



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: October 01, 2024, to September 30, 2025
- Tasks:
 1. Spray characterization and measurement of non-volatile particulate matter (nvPM) formation of Jet-A and sustainable aviation fuel (SAF)
 2. Design of a new single piece additively manufactured combustor

Project Funding Level

The total amount of funding from the Federal Aviation Administration (FAA) is \$1,500,000. The funding match includes \$1,350,000 from Georgia Tech and \$150,000 from Honeywell.®

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Project Overview

Reducing nvPM from gas turbine engines is essential for improving air quality and decreasing the environmental impact of aviation. However, predicting and controlling nvPM remains a challenge because of the complicated physical and chemical processes at play. The proposed research will characterize the fuel spray and nvPM formation for optimizing the design of an aeronautical gas turbine fuel injector to reduce nvPM at flight-relevant conditions. In this project, we developed a sector combustor containing three fuel injectors. The sector combustor is a generic rich-quench-lean (RQL) jet engine combustor equipped with the actual fuel injectors used in Honeywell's auxiliary power unit (APU). The combustor was fabricated through three-dimensional (3D) printing, and the fuel injectors are directly provided by Honeywell. The combustor and high-pressure system were detailed in a previous report and are presented briefly in the next section. The research focus of this year is on conducting an experimental campaign to characterize fuel spray, drop-size, measure nvPM volume fraction distribution in the primary zone of the combustor, and obtain nvPM and gas emissions at the exhaust section of the combustor. The performance of combustion in the rich region along with the particulate and gas emissions at the exhaust dictates the overall performance and efficiency of the combustor, and therefore it is the focus of research of this project.

Task 1 – Spray Characterization and Measurement of nvPM Formation

Georgia Institute of Technology

Objectives

The objectives of Task 1 include the following:

- 1.1 Obtain drop-size distribution for spray injectors using phase doppler particle anemometry (PDPA).
- 1.2 Characterize spray breakup and spray penetration using Mie scattering.
- 1.3 Measure and quantify the nvPM mass concentrations at the exit of the combustor.

The above tasks are performed over a broad range of conditions for Jet-A fuel and SAF (hydroprocessed esters and fatty acids synthetic paraffinic kerosene [HEFA-SPK]), respectively.

Research Approach

In this year, droplet-size distributions are obtained to characterize liquid fuel spray using phase doppler particle anemometry (PDPA) at a larger set of operating pressure, and inlet preheat temperature in both reacting and non-reacting conditions. ***This is the first such measurement performed in a three-sector combustor housed in a pressure vessel due to its unconventional configuration.*** Simultaneously droplet Mie scattering is performed to characterize spray breakup and penetration for the same conditions as the PDPA measurements. Additionally, quantitative soot volume fractions along with soot particle diameter measurements are being performed using two-color laser-induced incandescence (LII) and a GHz camera at different operating conditions. Both these measurements are performed using Jet-A fuel and SAF to compare the combustion characteristics of both the fuels and their blends. The SAF employed in this study is the HEFA from World Energy.[®] Results are presented below in corresponding sections. At the exit of the combustor, nvPM mass concentrations are obtained using a photo-acoustic based micro soot sensor measurement system from AVL Test Systems, Inc. (AVL), by mounting the probe at the combustor exhaust.

Subtask 1.1: Obtain Drop-size Distribution for Spray Injectors Using Phase doppler Particle Anemometry

PDPA utilizes the light scattering interferometry technique wherein interference signals are created by two intersecting laser beams in a small measurement volume of interest. As individual particles/droplets move through this volume, a shift in the frequency of scattered light is detected which is proportional to the particle velocity. Additionally, there is a phase shift in the detected interference signal which is proportional to the size of the particle. Hence, simultaneous information on particle velocity and size can be obtained with high spatial and temporal accuracy using this technique. For environments with high spatial and temporal variations in density, the technique suffers from beam steering, giving rise to low signal to noise ratios.

For measuring droplet sizes, PDPA requires off-axis scattering angles in the range of 30° to 70°. This presents a challenge for confined combustors housed in pressure vessels wherein such scattering angles are not available. To overcome this difficulty, a creative mirror system has been proposed and mounted inside the pressure vessel to obtain scattering angles

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up to 40° in the plane of measurement. The PDPA system (from Dantec Dynamics, Inc.) consists of a diode-pumped solid state (DPSS) laser transmitter capable of emitting a pair of 1000 mW, 561 nm laser beams, with each beam frequency shifted by 40 MHz using a Bragg cell. Although the system can operate with two pairs of laser beams at 532 nm and 561 nm, only one pair is utilized for droplet-size measurements. The laser beam pair is then sent into a transmitter probe (from TSI, Inc.) through fiber optic cables, where a lens having a focal length of 61 cm is used to focus the two beams into the sample measurement volume. The phase-shifted light scattered from the droplet in the small measurement volume is then collected by a receiver module through two mirrors placed and aligned such that the collection angle of the scattered light is approximately 40° . The collected light passes through a three slit mask mounted onto the receiver, where the light through each of the slits is focused separately and transmitted through fiber optical cables into the BSA (Burst Spectrum Analyzer). The analyzer can measure signal bursts at frequencies up to 400 kHz and subsequently produce instantaneous drop-size distributions.

The combustor wall (liner) includes three Honeywell aircraft swirl injectors on the dome face, representing typical multiple sectors of an aeroengine combustor, as illustrated in Figure 1b. The combustion liner has four fused quartz windows on top provide visual access to the rich-burn and lean-burn regions. The mirror system is mounted onto the inner face of the quartz vessel window flange as shown Figure 1a. It consists of two mirrors, with the first mirror having a 7.5 cm diameter clear aperture and the second mirror having a 15 cm by 10 cm rectangular area. They are aligned together to collect the scattered light from the droplets and focus onto the PDPA receiver module. The entire mirror system mount is made of stainless steel to minimize material deformation from high temperature air flowing through the vessel. The measurement region was restricted to a 5 cm by 5 cm area on left-hand side of the central nozzle as shown in Figure 1a, due to the constraints on the current PDPA and mirror system.

