Project 027B Advanced Combustion (Area #3)

Georgia Institute of Technology
Oregon State University

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: 12/1/2017 to 11/30/2018
- Task(s):
  - Lean Blowout. This task measures the lean blowout characteristics of alternative jet fuels and compares them to the lean blowout characteristics of jet A.
  - Ignition. This task measures the ignition probabilities of alternative jet fuels and compares them to the ignition probabilities of jet A.

Oregon State University

- P.I.(s): David Blunck
- FAA Award Number: 13-C-AJFE-OSU-02
- Period of Performance: 12/1/2017 to 11/30/2018
- Tasks:
  - Turbulent Flame Speed. This task measures the turbulent flame speeds of alternative jet fuels and compares them to the turbulent flame speeds of jet A.

Project Funding Level

Georgia Institute of Technology
FAA Funding: $206,000
Cost Share: $206,000 provided by Georgia Institute of Technology

Oregon State University
FAA Funding: $59,000
Cost Share: $59,000 provided by Oregon State University

Investigation Team

Tim Lieuwen (Georgia Institute of Technology): Principal Investigator. Professor Lieuwen is the PI overseeing all tasks, and is manager of Task 1.
Jerry Seitzman (Georgia Institute of Technology): Co-Principal Investigator. Professor Seitzman is the manager of Task 2.
David Blunck (Oregon State University): Co-Principal Investigator. Professor Blunck is the manager of Task 3.
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 at Urbana-Champaign): Co-Principal Investigator. Professor Lee is the lead diagnostic expert.
Benjamin Emerson (Georgia Institute of Technology): Research Engineer. Dr. Emerson is responsible for designing and maintaining experimental facilities, experimental operations and management & safety of graduate 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, experimental operations and management & safety of graduate students.
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 leading the lean blowout task.
Hanna Ek (Georgia Institute of Technology): Graduate Student. Ms. Ek is the lead data analyst for the lean blowout task.
Sheng Wei (Georgia Institute of Technology): Graduate Student. Mr. Wei currently leads the ignition task.
Jonathan Bonebrake (Oregon State University): Graduate Student. Mr. Bonebrake was the lead grad student experimentalist on the turbulent flame speed task.
Nathan Schorn (Oregon State University): Graduate Student. Mr. Schorn recently started and has transitioned to leading the effort to operate the burner and collect and analyze data
Eric Mayhew (Graduate Student, University of Illinois at Urbana-Champaign): Graduate Student. Mr. Mayhew leads the execution of laser and optical diagnostics at ARFL.

Project Overview

The objective of this project was to provide advanced combustion testing of alternative jet fuels. We performed this advanced combustion testing to accomplish two goals. The first goal was to rank the lean blowout boundaries, ignition probabilities, and turbulent flame speeds of alternative fuels relative to conventional Jet A. The second goal was to produce data that could support the modeling and simulation tasks of other teams. For the second goal, data were measured as needed and as requested by the other teams. These data typically consisted of velocity field measurements, high speed flame images, and test rig boundary conditions.

During this program we tested twenty total fuel mixtures. Sixteen of the fuels have been pure (un-blended) fuels, known to the program as: A1, A2, A3, C1, C2, C3, C4, C5, S1, S2, S3, high TSI, C7, C8, C9, and n-dodecane. The A1, A2, and A3 fuels represent the range of conventional jet-A fuels. The other fuels have different physical and/or chemical properties. We have also tested three different sets of blends: A2/C1 blends, A2/C5 blends, a C1/n-heptane blend, and a C1/n-dodecane blend. These fuels have been tested under three different tasks, which are summarized next and which are detailed in the rest of this report.

(1) The first task consisted of lean blowout (LBO) measurements. The highest priority lean blowout measurement was fuel screening, where the blowout boundaries of various fuels were compared to the blowout boundary of jet A. This task also included measurements of the combustor velocity field, the spatio-temporal evolution of the flame position, and several thermodynamic rig boundary conditions. Thermodynamic boundary conditions included measurements such as air flow rates, surface temperatures, gas temperatures, and gas pressures.

(2) The second task consisted of forced ignition measurements. Like the blowout task, the highest priority forced ignition measurement was fuel screening. In the case of the forced ignition task, the fuel screening activity measured the ignition probabilities of various fuels and compared them to the ignition probability of Jet A. Ignition probability is a common measure of combustor ignitability. It was measured by sparking the igniter hundreds of times and measuring the fraction of spark events that successfully ignited the combustor. This task included a modeling

component which began to develop predictive capability for ignition probability. Such a predictive capability would take combustor conditions (pressure, temperature, and fuel-air ratio), in addition to key fuel properties (vaporization and chemical kinetic properties), as inputs and would produce an ignition probability as the output. To support this modeling effort, the forced ignition task produced measurements of detailed ignition physics. These detailed measurements captured fuel spray images, ignition kernel images, and flame images.

(3): The third task consisted of turbulent flame speed measurements. Like the other two tasks, the high priority measurement was fuel screening. For this task, fuel screening compared the turbulent flame speeds of various fuels to the turbulent flame speed of Jet A. This task additionally had a significant rig development aspect. The rig development added sub-atmospheric pressure capability.

These tasks were designed to address critical needs of the larger program. These needs are the rapid screening of alternative fuels and detailed measurements to support the modeling teams. The rest of this report details the specific activities that have been conducted under each of these tasks to address these important needs.

Task 1- Lean Blowout

Performance site: Georgia Institute of Technology

Objective(s)

The objective of this task was to obtain two types of measurements-fuel screening and detailed diagnostics- in a combustor rig operating near lean blowout. The objective of the fuel screening was to rank the blowout boundaries of each fuel relative to the blowout boundary of jet-A. The objective of the detailed diagnostics was to produce data that could support the modeling teams by providing physical insight and important simulation boundary conditions.

Research Approach

This task was performed with the combustor rig, shown in Figure 1. The rig is a high pressure, swirl-stabilized spray combustor with OEM-relevant hardware. The combustor was configured similarly to the referee rig at the Air Force Research Lab. The difference between the Georgia Tech rig and the referee rig is their dome and liner cooling arrangements. The referee rig has a greater level of complexity of these components, providing a closer simulation of a real combustor. However, the reduced complexity of the Georgia Tech rig enabled a greater rate of data generation. The reduced complexity of the Georgia Tech rig also enabled laser-based diagnostics that were not possible in the referee rig.

