Project 027(B) Advanced Combustion (Area #3)

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

Project Lead Investigator

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    - Professor Jerry Seitzman
    - Professor Wenting Sun
- FAA Award Number: 13-C-AJFE-GIT-008
- Period of Performance: 12/1/2014 to 11/30/2015
- Task(s):
    1. Task 1. Blowoff
    2. Task 2. Ignition

Oregon State University

- P.I.(s): David Blunck
- FAA Award Number: 13-C-AJFE-OSU-02
- Period of Performance: 12/1/2014 to 11/30/2015
- Tasks:
    3. Task 3. Turbulent Flame Speed

University of Illinois at Urbana-Champaign

- P.I.(s): Tonghun Lee, Associate Professor
- FAA Award Number: 13-C-AJFE-UI-005
- Period of Performance: 12/1/2014 to 11/30/2015
- Task(s):
    4. Optimize and apply laser diagnostics for application in the advanced combustion tests at GATech.

Project Funding Level

Georgia Institute of Technology
FAA Funding: $350,000
Cost Share: $350,039 provided by Georgia Institute of Technology

Oregon State University

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

University of Illinois Champaign
FAA Funding: $40,000
Cost Share: $40,039 provided by University of Illinois Champaign

Investigation Team

Tim Lieuwen (Georgia Institute of Technology): Principal Investigator. Professor Lieuwen is the PI overseeing all tasks, and is manager of Task 1. Blowoff
Jerry Seitzman (Georgia Institute of Technology): Co-Principal Investigator. Professor Seitzman is the manager of Task 2. Ignition
David Blunck (Oregon State University): Co-Principal Investigator. Professor Blunck is the manager of Task 3. Turbulent Flame Speed
Fred Dryer: Co-Principal Investigator. Professor Dryer is acting as an expert consultant on alternative jet fuel chemistry
Wenting Sun (Georgia Institute of Technology): Co-Principal Investigator. Professor Sun is acting as an internal expert consultant on kinetic mechanisms
Tonghun Lee (University of Illinois Champaign): Co-Principal Investigator. Professor Lee is the lead diagnostic expert.
Bobby Noble (Georgia Institute of Technology): Research Engineer. Mr. Noble is responsible for designing and maintaining experimental facilities, as well as experimental operations and management & safety of graduates students.
Benjamin Emerson (Georgia Institute of Technology): Research Engineer. Dr. Emerson is responsible for designing and maintaining experimental facilities, as well as experimental operations and management & safety of graduates students. He is also acting as the administrative coordinator for all three tasks.
David Wu (Georgia Institute of Technology): Research Engineer. Mr. Wu is responsible for designing and maintaining experimental facilities, as well as experimental operations and management & safety of graduates students.
Brandon Sforzo (Georgia Institute of Technology): Postdoctoral Fellow. Dr. Sforzo is the lead experimentalist in Task 2. Ignition
Glenda Duncan (Georgia Institute of Technology): Administrative Staff. Mrs. Duncan provides administrative support.
Tiwanna Williams (Georgia Institute of Technology): Administrative Staff. Mrs. Williams provides administrative support.
Seth Hutchins (Georgia Institute of Technology): Lab Coordinator. Mr. Hutchins maintains the core lab facilities and provides technician services.
Machine Shop Staff (Georgia Institute of Technology). The Aerospace Engineering machine shop provides machining services for experimental facility maintenance/construction
Nick Rock (Georgia Institute of Technology): Graduate Student. Mr. Rock is the lead rig operator in Task 1. Blowoff
Ianko Chterev (Georgia Institute of Technology): Graduate Student. Mr. Chterev is the lead diagnostitian in Task 1. Blowoff
Hanna Eck (Georgia Institute of Technology): Graduate Student. Ms. Eck is the lead data analyst in Task 1. Blowoff
Sheng Wei (Georgia Institute of Technology): Graduate Student. Mr. Wei is a research assistant under Task 2. Ignition
Aaron Fillo (Oregon State University): Graduate Student. Mr. Fillo was the lead grad experimentalist in Task 3. Turbulent Flame Speed
Jonathan Bonebrake (Oregon State University): Graduate Student. Mr. Bonebrake is the lead grad experimentalist in Task 3. Turbulent Flame Speed
Eric Mayhew (University of Illinois Champaign): Graduate Student. Mr. Mayhew executes laser and optical diagnostics at Georgia Tech.
Rajavasanth Rajasegar (University of Illinois at Urbana-Champaign): Graduate Student. Mr. Rajasegar performs optimization of laser diagnostics strategy.
Steve Hammack (University of Illinois Champaign): Graduate Student. Mr. Hammack executes laser and optical diagnostics at Georgia Tech.

