Project 027 Advanced Combustion (Area #3)

Georgia Institute of Technology
Oregon State University

Project Lead Investigator

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University Participants

Georgia Institute of Technology

- PIs:
    - Professor Tim Lieuwen
    - Professor Jerry Seitzman
    - Professor Wenting Sun
- FAA Award Number: 13-C-AJFE-GIT-008
- Period of Performance: 12/1/2014 to 3/31/2020
- Tasks:
    - Task 1 – Lean Blowout. This Task measures the lean blowout (LBO) characteristics of alternative jet fuels and compares them to the LBO characteristics of Jet A.
    - Task 2 – 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: 12/1/2014 to 3/31/2020
- Task:
    - Task 3 – 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 (Georgia Tech)
FAA Funding: $30,000
Cost Share: $30,000 provided by Georgia Tech.

Oregon State University (OSU)
During the reporting period, the remaining funds were spent and an additional $4,441 was provided by OSU to complete the project.

Investigation Team

Tim Lieuwen (Georgia Institute of Technology): Principal Investigator. Professor Lieuwen is the PI overseeing all tasks, and is manager of Task 1- Lean Blowout.

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.
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.
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 and 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, as well as experimental operations and management and 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 Task 1.
Hanna Ek (Georgia Institute of Technology): Graduate Student. Ms. Ek is the lead data analyst for Task 1.
Sheng Wei (Georgia Institute of Technology): Graduate Student. Mr. Wei currently leads Task 2.
Jonathan Bonebrake (Oregon State University): Graduate Student. Mr. Bonebrake was the lead grad student experimentalist on Task 3.
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.

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 (LBO) 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 this 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 have tested twenty total fuel mixtures. Sixteen of these 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 LBO measurements. The highest priority LBO 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. As with Task 1, the highest priority forced ignition measurement was fuel screening. In the case of this 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, Task 2 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.

This report covers the last 1.5 years of a 5.5-year program. This report is nearly identical to the year 5 report because funding was expended during year 5 and no further work was performed. The following sections provide a summary of the most important results from all five years and for each of the three Tasks. The first and third Tasks were funded during the fifth year, so new results are included relative to previous years' reports. The second Task was not funded during the fifth year, so its results are repeated from the year 4 report.

Task 1 – Lean Blowout

Georgia Institute of Technology

Objectives

The objective of this Task was to obtain two types of measurements in a combustor rig operating near LBO. The two types of measurements were fuel screening and detailed diagnostics. 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. These data would support the modeling teams by providing physical insight and by providing important simulation boundary conditions. To summarize, the objectives of this Task were to obtain fuel screening data and detailed diagnostic measurements.

Research Approach

This Task was performed with a combustor rig, shown in Figure 3. The rig was a high-pressure, swirl-stabilized spray combustor with original equipment manufacturer (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 was their dome and liner cooling arrangements. The referee rig had 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 as well as other stakeholders such as the referee rig team and the modeling teams. Together, these teams selected one combustor pressure and three air preheat temperatures for LBO testing. These were designed to simulate idle and altitude conditions where LBO 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 LBO 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 LBO 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. Figure 1 shows the screening data that was measured during the third year of the project. Correlations between the cetane number and the blowout equivalence ratio at elevated temperatures first became evident from this third-year dataset. For example, Figure 1 shows greater correlation of the blowout equivalence ratio to cetane number at the two higher inlet temperatures (450 K and 550 K) versus the lower inlet temperature (300 K).

