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

Georgia Institute of Technology

Project Lead Investigator

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- P.I.: Dr. Wenting Sun
- FAA Award Number: 13-C-AJFE-GIT-080
- Period of Performance: August 11, 2020 to August 10, 2021
- Tasks:
    1. Measurements 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 FAA is $500,000. The matching funding includes $400,000 from Georgia Institute of Technology and $100,000 from Honeywell.

Investigation Team

Lead PI, Wenting Sun from the Georgia Institute of Technology will oversee the entire project and coordinate among different 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 from the Georgia Institute of Technology, will work with two graduate students to lead Task 1.

Co-PI, Rudy Dudebout 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 a challenge due to the complicated physical and chemical processes at play. 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) conduct optical diagnostics to measure nvPM volume fraction and primary particle size; polycyclic aromatic hydrocarbon (PAH) and hydroxyl (OH) radical distributions; and the flow field for a set of fuel injectors.
(2) develop empirical correlations describing nvPM formation/oxidation using data obtained in experiments.
(3) validate computational fluid dynamics (CFD) simulations to facilitate fuel injector design optimization.

Task 1 – Measurements of nvPM Formation and Oxidation Processes

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Objectives

In this task, laser-induced incandescence (LII) measurements will be conducted to quantify 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 owing 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)), providing further 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, as the ultimate aim is to measure multiple parameters simultaneously.

Since this is a new project, detailed results will be reported in the next report.

Subtask 1.1 – LII Measurement

LII utilizes short laser pulses to heat small particles to vaporization temperatures. The light emission, or incandescence, of the nvPM is then measured in order 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, it is then possible to determine absolute volume fractions.

For nvPM particle sizing, time-resolved LII (TiRe-LII) techniques can be used to obtain the incandescence decay over time. This approach utilizes the fact that small particles cool down faster than large ones after laser heating due to their larger surface-to-volume ratio. By solving energy and mass balances, the primary particle size can be evaluated. In order 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 were able to demonstrate a single-camera single-laser-shot technique for making 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, 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.

For the high pressures associated with flight-relevant conditions, however, the incandescence time constants decrease to the order of ~50 ns. This is faster than the imaging rate of many single-chip ultra-high-speed cameras. In order 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 ns 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 using the fundamental 1064 nm output of a solid-state neodymium-doped yttrium aluminum garnet (Nd:YAG) laser operating at 5-10 kHz in order 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 is then measured with time-gated cameras using the appropriate filters (near 640 nm) to avoid C_2 Swan band emissions. Calibrations using well-characterized laminar flames will be conducted to produce quantitative measurements for nvPM volume fraction and particle size in the gas turbine combustor at the conditions of interest.

Subtask 1.2 – OH PLIF Measurement
Oxidation through reaction with 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.

Hydroxyl radicals, OH, 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 with performing OH PLIF in the combustor of interest here are laser power absorption and signal trapping through the high-density gas at 10 bar.

We will perform OH PLIF measurements simultaneously with the 2D LII measurements to understand the interaction between nvPM and OH. Measurements will be made at a 5-10 kHz repetition rate 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 signal 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 (around 307 nm) and recorded using 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 to the 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 aliphatics during combustion. Since PAHs play a key role in nvPM growth, understanding their position 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. It therefore is possible to perform PAH PLIF with a similar laser wavelength 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 using the same experimental configuration as employed for the 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. While simultaneous OH and PAH PLIF will not be obtained, 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) allows measurement of all three velocity components in the plane by simultaneously viewing the particle motion from two different viewing angles. While 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. This is due to 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 recently demonstrated S-PIV in a 10-bar rich-burn gas turbine combustor similar to the one being 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 mitigates window contamination relative to other commonly used solid tracers. 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 for 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—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 using 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 that controls 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 measurements of the elastic light scattering. However, quantification of the spray properties from Mie scattering is challenging, predominantly due to 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 on the fuel spray trajectory, including spray angle, penetration, and the relative locations of the liquid fuel, flame, and nvPM.

To study 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 5-10 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 using a high-speed camera. This signal will then be separated from the PIV seed particle scattering using 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 on large hydrocarbons formed during the combustion of Jet-A, such as detailed structure 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 mechanism 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 using chemical and morphology analysis. Solid particles formed due to wall wetting features lower carbon but significantly higher oxygen content (e.g., 70-80% carbon and 20% oxygen) and small amounts of hydrogen and nitrogen. This is 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, solid particles formed due to wall wetting exhibits amorphous structures while solid particles formed from flame products feature spherical particles with diameters that are typically 4-5 microns. 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

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 using a dynamic Smagorinsky model. The combined heat release/turbulence model consists of non-premixed diffusion flamelets generated using 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 modelled with Lagrangian tracking of droplets with stochastic secondary breakup, calibrated to experimental data. The domain is discretized 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 a further 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) at different flow conditions employing different fuel injectors. The numerical model will then be validated and optimized for further fuel injector design towards the minimization of nvPM emission.

Task 2 will be conducted in year two of this project after obtaining the proposed experimental results in Task 1.

Task 3 – Experimental Facility Development and Operation

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In this task, we will design and fabricate a high-pressure vessel and the model gas turbine combustor for the proposed measurement. The preliminary design of the high-pressure vessel is presented in Figure 1, featuring three large optical windows.

The combustor to be built will be comprised of a single fuel injector. This reflects a single injector of an annular Rich Burn, Quick Quench, Lean Burn (RQL) combustor architecture. The test rig will have provisions for routing air to cool the combustor walls and will provide air to the quench holes, the injector, and the swirler. The sidewalls will also incorporate optical access with suitable features to discourage accumulation of nvPM or S-PIV tracer particles. Non-optical components of the liner will be multi-holed angle cooled (i.e. effusion cooled) at an appropriate cooling flux with no additional thermal barrier coating. Honeywell will design 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 will yield both data that are publishable and proprietary data that can directly translate to design improvements. The estimated design conditions are combustor inlet temperatures between 600 F to 800 F, combustor inlet pressures between 6 atm to 10 atm, pressure drop of approximately 3%, primary zone equivalence ratio of 1.2 to 1.8, and combustor exhaust temperatures of 2000 F to 3000 F.

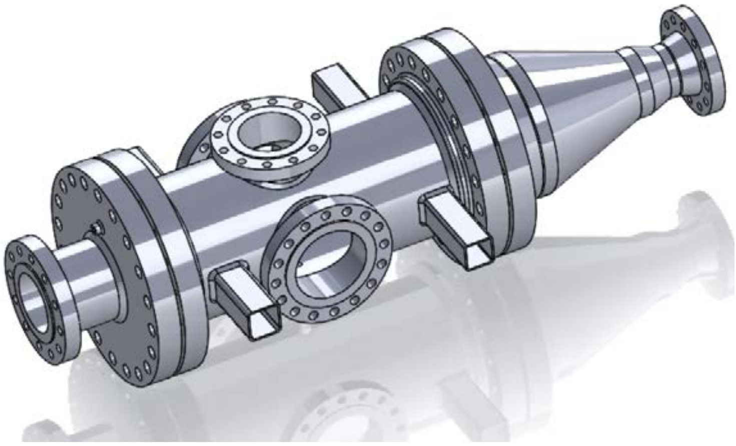

Figure 1. Rendering of high-pressure vessel.

Milestones

Project 70 is a new project, so no milestones have been achieved yet.

Major Accomplishments

Project 70 is a new project, so no accomplishments are reported.

Publications

None

Outreach Efforts

None

Awards

None

Student Involvement

Project 70 is a new project. Students are being hired for this project.

Plans for Next Period

In the following year, Task 1 and Task 3 will be executed.