Project 027 (A) National Jet Fuels Combustion Program – Area #3: Advanced Combustion Tests (Year II)

Georgia Institute of Technology, Oregon State University, University of Illinois

*this report covers portion of University of Illinois

Project Lead Investigator

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- P.I.(s): Tonghun Lee, Associate Professor
- FAA Award Number: 13-C-AJFE-UI-013
- Period of Performance: 12/1/2015 to 12/31/2017
- Task(s):
    1. Optimize and apply laser diagnostics for application in the Referee Combustor (AFRL).
    2. Optimize and apply laser diagnostics for ignition experiments at Georgia Tech.

Project Funding Level

Funding Level: $120K
Cost Share: In-kind academic time of the PI, cost share contribution from NRC-Canada.

Investigation Team

- Eric Mayhew (Graduate Student, University of Illinois at Urbana-Champaign): Execution of laser and optical diagnostics at ARFL.
- Rajavasanth Rajasegar (Graduate Student, University of Illinois at Urbana-Champaign): Optimization of laser diagnostics strategy.
- Brendan McGann (Graduate Student, University of Illinois at Urbana-Champaign): Execution of laser and optical diagnostics at GATech.

Project Overview

The objective of this proposal is to support the advanced laser and optical diagnostics in the referee rig combustor (AFRAL) and area #3 (Advanced Combustion Tests) of the FAA COE ASCENT's combustion program. The diagnostics effort will strive to meet two critical targets. The first is to optimize diagnostics that has enough fidelity to discern the combustion characteristics of candidate jet fuels in their respective testing conditions (support fuel screening). The second goal is to organize and analyze the data in a structured way that allows partners in the combustion program to refine and validate their numerical models. The success of this program will substantially accelerate the efforts of the FAA and the OEMs to certify alternative, fit for purpose fuels.

Task 1 – Optimize and apply laser and optical diagnostics to characterize fuel spray and fluid mechanics in advanced combustor tests at the referee combustor

University of Illinois at Urbana-Champaign

Objective(s)

The objectives in this proposal are to work with AFRL in their referee rig experiments and achieve the following goals:

- Design and set up laser diagnostic and optical diagnostics for referee rig measurements.
- Implement phase Doppler anemometry to determine fuel spray characteristics, including droplet diameters and velocities.
- Implement high-repetition rate Schlieren imaging to examine flow structures.

Research Approach

Diagnostics Optimization and Setup

A 2D PDPA system was used to characterize the fuel droplets during combustion, measuring diameter and two components of velocity. The 2D PDPA (Dantec 112mm fiber PDPA) measures the frequency of the Doppler burst signal to determine velocity (one component from each pair of beam wavelengths) and the phase difference between two Doppler bursts to calculate the droplet diameter. An argon-ion laser (Ion Laser Technology), which produces a continuous laser beam with wavelengths ranging from 457 nm to 514.5 nm, is directed into a transmitter where the beam is split up by wavelength and coupled into optical fibers. Four beams, two at 488 nm and two at 514.5 nm (about 4 mW of power per beam), are focused by a 500mm focal length lens on the PDPA transmitter head and directed into the combustion chamber. The transmitter head and receiver head, with an 800mm focal length lens, are mounted on traverses placed on either side of the combustor. The traverses, fitted with encoders, are linked and controlled via a LabVIEW code. Data is collected using BSA Flow Software, and the data is written to text files.

Milestone(s)

Include a description of any and all milestones reached in this research according to previously indicated timelines.

Milestones from Each Period

Proposed (3 Month): At the 3 month mark, we will conclude the analysis of the experimental setup and should be close to finishing the design of the laser and diagnostics setup.
Achieved: Design of the laser setup was completed and implementation of a PDPA system on a mock referee combustor setup was conducted at the University of Illinois. Preparations to deploy PDPA system were completed.

Proposed (6 Month): At the 6 month mark, we should be finished the droplet characterization testing campaign experimental set out in Task 1 of the proposal.
Achieved: Four-week droplet characterization testing campaign is completed. Initial analysis of the droplet data has been conducted.

Proposed (9 Month): At the 9 month mark, we should have completed initial analysis of the data collected during the test campaign and distributed summary data sets to modeling and other spray teams. Preparations for Schlieren imaging to examine combustor fluid mechanics should be completed.
Achieved: First test run at GATech for simultaneous PLIF and PIV successfully complete and results analyzed. Laser and optical setup successfully implemented and tested. Identified key problems such as fuel PLIF. Main measurement campaign set for last quarter.

