Project 098 Low Emissions Lean Pre-Mixed Pre-Vaporized Combustion Technology for Subsonic Civil Transport

Georgia Institute of Technology

Project Lead Investigator

Adam Steinberg
Professor
School of Aerospace Engineering
Georgia Institute of Technology
Phone: (404) 897-1130
E-mail: adam.steinberg@gatech.edu

University Participants

Georgia Institute of Technology

- P.I.: Dr. Adam Steinberg
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- Tasks:
  1. Experimental Measurement of Emissions, Lean Operation Limits, Spray, and Flame Structure
  2. Computational Fluid Dynamics (CFD) Simulations of LPP Combustor

Project Funding Level

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Georgia Institute of Technology (Georgia Tech): $486,000
General Electric (GE) Aerospace Research: $514,000

Investigation Team

Dr. Adam Steinberg (Georgia Institute of Technology [GT], PD/PI)
Dr. Ellen Mazumdar (GT, Co-PI)
Dr. Joseph Oefelein (GT, Co-PI)
Dr. Jerry Seitzman (GT, Co-PI)
Mr. Arihant Jain (GT, PhD student)
Mr. Alexander Stevens (GT, PhD student)
Ms. Ijeoma Obi (GT, MS student)
Ms. Jananee Dhanasekaran (GT, MS student)
Dr. Krishna Venkatesan (GE Research [GER], Co-PI)
Dr. Victor Salazar (GER, Co-PI)
Dr. John Hong (GER)
Ms. Sydney Borrello (GER)

Project Overview

Lean premixed prevaporized (LPP) combustion is a key enabling technology to further reduce nitrogen oxides (NO_x) and non-volatile particulate matter (nvPM) emissions from aeronautical gas turbine engines. However, achieving practical LPP combustion is challenging due to the need to rapidly vaporize and mix fuel, stabilize LPP flames across a wide operating envelope, and prevent unwanted combustion dynamics. Furthermore, the ability of current design methodologies to predict the operability and emissions of these combustors is unproven. Previous work during ASCENT Project 074 demonstrated positive results for an LPP combustor configuration at the conditions found in engines for supersonic transport aircraft and encouraged further exploration at conditions relevant for the conventional subsonic fleet (Jain et al., 2026; Passarelli et al., 2024). Hence, ASCENT Project 098 is characterizing the emissions and operability of an updated LPP combustor at key operating points for such subsonic aircraft engines, including low power (i.e., idle and taxi), cruise, and approach. It also is developing measurement techniques needed to study high-power (i.e., takeoff and climb) conditions that are challenging for LPP combustors. The high-quality experimental data at relevant conditions are being coupled with the development and validation of CFD simulations and reduced order models. These activities form a key first step in the development of both the LPP combustor technology and validated design tools for subsonic aircraft engine conditions.

Task 1 – Experimental Measurement of Emissions, Lean Operation Limits, Spray, and Flame Structure

Georgia Institute of Technology
GE Aerospace

Objectives

The objectives of this task under the current project scope are to:

- Redesign and optimize the ASCENT Project 074 LPP combustor geometry to have a pilot system that is more relevant for subsonic aircraft engines.
- Fabricate and commission this new combustor.
- Experimentally test the combustor at conditions representing idle, taxi, approach, and cruise to establish emissions levels and blow-off limits.
- Collect data using optical diagnostics with which to validate large eddy simulations (LES) and better understand the combustor.
- Develop and demonstrate novel measurement techniques that can be applied under high-power conditions (takeoff, climb) for studies in future years.

Research Approach

Experiments have been performed in the same basic test article as used for Experimental Campaign 2 in ASCENT Project 074 (see Figure 1) (Jain et al., 2026), with some facility and premixer modifications to accommodate the different operating conditions for subsonic aircraft engines compared to supersonic aircraft.

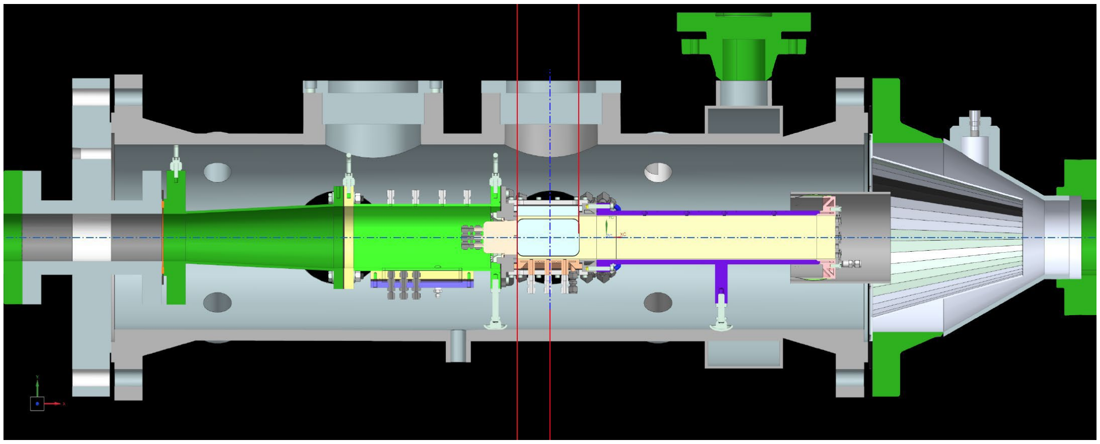

Figure 1. Conceptual schematic of experimental test article.