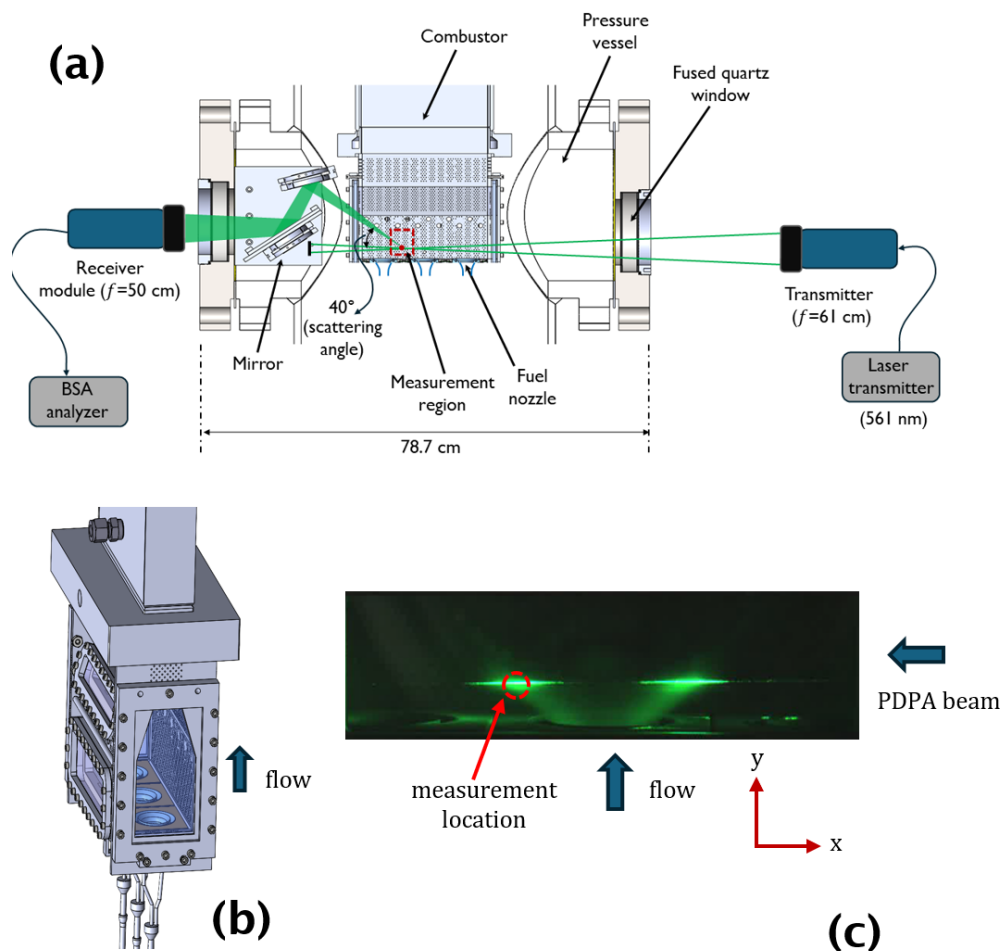


Figure 1. (a) Schematic of the phase doppler particle anemometry (PDPA) setup showing the two-mirror configuration to obtain required scattering angles in a confined vessel for the depicted measurement region. (b) View of the combustor depicting the three fuel nozzles and quartz windows for optical access. (c) Raw image of Mie scattering from the central injector spray along with the PDPA laser beam oriented in the vertical plane (perpendicular to the flow direction) passing through the spray.

Experiments are performed at both cold flow and reacting flow conditions to study the effect of combustion environment on droplet vaporization and subsequent drop-size. In all cases, only the central injector is operated so that the droplets do not cover the combustor windows which will affect PDPA measurements, especially in cold-flow conditions. The test conditions included five operating pressures (14.7 psig, 35.3 psig, 58.8 psig, 85.3 psig, and 120 psig) and four preheat temperatures (450 K, 540 K, 600 K, and 660 K), with a global equivalence ratio of 0.264 for both Jet-A and SAF fuels. It is to be noted that since the combustor is run on a RQL concept, the local equivalence ratios in the rich-burn region immediately downstream of the nozzles may vary from 1.22 to 1.45, depending on the global equivalence ratio. Although only the central injector is utilized while operating the combustor for PDPA measurements, the local equivalence ratio for that injector should remain the same.

At every spatial location, a total of 10,000 instantaneous measurements were made for all cases. But in certain conditions where the signal to noise ratio was slightly poor, the total measurement counts reduced. Nonetheless, the frequency distributions were repeatable for all conditions. The current fuel injectors utilized in this study are pre-filming air blast type assisted with surrounding swirl air for jet breakup. Figure 2 shows the number frequency distributions at a given spatial location for non-reacting Jet-A fuel spray at different operating pressures and preheat temperatures. The droplet



diameters are typically in a broad range of 1-100 μm at most locations, although the maximum frequencies are within the small range of 10-40 μm suggesting good atomization at these operating conditions. It is to be noted that the present PDPA system can detect droplets only in the range of 0.1-170 μm based on the slit size and mask used on the receiver module. As seen from the frequency distributions, this range was sufficient to cover the entire spray as the probability of detecting droplets larger than 150 μm was almost negligible. Due to the right skewed nature of the number frequency distributions, the Sauter mean diameter (SMD) values will tend to shift towards larger diameters, but the peak diameters are always lower. With increasing preheat, the droplet diameter distributions tend to shift towards smaller diameters at a given operating pressure. A similar trend is also seen for increasing pressure at a given preheat. This is clearer from the SMD values shown in Figure 3 for all spatial locations.

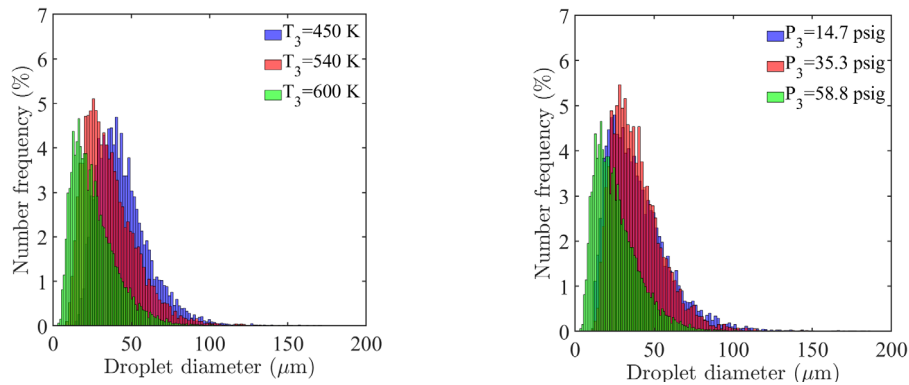


Figure 2. Comparison of number frequency distributions for Jet-A fuel at non-reacting conditions at spatial location $x=25$ mm, $y=10$ mm. (left) varying preheat at 58.8 psig pressure (right) varying pressure at 600 K preheat temperature.

