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

Georgia Institute of Technology
Oregon State University
University of Illinois at Urbana-Champaign

Project Lead Investigator

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University Participants

Georgia Institute of Technology

- P.I.(s):
  - Professor Tim Lieuwen
  - Professor Jerry Seitzman
  - Professor Wenting Sun
- FAA Award Number: 13-C-AJFE-GIT-008
- Period of Performance: 12/1/2015 to 11/30/2016
- Task(s):
  1. Task 1. Blowoff
  2. Task 2. Ignition

Oregon State University

- P.I.(s): David Blunck
- FAA Award Number: 13-C-AJFE-OSU-02
- Period of Performance: 12/1/2015 to 11/30/2016
- Tasks:
  3. Task 3. Turbulent Flame Speed

University of Illinois at Urbana-Champaign

- 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):
  4. Optimize and apply laser diagnostics for application in the Referee Combustor (AFRL).
  5. Optimize and apply laser diagnostics for ignition experiments at Georgia Tech.

Project Funding Level

Georgia Institute of Technology
FAA Funding: $340,000
Cost Share: $340,000 provided by Georgia Institute of Technology

Oregon State University
FAA Funding: $80,000
Cost Share: $80,000 provided by Oregon State University

University of Illinois at Urbana-Champaign
FAA Funding: $120K
Cost Share: In-kind academic time of the PI, cost share contribution from NRC-Canada.

Investigation Team

Tim Lieuwen (Georgia Institute of Technology): Principal Investigator. Professor Lieuwen is the PI overseeing all tasks, and is manager of Task 1. Blowoff
Jerry Seitzman (Georgia Institute of Technology): Co-Principal Investigator. Professor Seitzman is the manager of Task 2. Ignition
David Blunck (Oregon State University): Co-Principal Investigator. Professor Blunck is the manager of Task 3. Turbulent Flame Speed
Fred Dryer: Co-Principal Investigator. Professor Dryer is acting as an expert consultant on alternative jet fuel chemistry
Wenting Sun (Georgia Institute of Technology): Co-Principal Investigator. Professor Sun is acting as an internal expert consultant on kinetic mechanisms
Tonghun Lee (University of Illinois Champaign): Co-Principal Investigator. Professor Lee is the lead diagnostic expert.
Bobby Noble (Georgia Institute of Technology): Research Engineer. Mr. Noble is responsible for designing and maintaining experimental facilities, as well as experimental operations and management & safety of graduates students.
Benjamin Emerson (Georgia Institute of Technology): Research Engineer. Dr. Emerson is responsible for designing and maintaining experimental facilities, as well as experimental operations and management & safety of graduates students. He is also acting as the administrative coordinator for all three tasks.
David Wu (Georgia Institute of Technology): Research Engineer. Mr. Wu is responsible for designing and maintaining experimental facilities, as well as experimental operations and management & safety of graduates students.
Brandon Sforzo (Georgia Institute of Technology): Postdoctoral Fellow. Dr. Sforzo is the lead experimentalist in Task 2. Ignition
Glenda Duncan (Georgia Institute of Technology): Administrative Staff. Mrs. Duncan provides administrative support.
Tiwanna Williams (Georgia Institute of Technology): Administrative Staff. Mrs. Williams provides administrative support.
Seth Hutchins (Georgia Institute of Technology): Lab Coordinator. Mr. Hutchins maintains the core lab facilities and provides technician services.
Machine Shop Staff (Georgia Institute of Technology). The Aerospace Engineering machine shop provides machining services for experimental facility maintenance/construction
Nick Rock (Georgia Institute of Technology): Graduate Student. Mr. Rock is the lead rig operator in Task 1. Blowoff
Ianko Chterev (Georgia Institute of Technology): Graduate Student. Mr. Chterev is the lead diagnostitian in Task 1. Blowoff
Hanna Eck (Georgia Institute of Technology): Graduate Student. Ms. Eck is the lead data analyst in Task 1. Blowoff
Sheng Wei (Georgia Institute of Technology): Graduate Student. Mr. Wei is a research assistant under Task 2. Ignition
Aaron Fillo (Oregon State University): Graduate Student. Mr. Fillo was the lead grad experimentalist in Task 3. Turbulent Flame Speed
Jonathan Bonebrake (Oregon State University): Graduate Student. Mr. Bonebrake is the lead grad experimentalist in Task 3. Turbulent Flame Speed
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 activity is to provide advanced combustion testing support to the FAA's alternative jet fuels program. We are performing advanced combustion testing to accomplish two goals. The first goal is to screen candidate jet fuels for sensitivities of their burning properties to fuel physical and chemical properties. The second goal is to provide empirical data to combustion modeling partners to facilitate the refinement and validation of their models, which aim to develop predictive capability for fuel composition sensitivities. The success of this program will substantially accelerate the efforts of the FAA and the OEMs to certify alternative, fit for purpose fuels.

In the second year of the program, we repeated testing of A1, A2, A3, C1, C2, C3, C4, C5, and n-dodecane fuels. Additionally, we tested blends of A2/C1 and A2/C5, and two surrogate fuels known as S1 and S2. For this second year, we had proposed three tasks that address the most critical challenges associated with advanced combustion model development and differentiating differences in fuel chemistries:

(1) Task 1: flame stabilization, extinction, and blowoff in high shear flows
(2) Task 2: forced ignition
(3) Task 3: turbulent flame speed

As detailed in their respective sections, these tasks have been developed toward supporting the overall program goals culminating in referee rig capabilities, as well as acquiring data to differentiate potentially subtle fuel effects that can be used for model validation. Each task has a strong focus on supporting model development and evaluating fuels, and a strong connection to understanding engine operational limits. They were designed toward addressing critical gaps associated with both objectives of the larger program, namely an improved combustor rig evaluation process for ASTM D4054 and validated models for combustor evaluation. This second year extended the first year's work with repeatability datasets, datasets at new conditions, new detailed data to support modeling teams, and improved physical understanding.

Advanced combustion tests, which couple chemical kinetic processes with complex fluid mechanic and/or atomization/evaporation processes, are a critical link in the path from fundamental knowledge to prediction of how fuel composition impacts engine operation. The investigators and the consultant have extensive experience in this field, including developing surrogate mixtures for Jet-A, characterizing changes in pollutants when alternative and conventional jet fuels are burned, and having successfully completed and transitioned similar approaches for synthesis gas fuels and for natural gas fuels.

From a diagnostics standpoint, the objective of this work 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. Blowoff

Georgia Institute of Technology

Objective(s)

The objectives of this task were to measure detailed operational data near the blowoff limits of a swirl combustor that mimics OEM hardware. The proposed combustor, used in year 1 of this program, was a swirl-stabilized spray combustor, which was configured similarly to the referee rig, but without dome cooling and liner-cooling flows. The benefits of this task were threefold. The first benefit of this task was the measurement of detailed boundary conditions and validation data that are critical to a successful modeling effort. These measurements were selected collaboratively with our modeling partner at United Technologies Research Corp (UTRC), in order to support their refinement and validation cycle. The second benefit of this task was exploratory refinement of detailed diagnostics and best practices. The third benefit of this task was the capability to rapidly measure a wealth of screening data, in order to extend the existing datasets to new conditions, and also to obtain repeatability data.

Research Approach

The research approach consisted of four major activities: collaborative selection of test conditions, screening data acquisition, detailed data acquisition, and data analysis. The selection of test conditions was conducted collaboratively within a blowout subcommittee. The subcommittee converged on a test plan consisting of screening fuels at a pressure of 2 atmospheres, and three different preheat temperatures: 300 K, 450 K, and 600 K. The screening was to be performed on as many fuels as possible from year 1, as well as three blends of A2/C1 and two new surrogate fuels known as S1 and S2. The detailed diagnostic tests were to be conducted at 300 K of preheat and 2 atmospheres of pressure. These measurements were to obtain spatio-temporally resolved velocity fields, liquid fuel maps, and [OH] maps, with all three of these measurements synchronized together. These measurements were to be obtained for the A2, C1, and C5 fuels. Additionally, efforts would be made to capture a blowout event with the A2 fuel with as much of these high speed diagnostics as possible. For year 2 of task 1, the detailed diagnostics would be supported by AFRL and Spectral Energies, LLC.

The data analysis task operated on both the screening data and the detailed diagnostic data. Analysis of the screening data was conducted to assess repeatability and to correlate fuel performance trends with various fuel properties. The labor-intensive analysis of the detailed data converted the raw data into meaningful velocity fields, fuel maps, and [OH] maps, and delivered these data to UTRC for support and validation of computational models. Much of this analysis has been performed during the second year, and further analysis is proposed for year 3.