The FAA ASCENT Project 098 builds upon the success of the mixer technology developed during the ASCENT Project 007 for supersonic cruise conditions. However, the potential impact of LPP combustion on the future commercial subsonic aircraft fleet is much larger. Combustors for subsonic aircraft engines experience quite different air inflow pressures (p_3) and temperatures (T_3), which affect the performance of LPP combustion. Although the ASCENT Project 074 mixer achieved low emissions, its pilot design was relatively simple as it was based on a commercial pressure swirl atomizer employed as a placeholder pilot to ignite the main. Fuel atomization by this pilot is expected to be suboptimal. Therefore, to improve pilot fuel atomization and further reduce emissions, a key aspect of the ASCENT Project 098 is to improve the pilot design of the ASCENT Project 074 mixer by integrating a contemporary pilot.

Detailed design and trade studies for the ASCENT Project 098 pilot and mixer were performed using CFD; they are described in more detail under Task 2. Once designed, the mixer was three-dimensionally (3D) printed, and conventional heat treatment and post machined processes were performed. A thermal barrier coating was applied to the aft face of the mixer. Once all the manufacturing processes were completed, the mixer was flow checked and finally released for testing.

Two mixers, manufactured by two different 3D printed vendors, were tested in the rig show in Figure 1 using the measurement techniques described below. A skeletal test matrix is provided in Table 1. Note that the overall test matrix involved approximately 30 test points, including variations of other operating parameters, which are not described in detail here. Both mixers performed as expected at the various operating conditions and the observations were consistent with their specific designs.

This experimental campaign occurred from August to October 2025. The measurement techniques described below were transported from Georgia Tech (Atlanta, Georgia) to GE Aerospace Research (Niskayuna, New York). Georgia Tech students were present at GE Aerospace® Research throughout the campaign to setup and conduct the measurements, alongside GE scientific and technical staff who operated the combustor facility. Note that only preliminary results are included below since the experimental campaign ended after the reporting period. Analysis of the data is ongoing. The combustor currently is being installed in a different test cell at GE to measure pollutant emissions.

Table 1. Test Matrix. FAR: Federal Aviation Regulations.

Parameter	Measurements
p_3 [psia]	110 & 200
T_3 [˚F]	450, 550 & 650
Mixer FAR [-]	0.045, 0.050 & 0.055

Optical Diagnostics Measurements
To determine operability limits and examine flame and spray structure, a suite of state-of-the-art optical diagnostics techniques were deployed during the experimental campaign. These included hydroxyl (OH) planar laser induced fluorescence (PLIF), OH* and CH* chemiluminescence (CL), high magnification shadowgraphy, and fuel droplet Mie scattering (Jain et al., 2026). The diagnostics setup is schematically shown in Figure 2 and Figure 3.

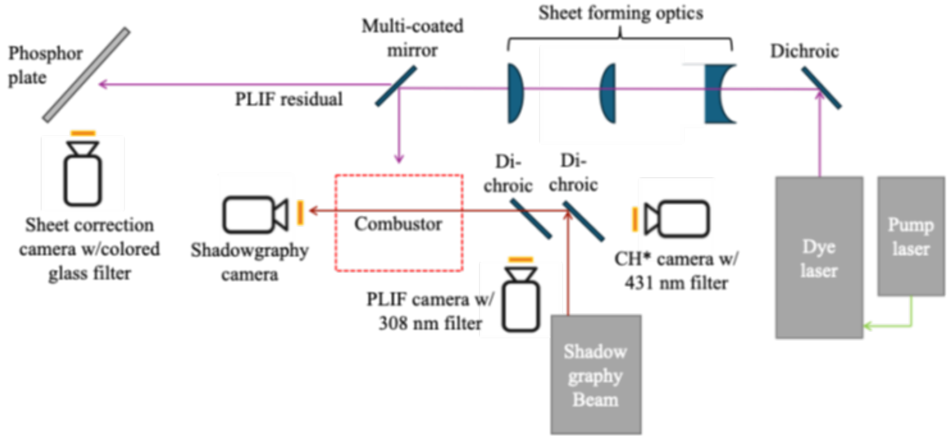

Figure 2. Simplified diagnostics schematic with shadowgraphy implemented. PLIF: planar laser induced fluorescence.

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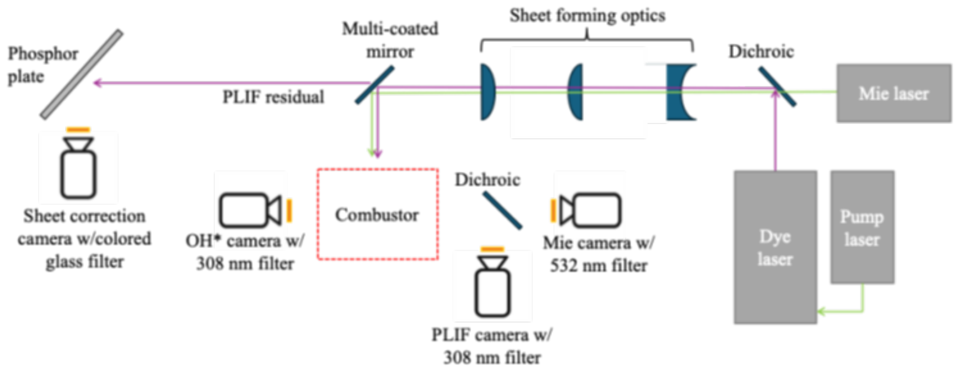

Figure 3. Simplified optical schematic with Mie scattering implemented.

