Project 070 Reduction of nvPM Emissions from Aero-Engine Fuel Injectors

Georgia Institute of Technology

Project Lead Investigator

Wenting Sun
Associate Professor
School of Aerospace Engineering
Georgia Institute of Technology
(404) 894-0524
wenting.sun@aerospace.gatech.edu

University Participants

Georgia Institute of Technology

- PI: Dr. Wenting Sun
- FAA Award Number: 13-C-AJFE-GIT-080
- Period of Performance: August 11, 2020 to August 10, 2021
- Tasks:
    1. Measurement of non-volatile particulate matter (nvPM) formation and oxidation processes
    2. nvPM model development and validation
    3. Experimental facility development and operation

Project Funding Level

The total amount of funding from the FAA is $1,000,000. The matching funding includes $900,000 from the Georgia Institute of Technology and $100,000 from Honeywell.

Investigation Team

Lead PI, Wenting Sun (Georgia Institute of Technology), will oversee the entire project and coordinate among the co-PIs. He will work with one graduate student and one research engineer to lead Task 3.

Co-PIs Adam Steinberg, Ellen Yi Chen, Timothy Lieuwen, and Jechiel Jagoda (Georgia Institute of Technology) will work with two graduate students to lead Task 1.

Co-PIs Rudy Dudebout and Fang Xu from Honeywell will lead Task 2.

Project Overview

Reducing nvPM from gas turbine engines is essential for improving air quality and reducing the environmental impact of aviation. However, predicting and controlling nvPM remains challenging because of the complicated physical and chemical processes involved. The proposed research will characterize the formation/oxidation of nvPM and optimize the design of an aeronautical gas turbine fuel injector to reduce nvPM at flight-relevant conditions. The goals of this project include:

1. Develop a high-pressure experimental platform suitable for combustor testing under practical conditions and enabling academic advanced diagnostics
2. Conduct optical diagnostics to measure the nvPM volume fraction and primary particle size; the polycyclic aromatic hydrocarbon (PAH) and hydroxyl (OH) radical distributions; and the flow field for a set of fuel injectors
3. Develop empirical correlations describing nvPM formation/oxidation by using data obtained in experiments
4. Validate computational fluid dynamics (CFD) simulations to facilitate fuel injector design optimization

Task 1 - Measurement of nvPM Formation and Oxidation Processes

Georgia Institute of Technology

Objective(s)

In this task, laser-induced incandescence (LII) measurements will be conducted to quantify the soot volume fraction and primary particle size; OH planar laser-induced fluorescence (PLIF) will be conducted to understand the soot oxidation process; PAH PLIF will be conducted to elucidate the formation pathway of soot; and particle image velocimetry (PIV) will be conducted to understand the fuel/air mixing process according to the characteristics of fuel injectors.

Research Approach

We will conduct LII to quantify soot volume fraction and primary particle size; PIV to measure flow fields; PAH PLIF and OH PLIF to understand the interaction between nvPM and important gas-phase species; and droplet Mie scattering to characterize the fuel spray. We will also conduct sampling measurements in the combustor exhaust to analyze the exhaust composition (via gas chromatography) and nvPM composition/morphology (via X-ray photoelectron spectroscopy [XPS] and scanning electron microscopy [SEM]), thus increasing the understanding of nvPM kinetics. All measurements will be performed in a model aeronautical gas turbine combustor operated with a liquid jet fuel at engine-relevant operating conditions. All subtasks under Task 1 will proceed in parallel, because the ultimate aim is to measure multiple parameters simultaneously.

In year 1 of this project, the focus is the development of a new high-pressure experimental platform. Until the newly designed three-fuel injector is commissioned, optical diagnostics cannot be performed to obtain experimental data. While waiting for the commissioning of the experimental system, the optical diagnostic tools were prepared and will be ready for use when the combustion experiments start. The following sections detail the mechanisms of the proposed optical diagnostics and describe several preliminary results acquired during the preparation of these optical diagnostics.

Subtask 1.1 - LII Measurement

LII uses short laser pulses to heat small particles to vaporization temperatures. The light emission, or incandescence, of the nvPM is then measured to deduce the relative volume fraction and primary particle size. Two-dimensional implementations of LII are performed by shaping the laser beam into a uniform sheet and capturing the incandescence at various wavelengths on sensitive time-gated cameras. The prompt emission immediately after the arrival of the laser pulse describes the volume fraction or spatial concentration of nvPM particles. By applying sufficient laser intensity to uniformly sublimate the nvPM and by calibrating these measurements against emissions from known flames, the absolute volume fractions can be determined.

