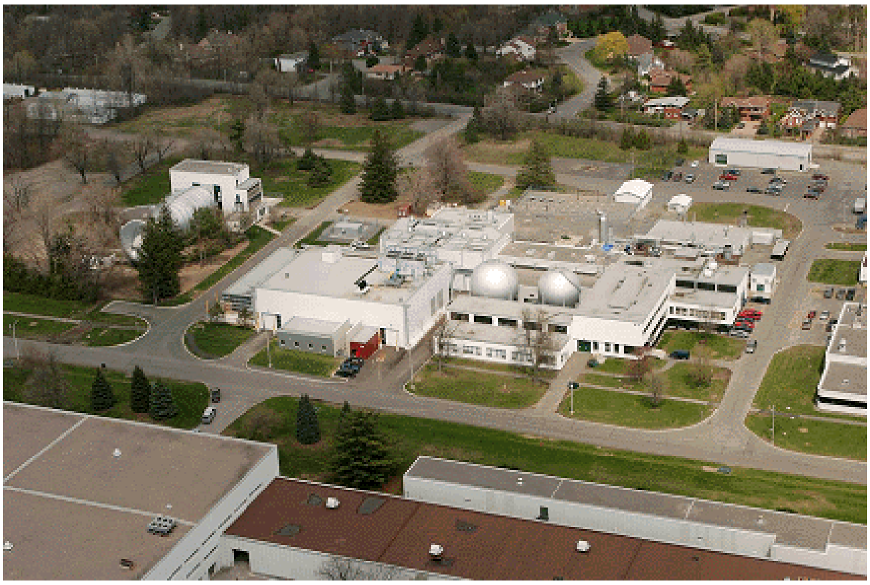

Fig. 1. GTL existing facility that houses the AFFORD setup

2 Description of the Facilities

The AFFORD facility provides a platform to significantly enhance alternative fuels research under realistic engine condition and facilitates the development of environmentally friendly technologies for gas turbine combustion, addressing energy and climate change objectives. The facility has the capability to support projects with Technology Readiness Level of 3 to 7.

The photograph of GTL facility that houses the AFFORD setup is shown in Fig. 1. The facility comprises of: a state-of-art air moving and fuel blending and sampling capability, four combustion test cells, a high altitude engine test chamber, a high-pressure and optically accessible combustion rig and high-pressure spray rigs with the capability of elevating the fuel and air temperatures. The main components of the facility are described in the succeeding sections.

2.1 The Air-Moving and Fuel-Supply and Blending Facilities

The air moving facility has the capability of providing 25 kg/s of air at 21 bars pressure and 650^{o}C temperature. The facility can supply both conventional and alternative gas turbine fuels. These fuels include Natural Gas (NG), Diesel, Jet A-1, Nitrogen (N_2), Carbon Dioxide (CO_2), Ethane, Propane, Butane, Di-Methyl Ether (DME), Hydrogen (H_2), Carbon Monoxide (CO), Bio-diesel, Ethanol and FT derived Kerosene.