In OH PLIF, a laser is used to excite OH radicals and their subsequent fluorescence is captured using an intensified camera. The OH PLIF system used here employed an Nd:YAG laser (Quantel® Q-Smart 850, 532 nm, 10 Hz, 300 mJ per pulse) to pump a tunable dye laser (Sirah PrecisionScan,™ Rhodamine 6G). The dye laser output at approximately 568 nm was frequency-doubled to yield an ultraviolet (UV) pulse with energy of approximately 21 mJ. The dye laser output was tuned to excite the Q1(9) transition of OH near 283.9 nm. To select, monitor, and tune the laser line, a reference laminar flame burner was used.

Images were recorded using a 308±10 nm filter, UV objective lens (Cercolens,™ 100 mm), and an sCMOS intensified camera (Andor™ iStar, gate time of 150 ns). The camera recorded 1,000 frames per test point with a projected pixel size of 40 μm. As shown in Figure 2 and Figure 3, the residual laser sheet that did not get reflected into the test section was impinged on a phosphor-coated plate placed after the final mirror. The resultant phosphorescence was imaged by a camera (FLIR Blackfly®) with a colored glass filter. These images were used to correct the PLIF data for shot-to-shot variation in laser sheet profile and intensity.

OH* and CH* CL images were recorded at 10 kHz using a high-speed camera (Photron® SA-5) coupled to an image intensifier (Invisible® Vision UVi 2550-10, gate time of 20 μs). The camera recorded 15,068 frames (1.5068 s) per test point. CH* images were recorded using a 431±10 nm filter and objective lens (DC Nikkor®, 105 mm), while the OH* images used a 308±10 nm filter and UV objective lens (Cercolens, 100 mm). Note that either OH* or CH* data were collected on a given test day (not both). During the first half of the test campaign, fuel droplet shadowgraph imaging was implemented and iteratively optimized (described below). Because the shadowgraph optical configuration occupied had particular optical access and layout requirements, CH* chemiluminescence was collected during these early runs, as shown in Figure 2.

To identify droplets within the combustor, shadowgraphy first was attempted with a high-speed light-emitting diode (LED) and parabolic mirror setup shown in Figure 4a. First, the 385 nm wavelength light from the LED source (Lightspeed hpls-36dd18b) is collimated through a lens. Then the dichroic mirror reflects the light through the combustor and into the mirror system. The light first hits an 80 mm elliptical mirror and then is reflected into the 304 mm parabolic mirror, after which it is reflected into the other identical parabolic mirror that focuses it on another 80 mm elliptical mirror and finally into the camera. Attached to the camera is a 280 nm ±10 nm filter to block out any flame luminosity.

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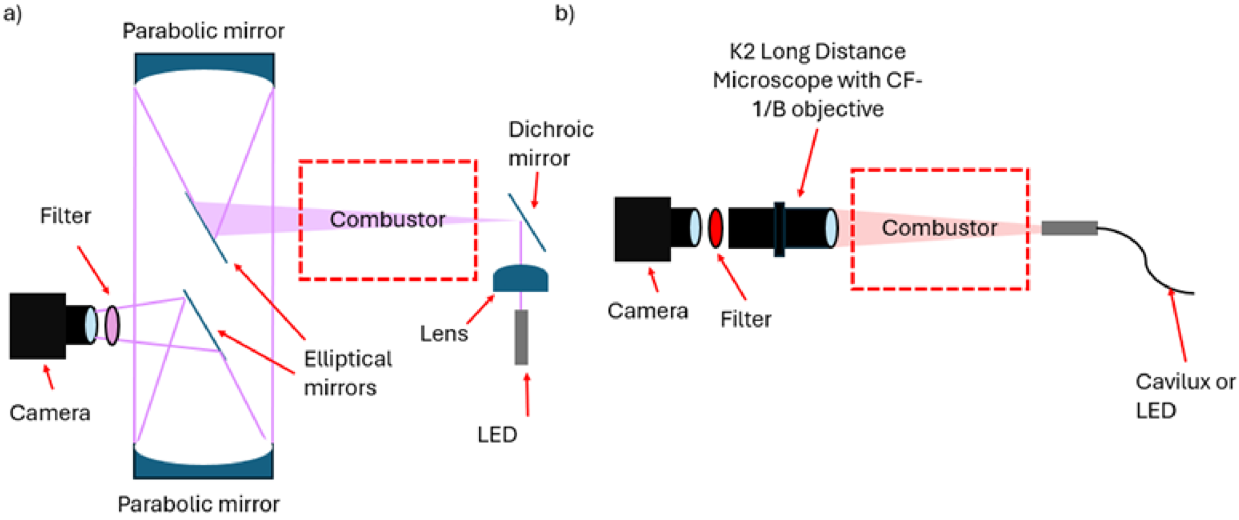

Figure 4. (a) Shadowgraphy system with mirrors and Lightspeed Technologies™ light emitting diode (LED) and (b) shadowgraphy system with the K2 long distance microscope with the CF-1/b and Cavilux® Smart UHS laser or the Lightspeed Technologies LED.