Proposed (12 Month): At the 12 month mark, we should have completed the Schlieren imaging test campaign and completed initial analysis of the imaging data.
Achieved: Schlieren imaging completed, and initial analysis of averaged images shows dilution jet bending.

Major Accomplishments

The main accomplishment of year 2 in this project was that we were able to set up and implement PDPA measurements to obtain fuel droplet diameters and velocities in the referee rig in combusting cases. We analyzed and distributed the data to the modeling teams to provide validation information for the fuel spray characteristics.

Fuel Droplet Characterization

Droplet axial and radial velocity distributions, SMD distributions, and data collection rates for the fuels studied are presented. For A-2 at ϕ = 0.096, data collection rate is shown in Figure 1 as a function of y-position at various axial locations. The origin is taken to be the intersection of the centerline of the injector and the downstream face of the heat shield. Positive z-position is taken to be positive downstream (flowing out of the combustor) and y-position is taken to be positive up (towards the top of the combustor). The axes and basic referee rig geometry is shown in Figure 2 for reference. The data rate is a good indicator of where the spray is located and can be used to calculate and report spray angles. The low data collection rate near the centerline verifies that the fuel injection is a hollow cone.

It is unsurprising that the width of each side of the spray increases with increasing distance downstream, and the overall width of the spray increases until it spans nearly the full height of the combustor (109 mm) by 35 mm downstream. At 35 mm downstream, the data collection rates are greatly diminished, which can be explained by further spread of the spray as well as evaporation due to combustion.

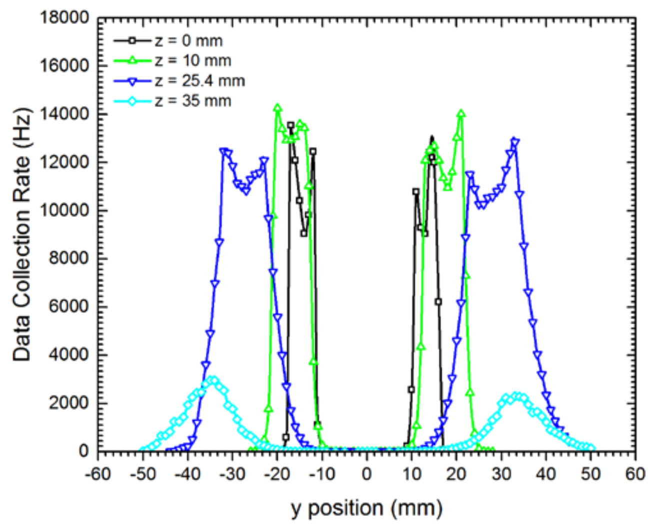

Figure 1. A-2 data collection rate. *Data collection rate versus y-position at various axial locations for A-2 at φ=0.096*

A. Comparison of Fuel Droplet Diameters

SMD is calculated at each position where diameter data is collected, and Figure 3a shows the SMD versus y-position 0 mm, 5 mm, and 10 mm downstream of the deflector plate for each fuel tested. SMDs are only reported at locations where more than 1000 droplets were measured. Figures 3b, 3c, and 3d show normalized histograms of the droplet diameters 10 mm, 15 mm, and 20 mm above the centerline at each axial location shown. The differences in SMD between the fuels are seen in the diameter histograms as a larger fraction of large droplets.

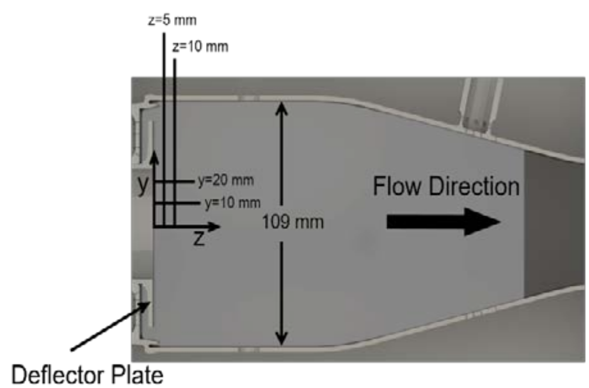

Figure 2. Cutaway of the single cup referee combustor. *The origin is taken to be at the intersection of centerline of the combustor with the front plane of the deflector plate as marked.*