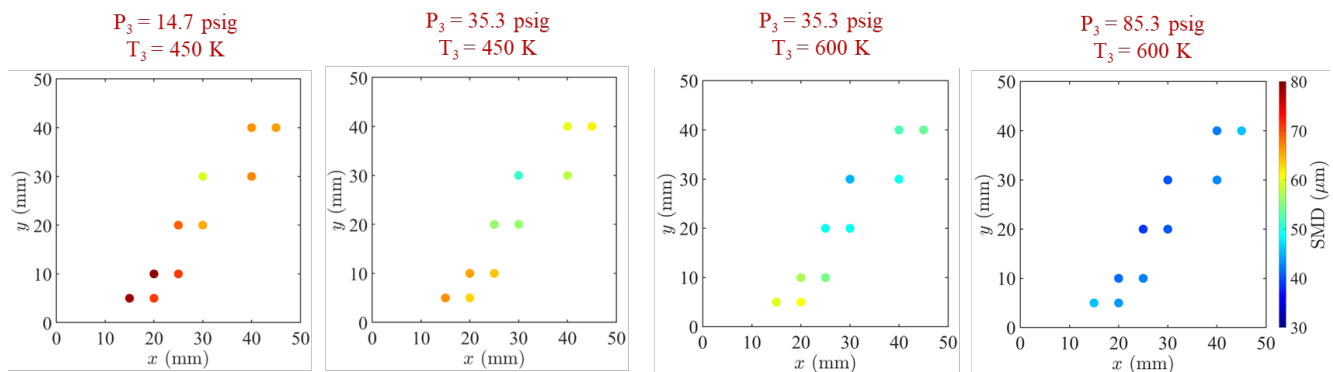


Figure 3. Spatial variation of Sauter mean diameter (SMD) values for non-reacting Jet-A fuel spray at different operating conditions.

It can be seen from the results shown in Figure 3, that the SMD values of the droplets generally reduces with increasing axial distance downstream of the injector along the spray cone as the swirling air assists in secondary atomization of the spray. Another reason for the decrease of SMD along the flow direction is vaporization of the droplets while flowing downstream. Apart from the general trend of decreasing diameters with increasing downstream distance, there are trends observed with different pressures and preheat temperatures. With increasing operating pressure, the SMD decreases for a given location and preheat temperature. This is due to the increase in Reynolds number of surrounding air causing larger relative velocities between the liquid and gas phase, thereby inducing faster primary breakup of liquid jet and subsequent smaller droplets. The amount of reduction is highly dependent on the Reynolds number range or the operating pressure. The reduction in SMD due to increasing preheat for surrounding air is due to droplets being able to evaporate faster as they travel downstream of the fuel nozzle. Compared to the low pressure conditions, the mean SMD values have decreased

by more than two times when the combustor is operated at 85.3 psig pressure at a preheat of 600 K (see Figure 4). Our results suggest that measurements and characterization need to be conducted at practical engine operating conditions.

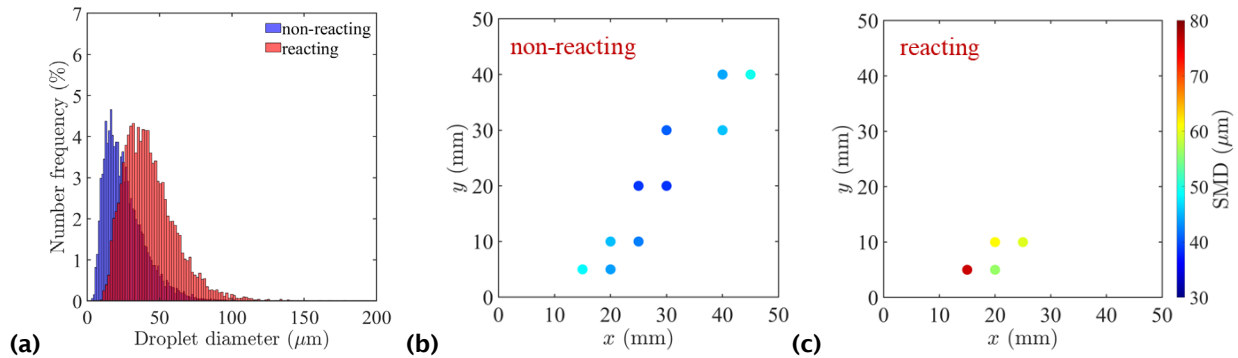


Figure 4. (a) Comparison of droplet diameters for Jet-A fuel at reacting and non-reacting conditions with 58.8 psig pressure and 600 K preheat temperature (a) number frequency distributions for locations $x=25$ mm, $y=10$ mm (b) Sauter mean diameter (SMD) at non-reacting conditions (c) SMD at reacting conditions.

To study the effect of reacting conditions on the spray, measurements were performed with the same PDPA configuration at the same operating conditions. It is to be noted that the current combustor operates liquid spray flames that produce large amounts of soot, especially in the primary zone of the combustor. Laser extinction can be very high in these regions leading to an overall drop in signal to noise ratio. To avoid this, the measurement region is confined to a small region 10- to 20 mm downstream of the dump plane within the spray cone. This region is largely devoid of soot, apart from small fluctuations in the flame where soot/flame can be entrained into these regions. A total of four measurement points (matching the non-reacting conditions) were possible for all the reacting conditions. The number frequency distributions for non-reacting and reacting conditions are compared in Figure 4 for Jet-A fuel at 58.8 psig pressure, and 600 K preheat for a given spatial location. For the reacting case, the distributions seem to shift towards larger diameters for all locations. This is counter-intuitive in the sense that reaction/flame should help the droplets evaporate faster adding to the preheat leading to smaller droplets. The plots in Figure 4 suggest that the smaller droplets not only evaporate faster but are almost non-existent, leaving only the larger droplets being detected. Hence, it is very possible that the SMD values are considerably higher in the reacting cases as compared to the non-reacting cases owing to the disappearance of small droplets which are vaporized promptly. An increase in almost 20 to 30 μm is observed for SMD in reacting cases compared to their non-reacting counterparts. This change was consistently observed for all cases at the same spatial location and operating conditions. Additionally, these distribution changes also provide information on the number of smaller diameter droplets available in reacting cases at any downstream location. It is worth mentioning that the signal to noise ratio was much lower in reacting cases at the same measurement location due to laser extinction as the laser beam passes through the flame/spray regions from the side nozzles before reaching the measurement zone.

