Project 027(B) 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: 12/1/2016 to 11/30/2017
- Task(s):
  - Task #1 - Lean Blowout. This task measures the lean blowout characteristics of alternative jet fuels and compares them to the lean blowout 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: 12/1/2016 to 11/30/2017
- Tasks:
  - 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
FAA Funding: $300,000
Cost Share: $300,000 provided by Georgia Institute of Technology

Oregon State University
FAA Funding: $80,000
Cost Share: $80,000 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. 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 & 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 & safety of graduate students.
Brandon Sforzo (Georgia Institute of Technology): Postdoctoral Fellow. Dr. Sforzo is the lead experimentalist in the ignition task. Dr. Sforzo left Georgia Tech during year 3.
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.
Ianko Chterev (Georgia Institute of Technology): Graduate Student. Dr. Chterev assisted with the diagnostics for the lean blowout task. Dr. Chterev graduated during year 3.
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.
Aaron Fillo (Oregon State University): Graduate Student. Mr. Fillo was the lead grad student experimentalist on the turbulent flame speed task. He is no longer working on this project.
Jonathan Bonebrake (Oregon State University): Graduate Student. Mr. Bonebrake is currently 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.
Rajavasanth Rajasegar (Graduate Student, University of Illinois at Urbana-Champaign): Graduate Student. Mr. Rajasegar led the optimization of laser diagnostics during year 1.
Brendan McGann (Graduate Student, University of Illinois at Urbana-Champaign): Graduate student. Mr. McGann executed the laser and optical diagnostics at GATech during year 1.

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 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 tested fifteen different pure fuels, known to the program as: A1, A2, A3, C1, C2, C3, C4, C5, S1, S2, 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 two different sets of blends: A2/C1 blends and A2/C5 blends. 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 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

Georgia Institute of Technology

Objective(s)

The objective of this task was to obtain two types of measurements in a combustor rig operating near lean blowout. 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 developing 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 1. The rig was 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 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.

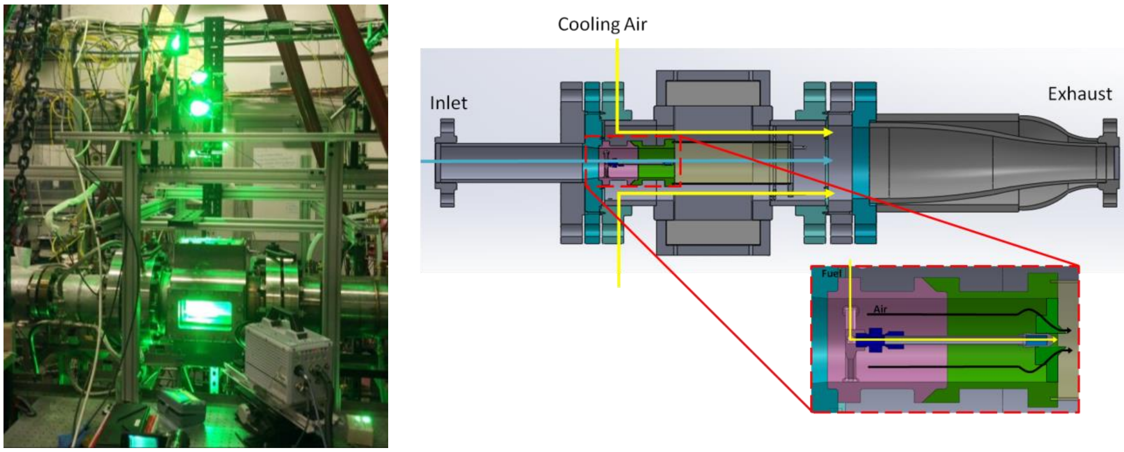


Figure 1. High shear swirl combustor, showing a) pressure vessel instrumented for high speed stereo PIV and OH PLIF, and b) a cross section with generic swirler holder/injector for illustrative purposes

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 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. 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 in order 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.

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 3 has been completed and is being analyzed to extract physical insight.
3. **Screening data.** This has been completed for all planned cases and is being analyzed and 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.