Unfortunately, this setup was unable to gather the light necessary to identify the droplets in the flame. A source of signal attenuation was from the center light rays being blocked by the elliptical mirror. The mirror system was designed to only see the diffraction pattern from the droplets and lost the center rays, accounting for most of the light. To capture the central light rays, the long-distance microscope system (Infinity K2 with the CF-1/B objective) was switched in place of the mirrors as shown in Figure 4b. However, the light captured on the camera was still insufficient to identify the droplets in the spray. When compared to the mirror system, the long-distance microscope had more light on the camera sensor, but the LED either had to be on for too long (leading to droplet smearing) or the light would not be bright enough to resolve the droplets. To resolve this issue a spoiled cavity laser system (Cavilux Smart UHS) was substituted in place of the LED, as also shown in Figure 4b. This system was able to identify some droplets in the flow at low temperature operating conditions.

As described above, modifications to the shadowgraph system were implemented during the test campaign. During the periods when the shadowgraph system was being modified, available optical table space and dichroic mirror arrangements allowed the diagnostics suite to be reconfigured, as shown in Figure 3. In this configuration, laser Mie scattering measurements were collected to characterize the fuel spray and the chemiluminescence system was transitioned to measure OH* instead of CH*.

Mie scattering used the output of an Nd:YAG laser (Quantel Evergreen EVG00200, 532 nm, 10 Hz, 160 mJ/pulse) to assess the fuel spray qualitatively. The Mie scattering beam path utilized the same optics as the OH PLIF system, enabling coincident laser sheets. Mie scattering images were isolated on a different camera (Andor Zyla) using a dichroic mirror, 532±10 nm bandpass filter, and objective lens (DC Nikkor, 105 mm). For each test point, 1,000 frames were collected at an exposure of 9.24 μs. An external pulse generator was used to synchronize the Mie and OH PLIF images.

A critical aspect of understanding the combustor's performance is understanding how the pilot flame interacts with the LPP main flames. Unraveling such interactions requires measurements to be made in multiple planes between the pilot centerline and the outer annulus of the main flames. To examine multiple planes, the sheet-forming optics, final multicoated mirror, and cameras were placed on remotely controlled translation stages. This allowed the laser sheet to be traversed across the combustor while keeping the images in focus. Images are captured at eight different planes ranging from the pilot centerline to the outer edge of the combustor for each operating condition. These measurements allow the

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development of the main and pilot flames to be mapped relative across the full combustor width, capturing the spatial extent of pilot's influence under different operating regimes. The approximate range of the laser sheet traverse and location of the shadowgraphy beam with reference to the dome face are shown in Figure 5.

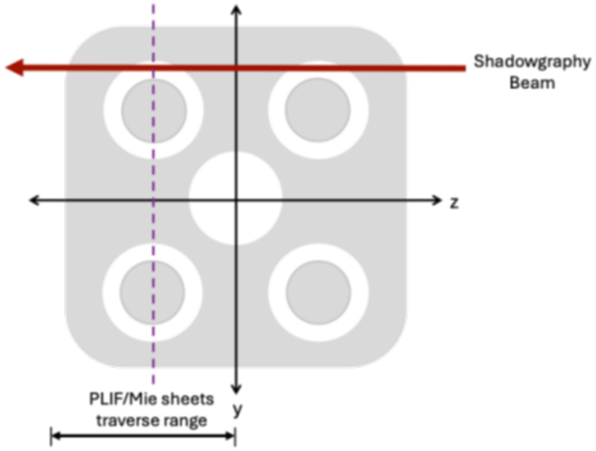

Figure 5. Dome face schematic, aft looking forward. PLIF: planar laser induced fluorescence.

In addition to the "conventional" diagnostic suite, an experimental fiber optic coupled spectrally resolved CL measurement technique was deployed as a demonstration for future high-power measurements in optically inaccessible combustor configurations. The top window in the combustion liner was replaced with a water-cooled blank. Four gold-coated multimode optical fibers (NA = 0.12, 200 μm pure fused silica core, Molex Polymicro[®]) were directly mounted via high-temperature epoxy to the blank. The gold-coated fibers can survive operating temperatures up to 973K, preventing damage as they are routed outside of the pressure vessel and coupled to a fiber bundle (Thorlabs[®] 1-to-4, linear, NA = 0.22). Light from the fiber bundle is captured by a spectrograph (Andor Shamrock 303i, 600 l/mm grating, 500 nm blaze) and imaged by a charge-coupled device (CCD) camera (Andor iDus 420A-BU).