The research approach consisted of four major activities. The first of these activities was to collaboratively select the test conditions. This activity was conducted through the LBO working group. Thus, test condition selection included input from the OEMS and other stakeholders such as the referee rig team and the modeling teams. Together, the teams selected one combustor pressure and three air preheat temperatures for lean blowout testing. These were designed to simulate idle and altitude conditions where lean blowout poses the greatest risk. The selected combustor pressure was 3 atmospheres and the selected air preheat temperatures were 300 K, 450 K, and 550 K.

The second activity was to acquire screening data. This was accomplished by outfitting the combustor test rig with an advanced fuel cart. The fuel cart had ten different fuel tanks, each of which could hold a different fuel. The cart could rapidly switch between these fuels, which enabled the lean blowout testing of ten different fuels in a single sitting. The testing of many fuels in one sitting was advantageous because it promoted repeatability by eliminating the potential for uncontrolled variations in test conditions between test days. Fuel screening was conducted by igniting the combustor and intentionally leaning it to the lean blowout limit. Conditions where the combustor blew out were recorded, and the process was repeated until the first fuel tank was empty. This repetition process typically produced 20-30 blowout points for a single fuel. This was then repeated for the fuels in the other nine tanks.

The third activity was detailed data acquisition. This activity produced data to support the modeling groups, and it also produced data to improve the program's understanding of the physics of lean blowout. In support of the modeling groups, the lean blowout team performed detailed laser-based measurements. These measurements were delivered to the modeling groups to help them refine and validate their simulations. The measurements incorporated several different laser-based techniques that were synchronized together at 5,000 frames per second. These diagnostics included:

- Stereoscopic particle image velocimetry (s-PIV) to obtain planar measurements of the three-component velocity field
- Planar laser-induced fluorescence of the OH molecule (OH PLIF) to obtain measurements of the flame position

- Planar laser-induced fluorescence of the liquid fuel (fuel PLIF) to obtain measurements of the liquid fuel spray location

The third activity also produced high speed chemiluminescence images. These measurements were easier to perform and analyze than the laser-based diagnostics outlined above. Therefore, the advantage of the chemiluminescence imaging was that it was faster to implement. Because it was faster to implement, it was applied for more fuels and test conditions than the laser-based techniques. The chemiluminescence images helped reveal the qualitative burning characteristics near lean blowout. The chemiluminescence images also produced data to help the program determine the roles of ignition and extinction in the lean blowout process. National Jet Fuel Combustion Program Area 3 and Area 7 have both been analyzing these data to try to make such a determination. In addition to these optical measurements, the third activity also produced measurements of combustor boundary conditions. The measured boundary conditions included air flow rates, air and fuel temperatures, combustor pressure, and surface temperatures.

The fourth activity was data analysis. This activity was very important because it converted the raw measured data into useful data. In the case of screening data, analysis was performed on the combustor operational data to identify lean blowout events and their associated operating points. Analysis of screening data also included uncertainty analysis. The uncertainty analysis was necessary to determine the statistical significance of the results, and in some cases it motivated the lean blowout group to take additional data in order to tighten the uncertainty. In the case of detailed data, analysis was performed in two steps: pre-processing and post-processing. Pre-processing was applied to the velocity field measurements, and consisted of an intensive cross-correlation algorithm to convert raw images into velocity fields. This was extremely time consuming and was the most difficult data analysis step. Post-processing was conducted to produce the time-averaged velocity field, to produce the rms velocity field, and to extract key vortical flow features. These post-processed data were the deliverable to the modeling teams.

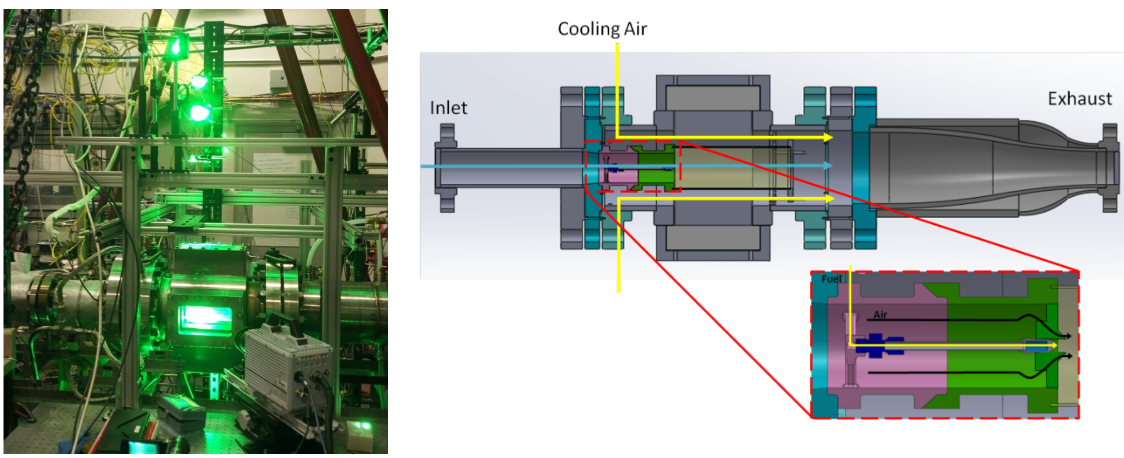

Figure 1. High shear swirl combustor, showing a) pressure vessel instrumented for high speed stereo PIV and OH PLIF, and b) a cross section with generic swirler holder/injector for illustrative purposes

Milestone(s)

1. Boundary condition measurements. All requested boundary condition measurements have been produced and delivered to modeling teams.
2. Detailed diagnostic measurements. All detailed diagnostic imaging that was planned for year 4 has been completed and is currently being analyzed to extract physical insight.
3. Screening data. This has been completed for all planned cases in year 4 and is being analyzed and has been disseminated to all project participants.
4. Analysis. Substantial data analysis has been completed this year and has delivered insight into the importance of the cetane number as well as the dynamics of lean blowout. These findings have been presented at the mid-year and monthly meetings.