The second part of the measurements involved utilizing SAF for the measurements at the same conditions as Jet-A fuel. The SAF used here is a HEFA-based fuel with almost negligible amount of aromatic content in it. Since the availability of SAF is limited at the current scenario due to production/supply issues, blending sustainable fuels with neat Jet-A fuel is considered a viable option. Due to small changes in physical and chemical properties of these blended fuels as compared to their neat counterparts, their spray and combustion characteristics are still not well known. Hence, measurements were also performed at the same locations by blending the neat fuels in 50-50% by volume. Figure 5 shows the comparison in number frequency distributions between Jet-A fuel and SAF in the non-reacting case for the same operating conditions. It is seen that the SAF spray produces slightly smaller droplets compared to Jet-A fuel, giving a smaller SMD value. But this difference is almost negligible in non-reacting cases. This is mostly due to the changes in physical properties of the two different fuels. The SAF utilized in this study has approximately 10% lower surface tension as compared to Jet-A fuel. Reduction in surface tension helps in formation of new surface areas promoting droplet/jet breakup, thereby creating smaller droplets. This can also be looked at in terms of the Weber number which is inversely proportional to the surface tension force. Higher the Weber number, better is the atomization quality of the liquid spray. The variation in SMD values at different operating conditions followed similar trends as Jet-A fuel at all the measurement locations.

For reacting cases, the difference in droplet diameters is slightly more pronounced as compared to the non-reacting case. This is apparent from Figure 6, where the distributions shift towards smaller diameters as we shift from neat Jet A fuel to neat SAF. Also, at temperatures above 100° C, the vapor pressure of SAF is approximately 5% higher than Jet-A fuel which can contribute to better vaporization and smaller droplets. The effect of vapor pressure seems to be more prominently observed in reacting conditions where temperatures are much higher than in non-reacting conditions. In the present study, physical properties such as surface tension, viscosity and density for the 50-50 blend generally lie in between their neat fuel properties. Hence, their behavior in spray breakup and atomization is expected to occur in the same trend.

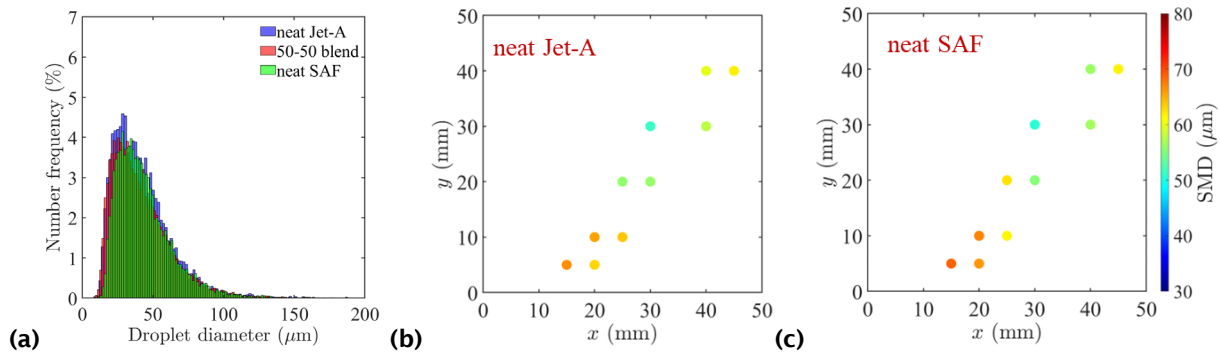


Figure 5. Comparison of droplet diameters for Jet-A fuel and sustainable aviation fuel (SAF) at non-reacting conditions with 35.3 psig pressure and 450 K preheat temperature for locations (a) $x=25$ mm, $y=10$ mm (b) neat Jet-A fuel, non-reacting (c) neat SAF, non-reacting. SMD: Sauter mean diameter.

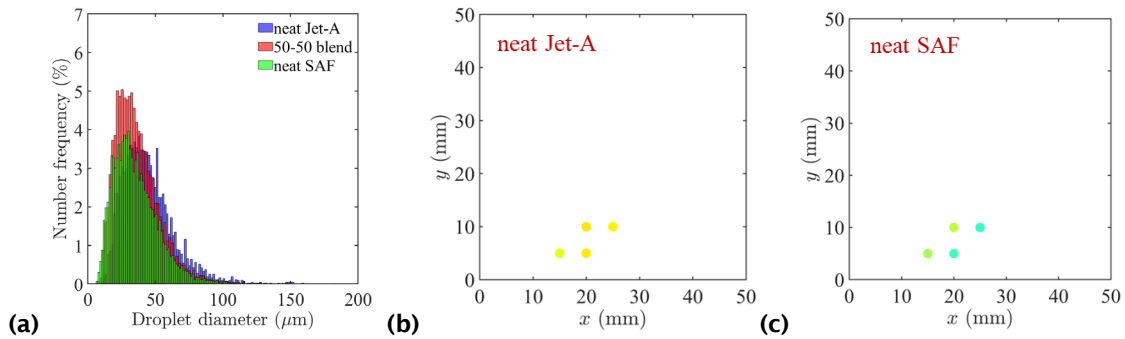


Figure 6. Comparison of droplet diameters for Jet-A fuel and sustainable aviation fuel (SAF) at reacting conditions with 35.3 psig pressure and 600 K preheat temperature for locations (a) $x=25$ mm, $y=10$ mm (b) neat Jet-A fuel, reacting (c) neat SAF, reacting.

Subtask 1.2: Characterize Spray Breakup and Spray Penetration Using Mie Scattering

To study the breakup characteristics of the fuel spray and obtain global spray parameters such as spray penetration and spray cone angles, droplet Mie scattering is performed for both non-reacting and reacting conditions at different operating conditions. Mie scattering is performed using a Nd:YAG laser (Mesa™-PIV) emitting 532 nm beam at the rate of 5kHz. The laser beam is shaped into a thin sheet of dimensions 50 mm x 0.5 mm using a combination of cylindrical lenses and passed through the primary zone of the combustor where fuel spray exists. The resulting scattering signal from the droplets is collected using a high-speed camera (Photron® SA-Z), equipped with a 100 mm camera lens (Tokina,® f/#=4.0) and 532 nm bandpass filter to avoid flame radiation. For obtaining global properties of the spray, a total of 5,000 images were averaged over time and subsequently post-processed to remove any background signal.