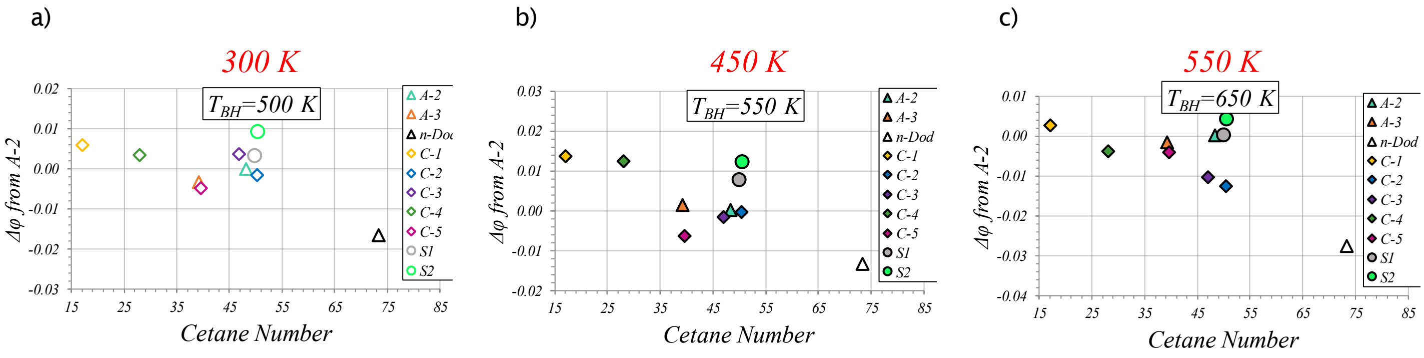

Figure 1. Sample of year 3 screening data at three different preheat temperatures and three different bulkhead temperatures, demonstrating the strong correlation of LBO withcetane number. The correlation coefficients between blowout equivalence ratio and the cetane number are -0.21 at 300 K, -0.79 at 450 K, and -0.76 at 550 K.

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 LBO. In support of the modeling groups, the LBO 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. Figure 2 shows an example of one chemiluminescence image. 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 LBO. The chemiluminescence images also produced data to help the program determine the roles of ignition and extinction in the lean blowout process. 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.

Figure 2. Sample flame chemiluminescence image from n-dodecane burning at 300 K air preheat temperature.

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 LBO events and their associated operating points. Analysis of screening data also included uncertainty analysis. The uncertainty analysis was necessary in order to determine the statistical significance of the results, and in some cases it motivated the LBO 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 root-mean square velocity field, and to extract key vortical flow features. These post-processed data were the deliverable to the modeling teams.

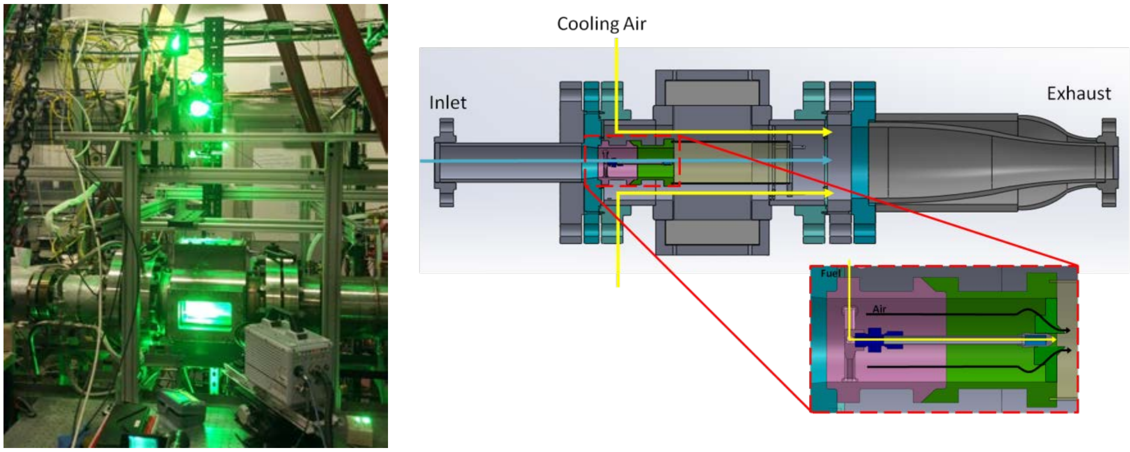

Figure 3. High shear swirl combustor, showing a) pressure vessel instrumented for high-speed stereo PIV and OH PLIF, and b) a cross section with generic swirler holder/injector for illustrative purposes.

Fifth Year Results

A supervised machine learning regression technique was conducted on the fuel screening data during the fifth year. The objective of this analysis was to determine cause-and-effect relationships between fuel properties and blowoff characteristics. These cause-and-effect relationships have been hard to identify with classical statistics because the fuel properties are strongly intercorrelated. These intercorrelations can be very misleading with classical statistics.

The regression procedure consisted of a Hierarchical Non-Negative Garrote with a two-step approach. This procedure has two steps. The first step is to identify important groups of variables or parameters. Examples of such groups would be “physical properties” and “chemical properties.” This step requires a physical understanding of the system. The second step involves a series of regressions of the data against the groups and the variables within the groups. The groupings used in this study are shown in Table 1.

Table 1. Hierarchical Non-Negative Garrote Groupings

Group 1	Group 2	Group 3	Group 4	Group 5	Group 6	Group 7
T_{10}	ν (mm^2/s) 313 (K)	T_{50}	% iso-Paraffins	H/C	% Aromatics	DCN
MW	ρ (kg/m^3) 288 K	T_{90}	σ (mN/m) 300 K	LHV (MJ/kg)	Smoke Point (mm)	Ri

The regression model consists of tuning parameters. These parameters are determined from the cross-validation procedure. During cross-validation, a subset of the data (the training data set) and the regression is tested against the remaining data (the validation data set). This is repeated with different portions of the data serving as the training data set until all data have served as training data. The cross-validation procedure is illustrated in Figure 4.