The four fibers are positioned along the centerline of one of the main flames at varying axial distances from the dome face. Light collected by the four fibers is relayed to the spectrograph entrance slit and imaged simultaneously onto the CCD sensor using a custom relay-imaging system. In this configuration, the fiber outputs are vertically stacked so that each fiber occupies a distinct and confined region of the detector's vertical pixel array. This arrangement allows all four spectral signals to be recorded concurrently on a single camera exposure while preserving spatial separation between channels. Figure 6 shows a schematic of the positioning of the fibers in the combustor and the subsequent relay imaging system.

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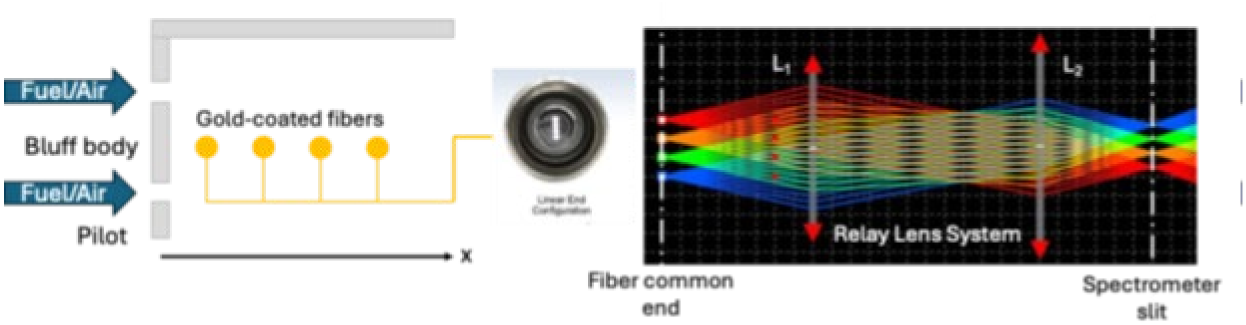

Figure 6. Spectrally resolved fiber optic coupled chemiluminescence schematic. Left: Approximate fiber axial position in combustor (side view). Right: Relay lens imaging system from fiber bundle to spectrometer. For visualization, each fiber is shown as a different color.

Optical Diagnostics Results

Figure 7 shows sample OH* chemiluminescence images for an attached and blown-off condition. The attached case on the left shows clear signal in the recirculation zone of both bluff bodies. Comparatively, the blown-off case shows no signal, as indicated by the red box in the figure. While OH* CL is a line-of-sight-integrated diagnostic method, and it is possible that one (or more) mains blow off while the others remain attached, it is a suitable diagnostic for identifying global blow off conditions. A systematic analysis of all the operating conditions identified the blow-off conditions as listed in Table 2. Across all cases where the pilot remained stably attached, the global lean blowoff boundary was dictated mainly by inlet temperature and global Federal Aviation Regulations (FAR), showing little dependence on pilot equivalence ratio. Conditions became pilot-limited only when the pilot neared its own lean extinction threshold, at which point further reductions in global FAR were not achievable.

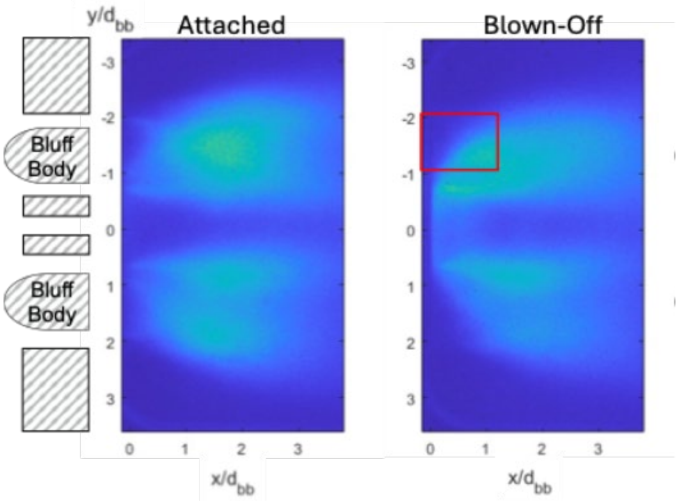

Figure 7. Sample mean OH* chemiluminescence images for attached cases (left) and blown-off cases (right).

Table 2. Lean Blowoff Conditions.

T_3 (F)	Φ_{pilot}	Φ_{mains}	Blown Off?
650	Low	0.69	No
650	Medium	0.65	No
650	High	0.59	No
550	Low	0.69	Could not reach condition
550	Medium	0.65	Yes
550	High	0.59	Yes
450	Low	0.78	Could not reach condition
450	Medium	0.74	Yes
450	High	0.68	Yes

Figure 8 shows sample temporal mean PLIF images for an attached case at the pilot and main centerline. The raw images show a region of high signal at $1 \lesssim x/d_{bb} \lesssim 2$, which corresponds to a region of high beam energy intensity. To correct for these nonuniformities, the shot-for-shot beam correction is applied to the raw images, creating a relatively more uniform distribution seen on the right for each set of images. Nonetheless, the beam profile corrected images along the means centerline show significant signal along the reactant jets, indicating strong fuel-PLIF crosstalk from the aromatic content in Jet-A. Indeed, mean Mie scattering images show unvaporized droplets entering the combustor, even at the highest T_3 conditions. Therefore, as images are further processed, overlayed mean Mie scattering images will be used to guide PLIF interpretation.