Project Overview

The objective of this activity is to provide advanced combustion testing support to the FAA's alternative jet fuels program. We are performing advanced combustion testing to accomplish two goals. The first goal is to screen candidate jet fuels for sensitivities of their burning properties to fuel physical and chemical properties. The second goal is to provide empirical data to combustion modeling partners to facilitate the refinement and validation of their models, which aim to develop predictive capability for fuel composition sensitivities. The success of this program will substantially accelerate the efforts of the FAA and the OEMs to certify alternative, fit for purpose fuels.

In the first year of the program, we have tested A1, A2, and A3 fuels, as well as all five Category C fuels and n-dodecane. During this first year, we had proposed three tasks that address the most critical challenges associated with advanced combustion model development and differentiating differences in fuel chemistries:

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

Each task has a strong focus on supporting model development and evaluating fuels, and a strong connection to understanding engine operational limits. They were designed toward addressing critical gaps associated with both objectives of the larger program, namely an improved combustor rig evaluation process for ASTM D4054 and validated models for combustor evaluation. These studies leverage existing flame stabilization, ignition, and turbulent flame speed facilities and infrastructure that enable operation at realistic conditions, as described below for each task, and so are well positioned to support the overall program schedule. For example, these rigs have been routinely used to obtain measurements that meet or exceed the high pressure/temperature conditions noted in the RFP of 75 psia, 450 F air preheat, and 250 F fuel preheat. This has enabled data to be obtained at elevated temperatures and pressures during the first year. Analysis and design in support of low temperature/pressure capabilities has also been part of the first year. We will initiate low temperature and measurements in the second year, using chillers and possibly ejectors for subatmospheric pressure measurements.

As detailed in their respective sections, these tasks have been developed toward supporting the overall program goals culminating in referee rig capabilities, as well as acquiring data to differentiate potentially subtle fuel effects that can be used for model validation.

This effort has implemented an extensive coordination plan integrates the other area teams and the steering group, in order to refine the experimental test matrices to best serve model validation efforts. It also extensively leverages other projects supported by OEM's and AFRL.

The objective of the first task is to empirically map combustor blowoff limits, to obtain validation data sets of a spray flame in a high shear flow, and to develop diagnostics and analysis approaches that can be utilized on the referee rig. The benefits of this task are threefold: (1) measurements of mapped blowoff limits will provide combustion modelers with a quick, macro-scale benchmark for validation, (2) data sets will provide modelers with high quality data with well characterized boundary conditions in a two-phase, physically relevant flow field, and (3) further develop advanced combustion diagnostic techniques, analysis approaches, and other best practices for the difficult multi-phase, combusting conditions of interest, that can be utilized in the referee rig. These tests should be sensitive to the fuel properties, as quantities such as extinction strain rate (which controls blowoff boundaries and local extinction under near-limit conditions) vary by approximately 50% as aromatic volume fraction varies between 10% to 25%, representative of the category A fuels.

The objective of the second task is to measure the forced ignition probability of various fuels under experimentally repeatable, engine-relevant, and readily modeled conditions (i.e., well defined boundary conditions and a computationally tractable flow field). The benefit of this task is that it can quickly determine if candidate fuels have different forced ignition response over a wide range of conditions. Simultaneously, this task measures the characteristics of the flow field and the spark discharge as inputs for ignition models. Measurements of the probability of successful ignition, and the space-time evolution of the ignition kernel and flame ball, serve as benchmarks for ignition models and their inherent kinetic models.

