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

- PI(s):
    - Prof. Tim Lieuwen
    - Prof. Jerry Seitzman
    - Prof. Wenting Sun
- FAA Award Number: 13-C-AJFE-GIT-008
- Period of Performance: December 1, 2018 to November 30, 2019
- Task(s):
    1. Lean Blowout. In this task, the lean blowout characteristics of alternative jet fuels are measured and compared to those of Jet A fuel.
    2. Ignition. In this task, the ignition probabilities of alternative jet fuels are measured and compared to those of Jet A fuel.

Oregon State University

- PI(s): David Blunck
- FAA Award Number: 13-C-AJFE-OSU-02
- Period of Performance: December 1, 2018 to November 30, 2019
- Tasks:
    1. Turbulent Flame Speed. In this task, the turbulent flame speeds of alternative jet fuels are measured and compared to those of Jet A fuel.

Project Funding Level

Georgia Institute of Technology
FAA Funding: $30,000
Cost Share: $30,000 provided by Georgia Institute of Technology

Oregon State University
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. Prof. Lieuwen is the PI overseeing all tasks and is the manager of Task 1. Lean Blowout.
- Jerry Seitzman (Georgia Institute of Technology): Co-Principal Investigator. Prof. Seitzman is the manager of Task 2. Ignition.
- David Blunck (Oregon State University): Co-Principal Investigator. Prof. Blunck is the manager of Task 3. Turbulent Flame Speed.
- Wenting Sun (Georgia Institute of Technology): Co-Principal Investigator. Prof. Sun is acting as an internal expert consultant on kinetic mechanisms.
- Tonghun Lee (University of Illinois Champaign): Co-Principal Investigator. Prof. Lee is the lead diagnostic expert.
- Benjamin Emerson (Georgia Institute of Technology): Research Engineer. Dr. Emerson is responsible for the design and maintenance of experimental facilities, experimental operations, and the 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 the design and maintenance of experimental facilities, experimental operations, and the 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 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 graduate 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 to collect and analyze data.

Project Overview

The objective of this project was to conduct advanced combustion testing of alternative jet fuels, with the aim of accomplishing 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 fuel. 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 other teams. These data typically consisted of velocity field measurements, high-speed flame images, and test rig boundary conditions.

During this program, we tested a total of 20 fuel mixtures. Sixteen of these fuels were pure (unblended) fuels, designated 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 also tested three 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 tasks, which are summarized below. The details of these tasks are given in the remainder of this report.

1. Lean blowout measurements. The highest-priority lean blowout measurement was fuel screening, in which the blowout boundaries of various fuels were compared to that of Jet A fuel. This task also included measurements of the combustor velocity field, the spatiotemporal evolution of the flame position, and several thermodynamic rig boundary conditions, such as the air flow rate, surface temperature, gas temperature, and gas pressure.
2. Forced ignition measurements. Similar to the blowout task, the highest-priority forced ignition measurement was fuel screening. In the forced ignition task, the fuel screening activity indicated the ignition probabilities of various fuels, which were then compared with the ignition probability of Jet A fuel. The ignition probability is a common measure of combustor ignitability and 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 has begun to exhibit the capability for ignition probability prediction. 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, measurements of detailed ignition physics were acquired, including images of the fuel spray, ignition kernel, and flame.

3. Turbulent flame speed measurements. Similar to the other two tasks, the high-priority measurement for Task 3 was fuel screening, in which the turbulent flame speeds of various fuels were compared with that of Jet A fuel. This task also had a significant rig development aspect, which provided subatmospheric pressure capability.

This report covers the 5th year of a 5.5-year program. The following sections provide a summary of the most important results from all five years for each of the three tasks. The first and third tasks were funded during the fifth year; thus, new results are included relative to the fourth-year report. The second task was not funded during the fifth year, and hence, its results are repeated from the fourth-year report.

Task 1– Lean Blowout

Georgia Institute of Technology

Objective(s)

The objective of this task was to obtain two types of measurements, i.e., fuel screening and detailed diagnostics, in a combustor rig operating near lean blowout. Fuel screening was performed in order to rank the blowout boundaries of each fuel relative to Jet A fuel. Detailed diagnostics were conducted 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 a combustor rig, as 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, although the dome and liner cooling arrangements of the referee rig differ. The referee rig has a higher level of complexity for these components, providing a closer simulation of a real combustor. However, the reduced complexity of the Georgia Tech rig enables a greater rate of data generation and allows laser-based diagnostics that are not possible in the referee rig.

This research project consisted of four major activities. First, the test conditions were collaboratively selected by the LBO working group. The test condition selection included input from the OEMS as well as other stakeholders, such as the referee rig team and modeling teams. Together, these teams selected one combustor pressure and three air preheat temperatures for lean blowout testing. These parameters were designed to simulate idle and altitude conditions at which lean blowout poses the greatest risk. The selected combustor pressure was 3 atm, and the selected air preheat temperatures were 300, 450, and 550 K.

Second, screening data were acquired by outfitting the combustor test rig with an advanced fuel cart. The fuel cart had ten 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 fuels in a single session; this capability is advantageous because it promotes 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. The conditions under which the combustor blew out were recorded, and the process was repeated until the first fuel tank was empty. This repetitive process typically produced 20–30 blowout points for a single fuel. This procedure was then repeated for the fuels in the other nine tanks. Figure **1** shows screening data measured during the third year of the project. Correlations between the cetane number and the blowout equivalence ratio at elevated temperatures first became evident in this third-year data set. For example, Figure **1** shows a stronger correlation between the blowout equivalence ratio and cetane number at the two higher inlet temperatures (450 and 550 K) vs. the lower inlet temperature (300 K).