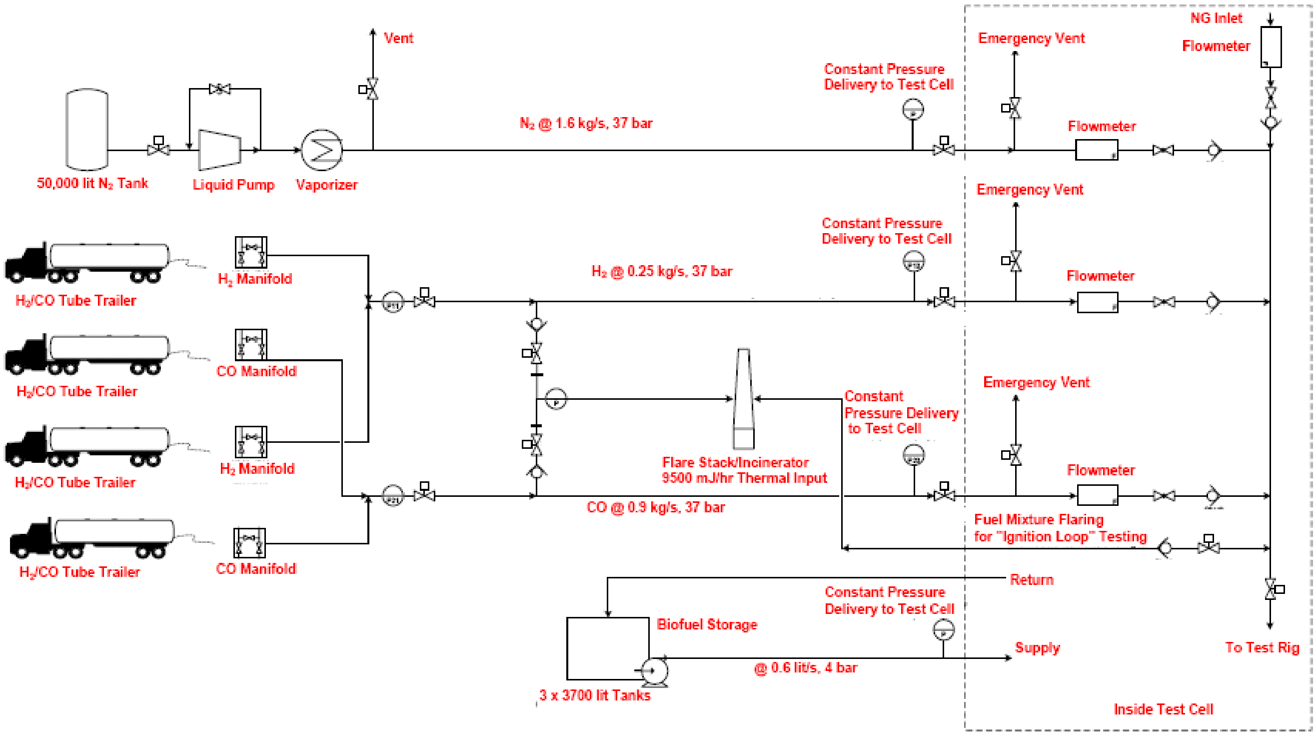

Fig. 2. The syngas supply facility

The syngas facility, shown in Fig 2, consist of a bank of four to six tube trailer docking stations designed to accept any combination of H_2, CO and N_2 trailers, with a maximum of up to four for H_2, two for CO and four for N_2. An additional N_2 supply system, in the form of a 50,000 lit cryogenic storage tank equipped with a bank of ambient vaporizers, is also available as part of the overall facility. The facility also features a centralized fuel blending and sampling station located close to the test cells. This feature facilitates supply of various simulated syngas fuels at preset pressures and compositions. The component fuels are delivered to the blending station under high pressure (37 bar) via underground transfer lines. The blending skid is also supplied with 37 bar of NG at flow rates of up to 1.1 kg/sec from the existing supply source. The current supply capability of the facility is 0.25 kg/sec of H_2, 0.9 kg/sec of CO and 1.6 kg/sec of N2.

The facility is also equipped with an enclosed Volatile Organic Compounds (VOC) incinerator system, used to minimize the release of hazardous gases to the environment during the operation of the syngas facility. The VOC incinerator is designed to operate under two purging conditions and one test condition, namely:

- Incinerate the gases released during facility shut-down sequence i.e., purging of the CO and H_2 feed lines with N_2.
- Incinerate gases during start-up sequence, where the above procedure is reversed to fill the lines with CO or H_2 initially filled with N_2.
- Incinerate pre-mixed gaseous mixture emanating from the combustion test cell and not flowing through the combustion test rigs.