As seen in Figure 3a), just downstream of the deflector plate (z = 0 mm), C-1 has a higher SMD than either A-2 or C-5, between 10 and 35 microns greater at y positions more than 12 mm above the centerline. This can be seen in Figure 3b, as C-1 has relatively few droplets with a diameter less than 20 microns compared with A-2 and C-5 at the same y positions. This seems to indicate that C-1 is either still undergoing fuel droplet breakup or that C-1 experiences less upstream evaporation compared to A-2 and C-5. At 5 mm downstream of the deflector plate, the A-2 and C-5 fuels have very similar SMDs at all measurement points where enough droplets were collected. The maximum difference between the SMDs for those two fuels is about 8 microns, occurring at y = 15 mm. The histograms in Figure 3c and 3d explain this difference; about 65 percent of the A-2 fuel droplets have diameters smaller than 20 microns while less than 50 percent of C-5 fuel droplets have diameters smaller than 20 microns. A-2 also has fewer than 4 percent of droplets with diameters larger than 40 microns while C-5 has about 10 percent of droplets with diameters larger than 40 microns. The C-1 fuel droplets have similar SMDs to A-2 and C-5 at y positions greater than 12 mm above the centerline, but below 12 mm, the SMDs of C-1 are

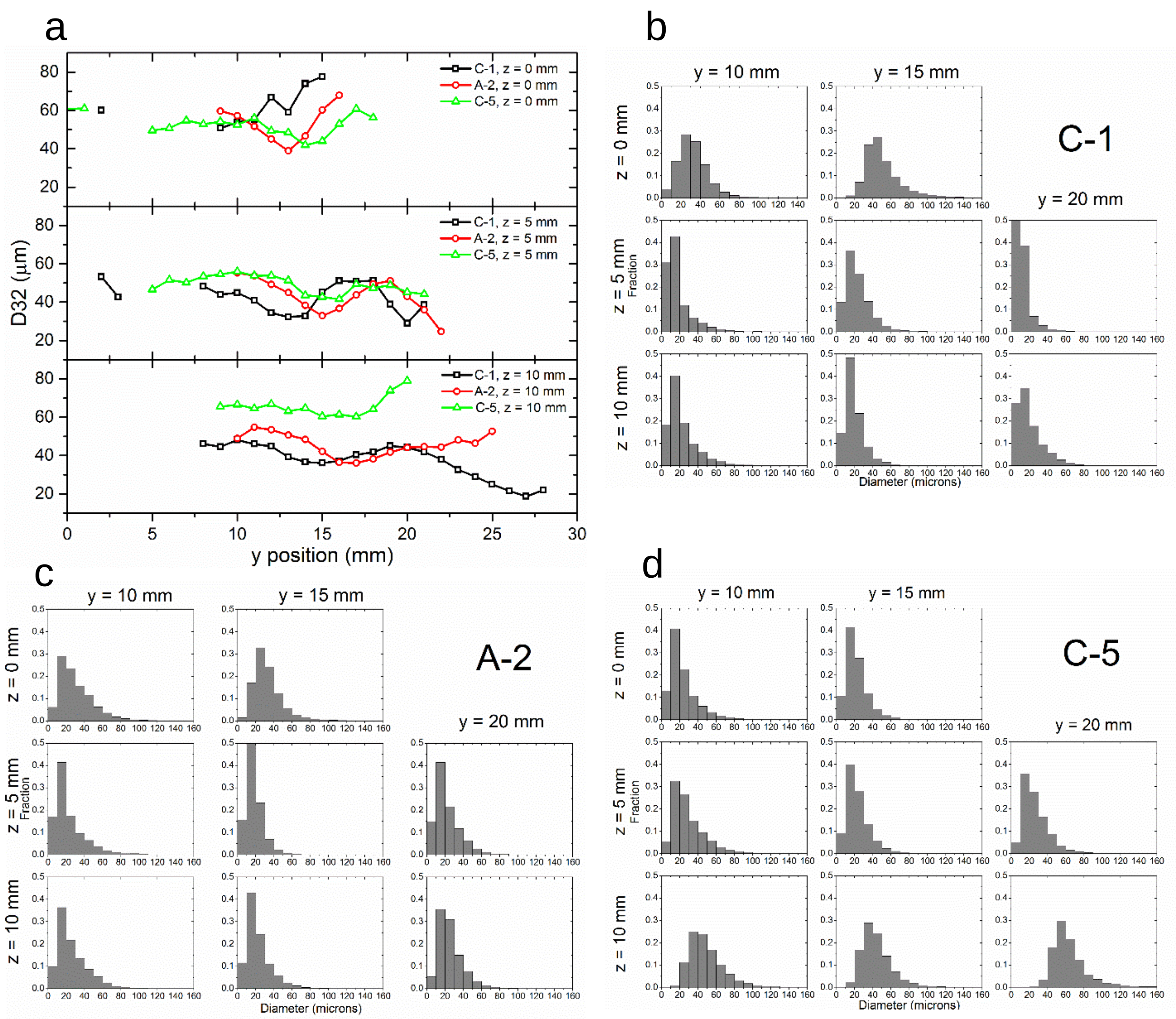

Figure 2. Sauter mean diameter and representative diameter histograms *a) Sauter mean diameter plotted versus y position for each fuel 0 mm, 5 mm, and 10 mm downstream of the deflector plate for comparison with b) C1 diameter histograms, c) A2 diameter histograms and d) C5 diameter histograms at y = 10 mm, 15mm, and 20 mm*

10 to 15 microns smaller than those of A-2 or C-5. It is also notable that the maximum C-1 SMD has dropped by about 25 microns, bringing it in line with the SMDs of A-2 and C-5.