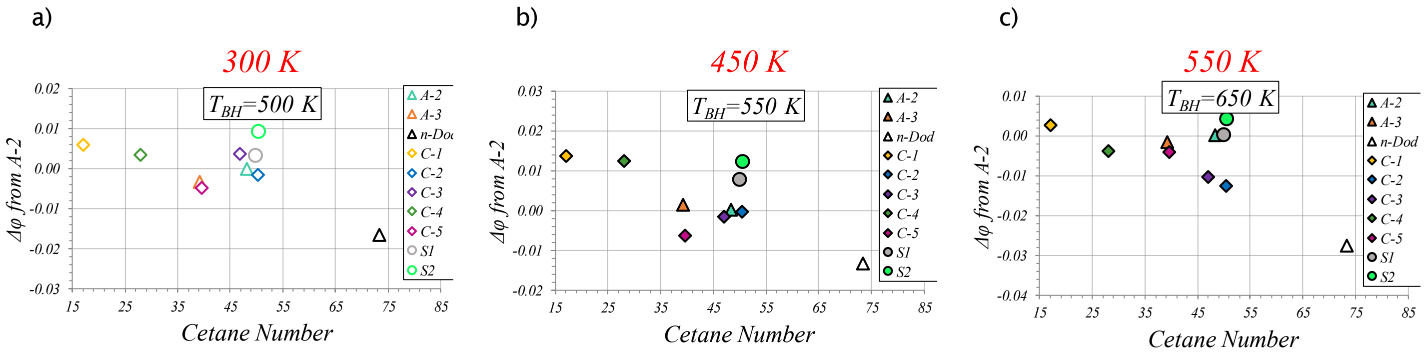

Figure 1. Sample of third-year screening data for three preheat temperatures and three bulkhead temperatures, demonstrating a strong correlation between lean blowout and cetane number. The correlation coefficients for the blowout equivalence ratio and cetane number are -0.21 at 300 K, -0.79 at 450 K,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

Third, detailed data were acquired to support the modeling groups and to improve the team's understanding of the physics of lean blowouts. The lean blowout team performed detailed laser-based measurements, which were provided to the modeling groups to help them refine and validate their simulations. The measurements incorporated several laser-based techniques that were synchronized at 5,000 frames per second, including the following:

- 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

High-speed chemiluminescence images were also acquired during the third step. Figure **2** presents a representative chemiluminescence image. These measurements can be more easily acquired and analyzed than the laser-based diagnostics outlined above; thus, chemiluminescence imaging has the advantage of rapid implementation. Due to this advantage, chemiluminescence imaging was applied for more fuels and test conditions than the laser-based techniques. The chemiluminescence images also helped reveal the qualitative burning characteristics near lean blowout and assisted the team in determining the roles of ignition and extinction in the lean blowout process. Area 3 and Area 7 are both currently analyzing these data in order to make such a determination. In addition to these optical measurements, the third activity also produced measurements of combustor boundary conditions, including air flow rate, air and fuel temperature, combustor pressure, and surface temperature.

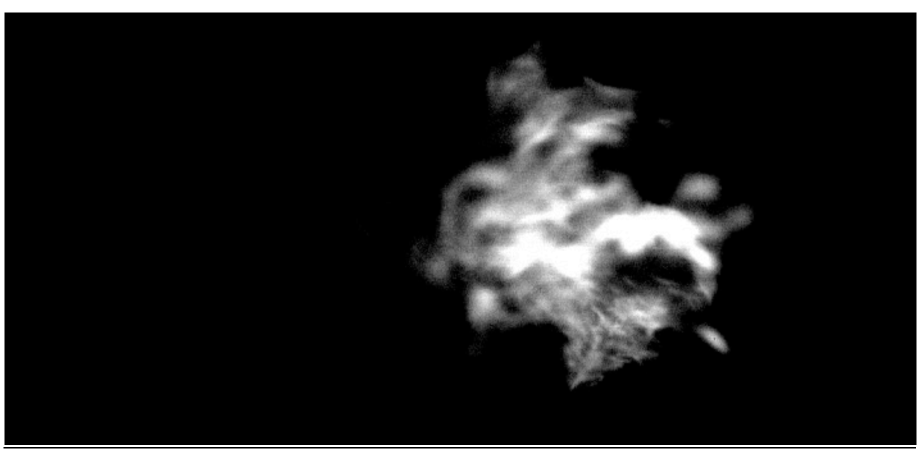

Figure 2. Sample chemiluminescence image of a flame burning n-dodecane at an air preheat temperature of 300 K.

Fourth, data analysis was performed to convert the raw measured data into useful data. In data screening, the combustor operation data were analyzed to identify lean blowout events and associated operating points. Uncertainty analysis was also performed in order to determine the statistical significance of the results. In some cases, the uncertainty analysis results motivated the lean blowout group to acquire additional data in order to reduce the uncertainty. The detailed data were analyzed 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 step was extremely time-consuming and difficult. Post-processing was conducted to produce time-averaged velocity fields, to produce the root mean square velocity field, and to extract key vortical flow features. These post-processed data were then provided to the modeling teams.

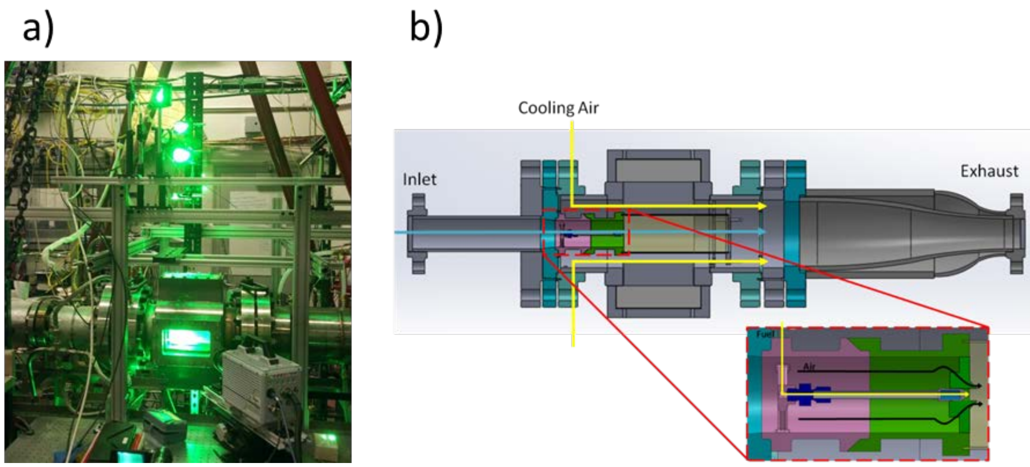

Figure 3. High-shear swirl combustor. a) Pressure vessel instrumented for high-speed stereo particle image velocimetry (PIV) and planar laser-induced fluorescence (PLIF) of OH. b) Cross-section of a generic swirler holder/injector.