Major Accomplishments

1. To date, we have expanded our screening dataset which consists of several thousand lean blowout measurements.
2. We have demonstrated that the cetane number nicely captures the lean blowout risk of a given fuel (see Figure 2), especially at higher temperatures.
3. We have demonstrated an intermittent burning stage that occurs on the approach to lean blowout. This provides an important qualitative picture for blowout simulations (see Figure 3 for a sample chemiluminescence image from this diagnostic).

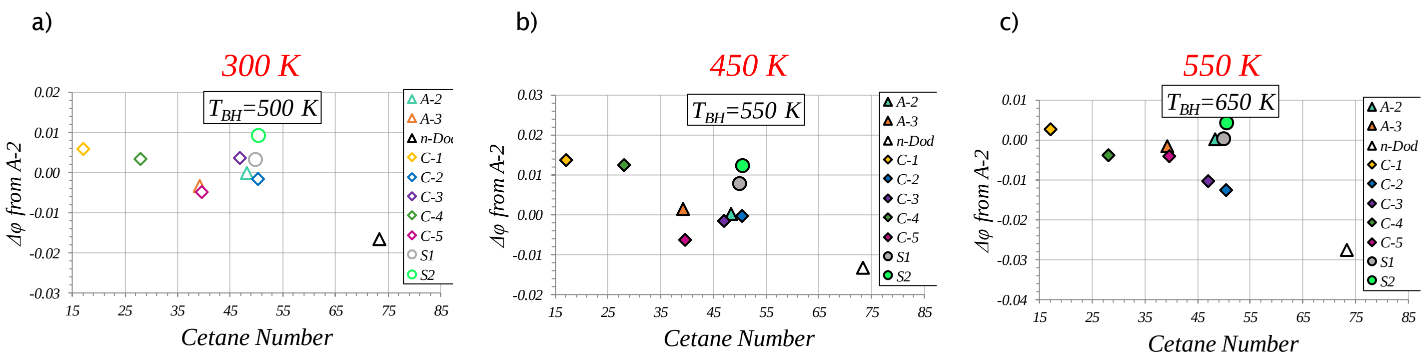


Figure 2. Sample of year 3 screening data at three different preheat temperatures and three different bulkhead temperatures, demonstrating the strong correlation of lean blowout with the cetane number

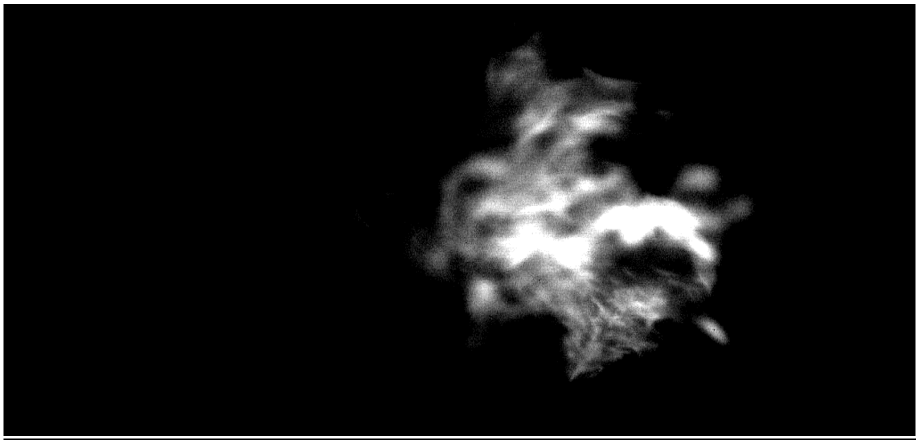


Figure 3. Sample flame chemiluminescence image from n-dodecane burning at 300 K air preheat temperature.

Publications

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.

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

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

Outreach Efforts

We have provided research opportunities to undergraduate students and a high school student with this program. We have submitted a paper for the 2018 ASME Turbo Expo 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.
- 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.
- 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.