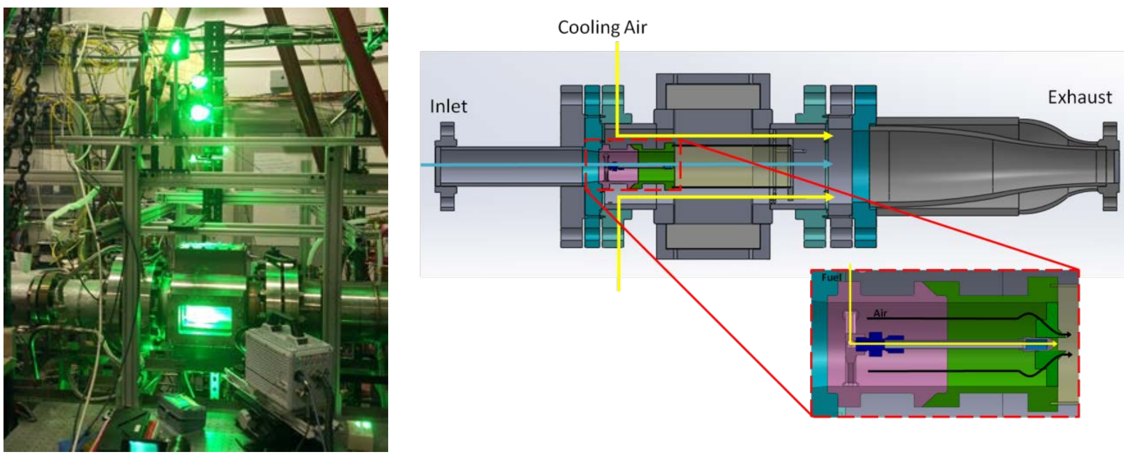

Figure 1. High shear swirl combustor, showing a) pressure vessel instrumented for high speed stereo PIV and OH PLIF, and b) a cross section with generic swirler holder/injector for illustrative purposes

Milestone(s)

1. **Measurements of inflow and boundary conditions.** This has been completed for all planned case and has been delivered to the modeling partners upon request.
2. **Measurement of lean blowout equivalence ratio, mapped over full screening test matrix (screening data).** This has been completed for all planned cases and has been disseminated to the community via the KSN.
3. **Summary of best diagnostic practices.** This has been completed and is being disseminated to the community through a series of publications.
4. **Final data analysis.** This has been completed to the extent that it was planned for year 2. The results have been transmitted directly to modeling groups as needed, and key findings have been disseminated to the community via the KSN and publications. Further analysis is in progress and will continue in year 3.

Major Accomplishments

1. To date, we have built a screening dataset consisting of several thousand blowoff measurements.
2. By building on the technique that we developed in year 1, we have obtained first of its kind quality detailed diagnostic combustion system measurements (see examples in Figure 2 and Figure 3).
3. We have delivered important boundary condition data to the modeling group at UTRC, and we have also delivered data that they have used to demonstrate an impressive level of validation.
4. We have demonstrated that blowoff tends to correlate with physical properties of the fuel at low temperatures and with poor atomization quality, and that it tends to correlate with other properties (e.g. chemical properties) at

higher temperatures and with better atomization, which has been a key hypothesis since the start of the program. Some sample correlations are shown in Figure 2.

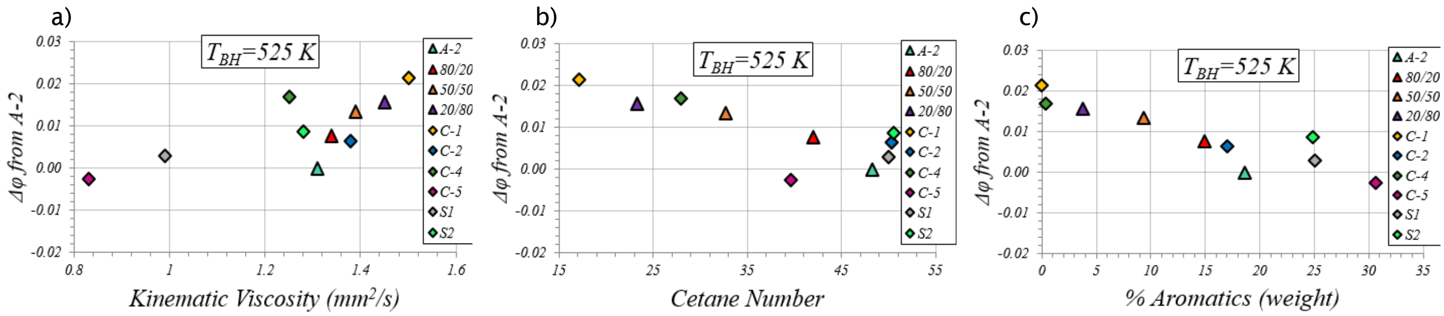

Figure 2. Sample of year 2 screening data at 450 K preheat, 2 atm pressure, showing correlation to a) kinematic viscosity, b) cetane number, and c) % aromatics

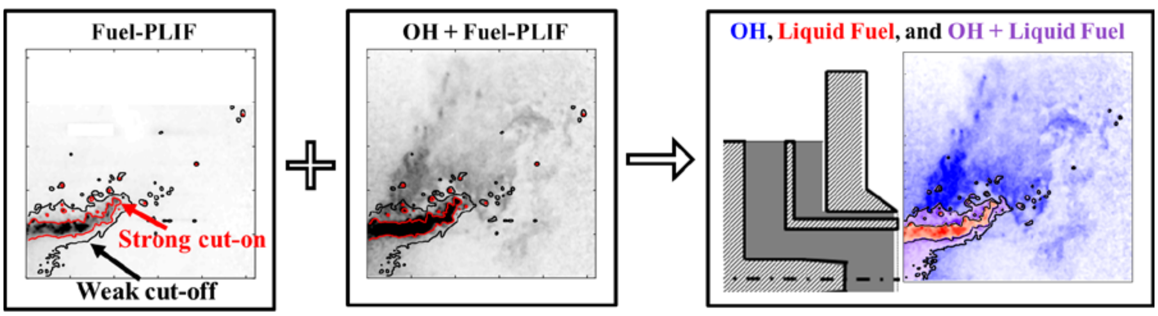

Figure 3. Sample of detailed diagnostic data, showing improved data quality since the first year and new analysis techniques.

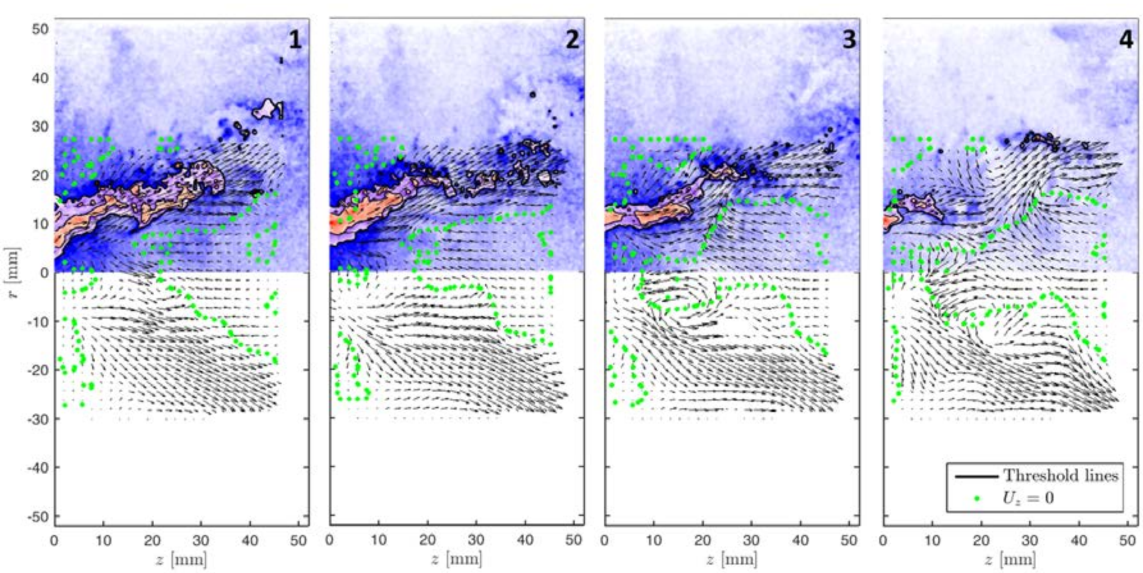

Figure 4. Film-strip of processed detailed diagnostic data, showing OH-PLIF (blue), fuel-PLIF (red), mixture of fuel and OH (purple), and in-plane velocity field (black). Green line indicates contour of zero in/out of plane velocity.