The Liquid Petroleum Gas (LPG) facility of the laboratory has the capability to provide various hydrocarbon fuels to the test cells through a centralized fuel compound. Ethane is supplied from a pack of cylinders, stored in high pressure gaseous state. Liquid propane, butane and DME are stored in four liquid tanks each having the capacity of 450 lit. Nitrogen from a bulk pack is used to pressurize the fuel tanks and to supply fuels in liquid state at high pressure. These liquid fuels are then converted to gaseous state via the use of an electric heater of 75kW capacity. Condensation in supply lines is prevented by heat-tracing and insulating the piping as well as monitoring the gaseous fuel temperature at every 7.5 m interval. This monitoring coupled with a feedback control system then ensures the required fuel temperature in the supply lines. The current flow rate capability of the LPG facility is 0.15 kg/s for ethane, 0.15 kg/s for propane and 0.10 kg/s for butane. If required the supplied LPG fuels can be mixed with other fuels such as NG and/or N_2 inside the test cells.

Table 1. Typical Test Cell Specifications

Air Supply									
	Supply #1			Supply #2			Supply #3		
Max. Flow Rate	21 kg/s			6.5 kg/s					
Max. Temperature	650 deg C @ 18 kg/s			38 deg C					
Max. Pressure	21.5 bar			21.5 bar					
Air Heaters									
	Air Heater #1			Air Heater #2			Air Heater #3		
Max Flow Rate (kg/s)	9.1			9.1					
Max Temperature (deg C)	650			650					
Max. MJ/hour	38,000			38,000					
Fuel System									
	Natural Gas			Diesel			Available Seed Gases*		
	Leg #1	Leg #2	Leg #3	Leg #1	Leg #2	Leg #3	Nitrogen	Ethane	Propane
Max. Flow Rate (kg/s)	0.55	0.55	0.45	0.77	0.77	0.45			
Pressure (psia)	37	37	37	33	33	33	19.5	19.5	19.5
Water System									
	Rig & Probe Cooling			Spray Cooling			Water Jacket Cooling		
Flow Rate Range (LPM)	850			750			570		
Delivery Temp. (deg C)	205			ambient			ambient		
Max. Pressure (bar)	68			30			33		
Instrumentation & DAS **									
	Range & Number of channels			Accuracy (%)			Scan Rate (Hz)		
Pressure Sensors	0 - 2 bar-d DSA Module, 64 channels			0.05			10		
	0 - 35 bar-d DSA Module, 64 channels			0.05			10		
	0 - 35 bar-g Transducers, 40 channels			0.15			10		
Thermocouples ***	Type S, 16			0.75 FS			10		
	Type N, 172			0.75 FS			10		
	Type K, 120			0.75 FS			10		
Strain Gauges	User Defined****						10000		
Noise	User Defined****						10000		
Mass Flowmeters	User Defined						10		
Flowmeters									
Emission System									
Species	Analyzer			Potential Ranges			Instrument Specification for Repeatability		
Carbon Monoxide (CO)	Rosemount Analytical NGA 2000 NDIR			min: 0-100 ppm; max: 0-3000 ppm			+/- 1% FS		
Carbon Monoxide (CO)	Rosemount Analytical MLT ULCO NDIR			min: 0-10 ppm; max: 0-2500 ppm			+/- 1% FS (for ranges > 20 ppm)		
Carbon Monoxide (CO)	Rosemount Analytical 880A NDIR			min: 0-1%; max: 0-12%			+/- 1% FS		
Carbon Dioxide (CO2)	Rosemount Analytical NGA 2000 NDIR			min: 0-2%; max: 0-20%			+/- 1% FS		
Oxygen (O2)	Rosemount Analytical NGA 2000 Paramagnetic			min: 0-1%; max: 0-25%			+/- 1% FS		
Nitrogen Oxides (NOx)	Rosemount Analytical NGA 2000 WCLD			min: 0-10 ppm; max: 0-1000 ppm			+/- 0.5% FS		
Unburned Hydrocarbons (UHC)	Rosemount Analytical NGA 2000 HFID			min: 0-10 ppm; max: 0-10000 ppm			+/- 1% FS		

Note: * Other higher hydrocarbons also possible.
** Up to 1000 signal channels available at scan rate of up to 10 Hz.
*** The other type of thermocouples are available, user defined.
**** 32 dynamic channels are available.