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Figure 7 shows the time-averaged Mie scattering images for Jet-A fuel at both non-reacting and reacting conditions. With varying pressures, the spray penetration seems to reduce at the same preheat temperatures of 600 K. From the PDPA results, it was observed that the averaged droplet diameters reduced considerably with increasing pressure.

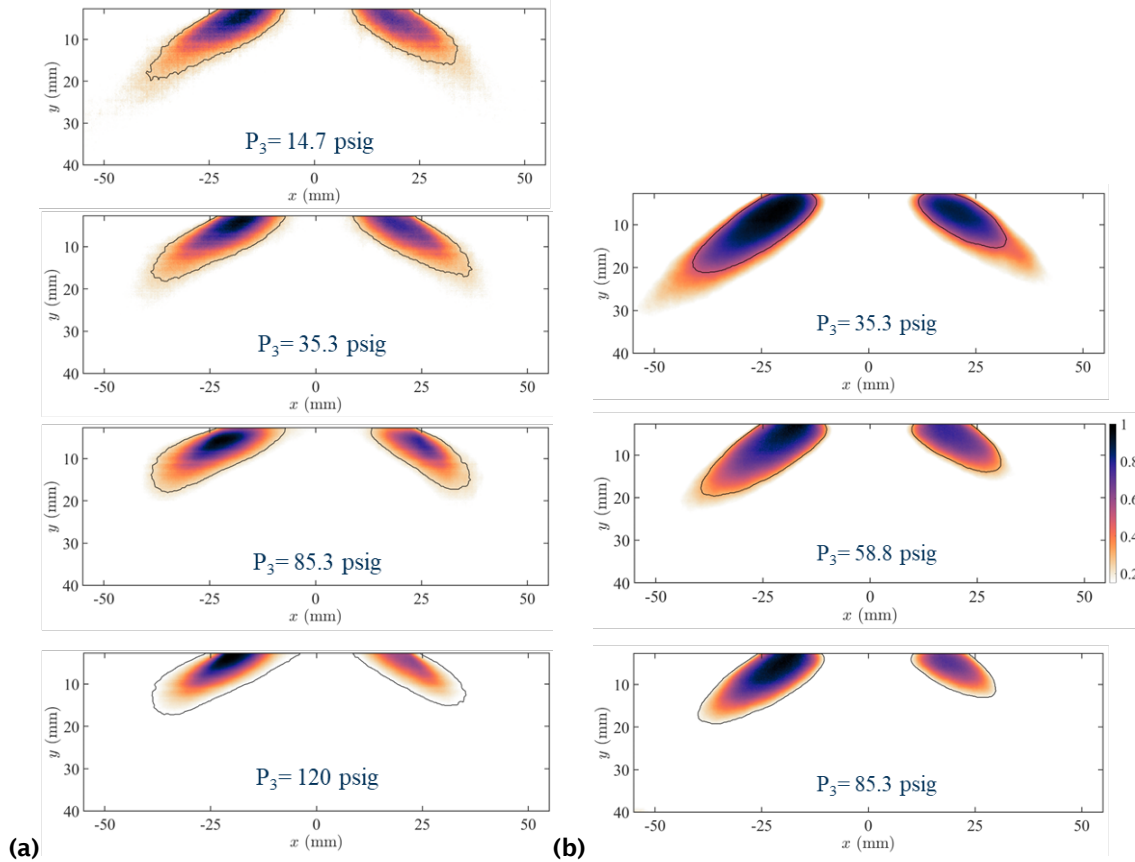


Figure 7. Comparison of averaged Mie scattering images with varying pressures for Jet-A spray at 600 K preheat. (a) Non-reacting conditions. (b) Reacting conditions. The color bar represents the relative density of droplets.

Hence, more smaller droplets are present in the flow which may evaporate faster at higher preheat leading to low Mie scattering signals as compared to larger diameter signals close to the injector exit. For reacting conditions, similar patterns in spray penetration are observed with increasing pressure. The intensities are slightly higher compared to non-reacting spray as much of the smaller droplets are vaporized faster in reacting conditions. Due to this, the Mie scattering signal from the larger droplets tends to be higher over larger spatial regions. This is very apparent from images in Figure 7b as compared to the images in Figure 7a. The spray cone angles do not seem to vary significantly and is seen to be nearly independent of operating pressure. More data are available for SAF and their blends, which is currently under processing.

Subtask 1.3: Measure and Quantify the nvPM Mass Concentrations at the Exit of the Combustor

The nvPM mass concentration measurements at the exit of the combustor are important as they provide the overall performance of the combustor in terms of emissions and combustion efficiency. The measurements in the current study are collected utilizing a commercial micro soot sensor system from AVL, which can measure particle mass concentrations at a given spatial location outside the combustor. The system works based on the photoacoustic measuring principle. With this measurement method, the sample gas with strongly absorbing soot particulates, is exposed to modulated light. The periodical warming and cooling and the resulting expansion and contraction of the carrier gas can be regarded as a sound wave and detected by means of microphones.



The soot sensor probe is equipped with temperature compensation to account for thermal deposition of nvPM particles in the sampling line due to cooling. The entire sampling line is heated, and constant temperature is maintained to avoid any major soot deposition and aggregate formation. The system can also be equipped with a pressure reduction unit for operation in pressurized environments. Since the current measurements are performed at the exit of the combustor exhaust, downstream of the choke, so pressure reduction unit was not necessary. The system is able to continuously measure the nvPM mass concentrations at a max data rate of 10 Hz by maintaining a constant internal acoustic cell temperature. At high gas temperatures exceeding 700 °C or at high mass concentrations (above 150 mg/m³), dilution air can be mixed to the sample gas which reduces the temperature/concentrations to operate the system within its limits. Figure 8 shows the AVL micro soot sensor system and its probe placement for measurements at the combustor exit, downstream of the exhaust choke.