Publications

Rock, N., Chterev, I., Smith, T., Ek, H., Emerson, B., Noble, D., Seitzman, J. and Lieuwen, T., 2016, June. Reacting Pressurized Spray Combustor Dynamics: Part 1—Fuel Sensitivities and Blowoff Characterization. In *ASME Turbo Expo 2016: Turbomachinery Technical Conference and Exposition* (pp. V04AT04A021-V04AT04A021). American Society of Mechanical Engineers.

Chterev, I., Rock, N., Ek, H., Smith, T., Emerson, B., Noble, D.R., Mayhew, E., Lee, T., Jiang, N., Roy, S. and Seitzman, J.M., 2016, June. Reacting Pressurized Spray Combustor Dynamics: Part 2—High Speed Planar Measurements. In *ASME Turbo Expo 2016: Turbomachinery Technical Conference and Exposition* (pp. V04AT04A020-V04AT04A020). American Society of Mechanical Engineers.

Outreach Efforts

We are preparing to present a paper at the 2017 AIAA SciTech conference, we are writing a paper for the 2017 ASME Turbo Expo.

Awards

The ASCENT community nominated Nick Rock for the DOT student of the year award, which is currently awaiting judgement.

Student Involvement

- Nick Rock has been actively involved in the Task 1 experimental effort for both years. Nick was the PhD student responsible for operating the experimental facility. He led the screening measurements and operated the facility for the detailed diagnostic efforts, and has also performed the analysis of the screening data.
- Ianko Chterev was also actively involved in both years of the Task 1 experimental effort. His primary responsibility was the design of experimental procedures and support of detailed diagnostic measurements.
- Hanna Eck was involved in the Task 1 effort as a data analysist. Hanna has been responsible for processing and analyzing the large volume of detailed data produced by the PIV, PLIF, and Mie scattering measurements.

Plans for Next Period

The work plan for the third year will reflect progress from the first two years. The work plan begins with detailed analysis of the PIV, spray, and OH PLIF data acquired in year 2, using the lessons learned during year 2 analysis of the year 1 data. This will elucidate the detailed physics that require the intersection of long analysis time (since this activity has begun in year 2) and high quality (i.e. year 2) data. While this type of analysis has been out of the focus of the first two years, it will be critical at the close of the program as the modeling groups try to determine if the dominant physics of their simulations are matching the dominant physics in the rig (such insight serves beyond the end of the program too, as success of the program will launch a train of modeling activity amongst OEMs). Additionally, the year 3 data analysis will incorporate basic processing of the year 3 datasets to produce velocity vector fields and [OH] fields and transmit these to the modelers. The plan will also execute additional detailed diagnostic campaigns, to be designed in close collaboration with Tonghun Lee, UTRC, Area 4, and OEMs. Finally, the work plan will include additional screening as needed by the program. Screening conditions will be selected from program-wide collaboration, particularly with the OEMs, Area 1, AFRL, and Area 6. Collaboration with Area 6 will ensure overlap at one or more nominal pressure and temperature conditions (as in year 1), while leveraging their sub-atmospheric/low temperature capability and our high pressure/high temperature capability to search for coupled fuel/pressure/temperature trends. For example, between the two teams, we can perform screening over a broad range of pressures to confidently answer the question: "How does pressure couple with fuel composition to influence flame shape and blowoff?" While the key figure of merit and primary focus of this task is blowoff, the detailed diagnostics will help complement the blowoff work by studying fuel effects on flame shape over a range of pressures, as flame shape has important influences on combustor operational characteristics. This type of flame shape screening has only recently become a possibility with the year 2 discovery of a new flame shape at higher preheat temperatures.

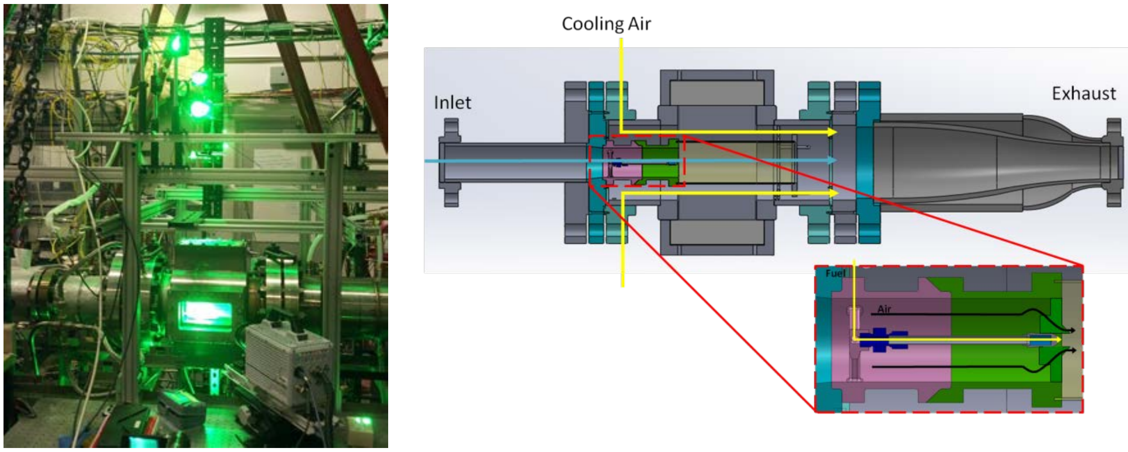

Figure 5. High shear swirl combustor, showing a) pressure vessel instrumented for high speed stereo PIV and OH PLIF, and b) a cross section with generic swirler holder/injector for illustrative purposes

Task 2. Ignition

Georgia Institute of Technology

Objective(s)

This task has two objectives. These objectives focus on the ignition figure of merit in an atmospheric pressure, preheated, pre-vaporized, liquid fueled rig. The rig simulates the ignition environment of an aircraft combustor by implementing an OEM igniter and by establishing an air film flow that separates the igniter from the flammable mixture. The first objective is to measure and demonstrate the sensitivity of the ignition probability to fuel composition, for a range of conventional jet fuels as well as fuels with varying physical and kinetic properties. The second objective is to measure detailed data that could be used by modelers in subsequent years of the program. A third, tangential objective of this task is to elucidate the fundamental physics that drive the observed fuel sensitivities.

Research Approach

The second year of the ignition task has been divided into three focus areas: screening studies for ignition of prevaporized fuels, reduced-order modeling of prevaporized ignition to examine fuel effects, and development of expanded capabilities for ignititon of two-phase (non-prevaporized) flow. The prevaporized experiments focused on ignition probability measurements of the down selected fuels: A-2, C-1, and C-5, and blends of these three parent fuels. These prevaporized experiments entail preheating of the test facility with 480K air flow and prevaporizing fuel into a 470K carrier air stream that is then injected into upper (fueled) flow of the stratified facility.

The goal of these experiments continues to be evaluation of fuel chemistry influence on the forced ignition process in a realistic non-premixed configuration, with the additional question in year two of the effect of fuel blending compared to neat fuels. The first tests in year 2 examined the neat fuels, looking at repeatability – including comparisons to results from year 1. Example results show good day-to-day repeatability (Figure 6a), and contain the previously observed trend of increasing ignition probability with increasing equivalence ratio. However, the magnitude of the ignition probability for all the fuels is lower than the results found in year 1 (Figure 6b). Because the relative ignition probability of the C3 and C1 fuels is nearly the same for both data sets (~3 at an equivalence ratio of 0.76), the hypothesis for this difference is either aging of the igniter or changes in the fuel distribution and uniformity within the flow; these possibilities are currently being examined. Preliminary results from the fuel blends have been acquired, and additional data will be acquired.

Numerical efforts have also continued for gaseous phase simulations to develop a reduced-order model for the entraining kernel. Ignition development simulations were conducted using chemical mechanisms developed and provided by Area 2 (Stanford). Ignition kernel evolution with A-2 fuel chemistry compared to C-1 chemistry has shown contradictory trends to experimental ranking of the ignition probability performance. Up to this point, Area 2 chemistry models have been validated by experimental autoignition results provided by Area 1. The important chemical pathways involved in these autoignition experiments may differ from forced ignition, and could be the cause of some evolutionary characteristic. Specifically, flame chemistry in forced ignition occurs at much hotter temperatures (>4000K) and at leaner conditions than those tested in the autoignition experiments. This has led to discussion with Area 2 on the development of the chemical models and what modificaitons may need to be implemented for forced ignition modeling.