The objective of the third task is to quantify the turbulent flame speed, S_T, of conventional and alternative jet fuels at varying pressures and preheat temperatures. This has two significant benefits. First, this work will help to enable chemistry effects of jet fuels to be captured in models to be used by other groups (UDRI) and OEMs (e.g., GE, Williams). Second, turbulent flame speed measurements may offer a metric for screening the significance of fuel chemistry of alternative fuels.

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

From a diagnostics standpoint, the objective of this work is to support the advanced laser and optical diagnostics in area #3 (Advanced Combustion Tests) of the FAA COE ASCENT's combustion program. The diagnostics effort strives to meet two critical targets. The first is to optimize diagnostics that has enough fidelity to discern the combustion characteristics of candidate jet fuels in their respective testing conditions (support fuel screening). The second goal is to organize and analyze the data in a structured way that allows partners in the combustion program to refine and validate their numerical models.

Task 1. Blowoff

Georgia Institute of Technology

Objective(s)

This task has two objectives. These objectives focus on the blowoff figure of merit, in a pressurized, preheated, liquid fueled, single-nozzle combustor. The first objective is to measure and demonstrate the sensitivity of the lean blowoff point to fuel composition, for a range of conventional jet fuels as well as fuels with varying physical and kinetic properties. The second objective is to measure detailed data for select flow conditions and fuels. These detailed measurements are designed to support modeling efforts by capturing key boundary conditions and providing validation information. A third, tangential objective of this task is to elucidate the fundamental physics that drive the observed fuel sensitivities.

Research Approach

The objective of this task is to empirically map combustor blowoff limits, to obtain validation data sets of a spray flame in a high shear flow, and to develop diagnostics and analysis approaches that can be utilized on the referee rig. The benefits of this task are threefold: (1) measurements of mapped blowoff limits provide combustion modelers with a quick, macro-scale benchmark for validation, (2) data sets provide modelers with high quality data with well characterized boundary conditions in a two-phase, physically relevant flow field, and (3) this effort is further developing advanced combustion diagnostic techniques, analysis approaches, and other best practices for the difficult multi-phase, combusting conditions of interest, that can be utilized in the referee rig. These tests should be sensitive to the fuel properties, as quantities such as extinction strain rate (which controls blowoff boundaries and local extinction under near-limit conditions) vary by approximately 50% as aromatic volume fraction varies between 10% to 25%, representative of the category A fuels [1].

Blowoff sets important operational limits on a combustor system – for a flame to exist inside the combustor requires low velocity regions where the flame can anchor and subsequently spread to the rest of the system. While blowoff is intrinsically a system-dependent phenomenon, the measurements conducted here provide key input needed for modeling blowout, as well as for correctly designing the blowoff measurement test approach and interpreting blowoff data. In particular, we focus on the dynamics of a spray flame in a high shear flow, and characterize the onset of local extinction as well as final blowoff. As detailed in [2], blowoff is preceded by a process involving two key steps: (1) local extinction of the flame, with growth in the size and frequency of extinction events as the blowoff boundary is approached; and (2) large scale fluid mechanic alterations as the fundamental hydrodynamic stability character of the flow is altered due to the significant disruption induced by the first stage. This review [2] also noted that Damköhler number correlations of the form $Da=\tau_{flow}/\tau_{chem}$ did a reasonable job in capturing fuel composition impacts on blowoff – however, they emphasized that the reason that these correlations work is because blowoff boundaries are ultimately correlated with the onset of local extinction.

With this in mind, this task specifically focuses on fuel screening and obtaining model validation data, as well as demonstrating methods for characterizing and understanding blowoff boundaries, flowfields, and flame dynamics in a configuration that captures the key physics that combustion models must capture – high shear, swirling, two-phase flows. These data are measured in a much simpler, more easily modeled configuration than the referee rig's (e.g., without dome and wall cooling flows). This has allowed the diagnostic developments and fuel screening to be carried out in detail in the early months of the program. The diagnostic, data analysis, and fuel screening lessons are then transitioned to the referee rig. We are currently partnering with Prof. Suresh Menon on a related project in this facility, in which he has performed simulations of the facility using gaseous fuel and have developed extensive experience in closely working with modelers in obtaining the data needed for model validation [3] and determining the controlling processes through data analysis and comparison with detailed kinetic calculations. We are using stereoscopic PIV and temperature measurements to characterize inflow and boundary conditions for CFD. In addition to mapping blowoff boundaries, we are also characterize the flow and flame topology, using high repetition rate stereo PIV, OH PLIF, and mie-scattering measurements of the spray. We are also leveraging two other ongoing project to accelerate the demonstration of advanced, planar measurements of gas and liquid fuel distribution on this same facility. The velocity field, and flame location data are being used by Area 4 modelers to verify their velocity field, and flame location predictions. Additionally, the modelers are using the inlet flow field and spray data as boundary conditions.