Major Accomplishments

1. To date, we have expanded our screening dataset which consists of several thousand lean blowout measurements. We have added data for three new fuels in year 4: S3, C-1/n-heptane, and C-1/n-dodecane.
2. We have shown supporting evidence of the preferential vaporization theory that has been hypothesized to this program by Sang Hee Won of the University of South Carolina.
3. We have further demonstrated that the cetane number nicely captures the lean blowout risk of a given fuel (see Figure 2), especially at higher temperatures.
4. During year 4 we have characterized the intermittent burning stage that we identified during year 3. Identification of the intermittent burning stage provides an important qualitative picture for blowout simulations (see
5. Figure 3 for a sample chemiluminescence image from this diagnostic). Characterization of this phenomenon provides quantitative statistics that could be used for assessment of models and simulations. An example of these statistics is presented in
6. Figure 4, which shows distributions of flame leading point velocity. The leading point velocity is a physically relevant flame feature which is easily extracted from both experimental and CFD data.

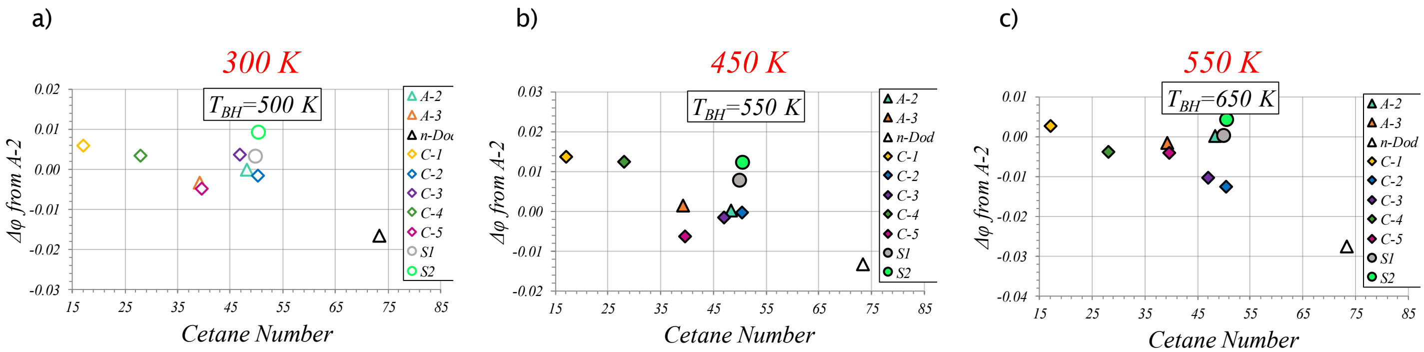

Figure 2. Sample of year 3 screening data at three different preheat temperatures and three different bulkhead temperatures, demonstrating the strong correlation of lean blowout with the cetane number

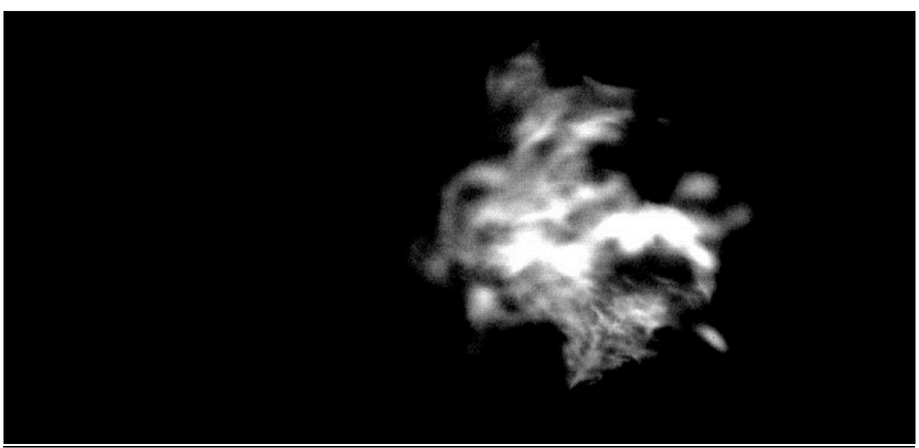

Figure 3. Sample flame chemiluminescence image from n-dodecane burning at 300 K air preheat temperature.

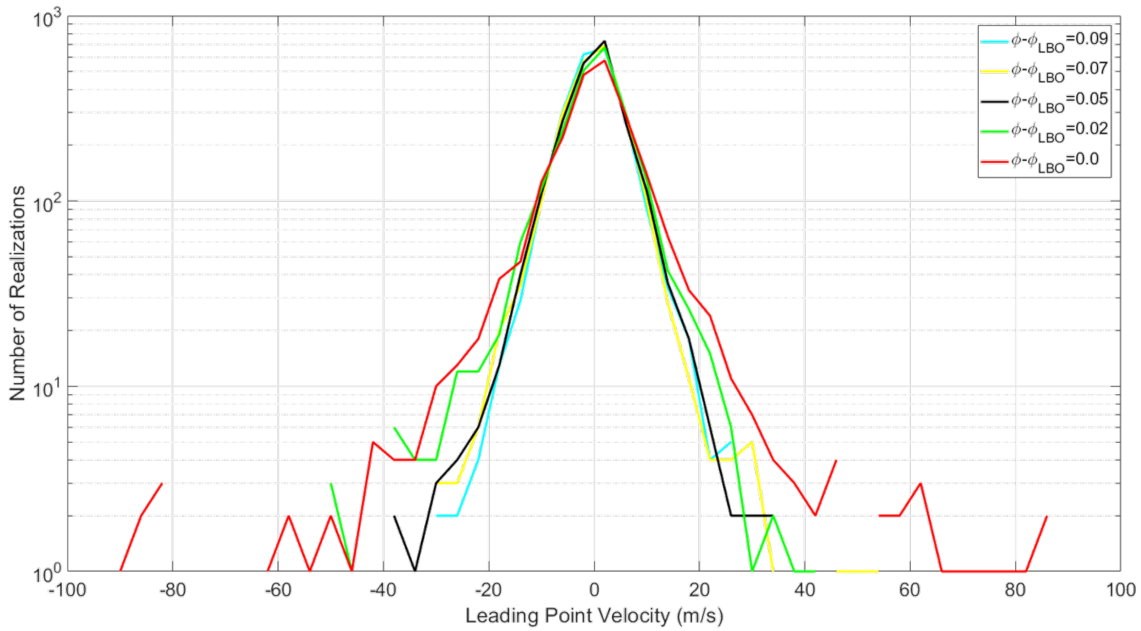

Figure 4. Flame leading point velocity statistics at five different equivalence ratios

Publications

Chterev, I., Rock, N., Ek, H., Emerson, B.L., Seitzman, J.M., Lieuwen, T.C., Noble, D.R., Mayhew, E. and Lee, T., 2017. Simultaneous High Speed (5 kHz) Fuel-PLIE, OH-PLIF and Stereo PIV Imaging of Pressurized Swirl-Stabilized Flames using Liquid Fuels. In 55th AIAA Aerospace Sciences Meeting (p. 0152).