Finally in year 2, we have designed, fabricated and made preliminary tests of a liquid spray modification to the facility, and designed a fuel chilling system to achieve fuel temperature down to approximately -30°C. The fuel is cooled by passing it through a simple immersion heat exchanger placed in a phase change bath to provide temperature control and an expendable heat sink. The heat transfer bath fluid is a propylene-glycol solution, with a freezing point tuned to achieve the desired liquid fuel temperature, and the bath is cooled by a replaceable dry ice pack.

Adaptation of the numerical model (Figure 8a) to incorporate two phase physics is also part of the effort in year two. The gaseous reactor model relies on a perfectly stirred reactor set of physics, coupled with an air plasma chemical mechanism for the initial unfueled reactions and the appropriate fuel chemical mechanism for the kernel-fuel interaction. The addition of a new liquid droplet sub-model (Figure 8b) to the reactor network serves as the gaseous fuel source term. Additionally, the evaporation of the fuel transfers thermal energy away from the kernel. This work continues to be developed and will lead to simulations that incorporate the different chemical mechanisms provided by Area 2 and the physical fuel properties supplied by the program.

Milestone(s)

- **Rig modification completion.** This milestone was completed early in the year when we began testing liquid sprays.
- **Post-process year 2 detailed data.** This has been completed.
- **Ignition measurement data.** This has been completed for several fuels, and is under way for additional fuels that the program has asked us to test.
- **Final data analysis.** This is underway as new data become available.
- **Final data archiving.** Data are uploaded to the KSN as they become available and are processed.

Major Accomplishments

This task has produced three major accomplishments, which are detailed here.

- The first major accomplishment is extension of the fuel screening ignition dataset. This extension includes repeatability data (see example in Figure 6) as well as new tests with liquid spray.
- High speed OH PLIF imaging (see example sequence in Figure 7) has been performed to help visualize the time-resolved physics of the evolving ignition kernel and eventual propagating flame front.
- The reduced order ignition model has been further developed (shown in Figure 8), and has helped inform the chemical kinetics modeling team as well as elucidate some of the fuel sensitivities observed in ignition.

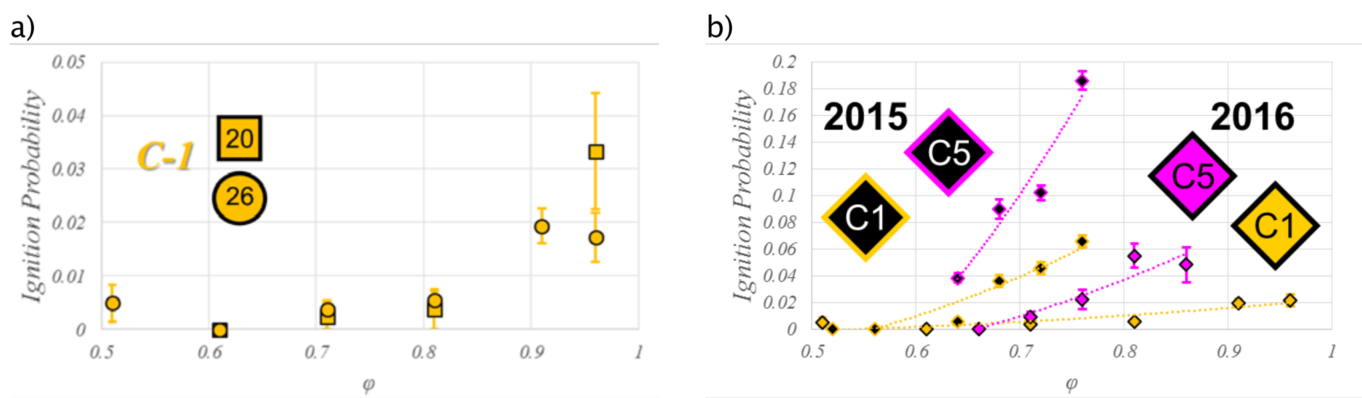

Figure 6. Example of repeatability results for forced ignition testing of igntion, showing a) day-to-day repeatability for current tests (numbers correspond to the day of the month they were taken), and b) repeatability check between 2015 and 2016 data

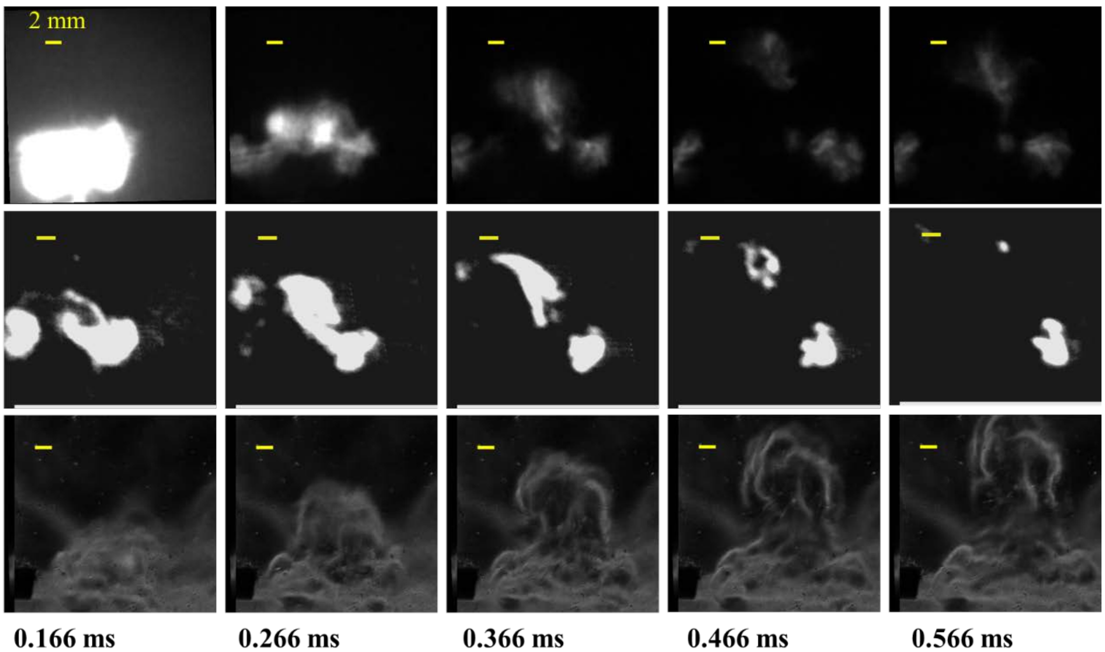

Figure 7. Top row) emission imaging, middle row) OH PLIF imaging, bottom row) Shclieren imaging of an evolving ignition kernel.

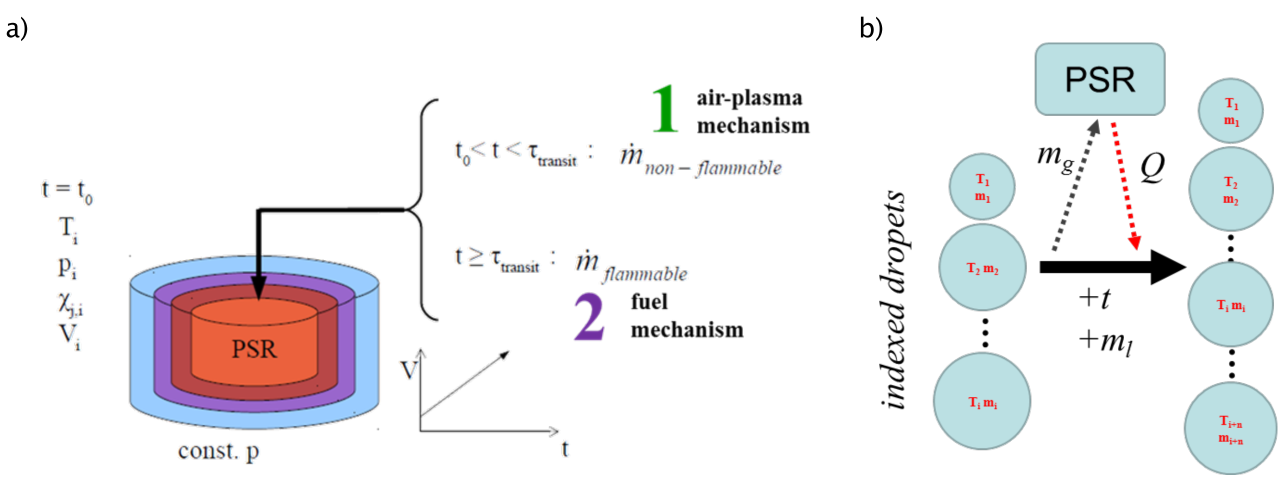

Figure 8. Reduced order ignition model development, showing a) the conceptual model, comprised of a perfectly stirred reactor growing in volume at constant pressure as mass is added, operating on a 1-air plasma chemical mechanism and then 2-a fuel mechanism, and c) the droplet evaporation sub-model which will include two-phase physics into the numerical scheme.