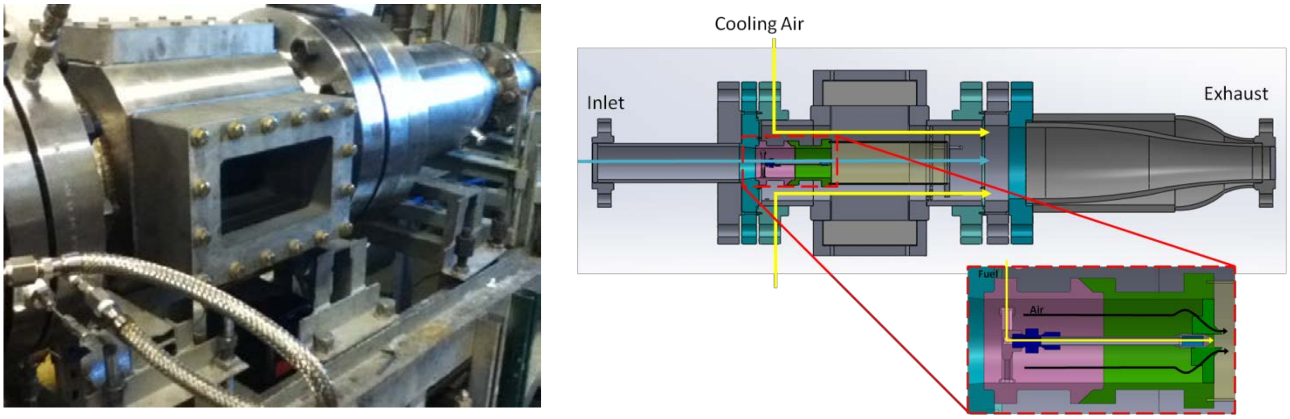


Figure 1. High shear swirl combustor, showing a) pressure vessel and b) cross section

Milestone(s)

1. Measurements of inflow and boundary conditions. This has been completed and is being delivered to Area 4.
2. Measurement of lean blowout equivalence ratio, mapped over full screening test matrix. This has been completed, with over 1,230 blowoff measurements obtained this year!
3. Measurement of flame shape and anchoring location for full detailed test matrix. This has been completed and is being analyzed to hunt for sensitivities to fuel type and flow conditions.
4. Development of optimized approaches for high repetition rate PIV and OH and/or CH PLIF measurements in high shear, two-phase flow. This has been completed, we have developed best practices for stereo PIV in this type of environment, and we have developed a methodology to isolate OH PLIF from the fuel PLIF that naturally contaminates the measurement.
5. Measurements of other local quantities, such as velocity and strain rates along reaction layer near flame stabilization points, with accompanying extinction strain rate calculations, for conditions of greatest interest to Area 2 researchers. This analysis is in progress.

Major Accomplishments

1. We have completed over 1,230 blowoff measurements, which span all fuels of interest, all flow conditions of interest, and two different types of fuel injector. A sub-sample of these measurements is presented in Figure 2. With these measurements we demonstrated clear fuel sensitivities, which enabled the program to down-select the fuels of interest for the rest of this year. We have also used these measurements to correlate the blowoff process to physical fuel properties, and we have shown how certain physical properties dictate the blowoff behavior of the fuels for select flow conditions and injection schemes (see Figure 3 for an example).
2. We have also collected two databases of detailed diagnostic data, one for each type of injection scheme. This has two important merits for the program. The first important merit is that this has provided the necessary boundary conditions and validation data to Area 4 so that they could proceed with CFD simulations of our rig. Figure 4 shows an example velocity field measured under reacting, pressurized conditions. The second important merit is that we have used these measurement campaigns to further develop the detailed diagnostics, which is noted as a third accomplishment.
3. We have demonstrated that the OH PLIF measurement can be significantly enhanced to reduce noise from fuel PLIF, even if only one tunable laser is available. The approach that we developed is a two-camera approach, where one camera is optimized to measure OH PLIF, the other camera is optimized to measure fuel PLIF, and the composite of this information is then used to isolate the OH PLIF. Figure 5 illustrates this diagnostic improvement.