Plans for Next Period

Four new activities are planned for the next period. These activities are very closely related to the current period's activities. The first of these activities is the analysis of the year 3 chemiluminescence data. Early analysis of the chemiluminescence data showed clear evidence of both ignition and extinction as the combustor approached lean blowout. Evidence of extinction and ignition were most pronounced for the n-dodecane fuel, which had a vastly different cetane number than the other fuels. This is especially interesting, since this program has strongly hypothesized that the cetane number is the most important fuel property for assessment of lean blowout risk. Therefore, we see strong potential for the chemiluminescence data to support this hypothesis. Since the chemiluminescence data are relatively new, much of their analysis has been qualitative. Therefore, analysis efforts in the next period will quantify the rate of extinction and ignition during lean blowout. This will be repeated for all fuels so that the extinction and ignition rates can be correlated to the cetane number. This correlation will test the hypothesis that the cetane number is an important fuel property for assessment of blowout risk. We also hope that this activity will help us answer four important questions that the community has asked about the blowout process:

- What is the primary mode of flame anchoring near blowout?
- How broad in equivalence ratio is the extinction/ignition stage, and is this fuel-dependent?
- Are the statistics (extinction event arrival rates, durations, etc.) of this intermittent burning stage fuel-dependent?
- Does it make more sense to correlate fuel properties with the onset of the intermittent burning stage than with the terminal blowout event?

The analysis task outlined above will need additional data to answer those four questions. Therefore, the second activity will generate additional data to answer those questions. These two activities (analysis and measurement) are anticipated to occur iteratively to fine-tune the measurements. For example, preliminary analysis of the detailed data have shown that we will need some high repetition rate chemiluminescence images to answer the flame anchoring physics question, and analysis of photomultiplier tube (PMT) data have shown that we will need longer PMT records, particularly at higher air preheat temperatures. Therefore, we have included a task to measure improved datasets based on the results of year 3 data analysis.

The third activity will be additional fuel screening. The goal of this additional screening will be to address the inter-correlation of fuel properties. The inter-correlation of fuel properties has historically been a challenge for this program, because fuels that have one extreme property tend to have many extreme properties. For example, fuels with especially low T10 boiling points tend to also have low flash points, low aromatic content, and high cetane numbers. This makes it difficult to determine which property causes the blowout risk. In year 3, the program started to address this through the introduction of neat n-dodecane, which has an extremely high cetane number but which does not have other extreme property values. This demonstrated the value of fuels that have been carefully selected or engineered to possess targeted physical or chemical properties. These targeted properties can be selected in order to break the inter-correlation of fuel properties. The program has developed several new fuels to accomplish this. Some of these fuels have already arrived at Georgia Tech. The year 4 screening activity will therefore test these new fuels to expand the fuel screening database. This expanded database will help determine which fuel properties are truly correlated to lean blowout risk.

The fourth activity will be measurements of additional boundary conditions as needed by modeling groups. This potentially has very large scope, and thus will be limited to the available resources of year 4. However, we acknowledge that this will be an important activity and will make every attempt to characterize additional wall temperatures, exhaust temperatures, spray behavior, or other items which may not yet be characterized but which may be needed to refine the models.

Task #2: Ignition

Georgia Institute of Technology

Objective(s)

The ignition task had three objectives. The first objective was to analyze the prior year's data to better understand the kernel ignition process. This is important for the development of ignition models. The second objective was to acquire and analyze ignition probability data for liquid fuel sprays (in prior years we investigated only pre-vaporized fuels). This is important, because ignition poses the greatest risk at conditions where the fuel does not vaporize. The third objective was to develop a chiller to enable ignition testing of cold fuels. This is important because ignition is an even greater challenge with cold fuels.