A supervised machine learning regression technique was applied to the fuel screening data during the fifth year, with the aim of identifying cause-and-effect relationships between the fuel properties and blowout characteristics. These cause-and-effect relationships are difficult to identify via classical statistics because the fuel properties are strongly intercorrelated, which can lead to inaccurate interpretations.

The regression procedure consisted of a hierarchical non-negative garrote with a two-step approach. First, important groups of variables or parameters, such as “physical properties” or “chemical properties”, are identified. This step requires a physical understanding of the system. Second, a series of regressions are applied to the data based on 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 determined from a cross-validation procedure. During cross-validation, a subset of the data (the training data set) and the regression are tested against the remaining data (the validation data set). This process 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.

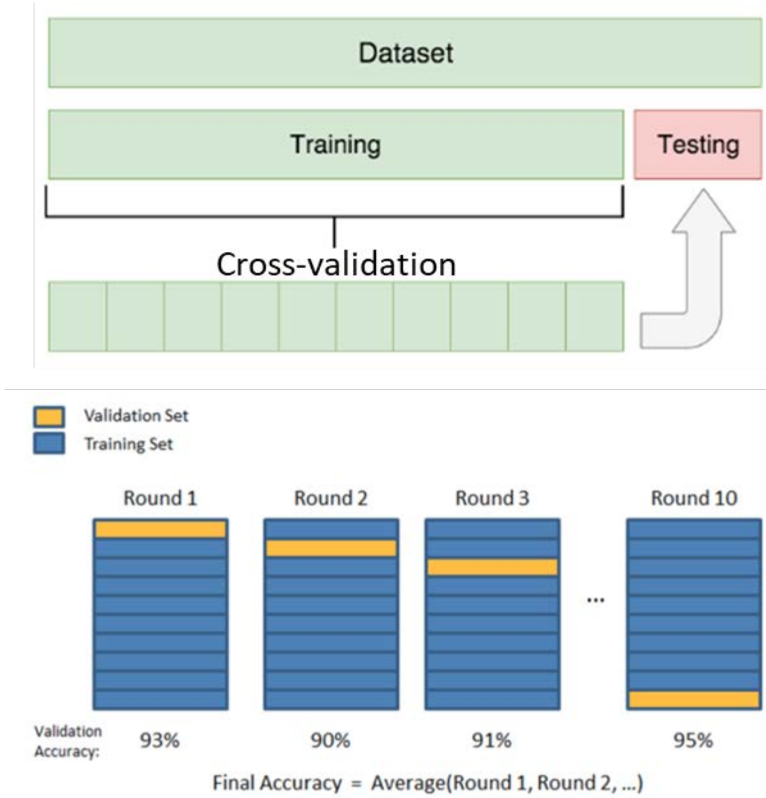

Figure 4. Illustration of the cross-validation procedure.

The results of this analysis indicated that different parameters influence the blowout at different combustor inlet temperatures. These results are shown graphically in Figure 5, which presents the regression coefficients that relate the 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 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 most important individual parameters. Finally, we note that the regression model exhibited the best performance when we adjusted the DCN for the 20% most volatile fuel constituents, which supports the preferential vaporization hypothesis proposed by other teams.

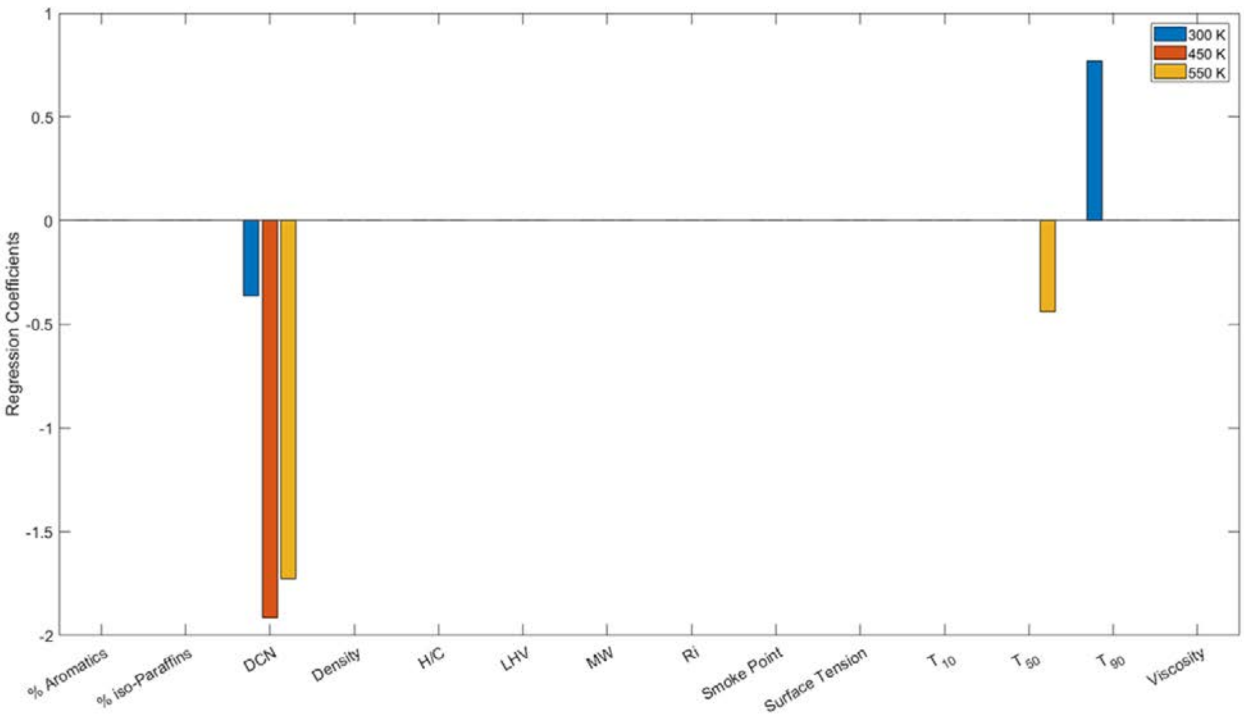

Figure 5. Results of the hierarchical non-negative garrote for three combustor inlet temperatures.