Publications

Sforzo, B., Dao, H., Wei, S. and Seitzman, J., 2017. Liquid Fuel Composition Effects on Forced, Nonpremixed Ignition. *Journal of Engineering for Gas Turbines and Power*, *139*(3), p.031509.

Outreach Efforts
We presented a poster at the UTSR workshop, and we are writing one conference paper to be presented at the ASME Turbo Expo 2017 conference.

Awards
None

Student Involvement
- Hong Dao was actively involved in the Task 2 experimental effort, prior to graduating in May 2015. Hoang was the student responsible for adapting the ignition facility for vaporized jet fuel and collecting ignition probability measurements.
- Sheng Wei has been actively involved in the Task 2 detailed diagnostic effort. Sheng supported the ignition probability measurement collection and was the primary student responsible in collecting schlieren and chemiliuminescence data. Sheng is also the lead student involved in modeling efforts.
- Edwin Goh has been actively involved in the Task 2 modeling efforts. Edwin has been responsible for adapting the model code to accommodate the jet fuel mechanisms and has collected and analyzed the majority of sensitivity studies
- Hee Yong "Bill" Jeon has been involved in the Task 2 modeling effort. Bill has supported the execution of many simulations for sensitivity studies and aided in reduction of the resulting data.

Plans for Next Period
The objectives of this task are threefold. First, the ignition task aims to measure the spark ignition probability of various fuels under experimentally repeatable, engine-relevant, and readily modellable conditions. Secondly, this task will provide detailed data that can help elucidate the physical mechanisms behind (successful) forced ignition. Thirdly, this task aims to continue the past two years of ignition model development (see Figure 8) which offers an additional capability that can predict fuel sensitivities; this objective is closely coupled to detailed experimental measurements. The benefits of this task are: it can quickly determine the forced ignition response over a wide range of conditions and fuels; it can clearly demonstrate fuel sensitivities; it provides feedback to Areas 1 and 2 to enhance the development of relevant jet fuel chemical kinetic mechanisms; and it provides controlled measurements in a facility amenable to modelling.

1.1.1.1 Analysis of detailed diagnostics on pre-vaporized ignition data and 2-phase (year 2) data, including 2-phase model comparisons

Similar to the blowoff task, the ignition task has gathered large quantities (several terabytes) of experimental data in year 1 and 2 with additional measurements planned for the remainder of year 2. Specifically, detailed diagnostics campaigns conducted during year 2 obtained high speed OH PLIF, chemiluminescence, and schlieren measurements which provide vast information about the spatial and temporal evolution of flame chemistry initiation with respect to the ignition kernel. As improved or additional chemical kinetics models become available from Area 2, the experimental results will also be compared to the results of the reduced order modeling to provide evaluation of the mechanisms' ability to capture fuel effects. In addition, this data base will allow OEM's to pursue ignition modeling even beyond the scope of this program.

1.1.1.2 Continuation of detailed measurements of liquid spray ignition and detailed characterization at targeted conditions

Two-phase screening measurements have been conducted during Q4 of year 2. The ignition probability measurements from these experiments will help differentiate the ignition performance sensitivity to physical fuel effects versus fuel chemistry effects. This information will help modelers incorporate the appropriate influences on forced ignition prediction. Furthermore, comparisons between two-phase experiments and results from the two-phase reduced-order model will help elucidate these effects. The year 3 measurements will include low temperature fuel studies using the liquid chilling device developed in year 2. These measurements are important to provide a reference for some of the detrimental effects associated with cold starts and high altitude relight. In addition, year 3 will include detailed diagnostics of the liquid spray ignition events at select conditions. This characterization is important to (future) CFD simulations in order to match boundary conditions to the properties in the combustor for these cold liquid experiments.

1.1.1.3 Liquid spray ignition model comparisons

Similar to the prevaporized work, the spray ignition results will be compared to the results of the reduced order model to provide evaluation of the mechanisms' ability to capture fuel effects and to better understand the effect of fuel physical properties on ignition success. If successful, this reduced order model may be incorporated (possibly as a post-processing option) into OEM CFD models.

1.1.1.4 Fuel aging effects and performance retention screening

Nominally identical fuels delivered in years 1 and 2 will be retested to study of the effects of fuel aging . There have been recommendations that the jet fuel is compositionally stable under ideal storage conditions, though degradation of fuels may be highly dependent on the base compositions of those fuels. Characterizing the performance retention of these fuels can be an important deciding factor if the fuel composition is highly influential.

1.1.1.5 Screening of any new/additional fuels or blends of interest

Just like for the blowoff task, fuel screening is anticipated to be a lower priority activity in the third year than in the first two years. However, the ignition team will accommodate additional screening at new conditions, with new fuels, or at repeat conditions as needed by the program. One likely source for additional screening needs that may arise during year 3 is the fuel-X endeavor. This endeavor may require a larger database of ignition probabilities for fuel blends, in order to test the robustness of (or potentially refine) the blending rules developed during year 2.

Citations

[4] Rosfjord, T., and Cohen, J., 1990, "Air and Spray Patterns Produced by Gas Turbine High-Shear Nozzle/Swirler Assemblies," AIAA 90-0465.
[5] Li, X., Soteriou, M. C., Kim, W., and Cohen, J. M., 2014, "High Fidelity Simulation of the Spray Generated by a Realistic Swirling Flow Injector," Journal of Engineering for Gas Turbines and Power.
[6] Sforzo, B., Kim, J., Jagoda, J., and Seitzman, J., 2014a, "Ignition Probability in a Stratified Turbulent Flow with a Sunken Fire Igniter," GT2014-26667, Proceedings of the ASME/IGTI Turbo Expo.
[7] Chen, Z., and Ju, Y., 2007, "Theoretical Analysis of the Evolution from Ignition Kernel to Flame Ball and Planar Flame," Combustion Theory and Modeling, 11, pp. 427-453.

Task 3. Turbulent Flame Speed
Oregon State University

Objective(s)
This task has three objectives. The first objective is to measure and identify the sensitivity of the turbulent flame speed to fuel composition, for a range of conventional and jet-like fuels at both atmospheric and subatmospheric conditions. The second objective is to build a database of turbulent flame speeds for pre-vaporized jet fuels. A third, tangential objective of this task is to elucidate the fundamental physics that control the observed fuel sensitivities.

Research Approach

Methodology
Turbulent flames are generated using a vaporizer and burner based on designs developed by the Air Force Research Lab and Lieuwen and colleagues. The experimental setup consists of fuel and air metering systems that deliver jet fuel and air to the burner. Fuel is vaporized using a series of heaters, and elevated to a temperature near 200 ºC. The air/fuel mixture is flowed through an adjustable turbulent generator which generates turbulent fluctuations ranging from 10 to 20% of the bulk flow velocity. Turbulence intensity (TI) is independent of bulk flow velocity. A premixed methane pilot flame is used for ignition and to stabilize the Bunsen burner flame.
Data is collected for each jet fuel variant (A2, C1 and C5) over $5{,}000 \leq Re \leq 10{,}000$, $0.75 \leq \Phi \leq 1.0$, and $10\% \leq TI \leq 20\%$. Measurements are taken using a 16-bit intensified charge-coupled device (ICCD) camera with a 1024 x 1024 pixel resolution and a 25 mm, f/4.0, UV camera lens. For each flow condition (Re, Φ, TI), data is collected over a 3 minute period at 2 Hz.

Measurements of turbulent flame speeds at subatmospheric conditions have been enabled by designing and building a pressure vessel with a vacuums system. Figure 12 shows a picture of a representative flame burning in the vessel at subatmospheric conditions. The vessel can currently operate down to 0.6 atm, although lower pressures are anticipated in the future.