Research Approach

During its third year, the ignition task approached its goals through three activities. The first activity was analysis of the prior year's detailed diagnostic imaging data. The detailed imaging included data from three high speed, synchronized diagnostic methods: Schlieren, planar laser-induced fluorescence (PLIF), and chemiluminescence. The acquisition rate was 10 kHz. Three pre-vaporized fuels were investigated with these techniques: A2, C1, and C5. Figure 4a presents an example of the raw data. The top row of Figure 4a shows an example of the chemiluminescence data, and the middle row of Figure 4a presents an example of the PLIF data. These measurements show that chemical reactions occur in the highly mixed regions of the vortical kernel structure. The PLIF measurement indicates that chemical reactions occur within tens of microseconds of the ignition kernel interaction with the fuel/air mixture. The bottom row of Figure 4a presents an example of the Schlieren images. These are useful for assessment of the plasma development. The images show the initial rapid volumetric growth of the hot plasma kernel after it is ejected from the igniter. The rapid growth is due to the mixing of the high temperature kernel gases with surrounding fluid. This entrainment of cold surrounding fluid results in a rapid reduction of the kernel's temperature. Consequently, the chemically active region of the kernel decays substantially after 400-500 μs. In cases where there is successful ignition (as seen in Figure 4a), these kernels eventually grow and transition into a self-sustaining flame (as verified by PLIF and chemiluminescence images from later times). This competition between cooling/entrainment and chemical heat release determines the outcome of an ignition event.

The chemiluminescence images also provide insight into the temporal development of the ignition kernel intensity. Figure 4b presents these results for successful ignition events. The results show an initial decrease in intensity (due to early air entrainment and cooling) followed by an increase in intensity (due to chemical heat release). The time at which the minimum intensity is observed indicates when flame growth becomes dominant. Interestingly, C1 exhibited the longest delay until flame growth dominated. This is interesting because C1 also had the lowest ignition probability in earlier screening studies. This correlation between long delay times and low ignition probabilities suggests the importance of early chemistry. This provides important guidance to the chemical kinetics community, since the early chemistry for this problem is classified as high temperature chemistry. Therefore, successful ignition modeling will likely require accurate high temperature chemistry models.

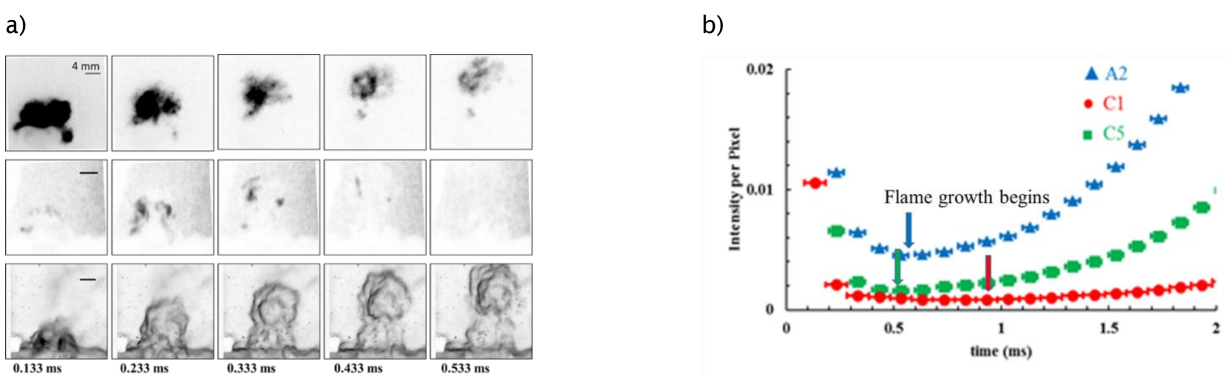


Figure 4. a) High-speed diagnostic imaging of a successful ignition event in pre-vaporized A2. Top row shows chemiluminescence images; middle row shows PLIF images; bottom row shows Schlieren images. Images from each row are spatially registered and temporally synchronized. Spark discharge occurs at $t = 0$ ms. b) Spatially integrated chemiluminescence for successful ignition events with fuels A2, C1, and C5. The points with lowest intensity are defined to be markers for the start of flame growth.

The second activity in the ignition task was to test ignition probabilities of liquid sprays. 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 modification was the installation of a solid cone pressure atomizer (a fuel injector) near the entrance to the test section. Also, the splitter plate was removed from the test rig to provide a single fresh 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. Therefore, the injector positioning was selected empirically. This empirical process used a HeNe laser-based Mie scattering measurement to monitor the spray trajectory. Figure 5a shows an example of the spray imaging.