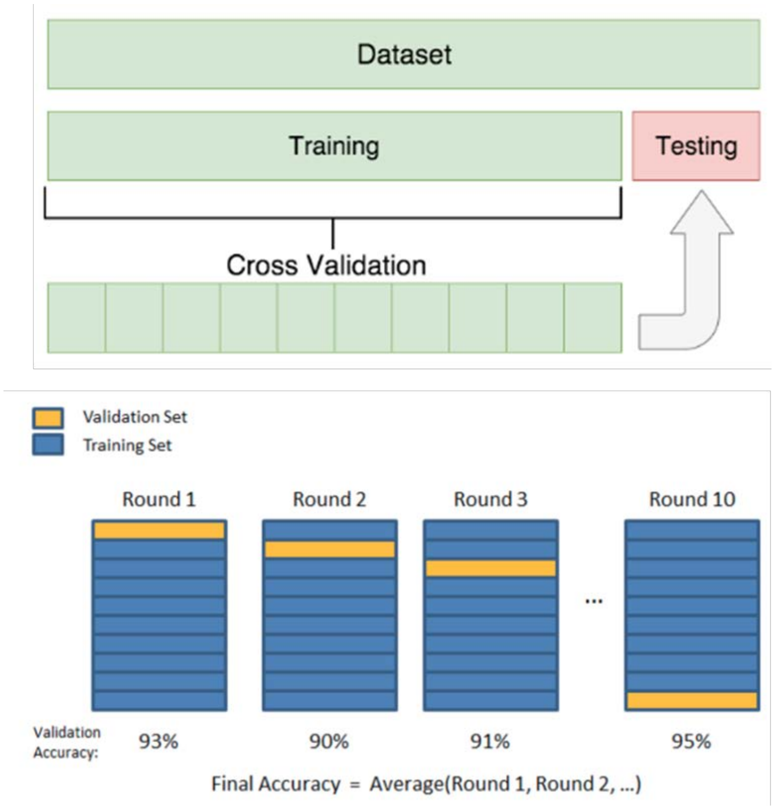

Figure 4. Illustration of the cross-validation procedure

The results of this analysis indicated that different parameters influenced blowout at different combustor inlet temperatures. These results are shown graphically in Figure 5, which shows the regression coefficients that relate LBO equivalence ratio to the fuel properties. At low combustor inlet temperatures, the 90% boiling point has the strongest influence on LBO characteristics (see the right-most blue bar in Figure 5). However, at higher combustor inlet temperatures, the Derived Cetane Number (DCN) has the strongest influence on LBO characteristics (see the left-most yellow and orange bars in Figure 5). This result strongly supports the hypothesis from the University of Dayton Research Institute (UDRI) that physical properties are important for LBO at low temperatures, and that autoignition properties are important for LBO at high temperatures. In addition, these results identify the individual parameters that are most important. Finally, we note that the regression model worked the best when we adjusted the DCN for the 20% most volatile fuel constituents. This is significant because it supports the preferential vaporization hypothesis that has been proposed by other teams.