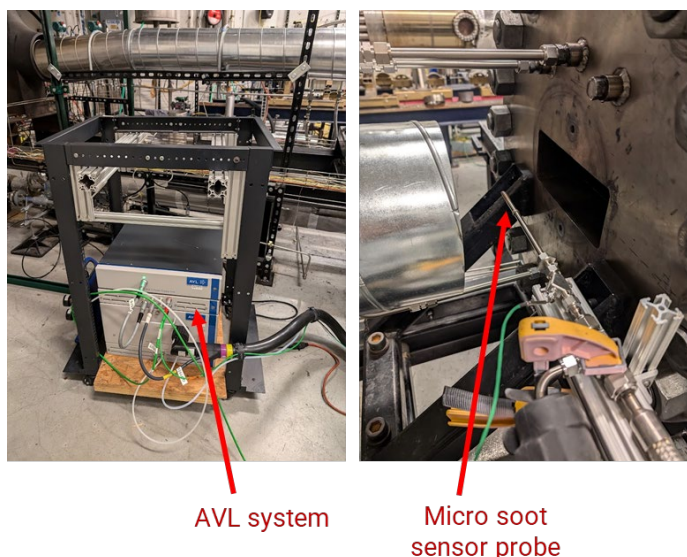


Figure 8. The AVL Test Systems, Inc. (AVL), micro soot sensor system with the probe attached and placed at the exit of the combustor exhaust outside the pressure vessel.

The current measurements are performed with all three injectors running at various operating pressures and two preheat temperatures with a fixed equivalence ratio for both Jet-A fuel and SAF. The dilution ratio of 3 was sufficient to maintain the probe temperature below 700 °C for continuous operation. The results are finally compensated for both the temperature compensation at the probe inlet and dilution ratio. The probe is mounted perpendicular to the flow direction at the exit of the pressure vessel. The downstream distance of the probe from the combustor dump plane is close to 92 cm.

The soot concentration measurements over time for 35.3 psig pressure and 540 K preheat with Jet-A fuel is shown in Figure 9a. The values remain nearly constant over time, indicating steady combustion, with minor peaks appearing instantaneously where large soot aggregates may have gathered at a small spatial location. Nonetheless, the overall measurement values can be considered steady over time. In addition, the concentration measured at the probe is compensated for dilution gas and temperature correction. Since the dilution ratio in the current measurements is 3, the concentrations increase by three times after the correction. Figure 9b shows the variation of soot concentrations with pressure for different neat fuels at two different preheats. The concentrations seem to have pressure scaling that is similar to the results predicted inside the primary zone of the combustor. This suggests that the nvPM volume fractions in the primary zone of the combustor can be correlated to the final exhaust mass concentrations. This will give a good overall picture of the combustor performance in terms of nvPM formation and subsequent oxidation downstream of the combustor zone. SAF produces much lesser soot concentrations compared to Jet-A fuel at the same operating conditions. This is expected since the SAF utilized in the current study has negligible amount of aromatic content reducing the tendency for soot formation. Additionally, for a given fuel and pressure, the concentrations are slightly lower for 600 K preheat as compared to 540 K preheat. Increasing preheat aids in vaporizing fuel droplets faster, improving mixing and



combustion efficiency, reducing soot formation. Also, higher preheat increases oxidation processes, thus reducing final particle concentrations as the combustion gases move along the exhaust section. Once the nvPM volume fractions are obtained in the combustor using laser induced incandescence, these results can be compared and correlated in detail.

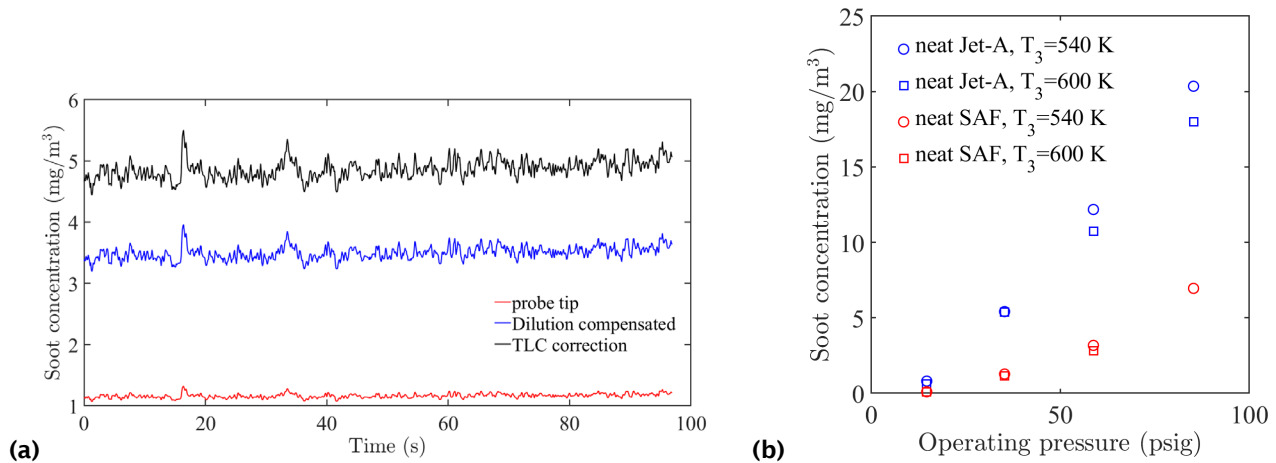


Figure 9. (a) Soot concentrations measured over time for Jet-A fuel at 35.3 psig pressure and 540 K preheat temperature. The measured concentrations at the probe and the final dilution and temperature compensated (TLC) values are provided. (b) Variation of soot concentrations with operating pressure for neat Jet-A fuel and SAF.

Milestone

- Conducted systematic PDPA, Mie scattering and exhaust nvPM mass concentration measurements at different combustor operating conditions with Jet-A fuel and SAF, respectively.

Major Accomplishments

- Spatially resolved droplet size measurements in a confined sector combustor using PDPA for Jet-A fuel and SAF were conducted.
- Conducted droplet Mie scattering measurements at high data rates up to 5 kHz to study droplet breakup and global spray characteristics for Jet-A fuel and SAF in both non-reacting and reacting conditions.
- Compared the differences between Jet-A fuel and SAF in terms of nvPM formation at the exhaust at different operating pressures through probe measurements using a micro soot sensor.