Chterev, I., Rock, N., Ek, H., Emerson B., Seitzman J., Jiang, N., Roy, S., Lee, T., Gord, T., and Lieuwen, T. 2017. Simultaneous Imaging of Fuel, OH, and Three Component Velocity Fields in High Pressure, Liquid Fueled, Swirl Stabilized Flames at 5 kHz. Combustion and Flame. 186, pp. 150-165.

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.

Ek H., Chterev I., Rock N., Emerson B., Seitzman J., Jiang N., Proscia W., Lieuwen T., Feature Extraction from Time Resolved Reacting Flow Data Sets, Proceedings of the ASME Turbo Expo, Paper #GT2018-77051, 2018.

Emerson, B., and Ozogul, H. 2018. Experimental Characterization of Liquid-gas Slip in High Pressure, Swirl Stabilized, Liquid-fueled Combustors, in Western States Section of the Combustion Institute – Spring 2018 Meeting.

Rock, N., Chterev, I., Emerson, B., Seitzman, J. and Lieuwen, T., 2017, June. Blowout Sensitivities in a Liquid Fueled Combustor: Fuel Composition and Preheat Temperature Effects. In ASME Turbo Expo 2017: Turbomachinery Technical Conference and Exposition (pp. V04AT04A022-V04AT04A022). American Society of Mechanical Engineers.

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.

Outreach Efforts
We have provided research opportunities to undergraduate students and a high school student with this program. We have submitted a paper for the 2019 AIAA Scitech conference which will give a graduate student the opportunity to attend the conference.

Awards
Graduate student Nick Rock was awarded ASCENT student of the year in April 2017.

Student Involvement
- Nick Rock has been actively involved in the lean blowout experimental effort for all 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.
- Hanna Ek was involved in the lean blowout 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.
- Ianko Chterev was also actively involved in the lean blowout experimental effort. His primary responsibility was the design of experimental procedures and support of detailed diagnostic measurements. Ianko has now graduated with his Ph.D.

Plans for Next Period
Three activities have been planned for the next period and are related to the close of the program. The activities are:

- Support the LBO chapter of the AIAA book that is being produced from this program.
- Complete the data analysis activity that characterizes flame leading point velocity statistics.
- Use the screening data from year 4 to assess the preferential vaporization hypothesis from the University of South Carolina.

These three activities will require no new measurements. The first task will compile the data and the results from the first four years of the program into part of the blowout chapter of the AIAA alternative fuels book. In addition, this activity will detail the experimental facility and test procedures for the book chapter.

The second activity will complete the analysis of flame leading point velocity statistics. This is a promising data analysis technique which could use experimental data to help validate models and simulations. It also provides additional physical insight into fuel effects. The methodology to produce these statistics from experimental data is still under development at the end of year 4, and will be completed during year 5.

The third activity will use screening data from year 4 to assess the preferential vaporization hypothesis. This hypothesis entered late in the program, and could explain some of the scatter in the test data that is observed across all experimental teams. Georgia Tech produced blowout data for three new fuels during the fourth year: S3, C-1/n-heptane, and C-1/n-dodecane. These fuels were selected for their unique preferential vaporization characteristics. Therefore, the fifth year will examine these test data in order to further support (or bust) the preferential vaporization hypothesis.

Task 2- Ignition
Performance site: Georgia Institute of Technology

Objective(s)
There were four objectives for this year's ignition task.

1. Expand the database of room temperature ignition probability measurements.
2. Acquire and analyze ignition probabilities for chilled fuels.
3. Characterize the droplet size distribution in the liquid spray.
4. Couple liquid droplet heating and vaporization physics to the previously developed Perfectly Stirred Reactor (PSR) model. This enhanced model would simulate the spark kernel development process to show the relative effect of chemical reactions, dilution cooling, and droplet heating and vaporization on the ignition process.

Research Approach

The first activity in year 2018 was to test ignition probabilities of liquid sprays for room temperature and chilled fuels. This began with modification of the test facility. The fuel delivery system was modified to provide liquid sprays rather than pre-vaporized fuels. The most important fuel system modifications were the installation of a solid cone pressure atomizer (a fuel injector) near the entrance to the test section and the addition of a fuel chiller. Also, the splitter plate was removed from the test rig to provide a single pure air stream. The fuel injector location was selected to produce ignition probabilities in the range of 1-10%. The injector location was also fine-tuned to prevent fuel droplet impingement on the igniter. Scattering of a HeNe laser from the liquid droplets was used to monitor the fuel spray trajectory. The schematic of the fuel delivery system is shown in Figure 5.

Liquid fuel testing was conducted with a crossflow air velocity of 10 m/s and an equivalence ratio of φ=0.55. The crossflow air temperature was 80˚F and its pressure was 1 atmosphere. For room temperature fuel sprays, ignition probabilities were measured for A2, A3, C1, C2, C3, C5, C7, C8, and C9. For chilled fuel, ignition probabilities were measured for A1, A2, A3, C1, C3, C4, C5, C7, and C8. Some fuels could not be chilled in this system as they would freeze. The ignition probabilities of each fuel relative to A2 are shown in Figure 6. For comparison, the figure also includes the results from earlier testing of pre-vaporized fuels. There are several noteworthy differences between the ignition probabilities of liquid versus pre-vaporized fuels. One of these noteworthy differences is a change in the ranking of ignition probabilities. For example, the ignition probabilities of A3, C2, and C3 are reduced relative to the other fuels when tested as liquid sprays. Another noteworthy difference is the range in probabilities is larger for chilled fuel sprays than for room temperature fuel sprays.