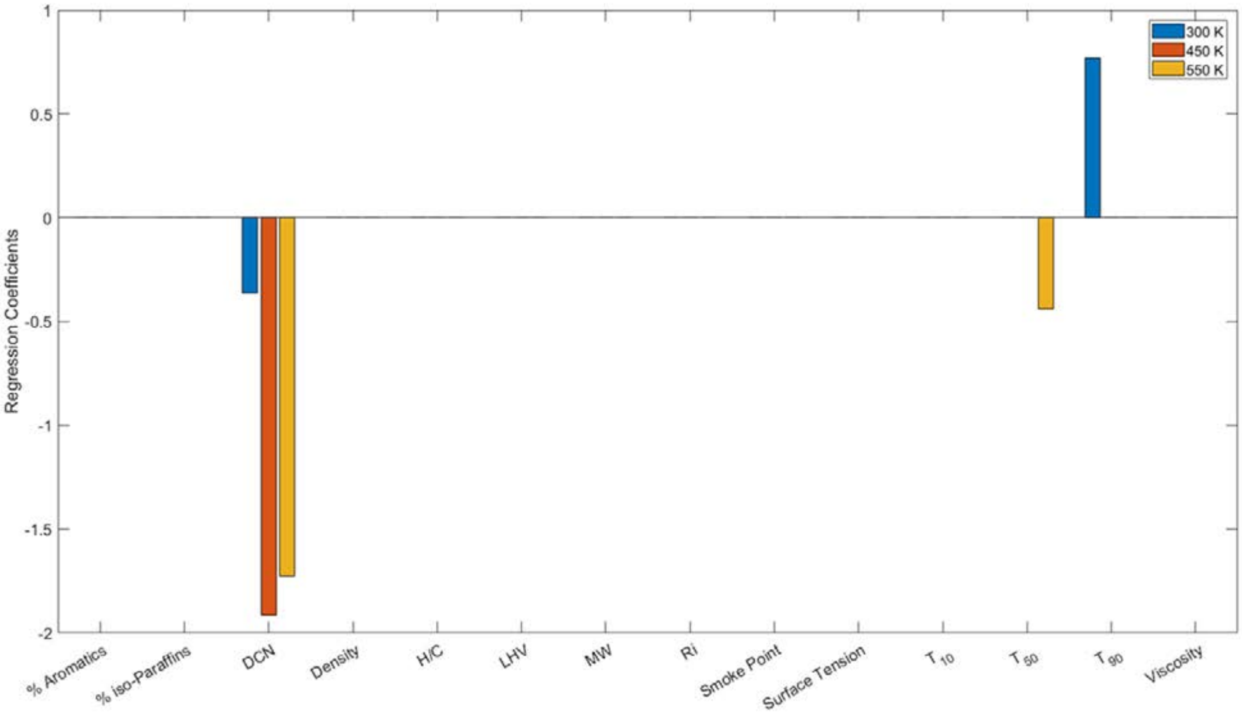

Figure 5. Results of the Hierarchical Non-Negative Garrote for three different combustor inlet temperatures.

Milestones

1. Boundary condition measurements. This was completed during years 1 and 2.
2. Detailed diagnostic measurements. This was completed during years 1 and 2.
3. Screening data. This was completed during year 4.
4. Analysis. This was completed during year 5.

Major Accomplishments

1. We have built a data analysis framework that explains the sensitivity of LBO to different fuel characteristics. This framework is robust against the intercorrelation of parameters. The results of the analysis support several hypotheses that have been presented by various National Jet Fuels Combustion Program (NJFCP) team members over the years.
2. We have supported the LBO chapter of the American Institute of Aeronautics and Astronautics (AIAA) book during year 5.

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 provided research opportunities to undergraduate students and a high school student with this program. We had a graduate student present his work at the 2019 AIAA Scitech conference. We had a graduate student complete his Ph.D. on the work conducted under this program.

Awards

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

Student Involvement

- Dr. Nick Rock has been actively involved in the LBO experimental effort for all years. Nick was the Ph.D. 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. Dr. Rock has now graduated with his Ph.D. and works for Spectral Energies in Dayton, OH.
- Hanna Ek was involved in the LBO 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.
- Dr. Ianko Chterev was also actively involved in the LBO experimental effort. His primary responsibility was the design of experimental procedures and support of detailed diagnostic measurements. Dr. Chterev has now graduated with his Ph.D. and works as a Postdoctoral Researcher for the German Aerospace Center (DLR) in Stuttgart, Germany.
- Dr. Eric Mayhew visited Georgia Tech from the University of Illinois at Urbana-Champaign. Dr. Mayhew helped lead the execution of the laser and optical diagnostics. Dr. Mayhew has graduated with his Ph.D. and works as a Postdoctoral Fellow at the U.S. Army Research Laboratory.

Plans for Next Period

We have completely expended our budget during the fifth year. We plan to continue to author and present papers from this work, and we will continue to support the LBO chapter of the AIAA book that is being produced from this program.

Task 2 – Ignition

Georgia Institute of Technology

Objectives

There were four objectives for this year's ignition task. The first objective was to expand the database of room temperature ignition probability measurements. The second objective was to acquire and analyze ignition probabilities for chilled fuels. The third objective was to characterize the droplet size distribution in the liquid spray. The fourth objective was to 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 the ignition task back in 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 6.

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 7. 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 8 and Figure 9.

The third activity in the ignition task was to measure the droplet distribution with a phased Doppler particle anaylzer (PDPA) system. 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 10. 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 computational fluid dynamics (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 11. 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 cooing, and the droplet heating and vaporization rates are shown in Figure 12. 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.

Fifth Year Results

This Task was not funded during the fifth year. There is no new technical progress to report.