2.2 Combustion Test Cells

All combustion test cells are equipped with the compressed air, cooling water and the complete range of fuels, mentioned above. Each test cell has the flexibility to be configured according to the requirements of the specific test. In addition, each test cell also offers a full host of data acquisition, diagnostics, emissions sampling and automation capabilities including instrumentation for measuring and recording gas and liquid temperatures, pressures and flow rates, combustor noise, liner temperatures and strains, and combustor exit-gas composition profiles. Up to 1000 signal channels are available for process monitoring at a scan rate of up to 10 Hz. In addition, 32 high acquisition rate channels are also available for noise and strain measurements. Detail specifications of a typical test cell are given in Table 1.

2.3 High Altitude Test Facility

The Research Altitude Test Facility (RATFac) is shown in Fig.3. The altitude chamber facilitates relight, ignition and blowout characterization under realistic altitude conditions for combustors and engines burning a variety of aviation fuels. The test chamber can also be used to evaluate characteristics of industrial combustors operating under cold-weather conditions. The fuels available are Jet-A, Jet-B and Ethanol. These fuels will soon be supplemented with Bio-diesel and FT kerosene. The chamber is equipped with a 5MW exhauster, capable of providing 12.5 kg/s air supply. Flow can be conditioned to 0.25 bar and -50 ^{o}C at a flow rate of 4.5 kg/s. Thus, ambient conditions from sea level up to 13,500m altitude may be simulated.

The altitude chamber is of cylindrical shape with the inside length of 9.8 m and diameter of 2.5 m. The facility has the capability for running both turbo-fan and turbo-shaft engines. It also has the provision to accommodate testing of dynamometers, electrical load-banks, hydraulic load equipment, ground start units and other ancillary equipment.

The facility is equipped with a data acquisition system, which includes: user interfaces, a signal processing front end, a pressure scanning system, vibration equipment and necessary hardware for process and engine controls. The data acquisition system has a capacity of 1000 channels for analog and temperature inputs with an aggregate scan rate of 50 Hz. In addition a capability of 100 channels at 100 kHz rate is also available.

Fig. 3. The research altitude test facility

2.4 Optically Accessible High Pressure Combustion Test Rig

The combustion rig, presently under fabrication, is a high-pressure, optically accessible facility and serves as a platform for the demonstration of the effects of fuel flexibility and use of alternative fuels on combustion dynamics, emissions and operability under representative gas turbine conditions. The solid model images of the rig and the research combustor liner are shown in Fig. 4 and Fig. 5 respectively. The rig has a modular construction, which enables it to be configured to house a variety of fuel injectors and combustor liner geometries. The rig can accommodate combustor liners with diameter up to 77 cm. The 5-way optical accessibility provides complete access to non-intrusive, laser-based diagnostics such as Particle Doppler Anemometry (PDA), Laser Doppler Velocimetry (LDV), Particle Image

Velocimetry (PIV) and Laser Sheet Imaging (LSI). Detailed experimental data set may be generated both for better understanding of combustion processes and for computational model validations. The rig also provides a mean for national and international research collaborations in the areas of diagnostics development and control of flame anchoring, flammability limits and combustion instabilities.

