Project 067 Impact of Fuel Heating on Combustion and Emissions

Purdue University

Project Lead Investigator

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- P.I.s: Dr. Robert P. Lucht
- FAA Award Number: 13-C-AJFE-PU-038
- Period of Performance: June 5, 2020 to June 4, 2021
- Task:
    1. Investigation of the effect of fuel heating on combustion and emissions for aviation gas turbines.

Project Funding Level

Project 67 is funded by the FAA at the level of $250,000 for the project period June 5, 2020 to June 4, 2021. The required cost sharing 1:1 match of $250,000 is provided by Purdue University.

Investigation Team

The principal investigator for the project is Prof. Robert P. Lucht and the co-principal investigator is Prof. Carson D. Slabaugh. Prof. Lucht is the major advisor for PhD graduate students Colin McDonald and Daniel Shin, and Prof. Slabaugh is the major advisor for PhD graduate students John Philo and Tristan Shahin. The graduate students are responsible for the design of system components such as the fuel heating system and will be responsible for executing test operations. Research Engineer Dr. Rohan Gejji is also working on the project and is helping the graduate students with their design projects and will be supervising the test operations.

Project Overview

The goal of this project is to determine the effects of heating jet fuel prior to injection in an aviation gas turbine combustor. In an aircraft engine, heat which would conventionally be wasted can be directed into the fuel to increase its sensible enthalpy prior to injection. Thermochemistry dictates that this increase in sensible enthalpy leads to lower fuel consumption for a given combustor exit temperature. However, the effects of elevated fuel temperature on combustion performance characteristics (such as the fuel spray pattern, spatial distribution of reaction zones, pollutant emissions, and combustion dynamics) are not yet well-understood. We will perform experiments with heated fuels using a piloted, partially premixed fuel injector that is located in an optically accessible combustor. This will allow us to apply advanced laser diagnostic techniques to compare the behavior of the combustor at different fuel temperatures over a wide range of operating conditions.

The platform for the planned experiments is the Combustion Rig for Advanced Diagnostics, which is referred to as COMRAD. The test rig, shown in Figure 1, is designed to operate at steady-state conditions with thermal powers up to 8 MW, inlet air pressures up to 600 psi, and inlet air temperatures up to 1400 ˚F. To facilitate operation at these conditions, the test article is made out of aviation-grade alloys and thoroughly water-cooled, and the inner windows are film-cooled with heated nitrogen. Prior to this project, extensive testing with ambient temperature fuels has been performed in this rig with a focus on 5 and 10 kHz particle image velocimetry (PIV) measurements in the downstream boundary condition window section and 50 and 100 kHz PIV measurements in the flame zone.

Task 1 – Investigate the Effects of Fuel Heating on Combustion and Emissions for Aviation Gas Turbines

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Objective

The goal of this project is to determine the effects of fuel heating on the performance of aviation gas turbines. Heating the fuel can potentially lead to higher efficiency but may also lead to changes in the fuel distribution pattern and in the location of reaction zones in the combustor. These changes may also impact pollutant emissions and combustion dynamics during engine operation. We will perform experiments using heated fuels and measure the fuel distributions, reaction zone distributions, pollutant emissions, and combustion dynamics at a range of fuel temperatures from near room temperature to above the supercritical temperatures for hydrocarbon fuels.

Research Approach

We will perform experiments with heated fuels using a piloted, partially premixed fuel injector that is located in an optically accessible combustor. This will allow us to apply advanced laser diagnostic techniques to compare the behavior of the combustor at different fuel temperatures over a wide range of operating conditions. These advanced diagnostic techniques include fuel planar laser-induced fluorescence (PLIF) imaging to monitor fuel distribution patterns, hydroxyl (OH) radical PLIF imaging to monitor reaction zones, and PIV to measure the flow fields. We will also measure emissions using probe sampling and pressure transducers to measure combustion dynamics.

Milestones

The major milestones accomplished in the first three months of the project are:

1. The design of the fuel heater was completed and nearly all of the components have been ordered.
2. Operating conditions for our initial tests have been developed. These operating conditions were defined with the significant input from researchers at GE Aviation.
3. Major improvements to the COMRAD test rig and associated infrastructure were accomplished, including significant upgrades to the control system and the nitrogen supply for film cooling system.