For nvPM particle sizing, time-resolved LII (TiRe-LII) techniques can be used to obtain the incandescence decay over time. This approach relies on the faster cooling times of small particles compared to large particles after laser heating, due to their larger surface-to-volume ratio. By solving energy and mass balances, the primary particle size can be evaluated. To measure the decays, which are on the order of several hundred nanoseconds in atmospheric-pressure flames, ultra-high-speed cameras are necessary. Recently, we have successfully demonstrated a single-camera single-laser-shot technique for performing these measurements by capturing the decay time constants at 10 million frames per second with a 50-ns gate. At these imaging rates, the flame motion appears stationary, thus enabling accurate pixel-by-pixel decay time measurements. The data from each pixel are then fit to a model to determine the instantaneous, primary nvPM particle sizes for the entire scene. The statistics for these images can then be compared to show regions of the flame where nvPM growth and nvPM oxidation typically occur.

However, for the high pressures associated with flight-relevant conditions, the incandescence time constants decrease to the order of ~50 ns, which is faster than the imaging rate of many single-chip ultra-high-speed cameras. To overcome this challenge and accurately measure the shorter time constants in these environments, a multi-camera variant of the TiRe-LII technique described above can be used. In this variant, two or more cameras sharing the same field of view can be gated to open a few tens of nanoseconds apart. The calibrated relative intensities of these images can then be used to estimate time constants and nvPM particle sizes. Hence, this method enables the determination of nvPM growth regions and oxidation regions, even in high-pressure environments.

The various LII measurements described in this subtask will be conducted by using the fundamental 1,064-nm output of a solid-state neodymium-doped yttrium aluminum garnet (Nd:YAG) laser operating at 5–10 kHz to avoid exciting the OH and PAH fluorescence. The laser beam will be formed into a sheet that is then passed through the combustor. The incandescence will then be measured with time-gated cameras by using the appropriate filters (near 640 nm) to avoid C_2 Swan band emissions. Calibrations using well-characterized ethylene turbulent jet flames were conducted to produce quantitative measurements for nvPM volume fraction and particle size in the gas turbine combustor under the conditions of interest. The experimental setup for LII is presented in Figure 1. The fundamental 1,064-nm output of a solid-state Nd:YAG laser was expanded into a laser sheet by using a combination of lenses. The laser sheet past the turbulent jet flame and LII signal was then collected with a high-speed camera.

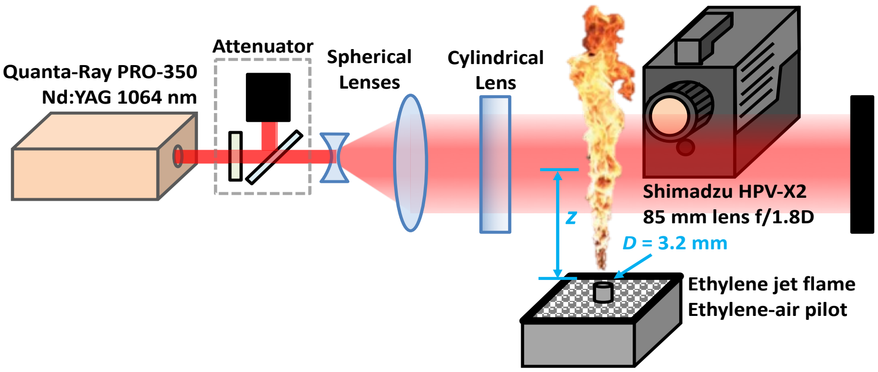

Figure 1. Experimental schematic of LII.

Figure 2 shows the measured particle size distribution in the ethylene turbulent jet flame. With variations in flow conditions (Reynolds number), the particle size distribution changes. Similar phenomena are expected in our combustor experiments using liquid jet fuel. We will implement these optical diagnostics after the high-pressure experiment is commissioned.

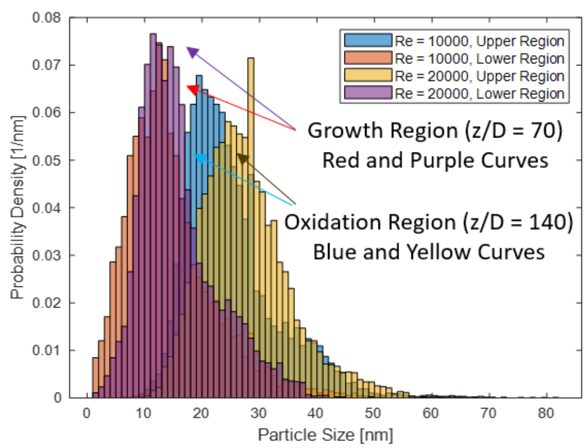

Figure 2. Distribution of soot particle sizes in a turbulent jet flame.