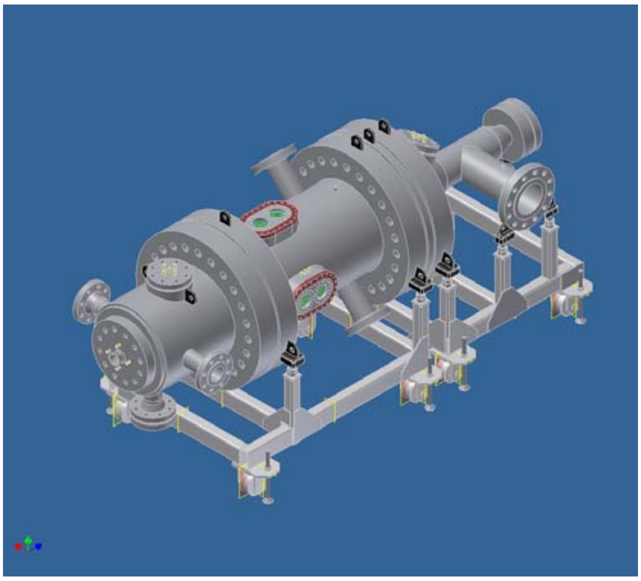

Fig. 4. The optically accessible combustion test rig

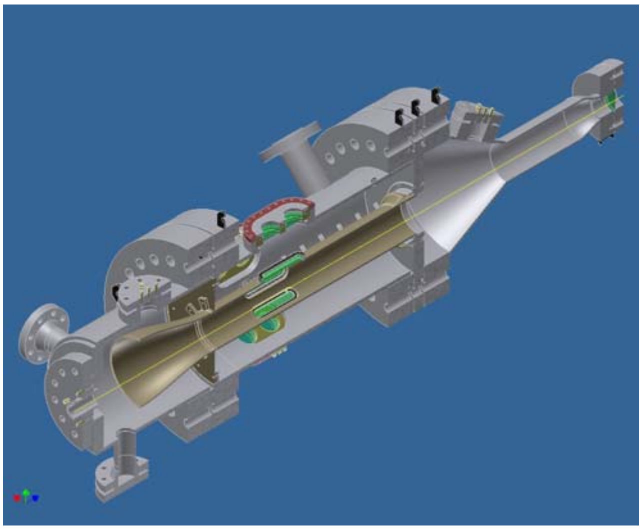

Fig. 5. Cut-away view of optically accessible combustion test rig with the generic combustion liner

The combustion rig facility will support research in the following specific gas turbine combustion areas:

- Fuel-air mixing
- Flame stability
- Thermoacoustic instabilities-diagnostics and control
- Novel atomizers for low emissions
- New optical diagnostic techniques for gas turbine health monitoring
- Combustion CFD code validation

2.5 Liquid Fuels Characterization Rigs

The fuel spray investigation setups consist of a high-pressure high-temperature Optically Accessible Single Injector Spray (OASIS) rig and a high-pressure, low-temperature multi-sector spray chamber. Photographs of the two rigs are shown in Fig. 6 and Fig. 7 respectively. Both rigs are equipped with 3-D traverse systems and are designed to accommodate all commercially available laser-based spray diagnostic analyzers like Malvern, PDPA and LDA. In addition, Laser Sheet Drop-sizing (LSD) and PIV may be conveniently conducted. Utilizing the two rigs, atomization and evaporation characteristics of alternative liquid fuels may be investigated. The OASIS rig is of particular significance as it may also be used to study the effects of preheating alternative fuels on the performance of fuel injectors and combustors. The rig has the capability of heating fuels to temperatures of 475^{o}C and can sustain a chamber pressure of 35 bars.