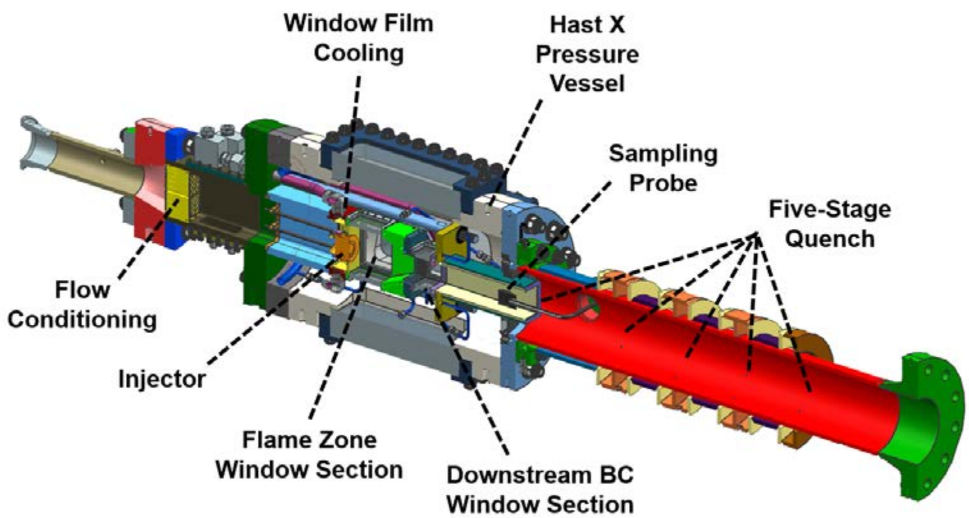

Figure 1. Schematic diagram of the Combustion Rig for Advanced Diagnostics (COMRAD).

Major Accomplishments

The focus of the activities for this project to date have been the design of the fuel heating system and improvements to the test stand and facilities. The fuel heater design ensures that the goals of the project will be successfully met by developing the capability to provide heated fuels to the experiment at conditions of interest to both GE Aviation and the broader research community. The critical design review (CDR) for the fuel heater was completed on August 11. The facility improvements that have been completed will help to streamline test operations so we can more efficiently and reliably perform the experimental measurements for this project.

A. Fuel Heater Design

We began the fuel heater design by consulting with GE Aviation to determine target design conditions. These conditions are similar to those that have been previously tested in COMRAD. We plan to perform equivalence ratio sweeps from 0.50 to lean blow-out at the listed inlet air pressures and temperature. This will be repeated at multiple fuel temperatures, with a baseline of 200 ˚F and a more detailed study around 600-650 ˚F.

Table 1. Heated fuel operating condition limits.

<table>
<tr><th>Test Condition</th><th>P_3
(psia)</th><th>T_3
(˚F)</th><th>Overall φ</th><th>Total Fuel Flow Rate (pph)</th><th>Pilot/Total
(%)</th></tr>
<tr><td>Cond001</td><td>150</td><td rowspan="6">900</td><td rowspan="3">0.37</td><td>117</td><td rowspan="6">30</td></tr>
<tr><td>Cond002</td><td>300</td><td>234</td></tr>
<tr><td>Cond003</td><td>400</td><td>313</td></tr>
<tr><td>Cond004</td><td>150</td><td rowspan="3">0.50</td><td>159</td></tr>
<tr><td>Cond005</td><td>300</td><td>317</td></tr>
<tr><td>Cond006</td><td>400</td><td>423</td></tr>
</table>

We decided to design the fuel heater to supply fuel for the highest expected fuel flow rate condition at up to 800 ˚F, because at this point the fuel will be supercritical at injection. The maximum required power is 18.0 kW for the pilot fuel and 42.0 kW for the main fuel. Assuming a maximum heater efficiency of 80%, the heater has been sized for 27 kW of power for the pilot fuel circuits and 54 kW of power for the main fuel circuit.

The fuel heater configuration is based on prior experience testing heated fuels at our laboratory. The fuel flows through stainless steel tubes, which are sandwiched between a pair of copper blocks. Inserted into the copper blocks are 5/8-inch-diameter, 480-V cartridge heaters, which distribute the heat evenly over the entire length of tubing. There are three independent heater circuits, two for the pilot and one for the main, which consist of zones of five cartridges that are controlled remotely with PID controllers. Sheets of ceramic fiber insulation isolate the individual pairs of heater blocks.