Milestones

- 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

This Task will not continue into the next period.

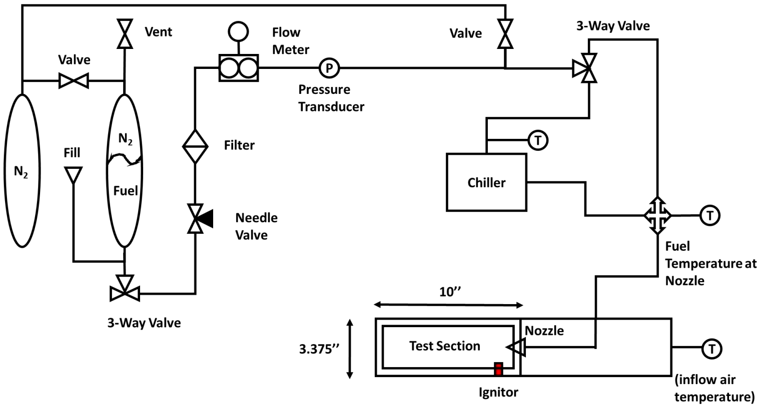

Figure 6. Schematic of the liquid fuel delivery system.

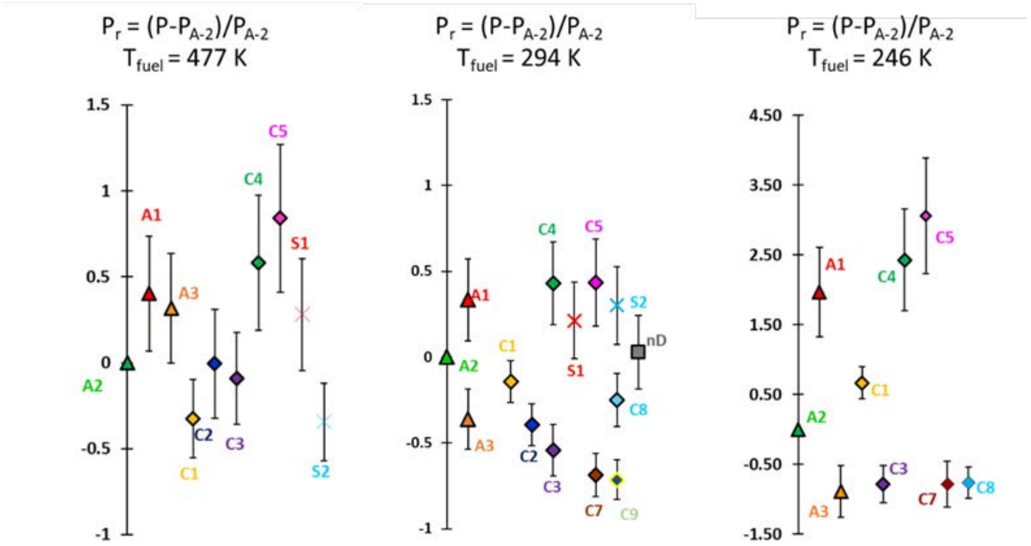

Figure 7. Ignition probability rankings, scaled with respect to A2 probability. Error bars show 68% uncertainty. Left: pre-vaporized fuel/air mixture. Middle: room temperature liquid fuel spray. Right: chilled liquid fuel spray.

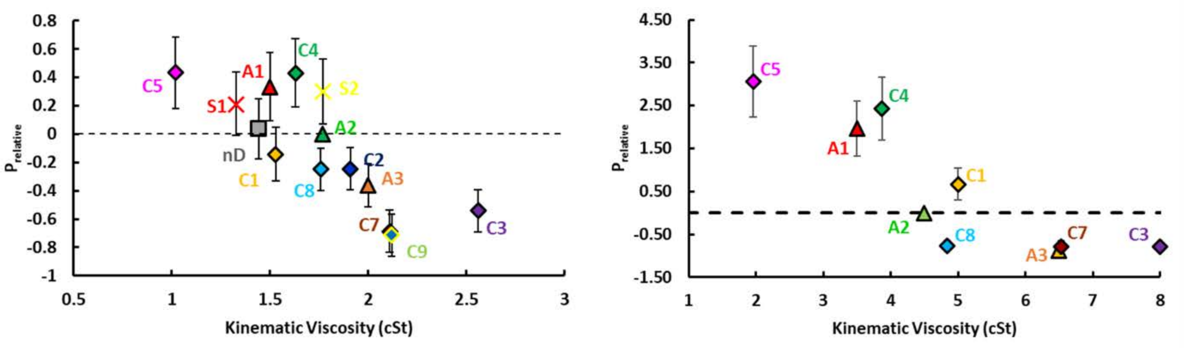

Figure 8. Relative probabilities versus relative viscosity for room temperature fuel. Left: probability results for room temperature fuel spray. Right: probability results for chilled fuel sprays.