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. Ignition probabilities were measured for eleven different fuels: A1, A2, A3, C1, C2, C3, C4, C5, S1, S2, and n-dodecane. Each of these fuels was tested as a liquid spray. The ignition probabilities of each fuel relative to A2 are shown in Figure 5b. 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 when tested as liquid sprays. Another noteworthy difference is the reduction of fuel sensitivity.

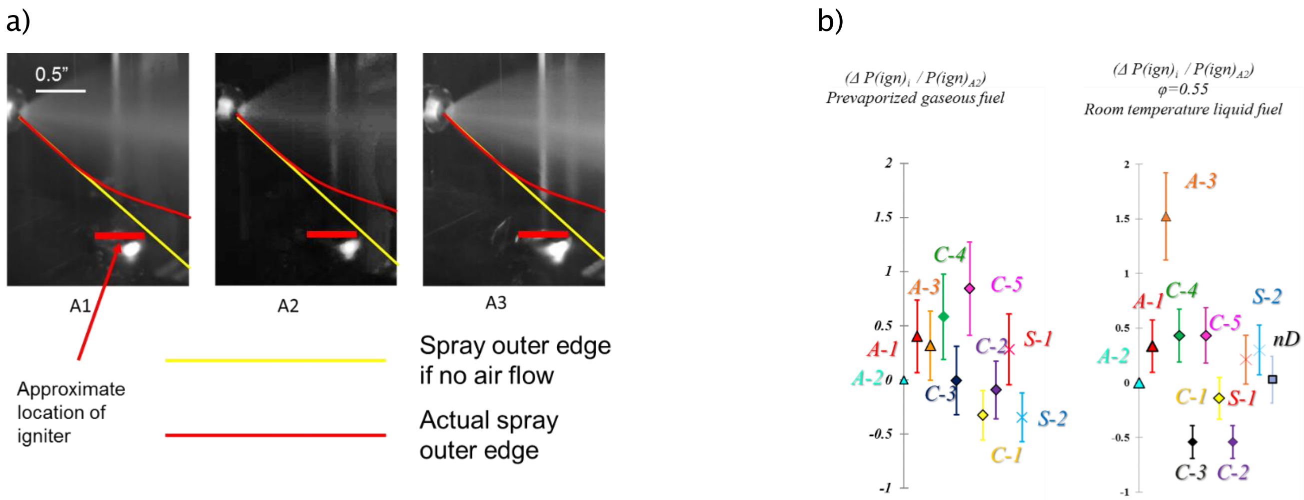
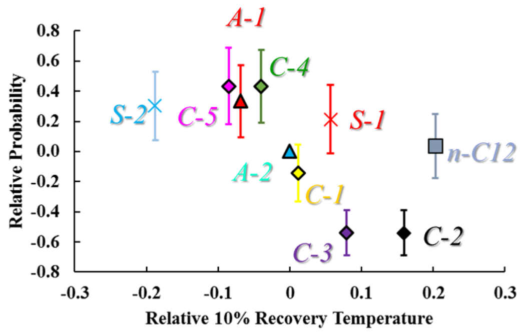


Figure 5. a) Spray pattern of fuels A1, A2, and A3 under broadband scattering. b) Relative ignition probability from pre-vaporized tests (left) and room temperature spray test (right).

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. Currently, this activity is trying to correlate ignition probability to physical properties. Special attention has been paid to properties that govern vaporization (recovery temperature, vapor pressure) and atomization (viscosity). An example from this work is shown in Figure 6a. Pearson correlation results (Figure 6b) indicated strong correlations to vaporization and atomization properties, and they indicated weaker correlations to chemical properties such as auto-ignition delay time and aromatic concentration.



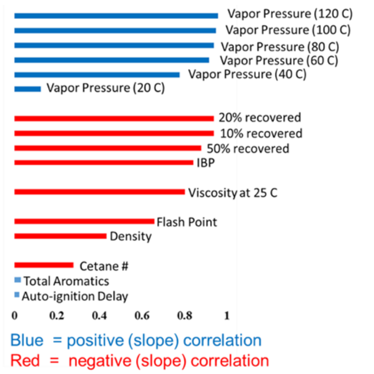


Figure 6. a) Ignition probabilities as a function of the 10% recovery temperature. b) Pearson correlation results for ignition probability versus fuel properties.