Subtask 1.2 - OH PLIF Measurement

Oxidation through reaction with hydroxyl radicals (OH) is expected to be a critical pathway through which nvPM is destroyed in the flame. Understanding the relative trajectories of nvPM and OH through the combustor is therefore critical to predicting the final nvPM output.

OH radicals form during high-temperature hydrocarbon oxidation, reaching super-equilibrium concentrations near the location of maximum heat release rate before relaxing to equilibrium in the products. Significant concentrations of OH occur in hot product gases at temperatures above ~1500 K. Fortunately, owing to its strongly absorbing energy transitions at wavelengths that are relatively accessible to high-energy pulsed lasers, OH can be readily measured using PLIF. The main challenges in performing OH PLIF in the combustor of interest herein are laser power absorption and signal trapping through the high-density gas at 10 bar.

We will perform OH PLIF measurements simultaneously with the two-dimensional (2D) LII measurements to understand the interaction between nvPM and OH. Measurements will be made at a 5- to 10-kHz repetition rate by using the frequency-doubled output of a dye laser (rhodamine 6G), pumped by a frequency-doubled solid-state laser (Nd:YAG). Over 7 W of ultraviolet (UV) laser light can be produced by our laser system, which is sufficient to acquire signals across the combustor domain. The laser beam will be formed into a sheet, made coincident with the LII laser sheet, and transmitted through the combustor. The OH PLIF signal will be filtered through an appropriate bandpass filter (approximately 307 nm) and recorded with a high-speed intensified camera. Appropriate corrections will be made for laser power absorption, intensity variations, and detector response. The resultant data will provide time-resolved 2D images of the OH distribution, which will be correlated with nvPM dynamics to better understand the oxidation process and how specific trajectories influence the nvPM that is ultimately output from the combustor.

Subtask 1.3 - PAH PLIF Measurement
PAHs occur naturally in jet fuel and also can be formed from small aliphatic compounds during combustion. Because PAHs play key roles in nvPM growth, understanding their positions relative to regions containing nvPM can help elucidate rate-controlling processes.

PAH molecules have high-absorption cross-sections across a wide range of wavelengths in the UV spectral range. Therefore, PAH PLIF can be performed with a laser wavelength similar to that used for the OH PLIF but slightly de-tuned from the narrow-band OH absorption line to avoid interference. Hence, PAH PLIF measurements will be acquired with the same experimental configuration as those with OH PLIF but with a wavelength shift on the order of 0.1 nm. Measurements will be obtained simultaneously with the LII to elucidate the relative positions of nvPM and PAH during formation. Although OH and PAH PLIF will not be obtained simultaneously, these species are related to different aspects of the nvPM dynamics and do not directly interact. Because the PAH PLIF laser beam is obtained by adjusting the wavelength of the OH PLIF beam, the different measurements can be obtained in close succession, thus maintaining identical operating conditions.

Subtask 1.4 - PIV Measurement
Measuring the fluid velocity field is critical for understanding the influence of turbulence and mixing on nvPM dynamics. PIV measures the velocity field in a plane by tracking the motion of micron-scale particles that are seeded into the flow. Stereoscopic PIV (S-PIV) enables measurement of all three velocity components in the plane by simultaneously viewing the particle motion from two different viewing angles. Although PIV (and S-PIV) has been successfully applied to study a wide range of flows, including in flames, its application in high-pressure fuel-rich combustion has been relatively limited because of the high-intensity background luminescence from the flame, beam steering through index-of-refraction gradients, and fouling of the optical windows due to seed particle deposition. Despite these challenges, we have recently demonstrated S-PIV in a 10-bar rich-burn gas turbine combustor similar to that studied in this work.

Here, S-PIV measurements will be made simultaneously with the LII and PLIF measurements. To enable these measurements, the flow will be seeded with micron scale ZrO_2 tracer particles. The high melting point of ZrO_2, as compared with other commonly used solid tracers, mitigates window contamination. Laser pulse pairs from a solid-state second-harmonic Nd:YAG laser will be formed into a sheet and transmitted through the combustor along the same path as those with the other measurement techniques. The particle-scattered light will be filtered through appropriate bandpass filters and collected by two high-speed cameras arranged in an angular stereoscopic viewing configuration. Image pre-processing routines—which are well established in our group—will be performed to reduce the effects of background flame luminosity and cross-signal interference, thus providing sharp particle images for subsequent vector processing. The resultant particle image pairs will be converted to three-component velocity vectors with a multi-pass image cross-correlation algorithm implemented in LaVision DaVis, a commercial software package.