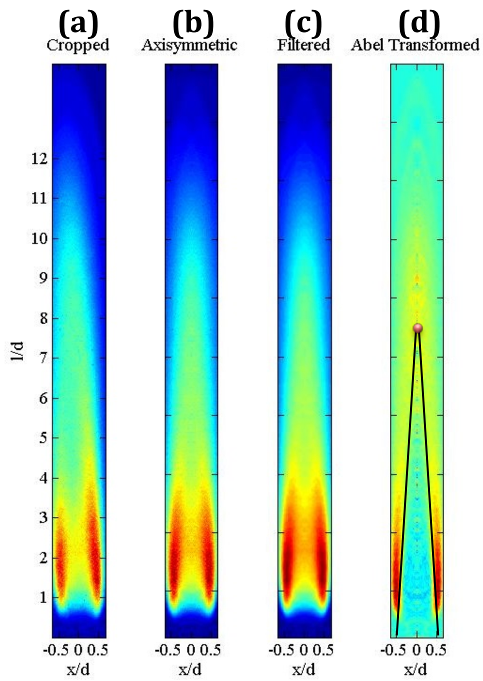

Figure 9. Step-by-step summary of image processing approach:(a) time-averaged, background subtracted and cropped (b) Axisymmetric (c) 2-D median filtered (d) Abel transform with ⟨c⟩=0.5 contour drawn.

Data Analysis
Image processing to determine the average flame sheet from the measurements was completed using the technique developed by Venkateswaran et al. and is summarized here. The line-of-sight images are time-averaged, the background is subtracted, and the image is cropped to include only the flame. The image is then checked for axis-symmetry, straightened, and filtered using a 2-D median filter with a kernel less than 2% of the burner diameter, as seen in Figure 9 (b) and (c). A 3 point Abel deconvolution is applied and the resulting axial distribution of the centerline intensity is fit to a Gaussian curve. The maximum intensity location is determined. This allows the leading edge of the time averaged flame-brush to be determined. This point is the most probable location of the flame brush, and is defined as the $\langle c \rangle = 0.5$ progress variable contour and corresponds to the location of maximum intensity, see Figure 9 (d). The estimated uncertainty in this process is 1%-2% [1].

Milestone(s)
- Pressure vessel and vacuum system designed and built to enable testing at subatmospheric conditions.
- Measurements of turbulent flame speeds at subatmospheric conditions.

Major Accomplishments

This task has produced two major accomplishments, which are detailed here.

- Additional turbulent flame (consumption) speeds have been measured at atmospheric conditions, with detailed measurements collected for three fuels at varying Reynolds numbers, equivalence ratios, and turbulence conditions. These are some of the only such data in the world reported for these types of fuels. Figure 10 shows representative data at two turbulence conditions. The legend for the data shown in Figure 10 is reported in Figure 11.
- A pressure vessel and vacuum system have been designed, built, and evaluated for operating the Bunsen burner at subatmospheric conditions. Data has been collected for the A2 and C1 fuels at 1 and 0.6 atm. Data collected at the two pressure conditions is reported in Figure 13.

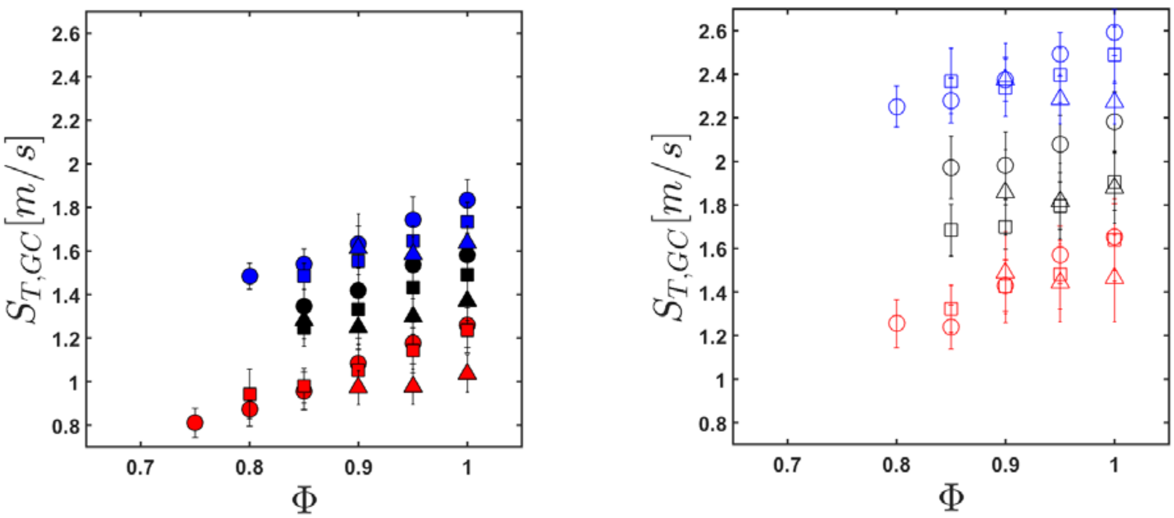

Figure 10. Sample turbulent flame speed data at atmospheric conditions for low (left panel) and high (right panel) turbulence conditions.

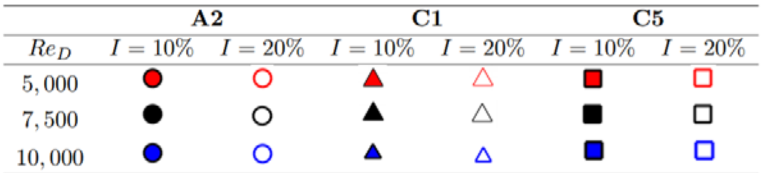

Figure 11. Legend for data shown in Figure 10.

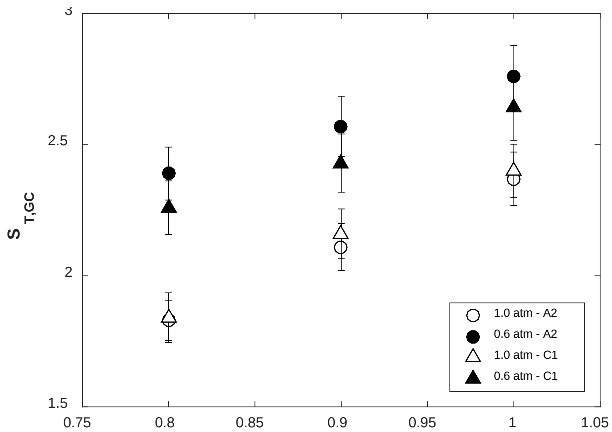

Figure 13. Turbulent consumption speed of C1 and A2 fuels at 1 and 0.6 atm.

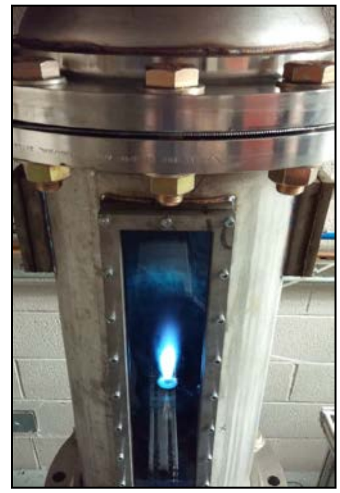

Figure 12. Picture of flame operating in pressure vessel at subatmospheric conditions.

Publications

Fillo, Aaron, M.S., Thesis, “The Global Consumption Speeds of Premixed Large- Hydrocarbon Fuel/Air Turbulent Bunsen Flames,” Oregon State University.

Plans exists for a peer-reviewed manuscript and multiple conference publications at the US Combustion Meeting in the Spring of 2017.

Outreach Efforts

None

Awards

None

Student Involvement

- Jonathan Bonebrake, a PhD student, has primarily lead efforts to collect and analyze data. He also designed and built the subatmospheric pressure vessel and vacuum system.
- Aaron Fillo, a PhD student, has worked tangentially on this project to analyze results and further investigate scientific phenomena.
- Nathan Schorn, a MS student, has recently started and has transitioned to leading the effort to operate the burner and collect and analyze data.
- Multiple undergraduate students, including underrepresented students have worked with the graduate students to operate the burner and collect data. This has provided a significant opportunity for the students to experience research.