The third activity in the ignition task was to develop a fuel chiller. The fuel chiller system is shown schematically in Figure 7. The chiller uses a mixture of propylene glycol and water to control the fuel temperature. This is accomplished by submerging dry ice in the mixture. Since the dry ice is colder than the freezing point of the mixture, this begins to freeze the mixture. The mixture remains at its freezing point throughout the freezing process. In this way, the phase change (freezing) of the mixture is used to control the mixture temperature. This maintains a mixture temperature of -50 F. Fuel is routed through a heat exchanger that is submerged in the -50 ˚F mixture. By the time the fuel reaches the fuel injector, its temperature is -19 ˚F. This low temperature capability is important, because viscosities (and therefore atomization characteristics) are very different at low temperatures versus room temperature.

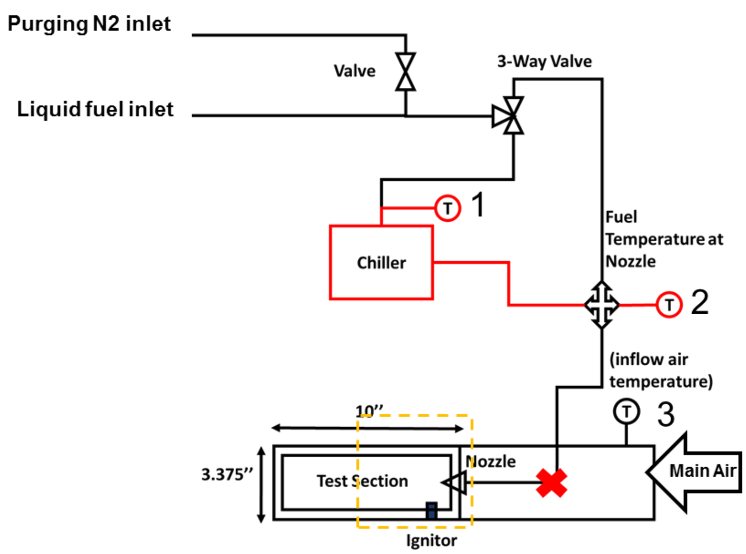


Figure 7. Schematic of fuel spray test setup with fuel chiller system.

Milestone(s)

- Achieve repeatable liquid fuel testing procedures. This milestone was completed early in the year when we began testing liquid sprays.
- Post-process year 2 detailed data. This has been completed, and significant understanding of ignition in stratified flow fields was gained.
- Ignition probability data for room temperature fuel spray. Ignition probability data were acquired for A1, A2, A3, C1, C2, C3, C4, C5, two surrogate fuels (S1 and S2) and n-dodecane.
- Probability data analysis. This has been completed.

- Final data archiving. The final data were uploaded to KSN.

Major Accomplishments

- Entrainment cooling and local chemical reactions were observed with high speed imaging. This enabled reduced order modeling by confirming the competition between entrainment cooling and chemical heat release during ignition.
- Room temperature liquid fuel ignition probability data were measured. The data show strong positive correlation to properties controlling vaporization and atomization, and only weak correlation was found among ignition probabilities and chemical properties.
- A fuel chiller was developed. The chiller can deliver fuels to the rig at -19 ˚F.

Publications

Wei, S., Sforzo, B., and Seitzman, J., 2017, "High Speed Imaging of Forced Ignition Kernels in Non-Uniform Jet Fuel/Air Mixtures," *ASME Turbo Expo 2017: Turbomachinery Technical Conference and Exposition*, Charlotte, NC, USA

Sforzo, B., Wei, S., and Seitzman, J., 2017, "Non-premixed Ignition of Alternative Jet Fuels," AIAA SciTech Forum, Grapevine, Texas, USA

Outreach Efforts

Conference presentation at ASME Turbo Expo 2017, Charlotte, NC, USA
Conference presentation at AIAA SciTech Forum 2017, Grapevine, Texas, USA

Awards

ASME Young Engineer Turbo Expo Participation Award

Student Involvement

- Sheng Wei has been actively involved in the Task 2 detailed diagnostic effort. Sheng supported the ignition probability measurement collection and was the primary student responsible in fuel spray ignition probability data. Sheng is also the lead student involved in design and modification of rig.
- Jared Delrose has been actively involved in ignition probability data acquisition and rig design.
- Daniel Cox has been actively involved in rig design and modification.