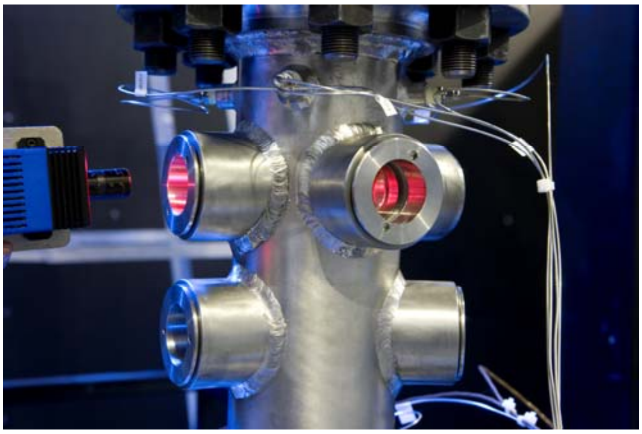

Fig. 6. The optically accessible single injector spray test rig

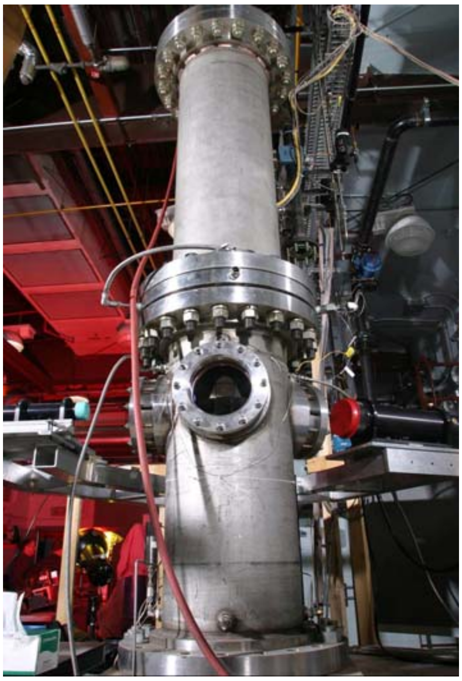

Fig. 7. The high pressure spray test rig

3 Research Program

A number of research and technology development projects have been identified in collaboration with industrial partners that benefit from the AFFORD test facility. These projects comprise of investigations on both synthetic gaseous as well as liquid fuels, as described below:

3.1 Syngas Research

The objective of this program is to understand the impact and influence of syngas fuels, having properties much different from the existing conventional fuels, on combustion and emission characteristics. These investigations focus on evaluating characteristics such as ignition, flame stability (including lean blowout and flashback), combustion efficiency and emissions of generic combustors at gas turbine operating conditions for a wide range of syngas compositions (with varying volume fractions of NG, N_2, H_2 and CO). These studies will be conducted utilizing the optically accessible combustion rig, which will allow in-depth understanding of flow characteristics and chemical species concentration during the combustion process. Also, a water injection facility will be made ready to see the effects of water injection on the combustion performance and operability.

3.2 Synfuel Research

The use of liquid synthetic fuels for gas turbine engines is becoming imperative from the stand points of energy sustainability and environmental safety. The knowledge of the ability of the current gas turbine combustion systems to handle these novel and drastically different fuels is very limited. The planned research in this area involves both reacting and non-reacting flow studies.

3.2.1 Combustion Characterization

These investigations involve combustion characterization, including flame stabilization, operation limits and emission profiling, using three alternative fuels namely, Biodiesel, Ethanol and FT Kerosene. The results will be compared with a baseline fuels like Jet-A for aero-engines and No. 2 Diesel for industrial machines. The investigation will be conducted utilizing the optically accessible high-pressure combustion rig facility.

3.2.2 Fuel Spray Characterization

Before the alternative fuels can be used for combustion they are required to be atomized and vaporized. The ability of combustors to efficiently burn these fuels and under controlled emissions depends greatly on the way the fuels are prepared i.e., atomized and vaporized. In addition the knowledge of the thermal stability of the subject alternative fuels and the ability of the current gas turbine injection systems to handle these fuels of very different characteristics is very limited. The projects in this area involve spray characterization of three fuels namely, Biodiesel, Ethanol and FT Kerosene and comparison with baseline fuels like Jet-A and No. 2 Diesel. The investigations will be conducted under high-pressure using the low-temperature multi sector spray chamber, as well as under high-temperature-high-pressure conditions using the OASIS rig. The spray characterization will be carried out using Diffraction and Phase Doppler Anemometry methods while the evaporation and thermal stability characterization will be conducted using LSD method.

4 Conclusions

The industrial scale combustion test and research facility developed at the Gas Turbine Laboratory of National Research Council Canada is intended to be utilized for fuel flexibility demonstration. The overall data set that will be gathered, utilizing the facility, is of importance and value to various stakeholders in gas turbine industry with interest in the application and use of alternative fuels. For example, the gas turbine OEM including fuel injector suppliers can benefit from the facility by investigating the capability of current combustors and fuel nozzles designs to handle alternative fuels. At the same time, bio-fuel processing companies can take advantage of the facility to certify candidate alternative fuels for use in current Kerosene based injectors and combustor designs.

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