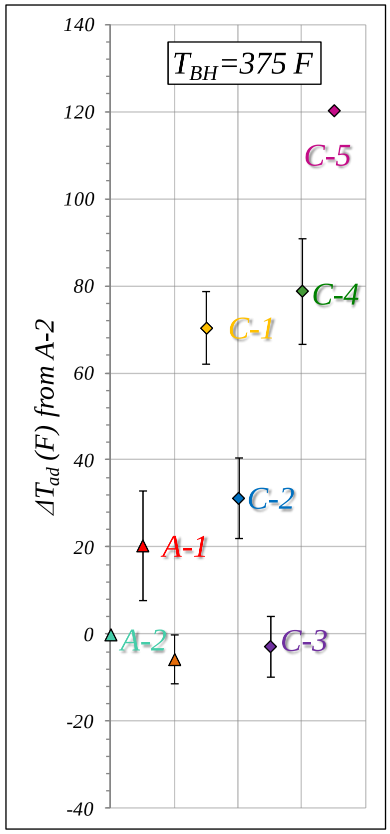


Figure 2. Sample of screening data showing blowoff points, expressed as adiabatic flame temperature at blowoff, relative to the A2 fuel

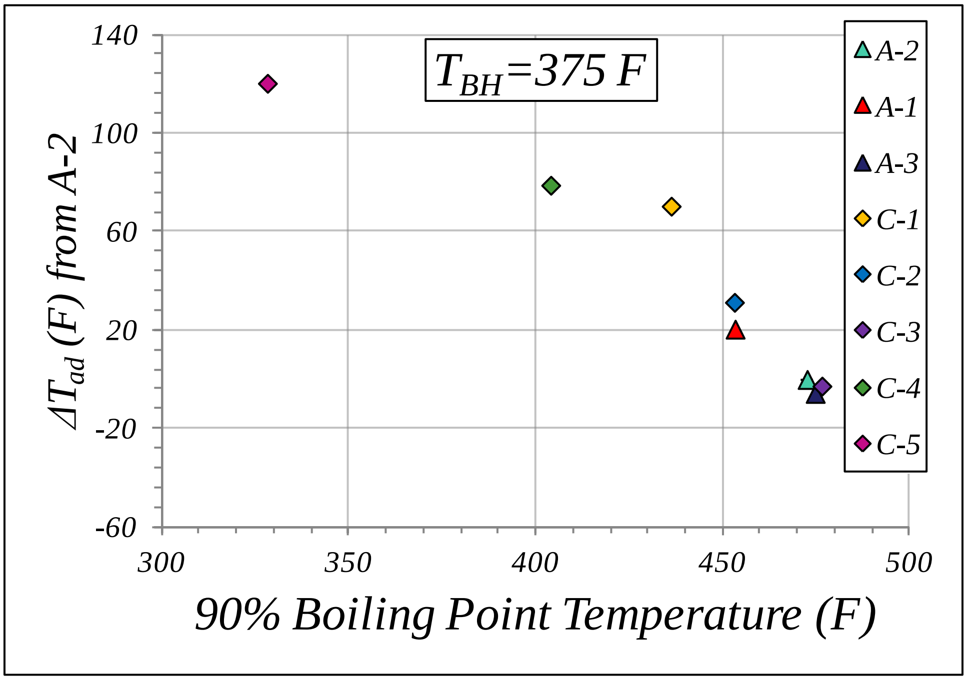


Figure 3. Subset of screening data showing correlation of blowoff point to 90% boiling point, when using a pressuter atomizing injector at low preheat temperature