Plans for Next Period

Four activities are planned for the next period. The first activity will be to obtain data for the chilled liquid fuel. This will implement the new fuel chiller that was developed during the current period. The second activity will be to characterize the fuel spray. This characterization will be performed for room temperature fuel and chilled fuel. These spray characterizations will be compared to confirm the impact of fuel temperature on fuel atomization. The third activity will be to produce a reduced order model of ignition probabilities of liquid sprays. In prior years the ignition task has had good success with the development of such models for pre-vaporized fuels. In the next period, we will use the data from the first two activities to expand these models for liquid sprays. The fourth activity will be to perform additional ignition probability screening as required by the program. Several new fuels have already been designed by the program, and some of these have been delivered to Georgia Tech. Therefore, this activity will test the new fuels.

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. 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. The third objective was to measure the sensitivity of turbulent flames to local extinction.

Research Approach

Two activities were conducted under the turbulent flame speed task. The first activity was experimental testing. Experimental testing was conducted in a laboratory test rig. The test rig was designed to produce turbulent flames. The rig featured a pre-vaporizer based on designs developed by the Air Force Research Lab, and a burner based on designs developed by Lieuwen and colleagues. The experimental setup 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 ºC. The air/fuel mixture flowed through an adjustable turbulence generator which produced turbulence intensities ranging from 10% to 20% of the bulk flow velocity. Turbulence intensity (TI) is independent of bulk flow velocity. A premixed methane pilot flame was used for ignition and to stabilize the Bunsen burner flame.

Data were collected for each three fuels (A2, C1 and C5). Test conditions included a range of Reynolds numbers (5,000<Re<10,000), a range of equivalence ratios ($0.75 \leq \Phi \leq 1.0$), and a range of turbulence intensities ($10\% \leq TI \leq 20\%$). The test data consisted of chemiluminescence imaging. 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 collected over a 3 minute period at 2 Hz.

The most important accomplishment of this activity was sub-atmospheric pressure testing. Measurements of turbulent flame speeds at sub-atmospheric conditions were enabled by the design and fabrication of a pressure vessel and vacuum system. The vessel can currently operate down to 0.6 atm, although lower pressures are anticipated in the future. Figure **8** shows a photograph of the rig operating at sub-atmospheric conditions.

Figure 8. Picture of flame operating in pressure vessel at sub-atmospheric conditions.

The second activity was data analysis. Data analysis was conducted to determine the time-averaged flame position. To accomplish this, the line-of-sight images were first time-averaged and then background-subtracted. Next, the images were checked to verify symmetry and they were median filtered. Finally, a three-point Abel deconvolution was applied. The results of this process were subjected to an edge detection algorithm. The output of the edge detection algorithm was defined as the time-averaged flame position. The height of this time-averaged flame position determines the turbulent flame speed. This process is illustrated by the sequence of images in Figure 9. Its estimated uncertainty is 1%-2% [1]. An example of turbulent flame speed results for several fuels is presented in Figure 10.

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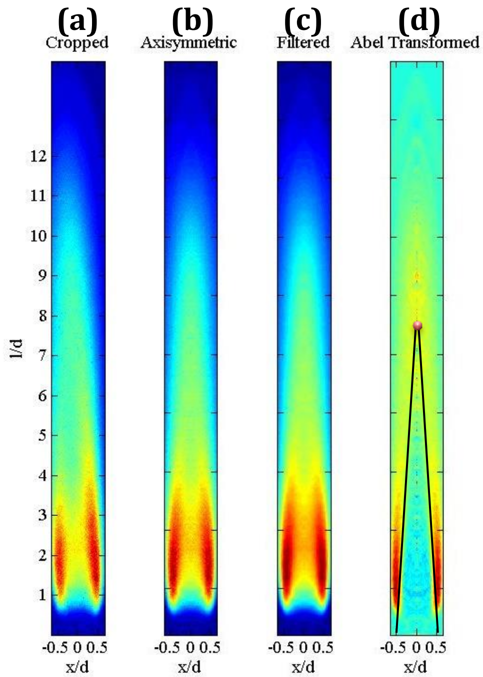

Figure 9. Step-by-step summary of image processing approach, showing (a) time-averaged and background subtraction (b) axi-symmetry verification (c) 2-D median filtering (d) Abel deconvolution with time-averaged flame position drawn.