B. Nitrogen Heating System Improvements

Our facility uses two separate natural gas-fired heaters for this project: one for heated air for the core flow and one for heated nitrogen for the window film cooling. In 2018, COMRAD was moved to a new test cell in ZL8, a building which recently opened adjacent to the building where the old test cell was located (ZL3). This required the piping downstream of the nitrogen heater to be reworked, because it is routed through the old test cells in ZL3. These changes have also required us to reroute tubing from our 6,000-psi nitrogen tank to the inlet of the heater, where the pressure is regulated to our target condition. Additionally, a control switching system was designed to switch control of the heater and the nitrogen system between the individual data systems in the ZL3 and ZL8 buildings. This is a significant upgrade to the capabilities of our facility, and it involved routing and landing many cables as well as wiring the control switching system. Presently, we are putting the finishing touches on this system and on the tubing to connect to the nitrogen system. We expect everything to be functional in mid-October.

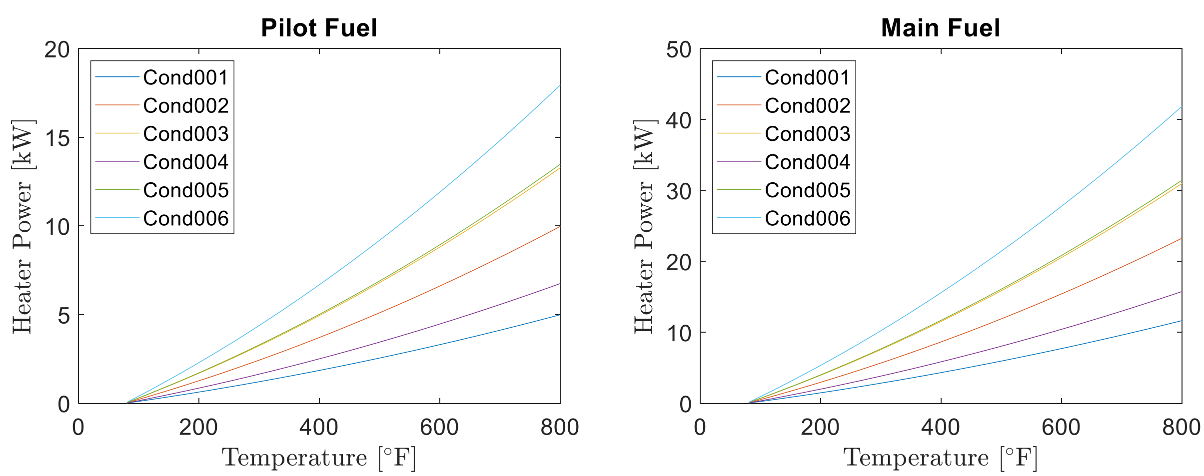

Figure 2. Required heater power for pilot and main fuel circuits.