Milestone(s)

- Boundary condition measurements. This step was completed during years 1 and 2.
- Detailed diagnostic measurements. This step was completed during years 1 and 2.
- Data screening. This step was completed during year 4.
- Analysis. This step was completed during year 5.

Major Accomplishments

1. We have developed a data analysis framework that explains the sensitivity of lean blowout to different fuel characteristics. This framework is robust against intercorrelated parameters, and the analysis results support several hypotheses that have been presented by various NJFCP team members.
2. We supported the LBO chapter of the AIAA book during year 5.

Publications

Peer-reviewed journal publications

Emerson, B., and Ozogul, H. 2020. Experimental Characterization of Liquid-gas Slip in High Pressure, Swirl Stabilized, Liquid-fueled Combustors. Accepted for publication in *Experiments in Fluids*.

Rock, N., Emerson, B., Seitzman, J. and Lieuwen, T., 2020. Near-lean blowoff dynamics in a liquid fueled combustor. Combustion and Flame, 212, pp.53-66.

Won, S.H., Rock, N., Lim, S.J., Nates, S., Carpenter, D., Emerson, B., Lieuwen, T., Edwards, T. and Dryer, F.L., 2019. Preferential vaporization impacts on lean blow-out of liquid fueled combustors. Combustion and Flame, 205, pp.295-304.

Wei, S., Sforzo, B. and Seitzman, J., 2018. High-Speed Imaging of Forced Ignition Kernels in Nonuniform Jet Fuel/Air Mixtures. Journal of Engineering for Gas Turbines and Power, 140(7), p.071503.

Chterev, I., Rock, N., Ek, H., Emerson, B., Seitzman, J., Jiang, N., Roy, S., Lee, T., Gord, J. 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.

Won, S. H., Rock, N., Lim, S. J., Nates, S., Carpenter, D., Emerson, B., Lieuwen, T., Edwards, T., Dryer, F. Preferential Vaporization Impacts on Lean Blow-Out of Liquid Fueled Combustors.

Published conference proceedings

Rock, N., Chterev, I., Emerson, B., Won, S.H., Seitzman, J. and Lieuwen, T., 2019. Liquid fuel property effects on lean blowout in an aircraft relevant combustor. Journal of Engineering for Gas Turbines and Power, 141(7).

Rock, N., Emerson, B.L., Seitzman, J. and Lieuwen, T., 2019. Dynamics of Spray Flames under Near-Lean Blowoff Conditions. In AIAA Scitech 2019 Forum (p. 1433).

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.

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).

Rock, N., Chterev, I., Smith, T., Ek, H., Emerson, B., Noble, D., Seitzman, J., Lieuwen, T. "Rreacting Pressureized Spray Combustor Dynamics, Part 1. Fuel Sensitivities and Blowoff Characterization" Proceedings of the ASME Turbo Expo 2016, Seoul, South Korea, 2016, GT2016-56346

Chterev, I., Rock, N., Ek, H., Smith, T., Emerson, B., Noble, D., E. Mayhew, T. Lee, N. Jiang, S. Roy, Seitzman, J., Lieuwen, T. "Rreacting Pressureized Spray Combustor Dynamics, Part 2. High Speed Planar Measurements" *Proceedings of the ASME Turbo Expo 2016, Seoul, South Korea*, **2016**, *GT2016-56345*

Dissertations

Chterev, I. Flow Characterization of Lifted Flames in Swirling, Reacting Flows. Ianko Chterev. August, 2017. PhD Dissertation. Georgia Institute of Technology.

Outreach Efforts

This program provided research opportunities to multiple undergraduate students and one high school student. In addition, one graduate student presented his work on this project at the 2019 AIAA SciTech conference, and one graduate student complete his PhD based 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 was actively involved in the lean blowout experimental effort for all five years. As a PhD student, Dr. Rock was responsible for operating the experimental facility. He led the screening measurements, operated the facility for the detailed diagnostic efforts, and analyzed the screening data. Dr. Rock has completed his PhD and now works for Spectral Energies in Dayton, OH.

Hanna Ek has been involved in the lean blowout effort as a data analysist. Ms. Ek 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 actively involved in the lean blowout experimental effort. His primary responsibility was the design of experimental procedures and support of detailed diagnostic measurements. Dr. Chterev has completed his PhD and now 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 and helped lead the execution of the laser and optical diagnostics. Dr. Mayhew has completed his Ph.D. and now works as a postdoctoral Fellow at the U.S. Army Research Laboratory.

Plans for Next Period

We 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

Performance site: Georgia Institute of Technology

Objective(s)

This year's ignition task had four objectives. The first objective was to expand the database of room-temperature ignition probability measurements, and the second objective was to acquire and analyze ignition probabilities for chilled fuels. The third objective was to characterize the droplet size distribution for a liquid spray, and the fourth objective was to couple liquid droplet heating and vaporization physics to the previously developed perfectly stirred reactor (PSR) model. This enhanced model simulates the spark kernel development process to elucidate the relative effects of chemical reactions, dilution cooling, and droplet heating and vaporization on the ignition process.

Research Approach

The first activity in the ignition task for 2018 was the testing of ignition probabilities for liquid sprays of room-temperature and chilled fuels. This task began with modification of the test facility. The fuel delivery system was modified to provide liquid sprays rather than prevaporized fuels. The most important fuel system modifications include the installation of a solid cone pressure atomizer (fuel injector) near the entrance of the test section and the addition of a fuel chiller. Moreover, 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% and was fine-tuned to prevent fuel droplet impingement on the igniter. Scattering of a HeNe laser from the liquid droplets was measured to monitor the fuel spray trajectory. A schematic of the fuel delivery system is shown in Figure 6.

As the second activity, liquid fuel testing was conducted with a cross-flow air velocity of 10 m/s, an equivalence ratio of φ = 0.55, a cross-flow air temperature of 80 °F, and a pressure of 1 atm. 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 results from previous assessments of prevaporized fuels are also displayed. There are several noteworthy differences between the ignition probabilities of liquid vs. prevaporized fuels; for example, the rankings of the ignition probabilities differ. The ignition probabilities of A3, C2, and C3 are reduced relative to the other fuels when tested as liquid sprays. As another noteworthy difference, the range of probabilities is larger for chilled fuel sprays than for room-temperature fuel sprays.