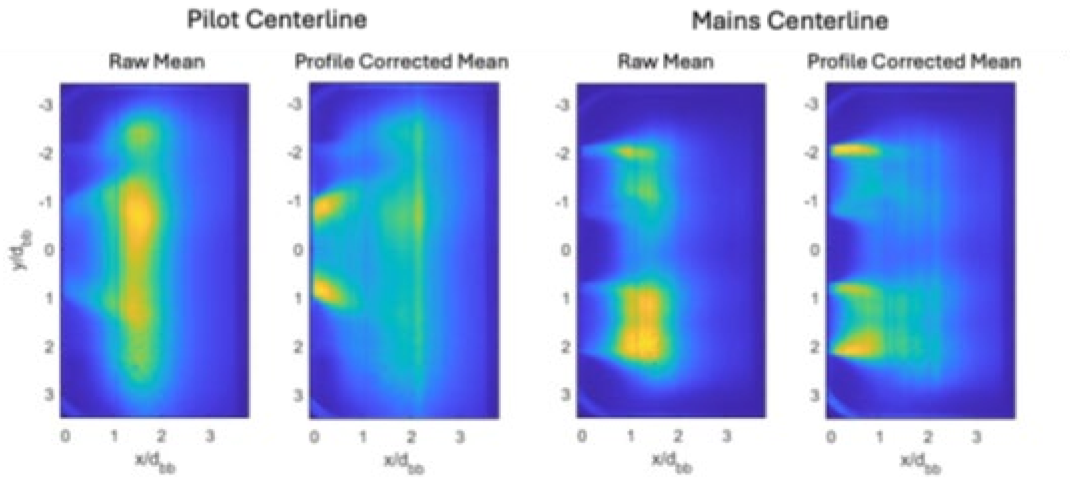

Figure 8. Sample temporal mean PLIF images along the pilot and main centerline. The left images in each set are the raw mean, and the right are beam profile corrected.

Figure 9 shows the combustor-facing side of the water-cooled window blank into which the fiber optics were mounted. The fiber locations are shown via the red arrows, although the holes are too small to see, as the fiber diameter with cladding and coating is 250 μm. The spectrometer was unable to capture any signal, likely because of the soot coating the blank and blocking any light. However, the epoxy held the fibers in place, and they did not become dislodged during testing. Therefore, future testing will benefit from an effusion cooled liner that provides a protective boundary layer of air for the fibers.

Figure 9. Combustor blank with mounted fiber optics after testing.

Shadowgraphy was able to identify droplets in the combustor at a low temperature. Figure 10 shows some of these droplets. As data processing continues droplet statistics may be able to be identified.

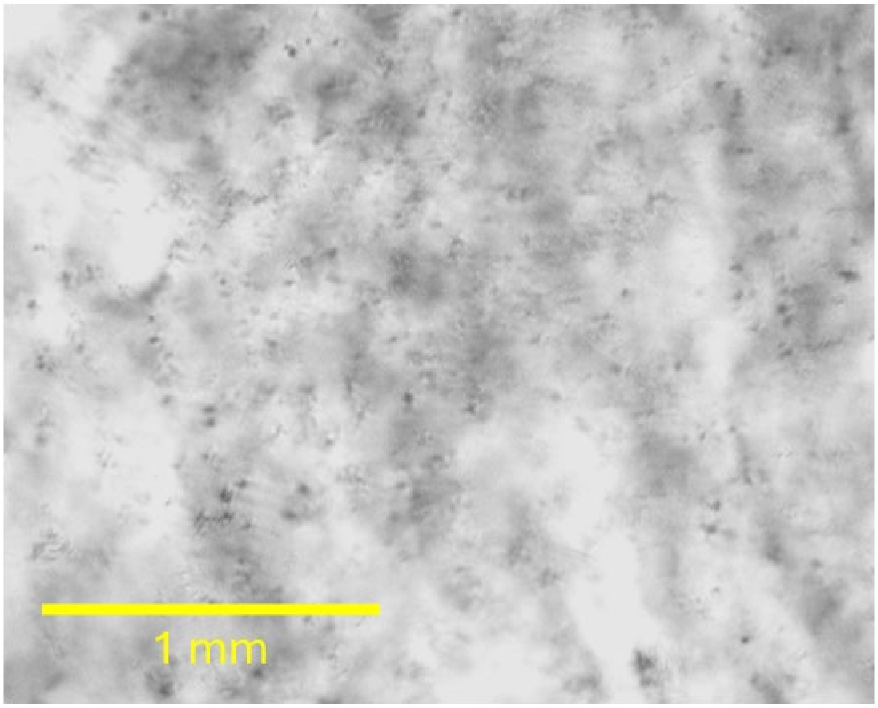

Figure 10. Sample image of droplets in the combustor.

Milestones

- Redesigned mixer and pilot for subsonic aircraft conditions.
- Fabricated combustor hardware, including mixer, pilot, liner, and window blank.
- Designed and optimized optical diagnostic configuration for multiple-simultaneous measurements.
- Successfully executed experimental campaign 1; data acquired across a range of conditions.
- Assess and improved novel fiber-coupled and shadowgraph techniques.

Major Accomplishments

- Acquired C=critical data on LPP combustor operation.

Publications
None.