Plans for Next Period

For the third year of this program, we will expand our database of turbulent flame speed measurements at atmospheric and subatmospheric conditions. Moreover, we will collect data for other fuels including a surrogate and fuel-X, as time permits. In addition, we will seek to understand how our results can be used to identify fuel sensitivities for lean blowout and ignition. These tasks should help address critical gaps associated with both objectives of the larger program, namely an improved combustor rig evaluation process for ASTM D4054 and validated models for combustor evaluation. The study will leverage existing facilities and infrastructure that were developed and demonstrated in years 1 and 2 of the current effort.

Two benefits can arise from measuring turbulent flame speeds. First, this work can be useful to help identify chemistry effects of jet fuels that should be captured in the modeling efforts of other groups (Area 4) and OEMs. Second, turbulent flame speed measurements may offer a metric for screening the significance of fuel chemistry of alternative fuels.

Citations

1. Venkateswaran, P., Marshall, A., Shin, D. H., Noble, D., Seitzman, J., and Lieuwen, T. "Measurements and Analysis of Turbulent Consumption Speeds of H2/CO Mixtures" *Combustion and Flame* 158, no. 8 (2011):

Diagnostics Task #1. Optimize and apply laser and optical diagnostics for application in the advanced combustion tests at Georgia Institute of Technology

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 $\phi = 0.096$, 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.

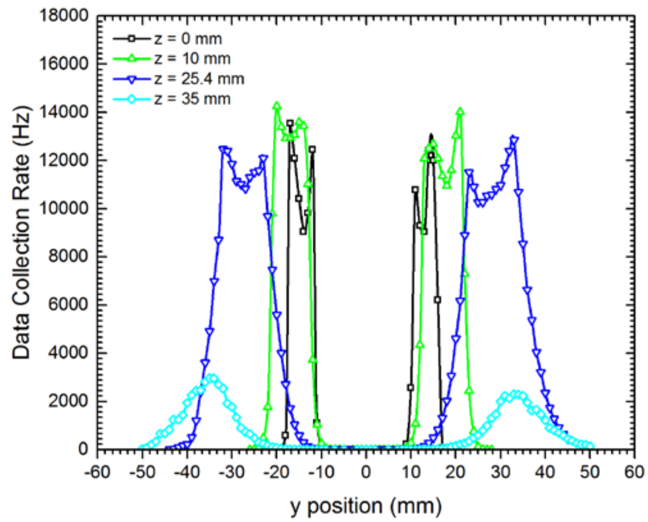

Figure 14. A-2 data collection rate. Data collection rate versus y-position at various axial locations for A-2 at φ=0.096

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, 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, 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.

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and

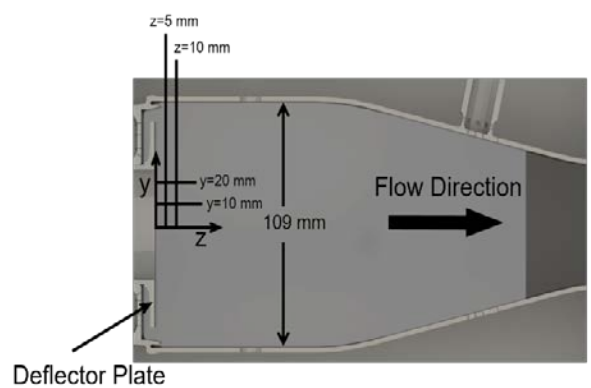


Figure 15. Cutaway of the single cup referee combustor. The origin is taken to be at the intersection of centerline of the combustor with the front plane of the deflector plate as marked.

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

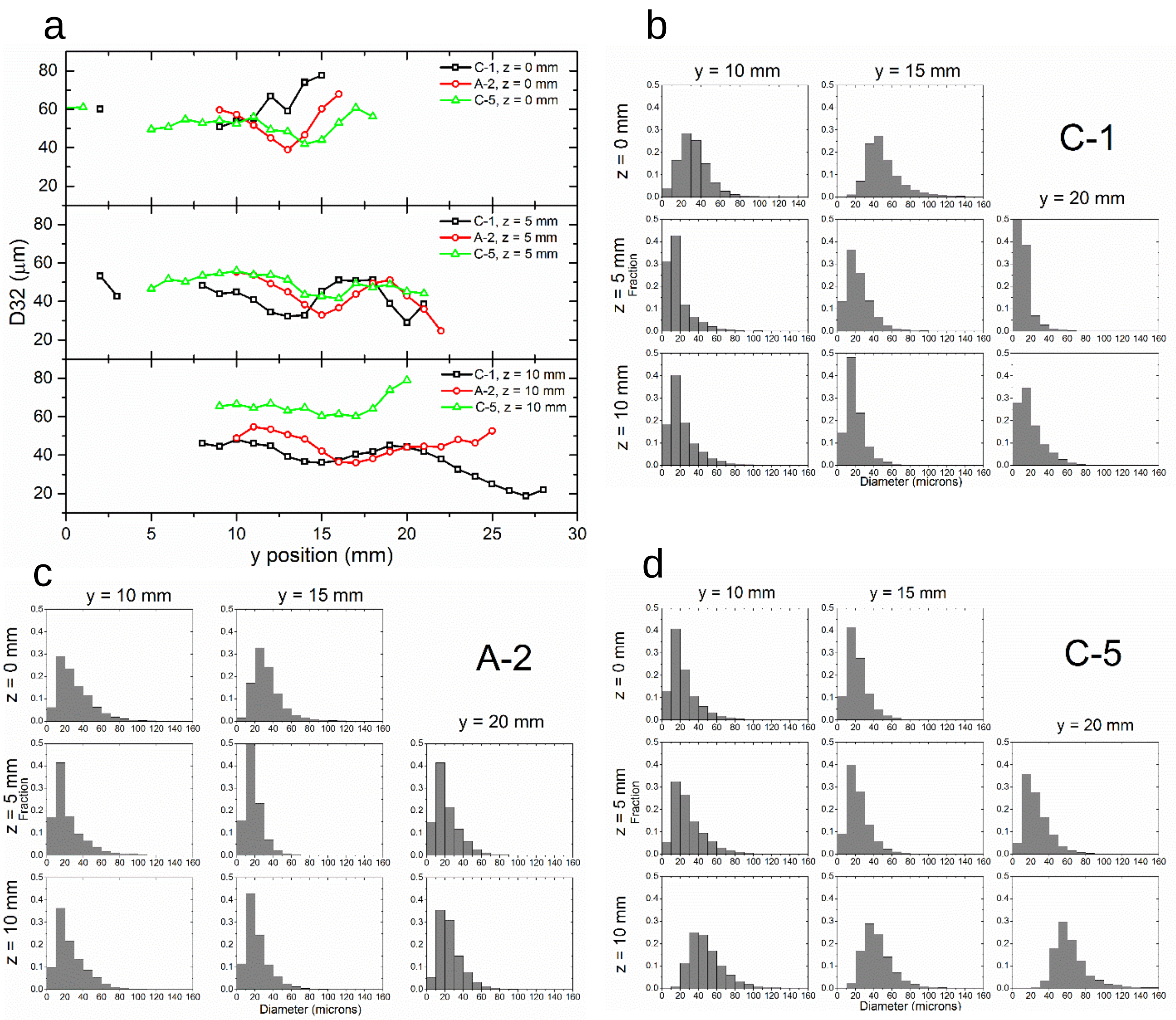


Figure 16. Sauter mean diameter and representative diameter histograms a) Sauter mean diameter plotted versus y position for each fuel 0 mm, 5 mm, and 10 mm downstream of the deflector plate for comparison with b) C1 diameter histograms, c) A2 diameter histograms and d) C5 diameter histograms at y = 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].