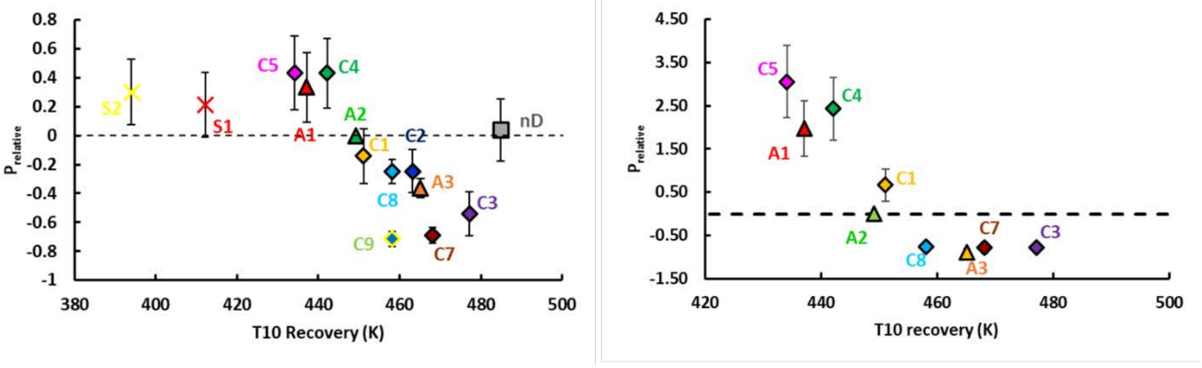

Figure 9. Relative probabilities versus 10% recovery temperature. Left: probability results for room temperature fuel spray. Right: probability results for chilled fuel sprays.

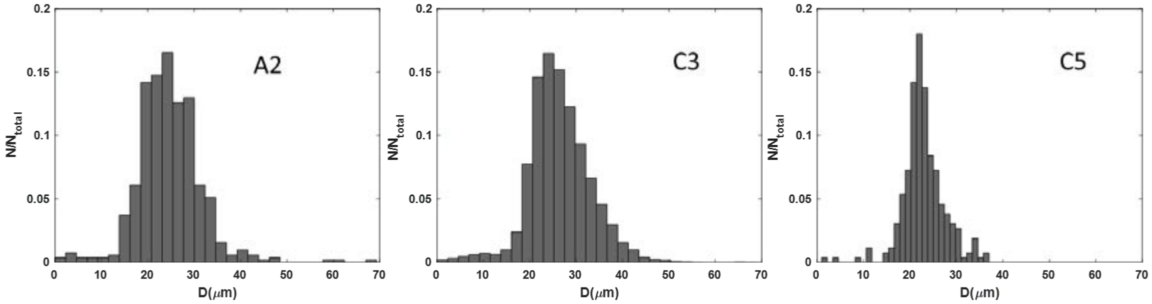

Figure 10. Normalized size distribution at 5 mm above the igniter center.

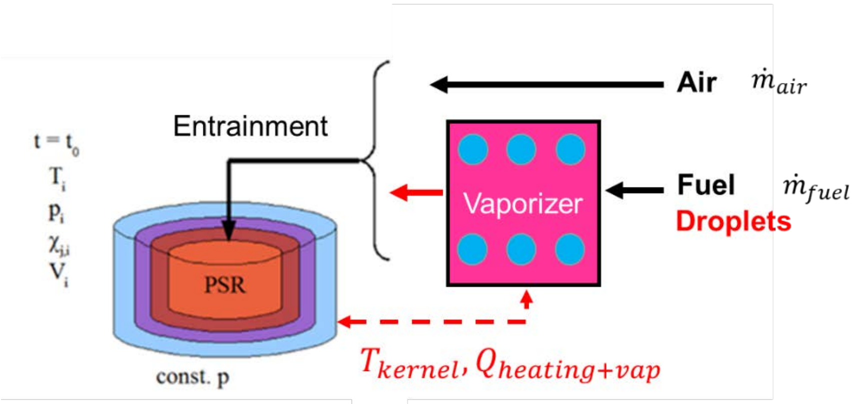

Figure 11. Conceptual model PSR modeling with droplet vaporization.