Publications

Conference Presentations

- Juergensmeyer, J., Miller, J., Bond, R., Mcgrath, R., Wehe, S., Sun, W., Mazumdar, Y. C., & Steinberg, A. (2025, June 16–20). Measurement of Particulate Matter and Its Oxidation in a Multi-Sector Rich-Quench-Lean Combustor. *Proceedings of the ASME Turbo Expo 2025: Turbomachinery Technical Conference and Exposition*. Memphis, Tennessee. <https://doi.org/10.1115/GT2025-153181>
- Vishwanath, R., Douglas, E., Wehe, S., Mazumdar, Y. C., Steinberg, A., & Sun, W. (2026). *Spray measurements in a sector combustor operating with conventional and sustainable fuels at elevated conditions*. Submitted to ASME Turbo Expo 2026.
- Vishwanath, R., Bibik, O., Olimid, D., Douglas, E., Wehe, S., Mazumdar, Y. C., Steinberg, A., & Sun, W. (2025, January 6-10). Drop-size measurements using phase doppler particle anemometry in a confined high-pressure sector combustor (AIAA 2025-1519). *AIAA SCITECH 2025 Forum*, Orlando, Florida. <https://doi.org/10.2514/6.2025-1519>

Outreach Efforts

None.



Awards

Wenting Sun: Hiroshi Tsuji Early Career Researcher Award, 2023. The Combustion Institute (recognizes early career researchers who have demonstrated excellence in fundamental or applied combustion science and have achieved a significant advancement in their field within four to ten years of completing a doctoral degree or equivalents.)

Wenting Sun: AIAA Associate Fellow, 2023

Adam Steinberg: Fellow of the Combustion Institute, 2023

Student Involvement

This task involves four graduate students (Eric Douglas, Harsh Dhayal, Adhav Arulanandan, Andrew Fan). Eric Douglas worked on OH-LIF (OH radical Laser Induced Fluorescence) related measurements. Harsh Dhayal and Adhav Arulanandan worked on sampling probe design. Harsh Dhayal and Andrew Fan worked on DMA (Differential Mobility Analyzer) setup and characterization.

Plans for Next Period

- Conduct PDPA, two-color LII and OH-PLIF measurements in a new combustor configuration for Jet-A, SAF and their blends at a large range of operating conditions. Currently, detailed combustor design and comprehensive thermal stress analysis are completed.

Task 2 – Design of a New Single Piece Additively Manufactured Combustor

Georgia Institute of Technology and Honeywell

Objective

The objective of this task is to develop a new sector combustor with three compact dual-tip fuel injectors and optical access. This will be an improved version of the previous liner, wherein the entire combustor will be additively manufactured as a single piece using Haynes 282.[®] This combustor will be operated under high-pressure and high-temperature conditions to replicate real engine conditions. This sector combustor will be used as a test bed to characterize the formation and oxidation of nvPM.

Research Approach

The sector combustor is initially modeled using computer-aided design (CAD) by adopting the geometry of a typical annular combustor, wherein three sectors of an annular combustor is unwrapped into a straight geometry to simplify the mechanical design and allow for optical access. The combustor will consist of effusion holes to cool down the combustor surface and maintain metal temperature limits, quench holes downstream of the primary combustion zone, optical windows on three sides, and fuel injector assembly (see Figure 10). Subsequent mechanical stress and thermal stress analysis is performed at maximum load to understand the mechanical performance and integrity of the combustor liner during continuous operation. To analyze flow patterns, spray and nvPM formation, computational fluid dynamics (CFD) analysis is performed at various operating conditions to optimize the combustor design and predict combustor performance.

[®] Haynes 282 is a registered trademark of Haynes International, Inc., Kokomo, Indiana.

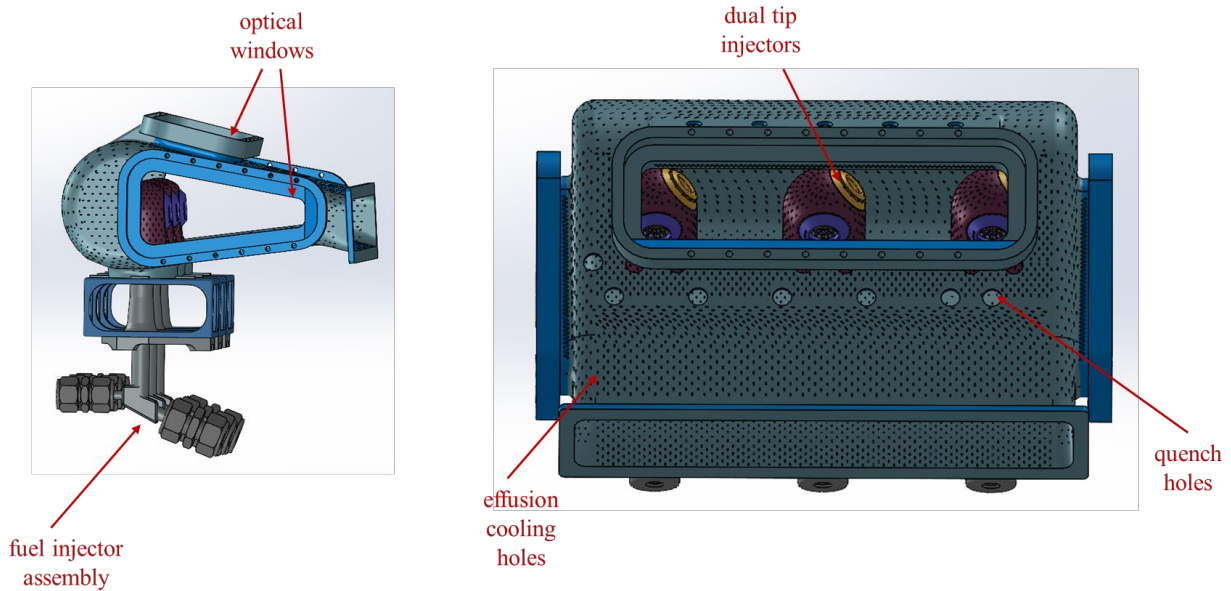


Figure 10. CAD design of the sector combustor with fuel injector assembly.