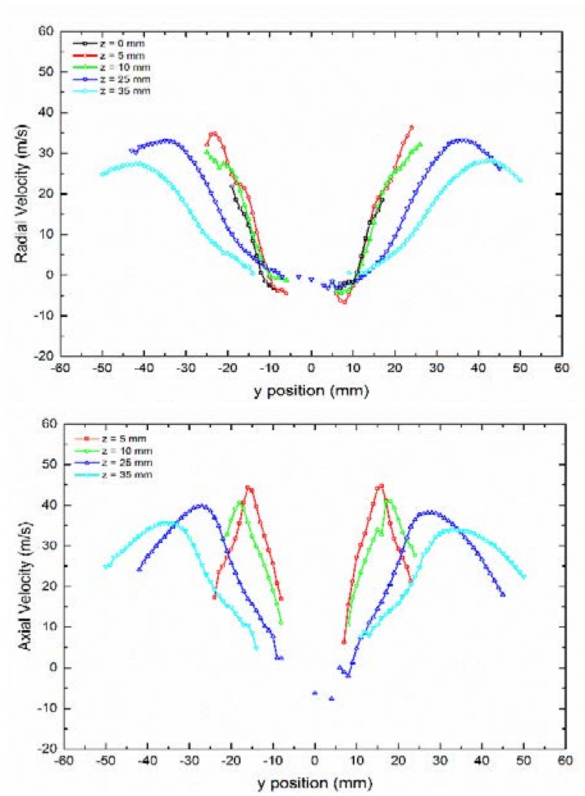


Figure 17. A-2 fuel droplet mean radial and axial velocity. Mean radial velocity plotted against y position (top) and mean axial velocity plotted against y position (bottom) at various distances from the deflector plate

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

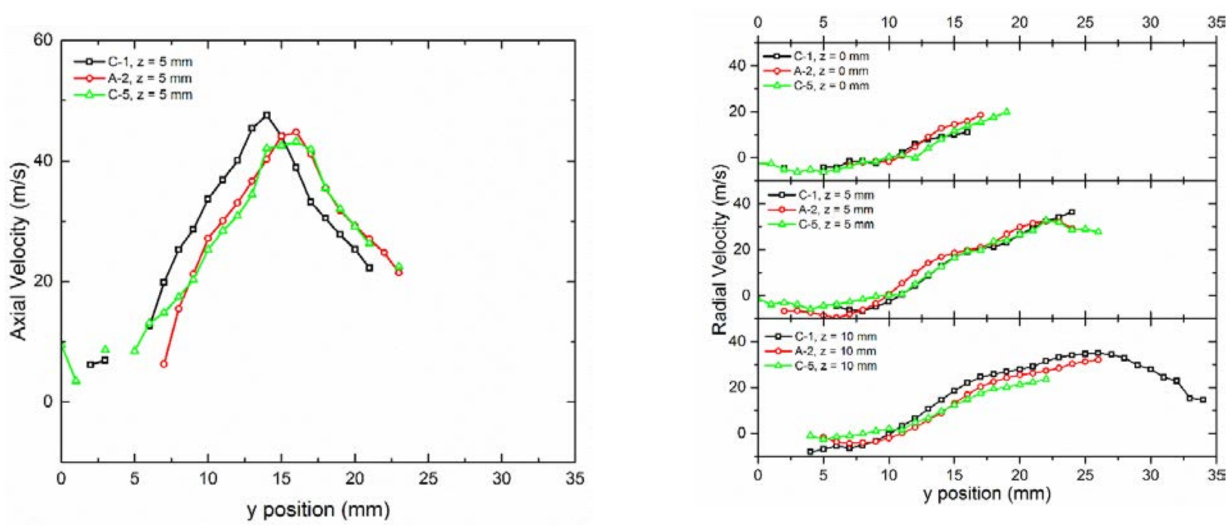


Figure 18. Axial and radial velocity profiles. a) Axial velocity plotted versus y position for each fuel 5 mm downstream of the deflector plate and b) radial velocity plotted as a function of y position at 0 mm, 5 mm, and 10 mm downstream of the deflector plate for each fuel

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

Diagnostics 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.

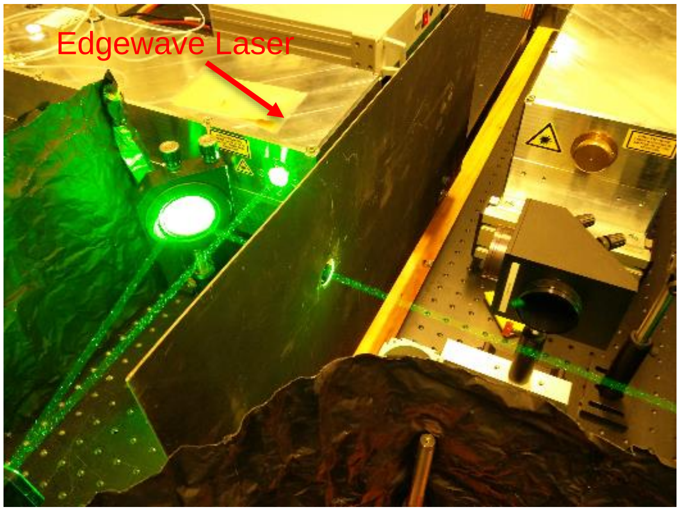
Proposed (12 Month): At the 12 month mark, we should have obtained the swirler and injector and made any modifications to the rig to ensure that they fit into the main body.
Achieved: The swirler and injector have been retrieved from Wright-Patterson Air Force Base. Preparations have been made to transport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



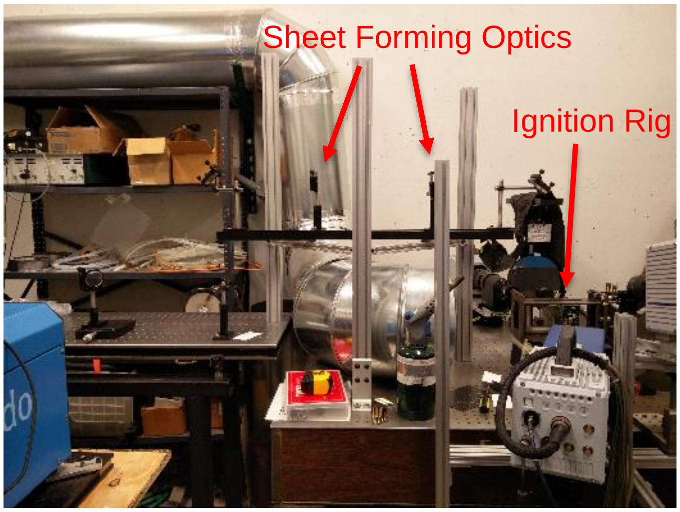
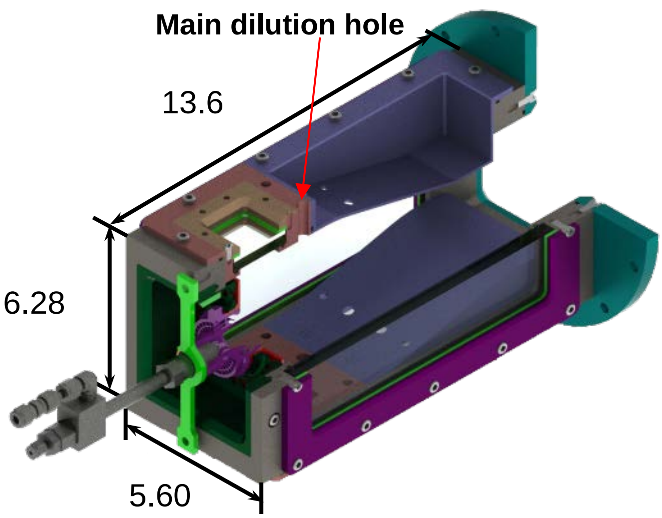


Figure 19. Edgewave pump laser (left) and dye laser with sheet forming optics, and the ignition rig

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.



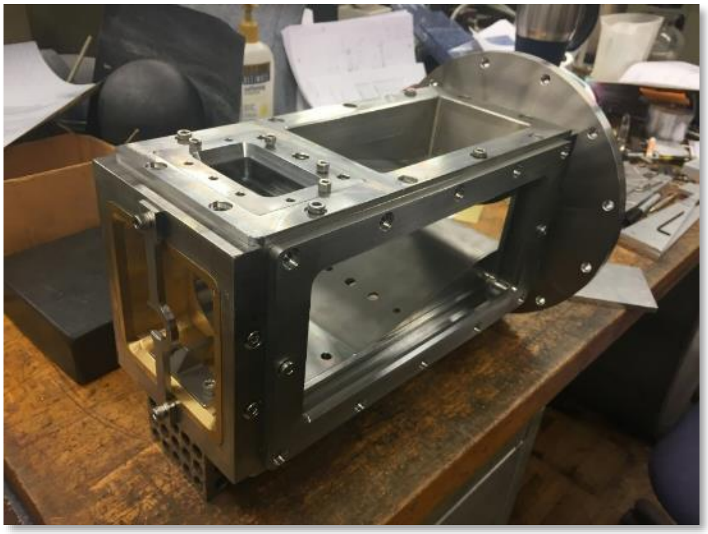


Figure 20. High altitude relight combustor model (left) and completed rig (right). The high altitude relight combustor replicates the key geometry and flow features of the referee rig, including dilution jet hole placement, overall size, swirler geometry, and injector geometry.

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