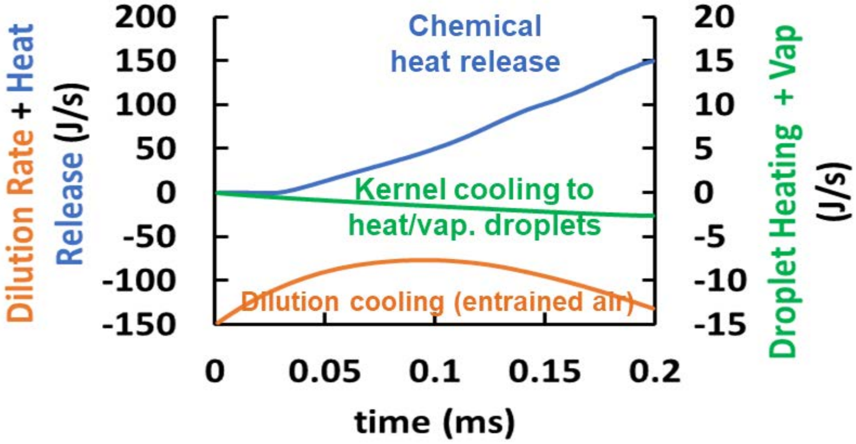

Figure 12. Chemical heat release, dilution cooling, and droplet heating/vaporization rates for a successful ignition of 5 μm droplets at an equivalence ratio of 1.

Task 3 – Turbulent Flame Speed

Oregon State University

Objectives

This Task had three objectives. The first objective was to 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). The second objective was to build a database of turbulent flame speeds for pre-vaporized jet fuels. This year we initiated a collaboration with Suresh Menon (Georgia Tech) who is performing simulations of the turbulent flames anchored to the burner. The third objective was to 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 (473 K). 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 one). Such measurements are relevant to relight conditions in engines at high altitudes. Figure 13 shows a photograph of the burner operating at sub-atmospheric conditions. Figure 14 (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 (Figure 15). The latter trend is consistent with the literature.

The second objective was partially addressed by initiating a collaboration with Suresh Menon (Georgia Tech). 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 three) 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 16 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.

Fifth Year Results

This Task had very modest funding. The focus was on completing data collection and analysis, as well as writing up and distributing the results. The publications and pending publications resulting from this period or work are shown below. The student funded by this project (Nathan Schorn) completed and defended his thesis.

Milestones

- Nathan Schorn successfully defended his M.S. thesis.
- Three publications were prepared. Two of these publications were from Nathan's work while the third was from the research from a previous student (Aaron Fillo).
- The experimental arrangement was used to support research for two undergraduate honors theses. One project focused on identifying how preheating the fuel alters flame speeds. The other project has focused on measuring the fraction of radiative heat released by a Bunsen flame with and without dilution.

Major Accomplishments (Cumulative)

- 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 can be important for the program's LBO tasks, which aim to understand how ignition and extinction influence the LBO process.
- It was found that the surrogate fuel (S1) has similar flame speeds as Jet A.

Figure 13. Picture of flame operating in pressure vessel at sub-atmospheric conditions.

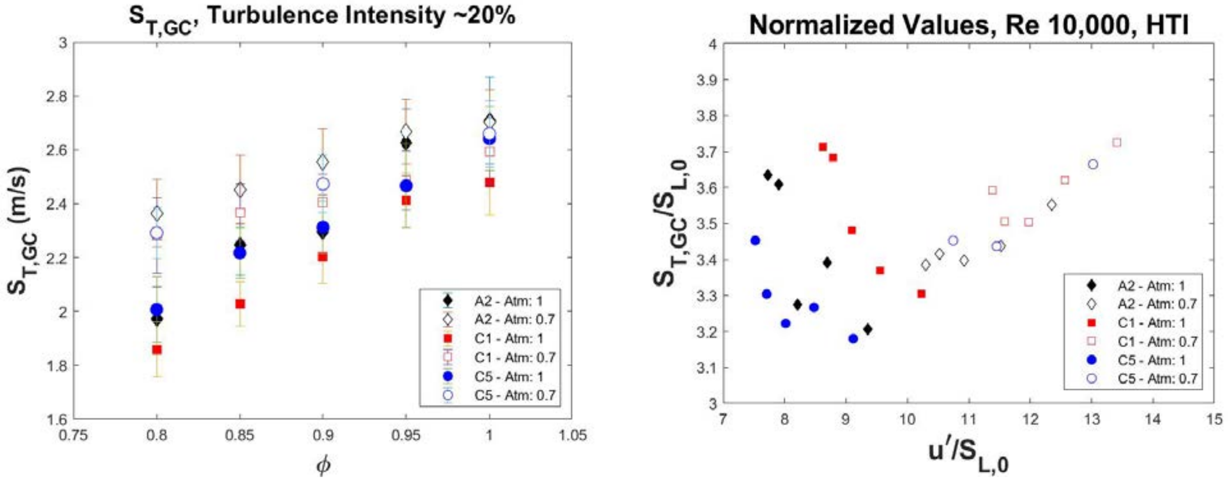

Figure 14. Turbulent consumption speeds (left panel) and normalized turbulent consumption speeds (right panel) for A2, C1, and C5 when tested at 1 and 0.7 atm.