The differences in the ignition probabilities of liquid sprays versus pre-vaporized fuels provide some important insight. For example, the rate-limiting properties of pre-vaporized fuels should be the chemical properties. This is because the physical properties govern the vaporization process, which has been bypassed by pre-vaporization. However, the rate-limiting properties for liquid sprays may include physical properties in addition to chemical properties. Therefore, the differences in ignition probability demonstrate the important role of physical properties (such as viscosity, boiling points, etc.) for ignition of liquid fuel sprays. Special attention has been paid to properties that govern vaporization (recovery temperature, vapor pressure) and atomization (viscosity). The correlations to the viscosities and the 10% recovery temperatures for the fuel sprays are shown in Figure 7 and Figure 8.

The third activity in the ignition task was to measure the droplet distribution with PDPA. In aviation gas turbine combustors, jet fuels are injected as liquid sprays. These liquid sprays transition to gaseous fuel vapors before they burn. The droplet sizes can play an important role in the phase transition process by affecting the droplet heat transfer process. Therefore, PDPA measurement of droplet size and velocity distribution for an array of fuels was acquired. Normalized size distribution data for fuel C3 (high viscosity), A2 (middle viscosity), and C5 (low viscosity) at ~ 5 mm above the igniter center are presented in Figure 9. Significant differences in droplet size distributions were observed. The C3 fuel has more droplets at the larger size range (above 30 μm), and the C5 fuel only has a small percentage of droplets in that size range. The PDPA data can be used for more advanced CFD simulation.

Lastly, a reduced order model was enhanced to study the physics of forced ignition in liquid fuel spray. The conceptual model construction is shown in Figure 10. An example case study simulates forced ignition in a spray of 5 μm single size droplets uniformly distributed with an equivalence ratio of 1. The heat release, the dilution cooling, and the droplet heating and vaporization rates are shown in Figure 11. The initial results show that the energy required to heat and vaporize a droplet is 10 times smaller than the heat release rate and the dilution cooling. Therefore, droplet during ignition heating is not expected to substantially affect the ignition kernel's temperature. Thus, the time delay that is observed before chemical heat release occurs is likely due the heating of the droplets. If this time is too long, the kernel will be cooled significantly by dilution and ignition will not occur.

Milestone(s)

- Produced high quality, repeatable ignition probability data for room temperature liquid fuel sprays
- Produced high quality, repeatable ignition probability data for chilled liquid fuel sprays
- Acquired droplet size and velocity distribution data for several fuels.
- Enhanced a reduced order ignition model that includes droplet heating and vaporization processes

Major Accomplishments

- Fuel spray ignition probabilities correlate to properties that controls droplet sizes and vaporization.
- The acquired droplet distribution data is useful for CFD modelers.

- The reduced order ignition model shows the magnitude of the droplet cooling effect is small compared to those of the chemical heat release and the dilution cooling.

Publications

Wei, S., Sforzo, B., and Seitzman, J., 2018, "Fuel Composition Effects on Forced Ignition of Liquid Fuel Sprays," *ASME Turbo Expo 2018: Turbomachinery Technical Conference and Exposition*, Oslo, Norway

Outreach Efforts

Conference presentation at ASME Turbo Expo 2018, Oslo, Norway

Awards

None

Student Involvement

- Sheng Wei was the lead student on all of the ignition task objectives.
- Daniel Cox was involved in data analysis.
- Sabrina Noor helped analyzed results for pre-vaporized ignition simulation.
- Vedant Mehta conducted a parametric study on droplet ignition.
- John Ryu helped with the multi-size droplet ignition study.

Plans for Next Period

As the program is concluding for Georgia Tech ignition, we are planning on using the available data and model analysis to write journal papers. At the moment, we have three journal papers in mind. The first paper will use the pre-vaporized ignition data and the reduced order model to study ignition fuel chemistry. The second paper will use the ignition data in fuel spray to develop new insight into droplet ignition processes. The third paper will use the droplet ignition model to better parameterize droplet ignition processes.

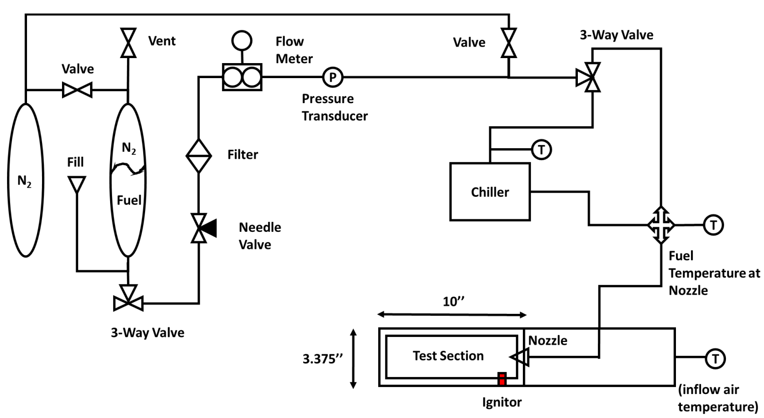

Figure 5. Schematic of the liquid fuel delivery system

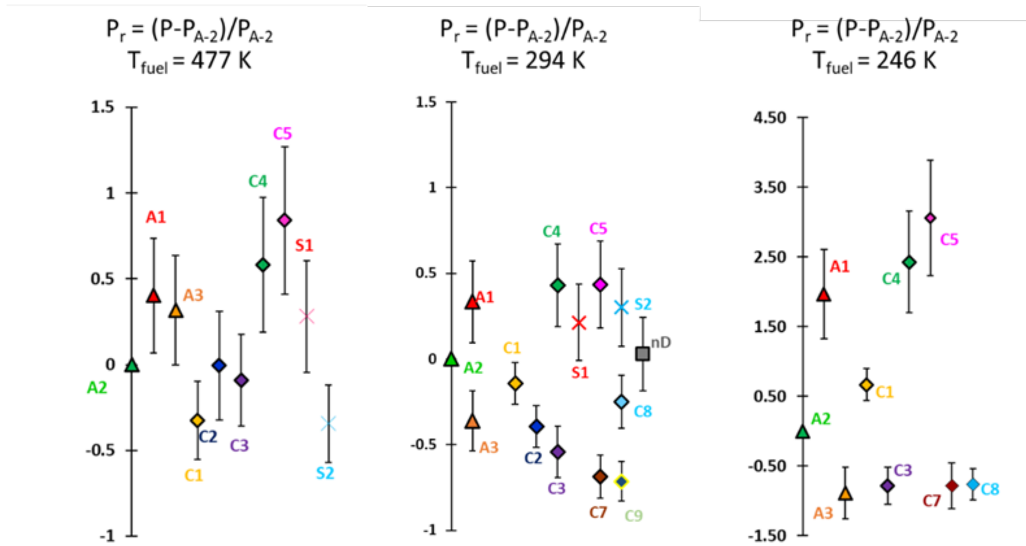

Figure 6. Ignition probability rankings, scaled with respect to A2 probability. Error bars show 68% uncertainty. Left: pre-vaporized fuel/air mixture; Middle: room temperature Liquid fuel spray; right: chilled liquid fuel spray