Subtask 1.5 - Fuel Droplet Mie Scattering Measurement
One important factor controlling nvPM formation is the mixing between the fuel from the injector spray and the air in the combustor. The fuel injector spray can be characterized by measuring the size and spatial distribution of liquid fuel droplets. Using Mie scattering imaging techniques, the spatial distribution of micro-sized fuel droplets can be determined via measurement of elastic light scattering. However, quantification of the spray properties from Mie scattering is challenging, predominantly because of multiply scattered photons, interference from PIV seed particles, and the relationship between scattering intensity and droplet size. Here, the objective is to obtain qualitative information regarding the fuel spray trajectory, including the spray angle; penetration; and relative locations of the liquid fuel, flame, and nvPM.

To study the fuel droplet distribution of different injectors at pressure in a non-reacting environment, the liquid fuel droplet distribution will be measured via Mie scattering at a 5- to 10-kHz repetition rate. The second harmonic of an Nd:YAG laser will be formed into a sheet and transmitted through the spray inside the experimental facility. The scattered light will be imaged at an angle perpendicular to the laser propagation with a high-speed camera. This signal will then be separated from the PIV seed particle scattering through adaptive threshold-based segmentation techniques.

Subtask 1.6 - Extractive Sampling Measurement

In this task, exhaust gas samples will be extracted and analyzed via gas chromatography (gas phase), XPS (solid phase), and SEM (solid phase). The gas chromatography (Inficon Fusion μGC) analysis will reveal comprehensive information regarding the large hydrocarbons formed during the combustion of Jet-A fuel, such as the detailed structures of PAHs, ethylene, and other intermediate species relevant to soot formation.

The XPS and SEM analyses will provide data on nvPM composition and morphology to help understand the detailed formation mechanisms of nvPM. There are two possible mechanisms for nvPM formation that can be detected during the combustor test. The first is due to the liquid fuel impinging on the wall, accompanied by chemical reactions at the wall. The other results from flame products, such as soot or coked droplets. These two types of solid particles can be differentiated through chemical and morphology analysis. Solid particles formed due to wall wetting features result in lower carbon content but significantly higher oxygen content (e.g., 70%–80% carbon and 20% oxygen) and small amounts of hydrogen and nitrogen, due to incomplete oxidation of fuel at low temperatures. Solid particles formed from flame products feature high carbon and low oxygen content (e.g., 98% carbon and 2% oxygen). In terms of morphology, the solid particles formed due to wall wetting exhibit amorphous structures, whereas the solid particles formed from flame products are spherical and are typically 4–5 μm in diameter. For these experiments, a water-cooled sampling probe will be used to collect samples of exhaust gas from the pressure vessel.

Task 2 – nvPM Model Development and Validation

Honeywell

Objective(s)

This task involves the comparison of the experimental measurements obtained in Task 1 with detailed numerical simulations for the purpose of model development and validation. A numerical framework to model the gas turbine combustor system will be established based on Honeywell's previous experience. In this numerical framework, a commercial solver will be used to obtain CFD solutions with a large eddy simulation (LES) turbulence model by using a dynamic Smagorinsky model. The combined heat release/turbulence model consists of non-premixed diffusion flamelets generated with a detailed Jet-A kinetic model that describes the formation of aromatic species up to pyrene. The simulation includes radiation with the discrete ordinate method due to H_2O, CO_2, and nvPM (weighted-sum-of-gray-gases model (WSGCM)). The liquid fuel spray is modeled with Lagrangian tracking of droplets with stochastic secondary breakup, calibrated to experimental data. The domain is discretized by using polyhedral cells and consists of the entire geometry from the inlet of the rig to the exhaust of the combustor. The simulation is initially converged with a Reynolds-averaged Navier–Stokes (RANS) solution, then run with five flow-throughs to initialize the solution and then an additional five flow-throughs to obtain statistical averages. The numerical simulation will be compared with experimental results from optical measurements (LII, OH/PAH PLIF, S-PIV, and Mie scattering) under different flow conditions with different fuel injectors. The numerical model will then be validated and optimized for further fuel injector design with the aim of minimizing nvPM emissions.

Task 2 will start in the second quarter of 2022 after the experimental results proposed in Task 1 are obtained.

Task 3 - Experimental Facility Development and Operation

Georgia Institute of Technology and Honeywell

In this task, we conducted detailed design of a high-pressure vessel and model gas turbine combustor for the proposed measurement. The design is challenging because it must accommodate both practical applications from an industrial perspective and academic applications involving advanced optical measurements. To achieve this goal, the Georgia Tech team and Honeywell team worked closely together and finalized a unique design of a combustor with three fuel injectors. This three-fuel-injector design can minimize injector–combustor wall interaction, which commonly occurs in conventional combustor designs with only one fuel injector. Our optical measurement will focus on the center fuel injector. Three large optical windows on the top and side walls of the combustor allow for optical diagnostics. The combustor will be placed inside a large high-pressure vessel with adequate optical access through two 10-inch-diameter windows and one 8-inch-diameter window. Figure 3 shows the overview of the high-pressure system. The high pressure is supported by a metal frame above the ground, and the combustor is housed inside the high-pressure vessel. Figure 4 shows the computer-aided-design (CAD) model of the high-pressure vessel. The high-pressure vessel has been successfully fabricated and certified, as shown by the direct photograph in Figure 5.