The differences in the ignition probabilities of liquid sprays vs. prevaporized fuels provide some important insights. For example, the rate-limiting properties of prevaporized fuels should be the chemical properties, because the physical properties govern the vaporization process, which has been bypassed by prevaporization. However, the rate-limiting properties for liquid sprays may include both physical and chemical properties. Therefore, the differences in ignition probability demonstrate the important role of physical properties (such as viscosity, boiling point, etc.) in the ignition of liquid fuel sprays, whereas special attention has been paid to properties that govern vaporization (recovery temperature, vapor pressure) and atomization (viscosity). The correlations between the viscosities and the 10% recovery temperatures for the fuel sprays are shown in Figure 8 and Figure 9.

For the third activity in the ignition task, the droplet distribution was measured via 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 size can play an important role in the phase transition process by affecting the droplet heat transfer process. Therefore, PDPA measurements of droplet size and velocity distribution for an array of fuels were performed. Normalized size distribution data for fuel C3 (high viscosity), A2 (intermediate viscosity), and C5 (low viscosity) at approximately 5 mm above the igniter center are presented in Figure 10. Significant differences in droplet size distributions were observed; for example, the C3 fuel has more droplets in the larger size range (above 30 μm), while the C5 fuel has only a small percentage of droplets in that size range. Thus, the PDPA data can be used for more advanced CFD simulations.

Finally, a reduced-order model was enhanced to study the physics of forced ignition in a liquid fuel spray. The conceptual model construction is shown in Figure 11. In an example case study, forced ignition is simulated in a spray of 5-μm single droplets uniformly distributed with an equivalence ratio of 1. The heat release, dilution cooing, and 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 dilution cooling, and therefore, the droplet is not expected to substantially affect the ignition kernel's temperature during ignition heating. Consequently, the time delay observed before the chemical heat release is likely due to heating of the droplets. If this delay is too long, the kernel will be significantly cooled by dilution, and ignition will not occur.

Milestone(s)

- Produced high-quality, reproducible ignition probability data for room-temperature liquid fuel sprays
- Produced high-quality, reproducible 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 control droplet size and vaporization.
- The acquired droplet distribution data could be useful for CFD models.
- The reduced-order ignition model shows that the magnitude of the droplet cooling effect is small compared to those of the chemical heat release and dilution cooling.

Publications

Peer-reviewed journal publications

Wei, S., Sforzo, B. and Seitzman, J., 2018. High-Speed Imaging of Forced Ignition Kernels in Nonuniform Jet Fuel/Air Mixtures. Journal of Engineering for Gas Turbines and Power, 140(7), p.071503.

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.

Published conference proceedings

S. Wei, B. Sforzo and J. Seitzman, "Fuel Composition Effects on Forced Ignition of Liquid Fuel Sprays," GT2018-77196 Proceedings of the ASME/IGTI Turbo Expo 2018, June 11-14, 2018 Oslo Norway.

Y. Tang, M. Hassanaly, V. Raman, B. Sforzo, S. Wei and J. Seitzman, "Simulation of Gas Turbine Ignition Using Large Eddy Simulation Approach," GT2018-76216 Proceedings of the ASME/IGTI Turbo Expo 2018, June 11-14, 2018 Oslo Norway.

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.

Sforzo, B., Wei, S. and Seitzman, J.M., 2017. Non-premixed Ignition of Alternative Jet Fuels. In 55th AIAA Aerospace Sciences Meeting (p. 0147).

Sforzo, B., Dao, H., Wei, S. & Seitzman, J. "Liquid Fuel Composition Effects on Forced, Non-Premixed Ignition" *Proceedings of the ASME Turbo Expo 2016, Seoul, South Korea*, **2016**, *GT2016-56163*

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 aided in data analysis for prevaporized ignition simulation. Vedant Mehta conducted a parametric study on droplet ignition. John Ryu helped with the multisize droplet ignition study. Sheng Wei graduated with a PhD.

Plans for Next Period
N/A

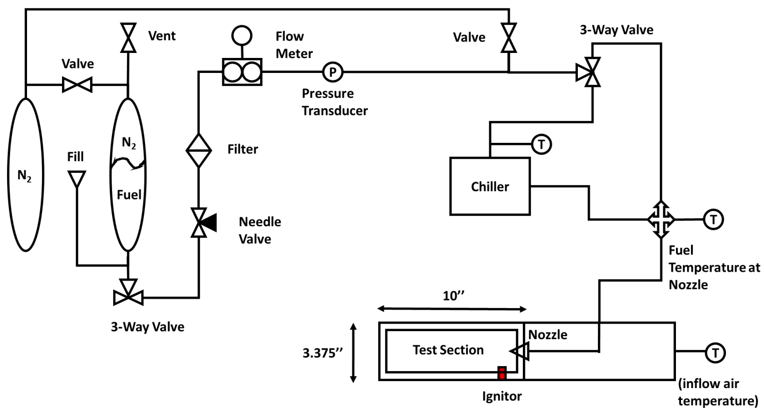

Figure 6. Schematic of the liquid fuel delivery system.

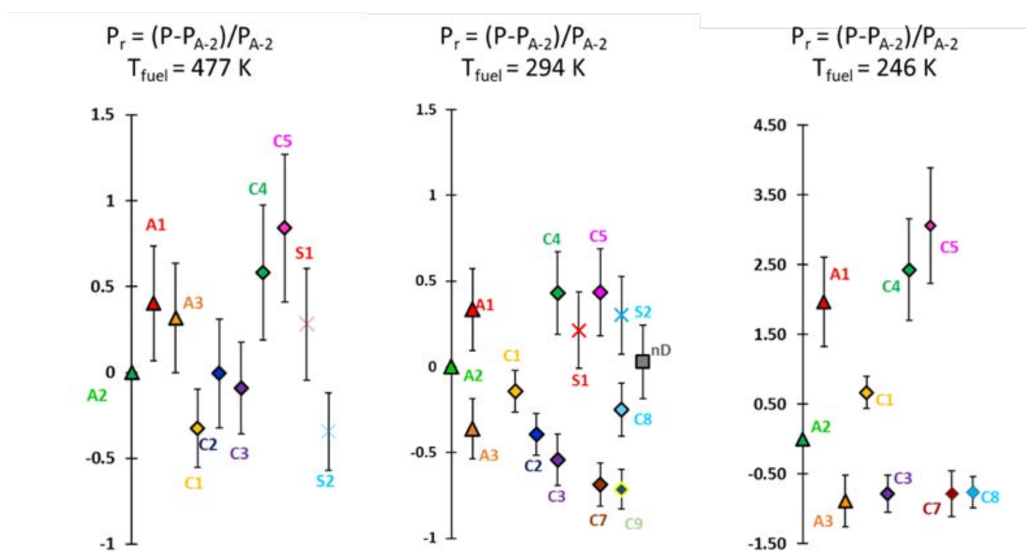

Figure 7. Ignition probability rankings, scaled with respect to the A2 probability. Error bars show 68% uncertainty. Left: prevaporized fuel/air mixture; middle: room-temperature liquid fuel spray; right: chilled liquid fuel spray.