Outreach Efforts
None.

Awards
Ari Jain received the AIAA Martin Summerfield Graduate Student Award.

Student Involvement
- Arihant Jain (PhD Student) – Laser induced fluorescence measurements, chemiluminescence measurements, overall optical layout, experimental execution, data post-processing and analysis.
- Alexander Stevens (PhD Student) – Shadowgraph measurements, Mie scattering measurements, experimental execution, data post-processing and analysis.
- Ijeoma Obi (MS Student, Graduated) – Shadowgraph measurements, Mie scattering measurements, experimental execution, data post-processing and analysis.
- Jananee Dhanasekaran (MS Student, Graduated) – Image segmentation for fluorescence measurements.

Plans for Next Period
- Analyze optical data from Experimental Campaign 1 to understand and characterize LPP combustor.
- Execute an experimental campaign to measure pollutant emissions from the combustor.
- Further advanced diagnostics, particularly fiber-coupled diagnostics needed for high-power conditions.

References
Jain, A., Obi, I. M., Salazar, V., Kodali, M., Venkatesan, K., Mazumdar, Y. C., & Steinberg, A. M. (2026). Characterization of a Lean Premixed Prevaporized Combustor with Conventional and Sustainable Fuel. *AIAA Journal*, 64(2), 767-779. https://doi.org/10.2514/1.J065617

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Task 2 – CFD Simulations of Combustor Operation and Emissions
Georgia Institute of Technology
GE Aerospace

Objective
The objective of this task under the current project scope is to perform CFD simulations of the LPP combustor to both aid in optimizing the combustor design and develop/validate best practices for simulating LPP combustors.

Research Approach
GE Aerospace has performed CFD simulations of the combustor test article. The solvers are being exercised to determine to what degree key processes can be represented both predictively and affordably. The central objective is to systematically establish a validated system of models for treatment of the device relevant processes emulated by the experimental rig. A major goal is to explore the ability of engineering-standard models to predict the trends observed as part of the experimental campaign and provide parametric analysis that provides additional insights with high levels of confidence. This validation effort will proceed during the upcoming performance period based on the data obtained in Task 1.

During the past reporting period, the CFD was leveraged to help redesign the ASCENT Project 074 geometry for the ASCENT Project 098 conditions (i.e., for subsonic aircraft engines). A legacy GE Aerospace pilot geometry was scaled via CFD to fit within the geometry constraints of the ASCENT Project 074 mixer while still meeting target aerodynamic design metrics. Select aero and combustion CFD iterations were performed by the GE CFD team to achieve the final design. The pilot integration also necessitated additional cooling and flow area changes that were not present in the original mixer. Thus, air assisted cooling for the pilot and dome was needed. Next, the CFD effort focused on modeling the full combustor using the newly designed mixer (see Figure 11). Both non-reacting and reacting runs were performed.

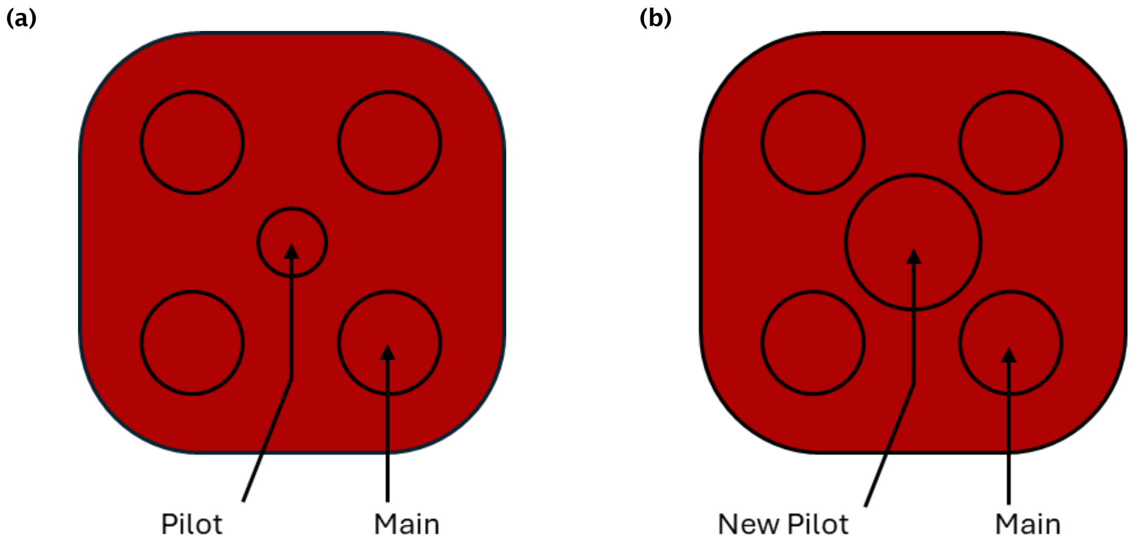

Figure 11. Schematic showing the pilot differences between mixers: (a) ASCENT Project 074 and (b) ASCENT Project 098.