At 10 mm downstream of the deflector plate, C-1 and A-2 have similar SMD profiles, with a maximum difference of about 11 microns from y = 10 mm up to 22 mm. The profiles diverge at y positions above 22 mm, with the A-2 SMDs increasing slightly, while the C-1 SMDs slowly decrease with increasing y position until it hits a minimum of 20 microns at 27 mm above the combustor centerline. The C-5 fuel droplets at 10 mm downstream of the deflector plate show a marked decrease in the fraction of droplets smaller than 20 microns in diameter as seen in the last row of Figure 3b). Less than 3 percent of C-5 fuel droplets measured 10 mm downstream of the deflector plate (at y = 5, 10, 15 mm) have diameter smaller than 20 microns. At those same locations, at least 40 percent of A-2 and at least 57 percent of C-1 fuel droplets are smaller than 20 microns in diameter. The result of this absence of small C-5 fuel droplets is an SMD that is 12 to 37 microns greater than the corresponding C-1 or A-2 SMD. This indicates that small C-5 fuel droplets have almost completely evaporated between 5 mm and 10 mm downstream of the deflector plate. The small droplets are expected to evaporate first because they have a larger surface area to volume ratio than larger droplets. The evaporation of the small C-5 droplets before those of C-1 and A-2 is consistent with C-5's flat boiling curve (0 to 95 percent distillation between 155˚C and 165˚C) [7]. The C-1 (0 to 95 percent distillation between 175˚C and 246˚C) and A-2 (0 to 95 percent distillation between 160˚C and 255˚C) fuels boil over a much wider range of temperatures[7].

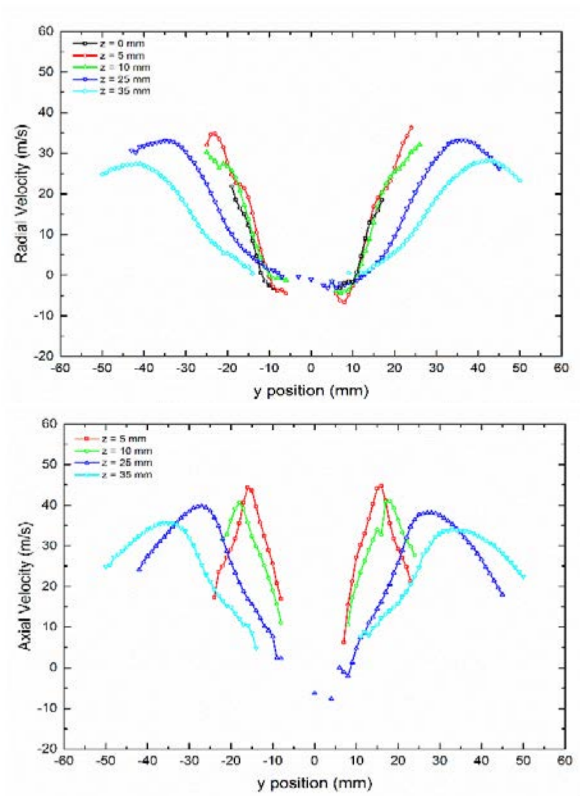

Figure 3. A-2 fuel droplet mean radial and axial velocity. *Mean radial velocity plotted against y position (top) and mean axial velocity plotted against y position (bottom) at various distances from the deflector plate*