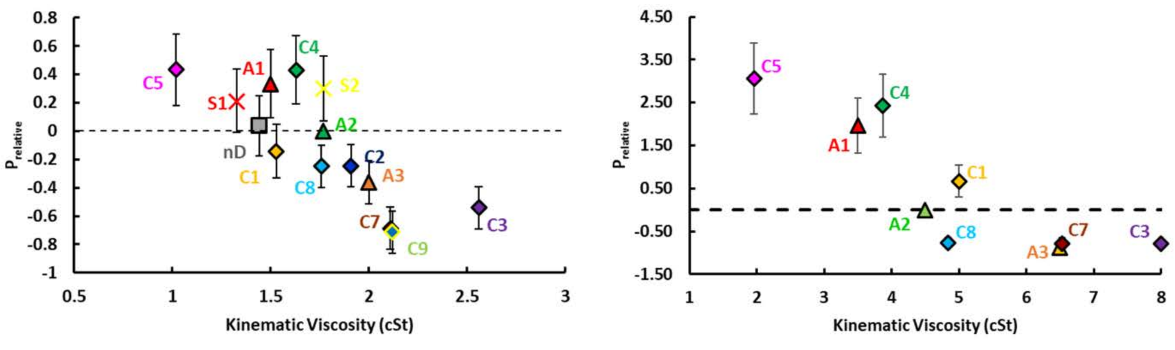

Figure 8. Relative probabilities vs. relative viscosity for room-temperature fuel. Left: probability results for room-temperature fuel spray; right: probability results for chilled fuel spray.

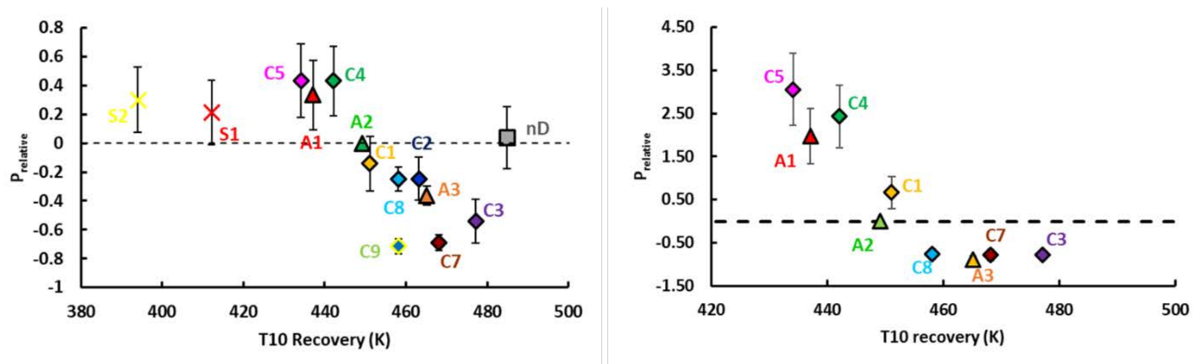

Figure 9. Relative probabilities vs. 10% recovery temperature. Left: probability results for room-temperature fuel spray; right: probability results for chilled fuel spray.

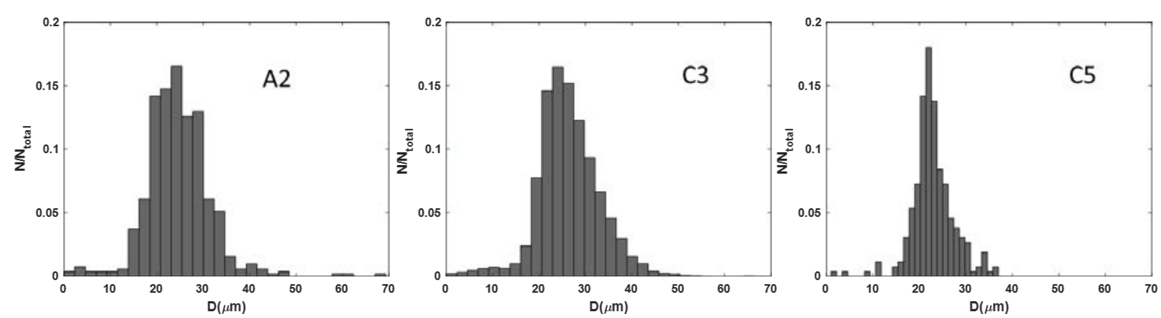

Figure 10. Normalized size distribution at 5 mm above the igniter center.

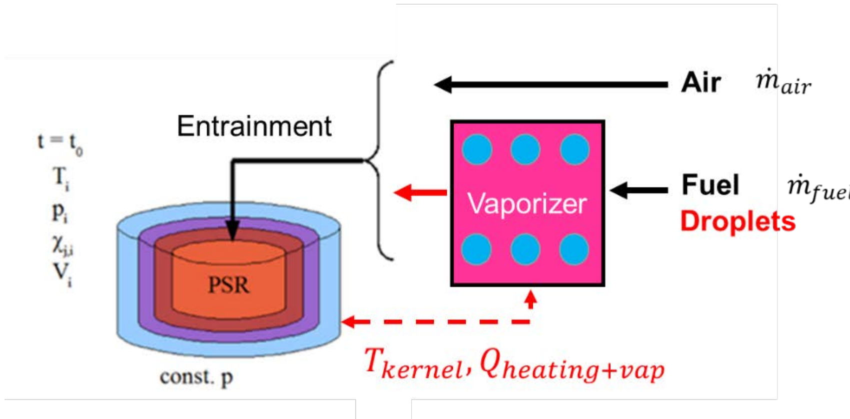

Figure 11. Conceptual perfectly stirred reactor (PSR) model with droplet vaporization.