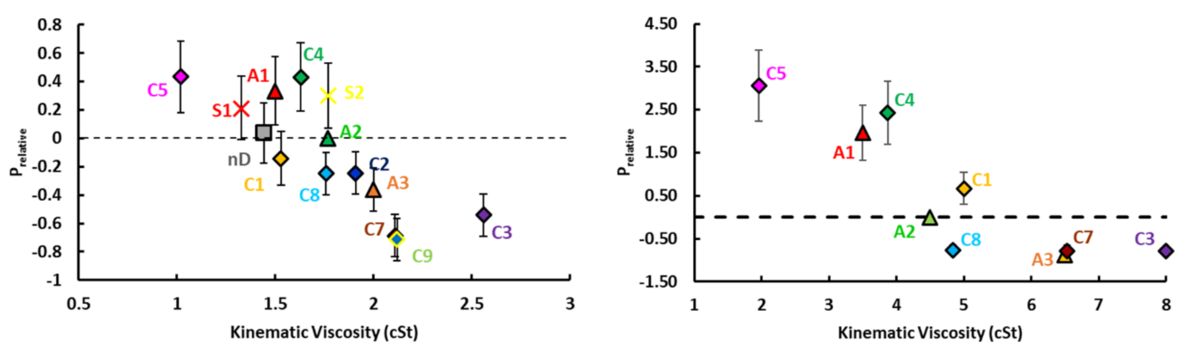

Figure 7. Relative probabilities versus relative viscosity for room temperature fuel Left: Probability results for room temperature fuel spray; right: probability results for chilled fuel sprays

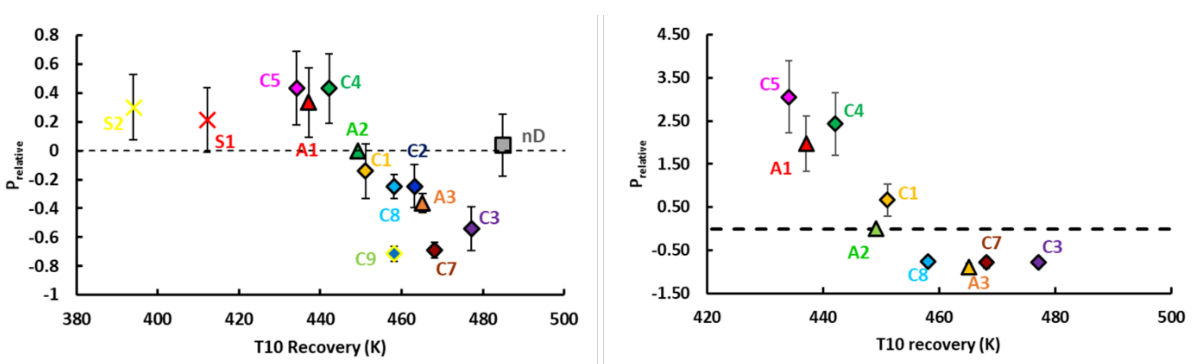

Figure 8. Relative probabilities versus 10% recovery temperature. Left: Probability results for room temperature fuel spray; right: probability results for chilled fuel sprays