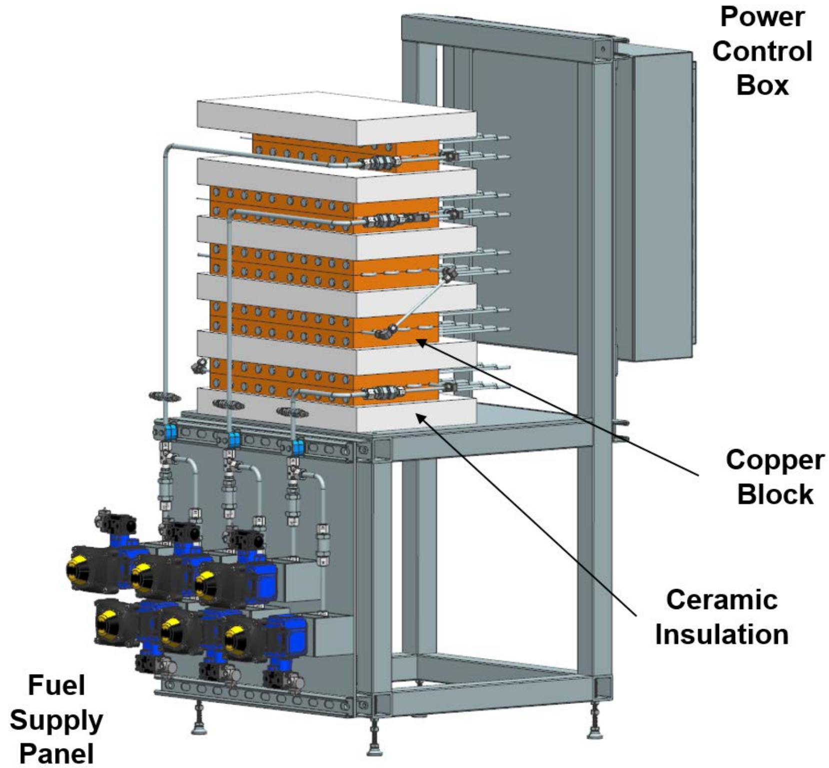

Figure 3. Schematic diagram of fuel heater design.

Publications

We have not generated any publications thus far for Project 67.

Outreach Efforts

We have not performed any outreach efforts thus far for Project 67.

Awards

None

Student Involvement

There are four PhD graduate students working on the project. The project provides outstanding research experiences for the graduate students including design of system components for and operation of a sophisticated aviation gas turbine combustion test rig, as well as application of advanced laser diagnostic methods for measurements in this test rig. As noted above, the graduate students have been responsible for the design of system components such as the fuel heating system and for the installation of components for the nitrogen window film cooling system. The students will be responsible for executing test operations.

Plans for Next Period

Multiple tasks are ongoing in preparation to resume testing the experiment as currently configured as well as to begin testing with heated fuel. The primary item that needs to be completed before preliminary measurements can begin is the integration of the emissions sampling system. Completion of the fuel heater fabrication will follow, allowing testing with heated fuels to commence.

A. Emissions Sampling System

For the planned test campaign, provisions have been made to install an emissions sampling probe designed by GE Aviation just downstream of the primary reaction zone. This probe will route a sample of exhaust gases to a Fourier-transform infrared spectrometer (FTIR) located near the test cell. The sample will be kept at 191 °C by electric heat tape to meet the inlet temperature required by the FTIR spectrometer. Installation of the heat tape, tubing, and valves needed for this system is in progress and is expected to be completed in early October.

B. Fuel Heater Fabrication

The fabrication of the fuel heater and associated systems is currently underway. All of the major orders have been placed, and many components have been received. The fuel heater stand, shown in Figure 4, has been welded and is waiting to be powder coated. The cartridge heaters should be arriving within a week or two, at which point the machining of the copper blocks will begin. This makes it possible to verify the cartridge heater dimensions and ensure a good fit in the copper blocks. The disconnect switch and associated electrical components will arrive by the end of the month. An electrician has been contracted to perform the installation and wiring of the 480 V, three-phase power to the fuel heater after the required electrical components are delivered. Additionally, all of the required fluid components, except for the high temperature valves needed downstream of the heater, should arrive by the end of October.

Figure 4. Fuel heater stand fabrication.

C. Summary and Timeline

After several months of work, we are very close to conducting our first measurements for this project. These first test operations will take place in mid-November 2020. Once the emissions system and the nitrogen heating system are ready for use, we are planning to run the experiment for 2–3 test days to obtain some data with ambient-temperature fuels. Data from these test days will complement past experiments with this hardware and allow us to try out the new facility systems before the fuel heater fabrication is completed. Planned milestones for the rest of the project period are listed in Table 2.

Table 2: Project timeline

Task	Planned Completion Date
Initial testing with ambient-temperature fuel	November 15, 2020
Heated fuels test readiness review	November 23, 2020
Parametric survey testing with heated fuel: Vary fuel temperature, pressure, and equivalence ratio with emissions measurements and chemiluminescence imaging	December 21, 2020
Initial test operations with large-scale flow and flame diagnostics: 10 kHz particle image velocimetry (PIV) and OH planar laser-induced fluorescence (PLIF) with chemiluminescence measurements	January 31, 2021
Development of detailed operational test plan	January 31, 2021
Continued test operations with large scale flow and flame diagnostics: Fuel PLIF, Mie scattering, and 100 kHz simultaneous OH PLIF/PIV measurements	June 4, 2021