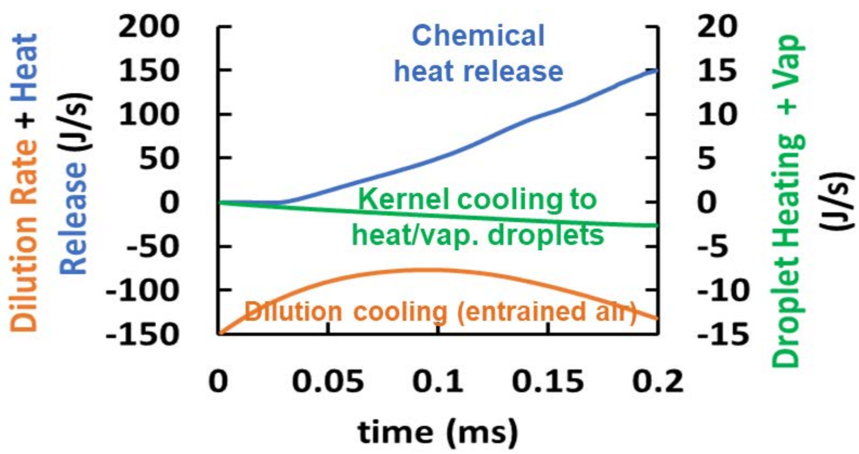

Figure 12. Chemical heat release, dilution cooling, and droplet heating/vaporization rates for a successful ignition of 5-μm droplets at an equivalence ratio of 1.

Task 3- Turbulent Flame Speed

Oregon State University

Objective(s)

This task had three objectives. The first objective was to measure and identify the sensitivity of the turbulent flame speed to fuel composition, for a range of jet fuels and test conditions (including atmospheric and subatmospheric pressures). The second objective was to build a database of turbulent flame speeds for prevaporized jet fuels. This year, we initiated a collaboration with Suresh Menon (GT), who is performing simulations of turbulent flames anchored to a burner. The third objective was to measure the sensitivity of turbulent flames to local extinction.

Research Approach

Testing was conducted using a laboratory test rig that produced turbulent flames. The rig featured a prevaporizer 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 prevaporized jet fuel and air to the burner. The fuel was vaporized using a series of heaters, reaching a temperature near 200 °C. The air/fuel mixture flowed through an adjustable turbulence generator, which produced turbulence intensities (TIs) ranging from 10% to 20% of the bulk flow velocity, independent of the bulk flow velocity. A premixed methane pilot flame was used for ignition and stabilization of the Bunsen burner flame.

Data were collected for three fuels (A2, C1, and C5), and 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 TIs near 20%. Chemiluminescence imaging was performed under all conditions, and high-speed imaging was conducted for a subset of the tests. Chemiluminescence imaging was conducted using a 16-bit intensified charge-coupled device 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-min period at 2 Hz.

The most important accomplishment of this activity was subatmospheric pressure testing (i.e., objective 1), which is important for relight conditions in engines at high altitudes. Figure **13** shows a photograph of a burner operating under subatmospheric conditions. Figure **14** shows measured turbulent consumption speeds for C1, C5, and A2 at 1 and 0.7 atm (left panel) and normalized turbulent consumption speeds (right panel). Note that the flame speeds increase as the pressure decreases, and a fuel sensitivity is observed between C1, C5, and A2. This trend indicates that the relight characteristics for C1, C5, and A2 may differ when an aircraft is at altitude. Further testing of practical systems is required to verify this postulate. It is also noted that although the turbulent consumption speed increases with decreasing pressure, the mass consumption rate of the fuel decreases with decreasing pressure (see Figure **15**), which is consistent with the literature.

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

In the third activity (addressing objective 3), we evaluated a methodology for detecting the onset of local extinction events in the flame brush. Previously in this program, a fuel sensitivity to the onset of flame instability was detected based on large changes in the apparent turbulent flame speed. However, this flame evaluation technique is highly time-consuming, and it is difficult to relate the physics of flame speed measurements to local extinction. During this year, efforts were made to develop a better method to more readily determine breaks in the flame front. High-speed flame images were acquired, and analysis tools were developed to quantify the turbulent statistics of emissions from the flames. Figure 16 provides a representative image of a turbulent statistical parameter (i.e., integral length scale) that was evaluated as a potential metric of the onset of breaks in the flame front. We are currently using the shape of the radial intensity distribution as a marker of flame tip opening. Further testing is required to verify the validity of this approach.

During the fifth year, this task had very modest funding. Hence, we focused on completing data collection and analysis and on reporting and distributing the results. The completed and pending publications resulting from this period and work are shown below. The student funded by this project (Nathan Schorn) completed and defended his thesis.

Milestone(s)

- Nathan Schorn successfully defended his MS thesis.
- Three publications were prepared: two from Mr. Schorn's work and one from research performed by a previous student (Aaron Fillo).
- The experimental arrangement was used to support research for two undergraduate honors theses. One project focused on the manner in which fuel preheating alters flame speeds. The second project focused on measurements of the fraction of radiative heat released by a Bunsen flame with and without dilution.

Major Accomplishments

- Turbulent flame speeds were measured under atmospheric and subatmospheric conditions, exhibiting an evident fuel sensitivity.
- The flame extinction was found to be sensitive to fuel composition. This finding may be important for the program's lean blowout tasks, which aim to understand how ignition and extinction influence the lean blowout process.
- It was found that the surrogate fuel (S1) has flame speeds similar to that of Jet A fuel.

Figure 13. Photograph of a flame in a pressure vessel under subatmospheric conditions.