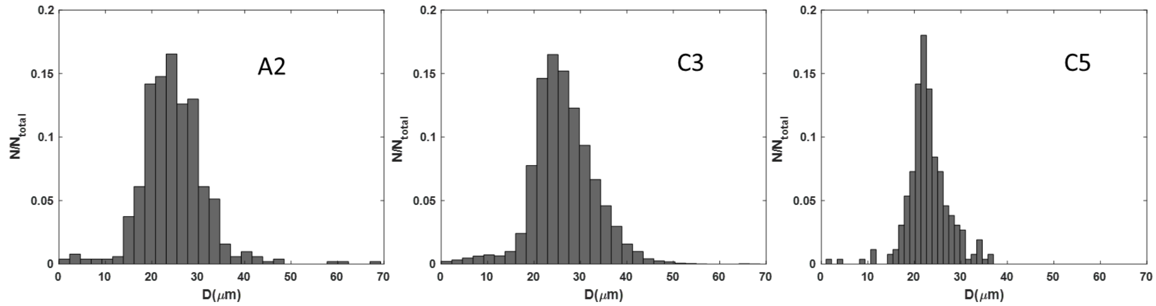

Figure 9. Normalized size distribution at 5 mm above the igniter center

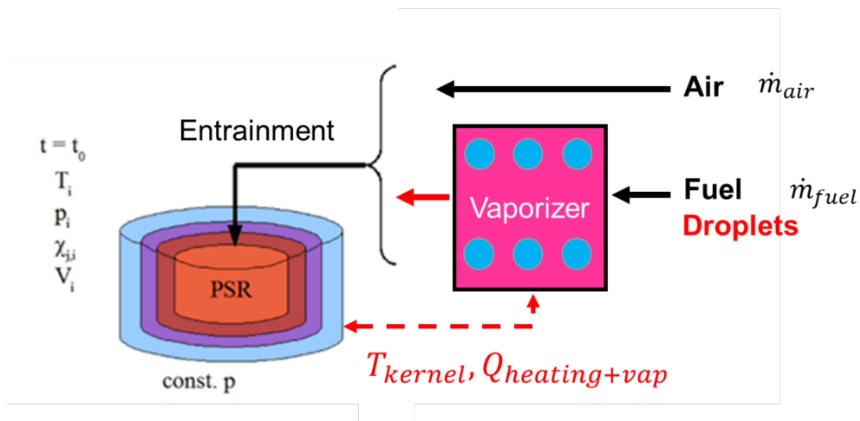

Figure 10. Conceptual model PSR modeling with droplet vaporization

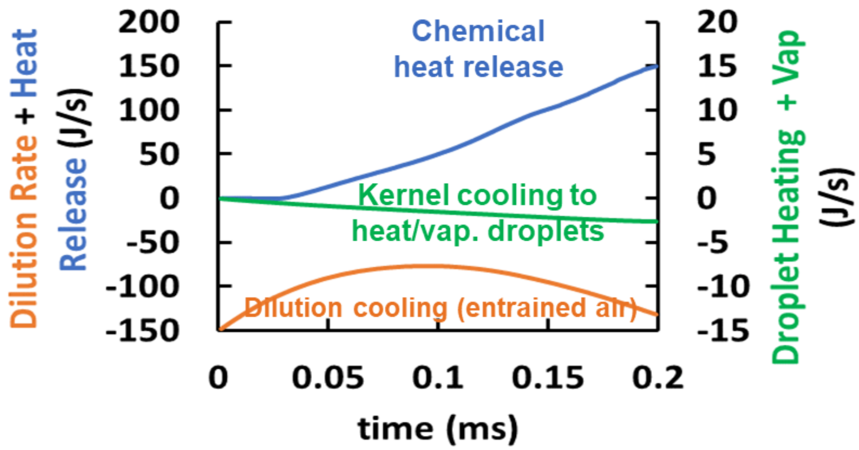

Figure 11. Chemical heat release, dilution cooling, and droplet heating/vaporization rates for a successful ignition of 5 μm droplets at an equivalence ratio of 1

Task 3- Turbulent Flame Speed

Performance site: Oregon State University

Objective(s)

This task had three objectives:

1. Measure and identify the sensitivity of the turbulent flame speed to fuel composition. This objective spanned a range of jet fuels and test conditions (including atmospheric and sub-atmospheric pressures).
2. Build a database of turbulent flame speeds for pre-vaporized jet fuels. This year we initiated a collaboration with Suresh Menon (GT) who is performing simulations of the turbulent flames anchored to the burner.
3. Measure the sensitivity of turbulent flames to local extinction.

Research Approach

Testing was conducting using a laboratory test rig that produced turbulent flames. The rig featured a pre-vaporizer based on designs developed by the Air Force Research Laboratory and a burner based on designs developed by Lieuwen and colleagues. The experimental arrangement consisted of fuel and air metering systems that delivered pre-vaporized jet fuel and air to the burner. Fuel was vaporized using a series of heaters, and elevated to a temperature near 200°C. The air/fuel mixture flowed through an adjustable turbulence generator which produced turbulence intensities (TI) ranging from 10% to 20% of the bulk flow velocity. The TI is independent of bulk flow velocity. A premixed methane pilot flame was used for ignition and to stabilize the Bunsen burner flame.

Data was collected for three fuels (A2, C1 and C5). Test conditions included two pressures (1 and 0.7 atm), Reynolds numbers near 10,000, a range of equivalence ratios ($0.75 \leq \Phi \leq 1.0$), and turbulence intensities near 20%. The test data consisted of chemiluminescence imaging for all conditions and high speed imaging for a subset of the tests. Chemiluminescence imaging was conducted 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, and TI), data were typically collected over a 3 minute period at 2 Hz.

The most important accomplishment of this activity was sub-atmospheric pressure testing (i.e., objective 1). Such measurements are relevant to relight conditions in engines at high altitudes. Figure 12 shows a photograph of the burner operating at sub-atmospheric conditions. Figure 13 (left panel) shows measured turbulent consumption speeds for C1, C5 and A2 at 1 and 0.7 atm. The right hand panel shows normalized turbulent consumption speeds. Note that the flame speeds increase as the pressure is reduced, and a fuel sensitivity is observed between C1, C5, and A2. This observation indicates that the relight characteristics between C1, C5 and A2 may be different when an aircraft is at altitude. More testing of practical systems are required to verify this postulate. It is noted that while the turbulent consumption speed increases with decreasing pressure, the mass consumption rate of the fuel decreases with decreases in pressure (see Figure 14). The latter trend is consistent with literature.

The second objective was partially addressed by initiating a collaboration with Suresh Menon (GT). His team has simulated the cold-flow conditions through the burner and has plans to simulate the reacting flow. It is anticipated that this collaborate will serve as a baseline for evaluating the chemistry models created as part of the NJFCP program.

The third activity (i.e., objective 3) was evaluating a methodology to detect the onset of local extinction events in the flame brush. Earlier in this program a fuel sensitivity to the onset of instabilities of the flame was detected based on large changes in the apparent turbulent flame speed. However, using this technique to evaluate fuels was quite time consuming and it was difficult to link the physics of flame speed measurements to local extinction. This year efforts were made to develop a better method to more readily determine breaks in the flame front. High speed images were collected of flames and analysis tools were developed to quantify the turbulent statistics of emissions from the flames. Figure 15 provides a representative image of a turbulent statistic (i.e., integral length scale) that was evaluated to determine if it could be used as a metric of the onset of breaks in the flame front. Our current approach is to use the shape of the radial distribution of intensity as a marker of flame tip opening. Further testing is required to verify that this approach is valid.

Milestone(s)

- A method for evaluating the onset of local extinction events is 80% complete. Additional testing is required to verify that the proposed method is consistent for different fuels and operating conditions.

- Collaboration with Suresh Menon (GT) was initiated. Suresh is modeling the turbulent Bunsen burner flame to evaluate if the model can capture fuel sensitivities. Data and boundary conditions have been shared.
- A portion of the introduction to the lean blowout chapter in the forthcoming AIAA book has been drafted.

Major Accomplishments

- Turbulent flame speeds at atmospheric and sub-atmospheric conditions were measured. A fuel sensitivity is evident.
- Observation was made that flame extinction is sensitive to fuel composition. This will be important for the program's lean blowout tasks, which aim to understand how ignition and extinction influence the lean blowout process.