B. Droplet Velocities

Figure 4 shows the A-2 fuel droplet mean axial and radial velocity distributions versus y-position at various axial locations. Both the axial and radial velocity distributions are symmetric about the centerline, and the distributions broaden with increasing downstream location. One interesting feature present in both the axial and radial velocity

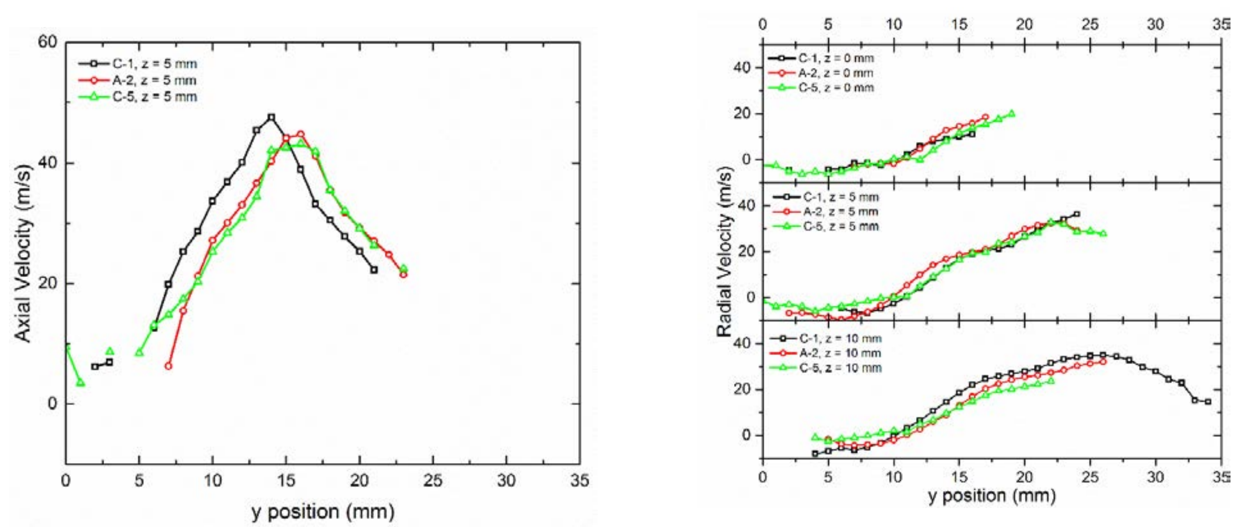

Figure 4. Axial and radial velocity profiles. *a) Axial velocity plotted versus y position for each fuel 5 mm downstream of the deflector plate and b) radial velocity plotted as a function of y position at 0 mm, 5 mm, and 10 mm downstream of the deflector plate for each fuel*

distributions is the near zero or slightly negative velocities along the centerline. This indicates the presence of an inner recirculation zone, but very few droplets are present in the center as indicated by the low data collection rates near the centerline. As seen in Figure 4, the mean radial velocity profiles at 0 mm, 5 mm, and 10 mm downstream of the deflector plate are very similar to each other. At 25 mm and 35 mm downstream of the deflector plate, the radial velocity profiles broaden and the maximum droplet velocities decrease. The axial velocity profiles at 5 mm and 10 mm for A-2 exhibit a sharp peak that roughly corresponds with the center of the spray as marked by the data collection rate. As with the radial velocity, the axial velocity profiles broaden and have a lower maximum value further downstream (25 mm and 35 mm).