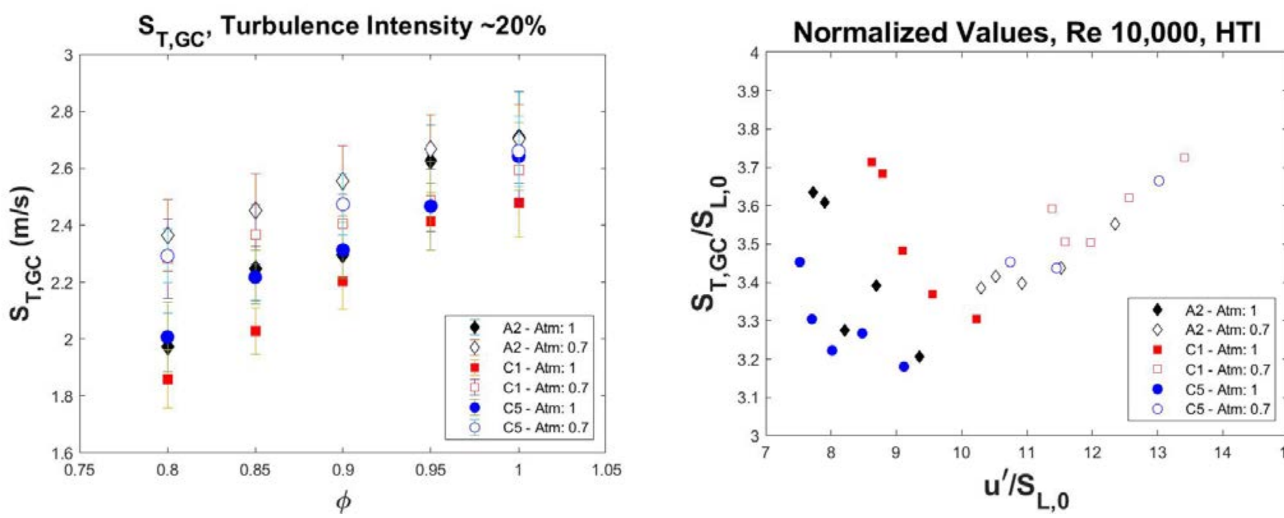

Figure 14. Turbulent consumption speeds (left) and normalized turbulent consumption speeds (right) for A2, C1, and C5 at 1 and 0.7 atm.

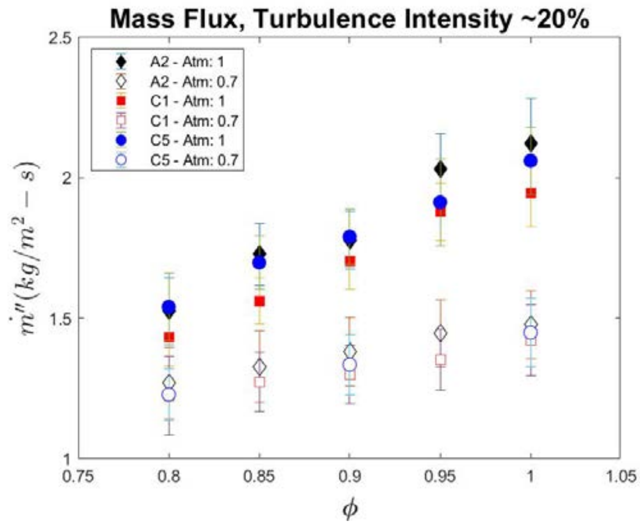

Figure 15. Mass consumption speeds of jet fuels at 1 and 0.7 atm.

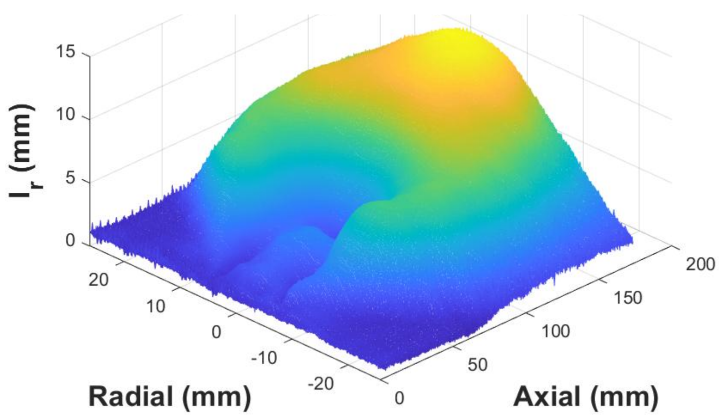

Figure 16. Radial integral length scale of visible light emissions from a turbulent Bunsen burner flame with A2 fuel. Such statistics have been considered as potential markers of the onset of openings in the flame brush.

Publications

Published conference proceedings

Schorn, N., Bonebrake, J., Pendergrass, B., Fillo, A., & Blunck, D. (2019). Turbulent consumption speed of large hydrocarbon fuels at sub-atmospheric conditions. AIAA Science and Technology Forum and Exposition 2019, San Diego, CA

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

Fillo, A., Bonebrake, J., Blunck, D. “Impact of Fuel Chemistry and Stretch Rate on the Global Consumption Speed of Large Hydrocarbon Fuel/Air Flames,” Western States Section Meeting of the Combustion Institute, (2017).

Fillo, A., Blunck, D., “Effects of Fuel Chemistry and Turbulence Intensity on Turbulent Consumption Speed for Large Hydrocarbon Fuels,” Western States Section of the Combustion Institute, Fall 2015.

J. Bonebrake, A. Fillo, D. Blunck, "Effect of Turbulent Fluctuations on Radiation Emissions from a Premixed Flame," Western States Section Meeting of the Combustion Institute, Provo, UT (2015).

E. Zeuthen, D. Blunck, "Radiation emissions from Turbulent Diffusion Flames Burning Large Hydrocarbon Fuels," Western States Section Meeting of the Combustion Institute, Provo, UT (2015).

E. Zeuthen, D. Blunck, "Radiation Characteristics of Turbulent Diffusion Flames Burning Alternative Aviation Fuels," 9th US Combustion Meeting, Cincinnati, OH (2015).

Dissertations

Fillo, A.J., 2016. The Global Consumption Speeds of Premixed Large-Hydrocarbon Fuel/Air Turbulent Bunsen Flames.

Outreach Efforts

N/A

Awards

Fillo, A. (2016). The global consumption speeds of premixed large-hydrocarbon fuel/air turbulent Bunsen flames. Oregon State University, 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 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, an MS student, has collected and analyzed data.

Multiple undergraduate students, including under-represented students, have worked with graduate students to operate the burner and to collect data, providing a significant opportunity for undergraduates to engage in 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. As our second contribution, we will support the LBO book chapter as needed. Our team has previously provided content for the introduction to the LBO section, and we will gladly help to revise the introduction or provide new content as requested.