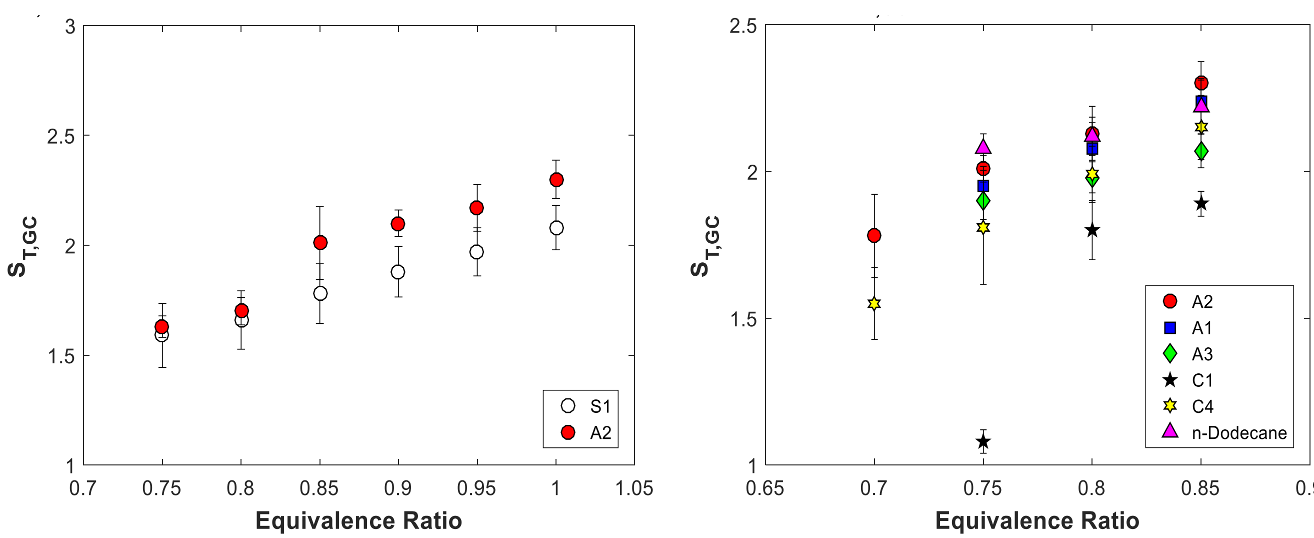

Figure 10. Turbulent consumption speeds for A2 and S1 (left panel) and a variety of other fuels (right panel). Data shown in the right panel were used to identify sensitivities to local extinction. The lowest equivalence ratio shown was the last equivalence ratio prior to local extinction being identified.

Milestone(s)

- An initial test campaign evaluating local extinction events was completed.
- Turbulent flame speeds for conventional and surrogate fuels were determined.

Major Accomplishments

- We have made the observation that the turbulent flame speeds of Jet-A and the surrogate fuels are similar.
- We have made the observation 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.

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 recently started and has transitioned to leading the effort to operate the burner and collect and analyze data.
- Multiple undergraduate students, including underrepresented students have worked with the graduate students to operate the burner and collect data. This has provided a significant opportunity for the students to experience research.

Plans for Next Period

Two activities are planned for the next period. The first activity will be additional measurements of turbulent flame speeds. This activity will utilize the recently developed sub-atmospheric testing capability. This activity will also focus on the fuels that the program determines to be of interest. The second activity will be analysis of the flame extinction observations. For example, flame extinction behavior will be compared to the lean blowout data from Georgia Tech. The results of this activity will determine if turbulent flame speed testing can provide early insight into the risk of lean blowout.

References

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