A comparison of fuel droplet radial velocity for the different fuels is shown on the left in Figure 5 at 0 mm, 5 mm, and 10 mm downstream of the deflector plate, and a comparison of fuel droplet axial velocity at 5mm is shown on the right in Figure 5. The radial velocity profiles for each fuel have a great deal of similarity across the fuels at each downstream position shown. Figure 5 also shows the axial velocity profile 5 mm downstream of the deflector plate. The C-1 axial velocity profile is slightly different from C-5 and A-2, reaching its peak about 2 mm inside of the peaks for C-5 and A-2.

Publications
None (in progress to AIAA Sci Tech)

Outreach Efforts
None

Awards
None

Task 2 – Optimize and apply laser and optical diagnostics for application in the advanced ignition tests at Georgia Institute of Technology and Army Research Laboratory
University of Illinois at Urbana-Champaign

Objective(s)
The objectives in this proposal are to work with Georgia Tech in their advanced ignition experiments and achieve the following two goals:

- Evaluate the experimental ignition testing setup and operating conditions for laser and optical diagnostics
- Design and set up laser and optical diagnostics for use in ignition experiments at Georgia Institute of Technology
- Design and construction of high altitude ignition combustor for ARL experiments.

Research Approach
Diagnostics Optimization and Setup on Georgia Tech Atmospheric Ignition Rig
The main goal here is the development of 2D diagnostics using Planar Laser Induced Fluorescence (PLIF), Schlieren, and OH* chemiluminescence to understand the ignition development at the boundaries and flame dynamics in the GATech atmospheric ignition rig. The goal will be to apply simultaneous measurements from high speed PLIF, Schlieren, and chemiluminescence. For each of the imaging sets, we will look to obtain spatially resolved data. We will configure and set up the laser and optical diagnostics equipment around the ignition rig at GATech. For the high speed PLIF measurements, we pumped a high speed dye laser (Credo, Sirah) with a high speed diode pumped Nd:YAG (Edgewave) for generation of the UV light. The PLIF, Schlieren, and chemiluminescence imaging will be 10 kHz. Energy per laser pulse at these conditions may be small (200 µJ/pulse) and light collection from the PLIF will be enhanced using a f/2.8 UV lens.

Design of High Altitude Relight Combustor
The primary goal here is to design and build a combustor that replicates the key geometry and flow features of the referee rig, while allowing three-sided optical access to conduct laser and optical diagnostics. The primary features from the referee rig that have been maintained include: overall combustor interior size, primary dilution jet hole placement, swirler geometry, and injector geometry.

Milestones from Each Period

Proposed (3 Month): At the 3 month mark, we will have identified the key features that are important in the design of the rig. Preliminary designs will have been shared with the OEMs for feedback.
Achieved: Two rounds of preliminary designs have been completed, and key features have been identified.

Proposed (6 Month): At the 6 month mark, we should be have finalized the design and sent the drawings to the machine shop for construction.
Achieved: The designs have been finalized and drawings sent to the machine shop. Materials for the rig have been ordered.

Proposed (9 Month): At the 9 month mark, we should have the main body of the high altitude relight rig constructed and windows for the rig purchased.
Achieved: The main body of the rig has been machined and assembled.

Proposed (12 Month): At the 12 month mark, we should have obtained the swirler and injector and made any modifications to the rig to ensure that they fit into the main body.
Achieved: The swirler and injector have been retrieved from Wright-Patterson Air Force Base. Preparations have been made to transport the rig to ARL.

Major Accomplishments

The main accomplishments of year 2 in this task was that we transported and set up the laser system around the ignition rig at GATech for the execution of simultaneous PLIF, Schlieren, and OH chemiluminescence imaging. The high altitude relight combustor was also completed and has been prepared to ship to ARL. The model and the finished body of the combustor are shown in Figure 6.

Georgia Tech Ignition Experiments

The primary effort on the ignition experiments was transporting the Edgewave Nd:YAG high repetition rate laser to Georgia Tech. The laser was coupled to the Sirah Credo Dye Laser, as shown in Figure 5 (left), and both lasers were tuned to optimize laser power and beam profile. Optics to form and steer the laser sheet in through the top of the combustor, as shown in Figure 5 (right). The primary ignition testing campaign was carried out by Georgia Tech personnel.