The CAD design and assembly of the new combustor design is shown in Figure 10. The effusion hole and quench hole pattern is optimized using CFD approach to obtain uniform temperature pattern across the combustor surface and avoid hot spots and non-uniform thermal expansion. The optical windows on either side of the combustor allow for laser-based diagnostics. Each window is equipped with film air channels to shield the quartz windows from sooting gases and cool down the surface. The top window is designed such that additional air can be provided and controlled to avoid soot build up at high soot load operating conditions. This is a major improvement from the previous combustor design where soot buildup was one of the major issues.

The thermal-mechanical CFD predictions involved steady state thermal analysis, along with combined thermal and pressure load analysis. The steady state thermal analysis revealed hot and cold side temperatures throughout the combustor surface as shown in Figure 11. This included convective and radiative heat flux predictions that would be seen at full load conditions. The results revealed that the maximum temperatures were within the temperature limits of Haynes 282 at the max operating pressures. Hot spots obtained from initial CFD predictions are eliminated by optimizing the cooling hole patterns and positioning of quench holes through several iterations.

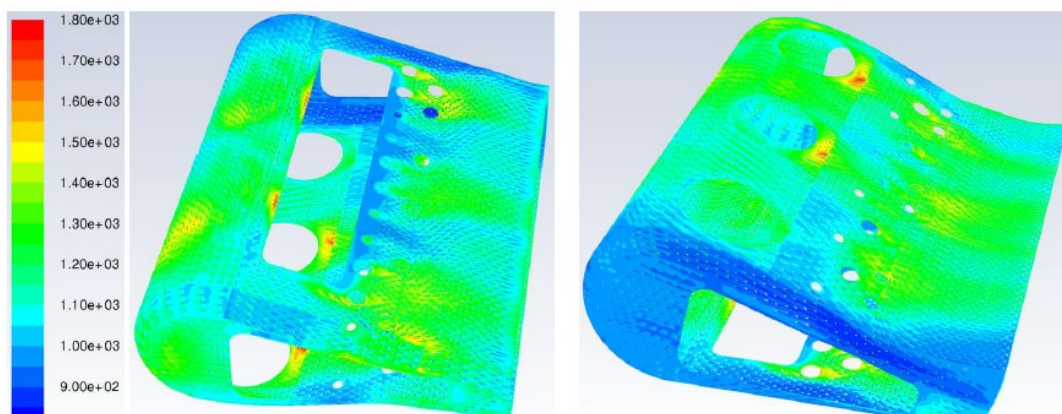


Figure 11. Steady state thermal analysis using CFD for the combustor.



Thermal loading analysis is performed based on the temperature variations obtained from the steady state thermal results wherein temperatures variation from 870°F to 1,750°F is assumed to occur at different locations over the combustor surface. This is done by assuming fixed boundaries at the combustor exit flange as it will be attached to the exhaust section and making the dome and the entire liner as the displacement boundary. The predicted stress values were below the material yield strength. In addition, pressure loading is added to this analysis to account for the pressure drop seen across the combustor during the operation. The peak stresses near the quench holes and window brackets were reduced over several iterations to minimize the overall stress. All the boundary conditions experienced by the combustor is applied during the overall analysis.

Once the combustor mechanical design is finalized, subsequent CFD analysis is performed at both non-reacting and reacting conditions to gather information on spray patterns, flame temperatures and nvPM formation within the combustor. Figure 12 shows the reacting flow predictions including spray pattern and penetration downstream of the injectors before combustion. The colored contours reveal nvPM volume fractions at 100 psig operating condition. These results will help in predicting soot formation sensitivity to pressure and fuel air ratios. It also helps in designing the combustor dimensions accurately to obtain reasonable temperature distribution on the liner surface and avoid soot deposition on the combustor windows before it can be manufactured for experiments. The results obtained will be later compared to optical diagnostic measurements to help in improving the numerical models and guide new fuel injector designs.

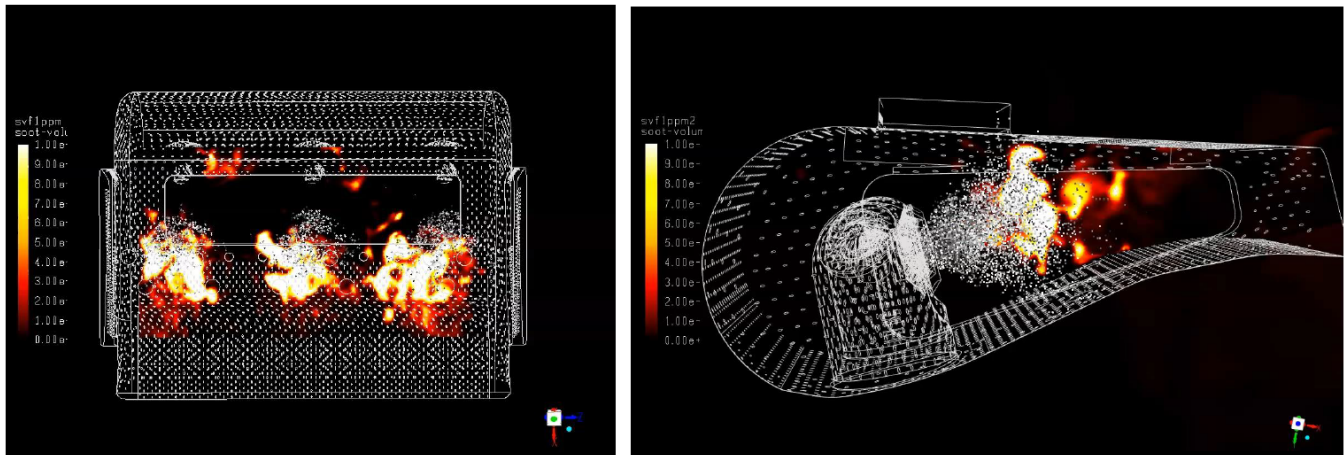


Figure 12. Spray pattern and soot formation prediction using CFD approach at 100 psig operating condition with three injectors spraying jet fuel.

Milestone

This task was completed in April 2025.

Publications

None.

Outreach Efforts

None.

Awards

None.

Involvement

Honeywell performed the overall CFD analysis and mechanical design. Georgia Tech assisted in designing the final combustor configuration to integrate with the pressure vessel, optimize the combustor window dimensions and placement for performing optical diagnostics, and provide required instrumentation ports.



Plans for Next Period

- Perform spray and nvPM measurements in the newly built single piece additively manufactured combustors having dual tip injectors.
- Undertake experiments over a wide range of engine operating conditions aligning with Honeywell auxiliary power unit.