A nominal condition of $T_3 = 1000$ F and P_3=350 psia was selected for the CFD simulations. These conditions would eventually be matched during testing. The non-reacting CFD simulations were performed to check that the main flow fields look similar to the baseline mixer and within design experience and expectations and ensure the mixer modifications perform as expected (see Figure 12). Next, the CFD modeling focused on reacting conditions, where both pilot-only, and pilot-with-mains operation modes were modeled. Fuel distribution, velocity and temperature maps were used to evaluate the performance of the mixer (see Figure 13). The CFD results were satisfactory for both operation modes and subsequent effort was focused on structural analysis.

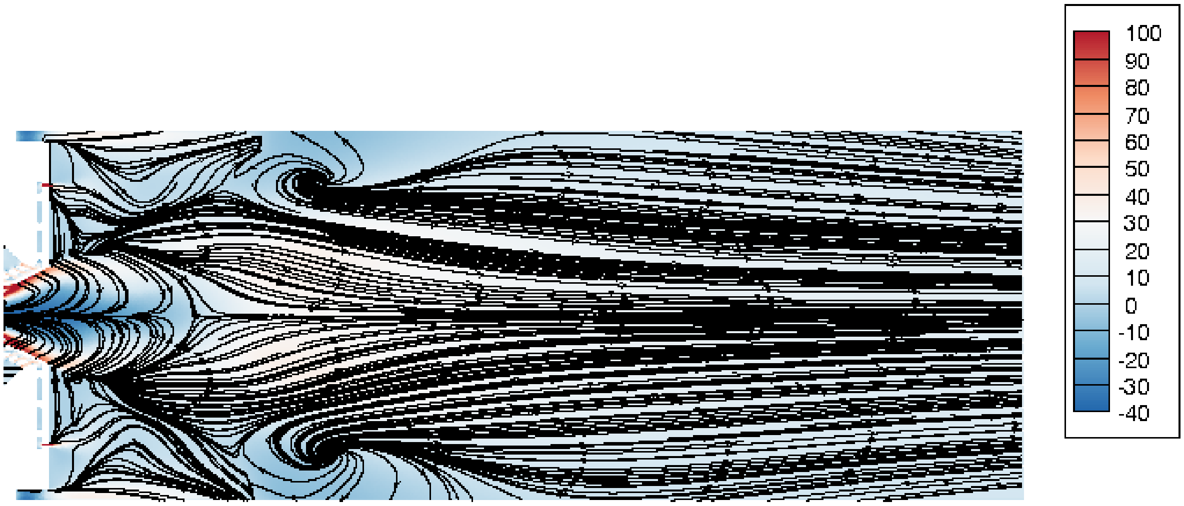

Figure 12. Streamlines showing key recirculation zones inside the combustor.

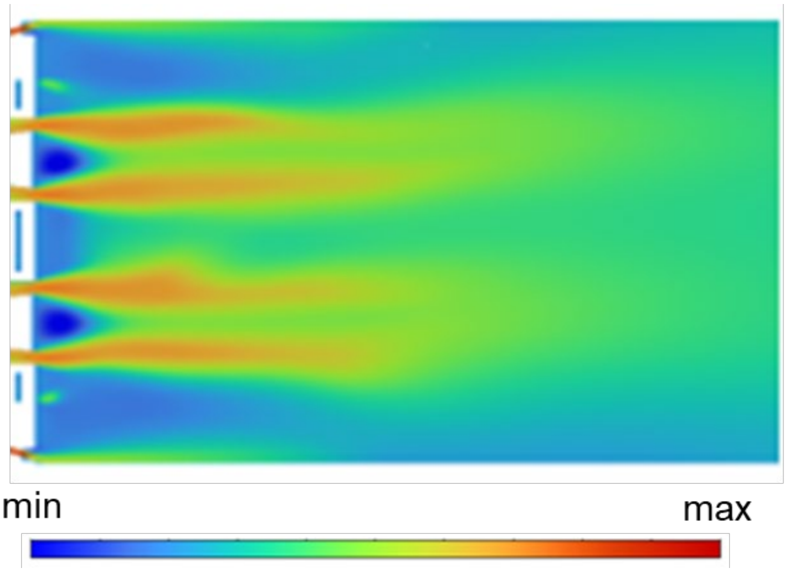

Figure 13. Axial velocities in the near dome region.

To meet the durability requirements at the higher pressure and temperature operating conditions and the inclusion of cooling flow features within the new mixer, the GE team performed a detailed thermal and structural analysis. The structural analysis relies on the input of temperature maps of the part to be analyzed. Thus, using a combination of CFD and GE Aerospace design tools, the necessary pressure and temperature and boundary conditions were provided to the thermal and structural model. The analysis was performed at conditions with pilot-only and pilot-with-mains modes. The first study highlighted regions that needed further optimization and locations needing increased dome cooling. Subsequent analysis after design update were deemed satisfactory after which the model was released for manufacturing.

Milestone

- Completed non-reacting CFD simulations for flow-field design and assessment.
- Completed reacting CFD simulations for assessment of fuel, flow, and temperature fields.
- Released a design for fabrication.

Major Accomplishments

Predicted CFD basic combustor behavior with sufficient fidelity for design.

Publications

None.

Outreach Efforts

None.

Awards

None.

Student Involvement

Arihant Jain (PhD Student) – Compilation of validation data, design consultations.

Plans for Next Period

Perform and validate LES of LPP combustor.