Figure 5. *Edgewave pump laser (left) and dye laser with sheet forming optics, and the ignition rig*

High Altitude Relight Combustor

Design and fabrication of a high altitude relight rig, replicating the key geometry and flow features of the referee rig has been completed. The model and completed body of the chamber are shown in Figure 6. Windows, made of UV-grade fused silica, have been ordered to prepare for UV laser and optical diagnostics. A metal 3D printed swirler and a pressure atomizing fuel injector, ones identical to those in the referee rig, were obtained from AFRL to use in the combustor. Construction of the main body of the combustor, as shown in Figure 6, was completed in September, and the swirler/injector combination was obtained from AFRL in November.

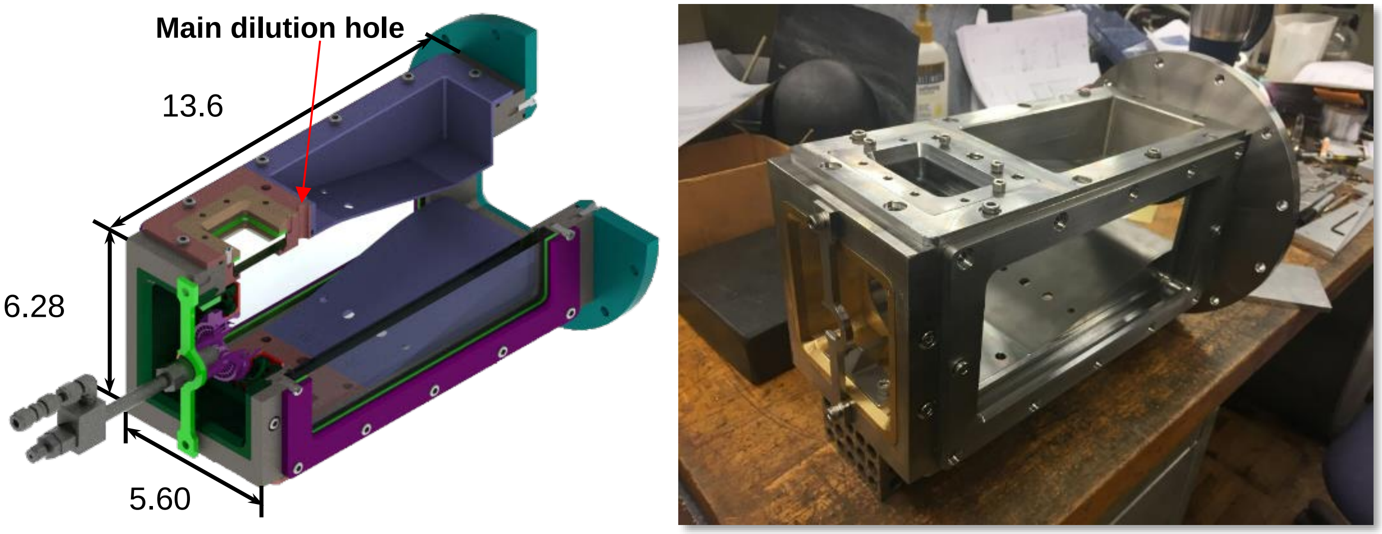

Figure 6. High altitude relight combustor model (left) and completed rig (right). *The high altitude relight combustor replicates the key geometry and flow features of the referee rig, including dilution jet hole placement, overall size, swirler geometry, and injector geometry.*

Publications
None

Outreach Efforts
None

Awards
None

Student Involvement
Three graduate students (listed above) have participated in this project on a rotational basis to address various aspects of the project. Two students executed (Brendan McGann and Eric Mayhew) set up and executed the PDPA measurements outlined in Task 1. Two students (Brendan McGann and Eric Mayhew) made trips to GATech to transport and couple the Edgewave Nd:YAG pump laser to the dye laser for use in the PLIF imaging. In addition, they assisted in the setup of the optics as well as participating in the initial phase of the measurements. The Edgewave as well as other optical and imaging equipment was taken down to GATech for testing. Rajavasanth designed and fabricated the high altitude relight chamber.

Plans for Next Period
In year III of the NJFCP, the main focus of our efforts will be execute high altitude ignition experiments at the Army Research laboratory. The test conditions will be worked out with OEM input and the work will also be coordinated with the ongoing ignition work at GATech. We will continue to support AFRL in any diagnostics efforts required in the referee rig combustor. Looking into the future, we anticipate either PIV or LDV measurements will be required in the referee combustor to measure velocity information. We have already designed the required hardware for this effort and will look for an opportunity to implement them with support from AFRL.

References
none