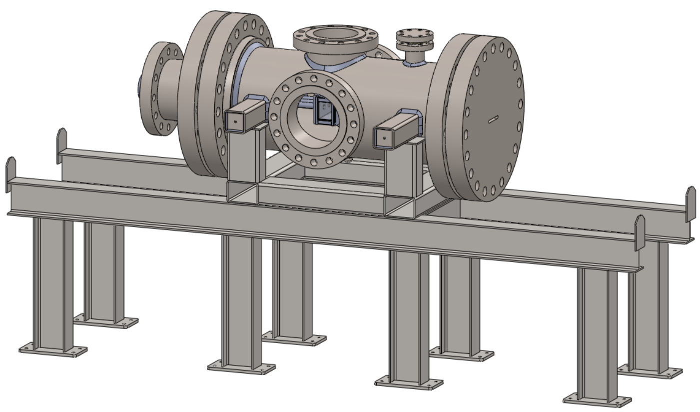

Figure 3. Overview of the high-pressure system.

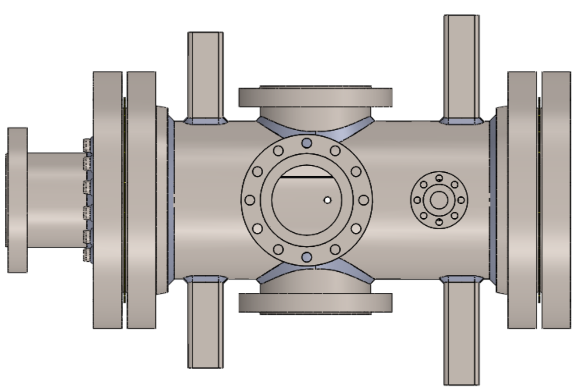

Figure 4. CAD model of the high-pressure vessel.

Figure 5. Direct photograph of the high-pressure vessel after completion of fabrication.

The combustor to be built will comprise three fuel injectors, in contrast to our initial proposal. As discussed above, the purpose of the three-fuel-injector design is to minimize injector–combustor wall interaction, which artificially affects the experimental results and causes them to deviate from those in a practical combustor. The current design of the combustor reflects a sector of an annular rich burn, quick quench, lean burn (RQL) combustor architecture. The test rig has provisions for routing air to cool the combustor walls and provides air to the quench holes, the injector, and the swirler. The sidewalls also incorporate optical access with suitable features to discourage the accumulation of nvPM or S-PIV tracer particles. Non-optical components of the liner are multi-holed angle cooled (i.e., effusion cooled) at an appropriate cooling flux with no additional thermal barrier coating. Honeywell will provide the dome/bulkhead and fuel injector with replaceable screw-on injector swirlers. In addition, Honeywell will fabricate the fuel injector and screw-on injector swirlers. A combination of proprietary and public-domain swirler configurations will be designed, fabricated, and tested. This effort should yield both publishable data and proprietary data that can directly translate to design improvements. The estimated design conditions are combustor inlet temperatures between 600 °F and 800 °F, combustor inlet pressures between 6 atm and 10 atm, a pressure drop of approximately 3%, a primary zone equivalence ratio of 1.2–1.8, and combustor exhaust temperatures of 2000–3000 °F.

Figure 6 shows the final design of the combustor. Fabrication is currently in progress.

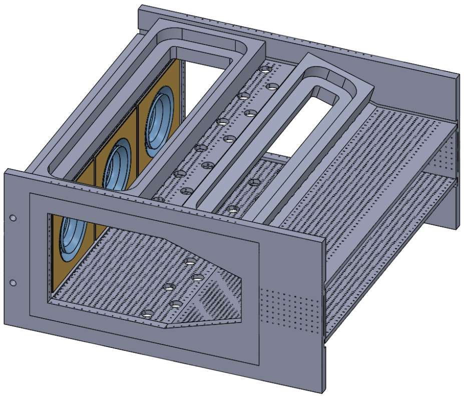

Figure 6. Rendering of the proposed combustor with three fuel injectors.

Another challenge in combustor design is the efficient cooling of liners and windows. To understand the thermal cooling effect of the current design, the Honeywell team conducted a CFD simulation of the entire high-pressure system including both the pressure vessel and combustor, with and without flames. The simulation was conducted with ANSYS FLUENT, by using a $k\varepsilon$ Reynolds-averaged Navier–Stokes (RANS) turbulence model, flamelet turbulent combustion model, soot and NO emission model, and discrete ordinate radiation model. Figure 7 shows the meshing of the simulation with 43.2 million polyhedral cells.