Figure 12. Picture of flame operating in pressure vessel at sub-atmospheric conditions

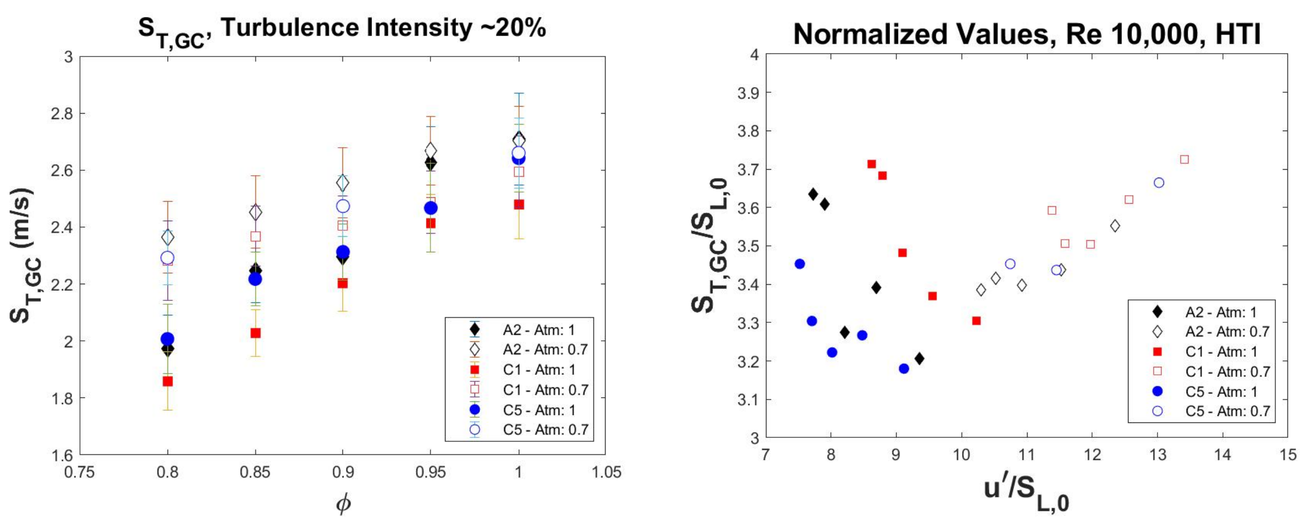

Figure 13. Turbulent consumption speeds (left panel) and normalized turbulent consumption speeds (right panel) for A2, C1, and C5 when tested at 1 and 0.7 atm

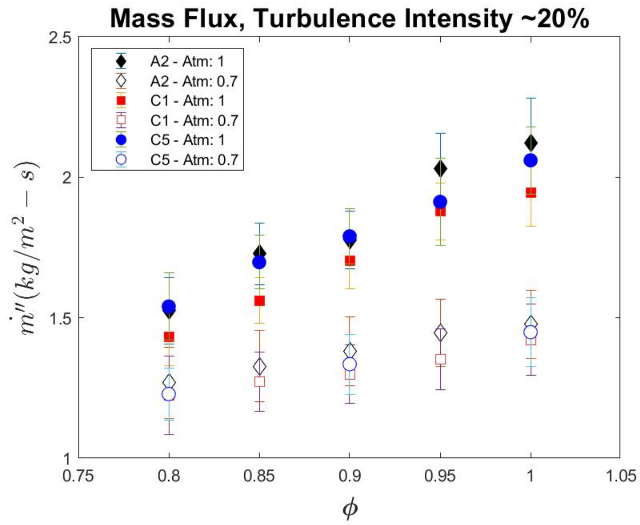

Figure 14. Mass consumption speeds of jet fuels for 1 and 0.7 atm

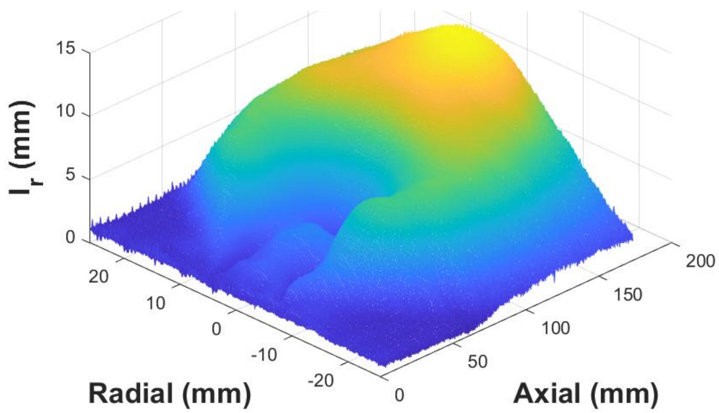

Figure 15. Radial integral length scale of visible light emissions from turbulent Bunsen burner flame burning A2 fuel. Such statistics have been considering as a marker of the onset of openings of the flame brush.

Publications

N. Schorn, **D. Blunck**, "Flame Stability of Turbulent Premixed Jet Flames of Large Hydrocarbon Fuels," *Western States Section of the Combustion Institute Meeting*, Laramie, WY (2017).

A. Fillo, J. Bonebrake, **D. Blunck**, "Impact of Fuel Chemistry and Stretch Rate on the Global Consumption Speed of Large Hydrocarbon Fuel/Air Flames," *10th US Combustion Meeting,* College Park, ME (2017).

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

Outreach Efforts

None

Awards

Fillo, Aaron, M.S., Thesis, "The Global Consumption Speeds of Premixed Large- Hydrocarbon Fuel/Air Turbulent Bunsen Flames," received a 2017 OSU Distinguished Master's Thesis Award.

Student Involvement

- Jonathan Bonebrake, a PhD student, has helped to collect and analyze data. He also designed and built the sub-atmospheric 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 taken over responsibility of the project is now collecting and analyzing 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

Three activities are planned to complete this project. The first activity is to complete measuring the turbulent flame speeds of the jet fuels at sub-atmospheric pressures. This activity will focus on the fuels that the program determines to be of interest. The second activity will be completing analysis of the flame extinction observations for different fuels. It is hypothesized that local extinction events observed on this burner coincide with the onset of extinction for other burners. The results of this activity can be used to help determine if turbulent flame speed testing can provide insight into the risk of lean blowout for practical systems. The third activity is an on-going collaboration with Suresh Menon at GT who is simulating the turbulent Bunsen burner flames. It is expected that data collected using this burner can be used to evaluate turbulent chemistry models. If successful, this evaluation can serve as an intermediate step between testing using shock tubes and three-dimensional simulations of practical combustors.