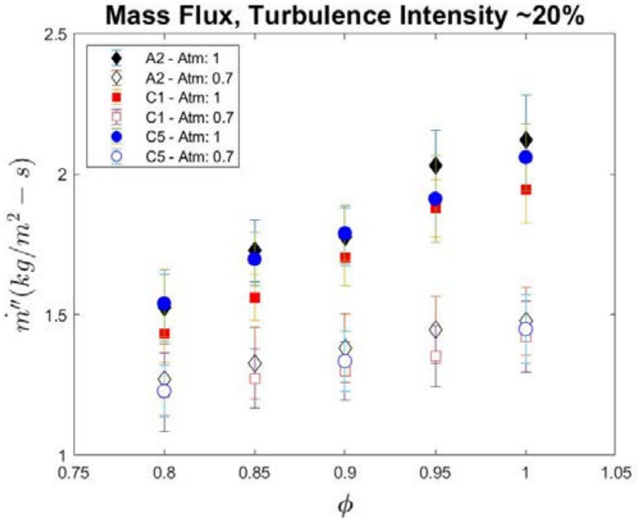

Figure 15. Mass consumption speeds of jet fuels for 1 and 0.7 atm.

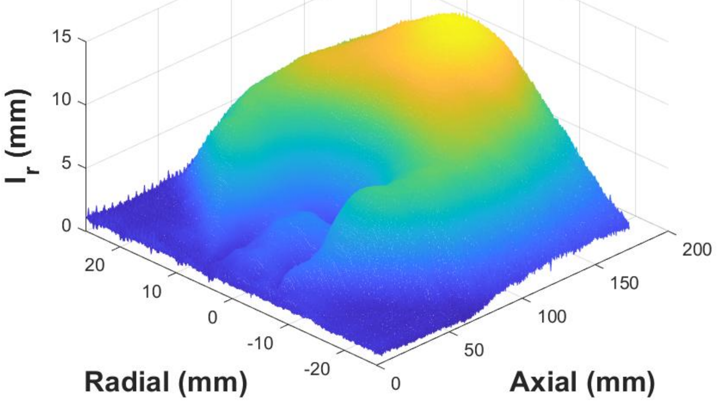

Figure 16. Radial integral length scale of visible light emissions from turbulent Bunsen burner flame burning A2 fuel. Such statistics have been considered as a marker of the onset of openings of the flame brush.

Publications (to date)

N. Schorn, Z. Hoter, D. Blunck, “Turbulent Combustion Behavior of a Surrogate Jet Fuel,” in preparation for submission to Fuels.

N. Schorn, J. Bonebrake, Z. Hoter, A. Fillo, D. Blunck, “Pressure Effects on the Turbulent Consumption Speed of Large Hydrocarbon Fuels,” *AIAA Journal,* under review.

N. Schorn, J. Bonebrake, B. Pendergrass, A. Fillo, D. Blunck, “Turbulent Consumption Speed of Large Hydrocarbon Fuels at Sub-Atmospheric Conditions,” *AIAA Science and Technology Forum and Exposition 2019*, San Diego, CA (2019).

Schorn, M, M.S., Thesis, “Turbulent Bunsen Burner Analysis,” Oregon State University (2019).

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 (2016).

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 (over the duration of the project)

- Jonathan Bonebrake, a Ph.D. student, has helped to collect and analyze data. He also designed and built the sub-atmospheric pressure vessel and vacuum system.
- Aaron Fillo, a Ph.D. student, has worked tangentially on this project to analyze results and further investigate scientific phenomena.
- Nathan Schorn, a M.S. student, has collected and analyzed 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

The team from OSU will provide two remaining contributions. First, we will complete the publication process. One paper is currently under peer review, a second paper will be submitted by the end of December, and a third paper will be revised and resubmitted for peer review. Our second contribution will be to support the LBO book chapter as needed. Previously, the team provided content for the introduction to the LBO section. We will gladly help to revise the introduction or provide new content as requested.