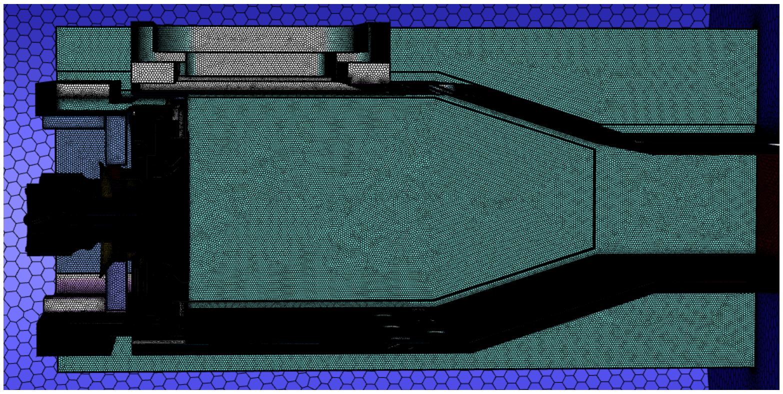

Figure 7. Meshing of the simulated combustor.

Because the combustor is symmetric, two cooling patterns were used: one with a single long slot (0.81 × 215 mm) at the top plate and the other with 48 small slots (1.2 × 3 mm) at the bottom plate. In this way, one simulation can evaluate two cooling patterns. The pressure of the combustor is 150 psi, and the hot air has a temperature of 900 °F. The air flow rate is 2.47 lb/s, and the flow rate of fuel is 223 lb/h. Figure 8 shows the static temperature contour, in degrees Fahrenheit, along the centerline of the combustor.

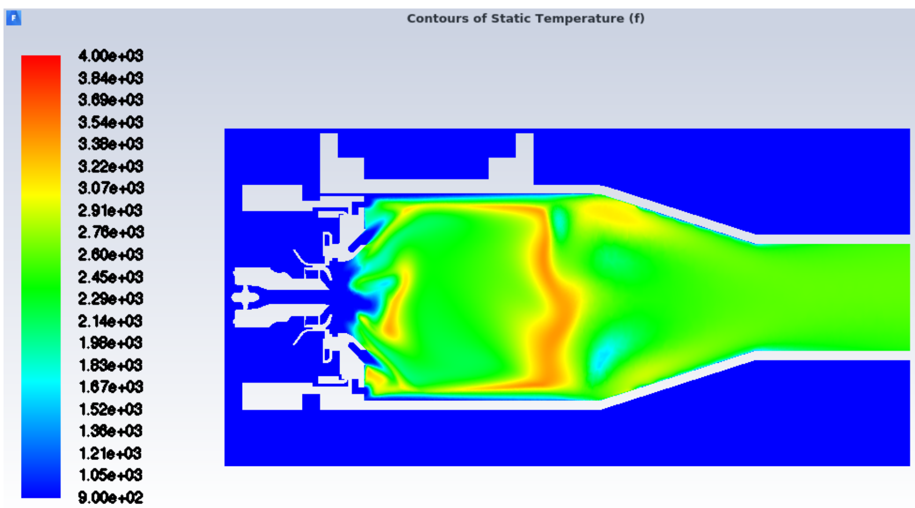

Figure 8. Contour of static temperature (°F) along the centerline of the combustor.

Based on the simulation results, we can identify potential hot spots that cause thermal severity and mechanical issues. Figure 9 shows the surface temperature of the combustor walls. From the results shown in Figure 9, several potential hot spots are located at the corner of the baseplate (combustor dome) where fuel injectors are mounted. The sidewall temperature is also high which may cause potential issues. Therefore, we added additional cooling holes along the edge of the baseplate and sidewall.

The simulation also indicated formation of soot (Figure 10) and NO (Figure 11) inside the combustor. The three cross-views in each figure represents the three center lines of three fuel injectors. It is clearly shown that the center fuel injector (with much less wall interaction) has different combustion properties, in terms of soot and NO formation. The simulation results confirmed that our change in combustor design from one fuel injector to three fuel injectors better mimics practical combustors in engines. With less artificial wall interaction, the soot formation is significantly greater from the combustion process.

Figure 12 shows the velocity profiles of window cooling film. In the simulation, we implemented two cooling patterns: one with a single long slot (0.81 × 215 mm) at the top plate and the other with 48 small slots (1.2 × 3 mm) at the bottom plate. The velocity profile from the single long slot is shown in Figure 12 (top), and the velocity profile from the 48 small slots is shown in Figure 12 (bottom). Interestingly, the two cooling patterns have essentially the same cooling effect, as supported by the very similar velocity profiles of cooling air at different locations. In consideration of possible air leakage and support of the combustor wall, we adopted the design with 48 small slots rather than the single long slot in the cooling holes at the combustor dome.

With the assistance of CFD simulation, our combustor design has been finalized.

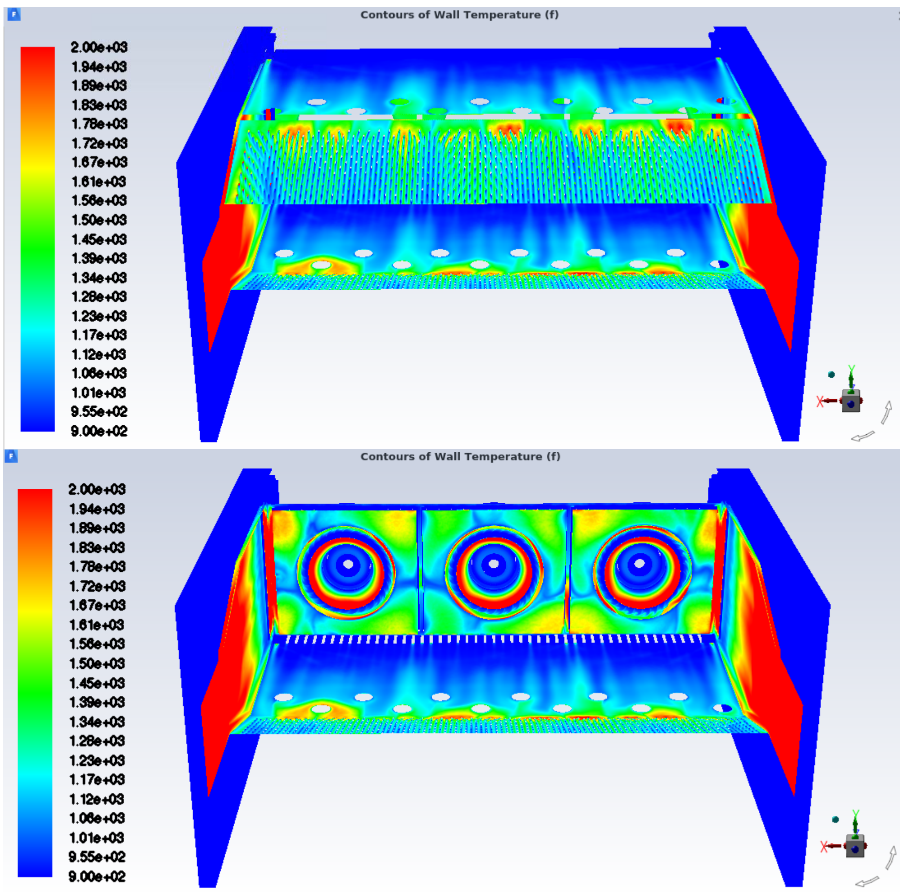

Figure 9. Contour of wall temperature (°F) of the liners (top) and baseplate and sidewall (bottom).

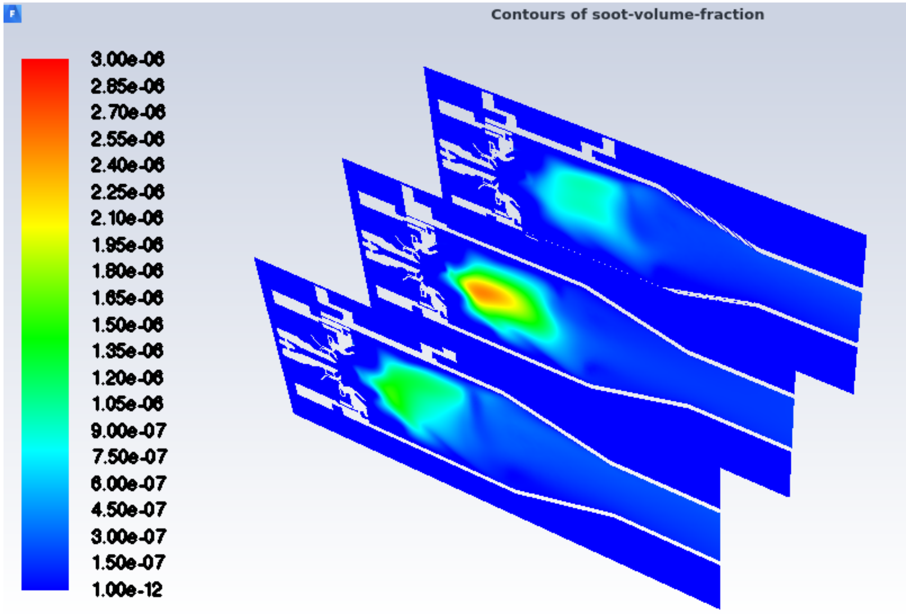

Figure 10. Contour of the soot volume fraction.

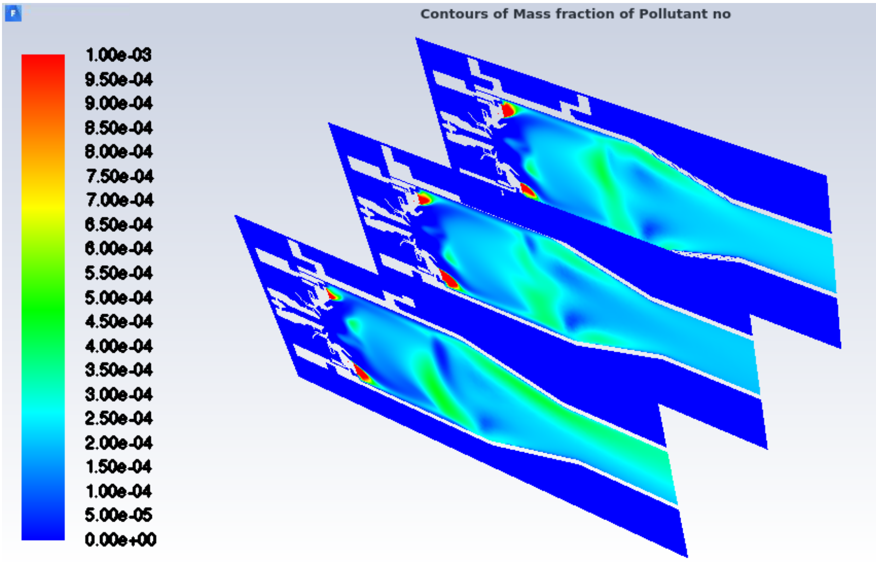

Figure 11. Contour of the mass fraction of NO.

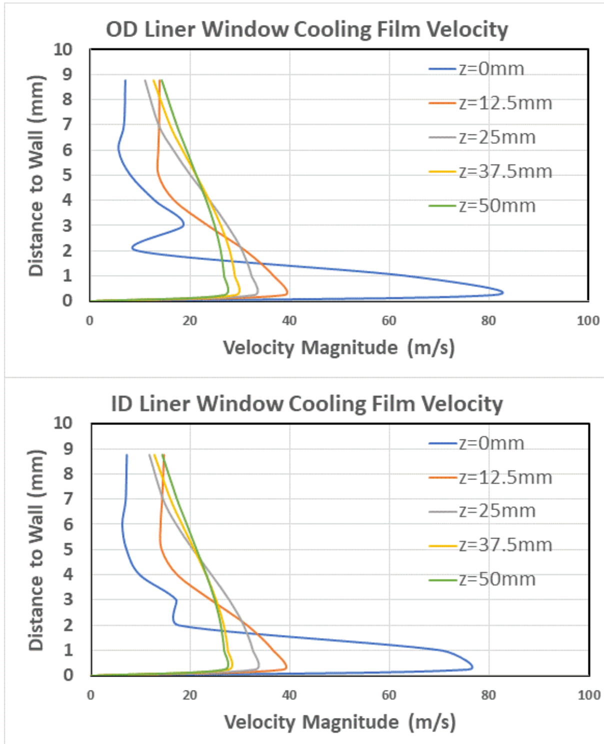

Figure 12. Velocity profiles of window cooling film of the long slot design (top) and multiple small cooling slots (bottom).

Milestone(s)

In the past year, five milestones were achieved:

1. Design and fabrication of the high-pressure vessel
2. Design of a unique combustor with three fuel injectors
3. CFD simulation of the designed combustor
4. Completion of the high-temperature, high-pressure air line final design
5. Completion of the liquid fuel supply system, GN2 pressurization, and purge system final design

Major Accomplishments

The major accomplishments of year 1 of this project include:

1. Design, fabrication, and delivery of the high-pressure vessel
2. Detailed design and CFD analysis of the combustor

Publications

None

Outreach Efforts

None

Awards

None

Student Involvement

Project 70 involves four graduate students (Jeremiah Jeurgensmeyer, Sundar Manikandan, Ezekiel Bugay, and Russell McGrath) and one research engineer (Henry Ballance).

Plans for Next Period

In the next year, our main goals are to (1) complete the fabrication of the designed combustor, (2) assemble the high pressure system, (3) conduct detailed optical measurements related to nvPM formation, and (4) conduct detailed CFD simulations and validate models according to experimental results.