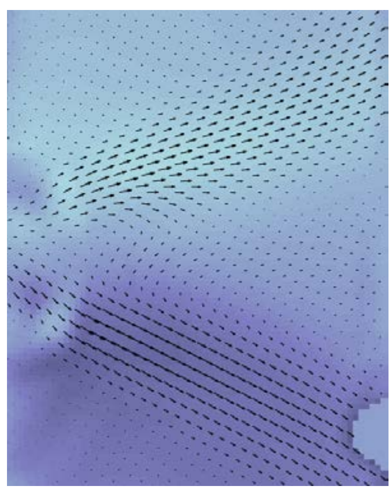


Figure 4. Sample mean flow field measured under reacting conditions. Vectors show axial and radial velocity components, and background color indicates azimuthal velocity component.

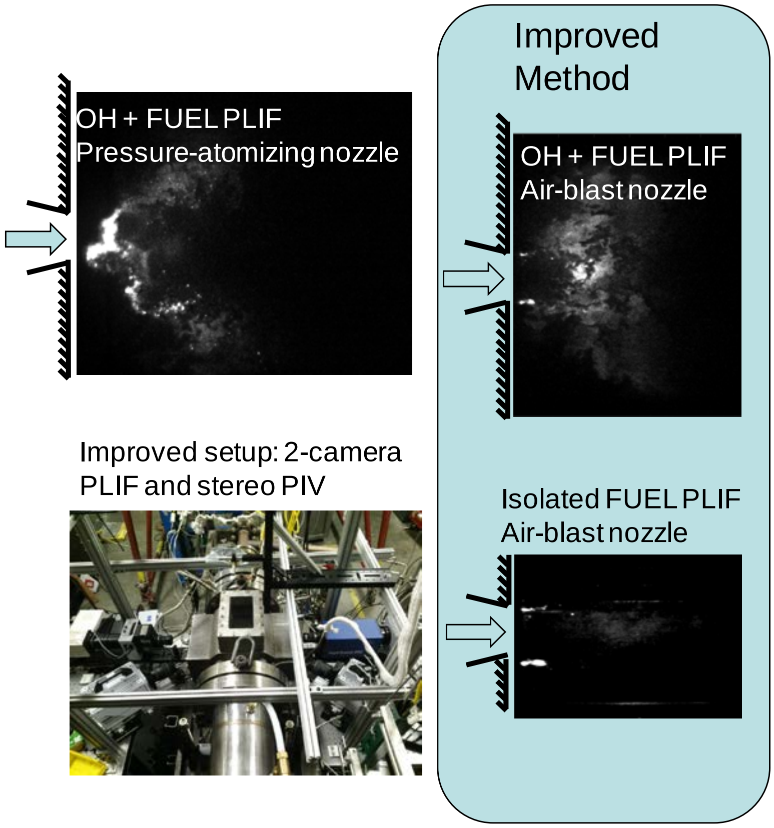


Figure 5. Illustration of improved, 2-camera OH PLIF methodology

Publications

None published to date.

Outreach Efforts

We are writing two conference papers to be presented at the ASME Turbo Expo 2016 conference.

Awards

None

Student Involvement

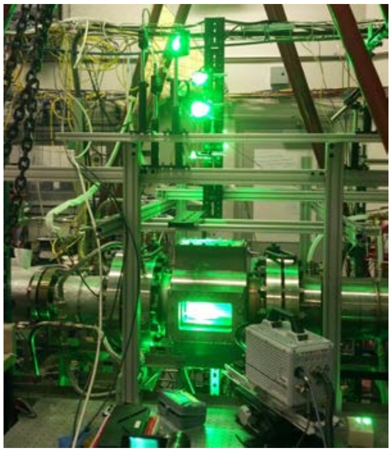
- Nick Rock has been actively involved in the Task 1 experimental effort. Nick was the PhD student responsible for operating the experimental facility. He led the blowoff measurements and operated the facility for the detailed diagnostic efforts.
- Ianko Chterev, Eric Mayhew, and Steve Hammack were also actively involved in the Task 1 experimental effort. These three PhD students were responsible for implementing the detailed diagnostic measurements.
- Hanna Eck was involved in the Task 1 effort as a data analysist. Hanna has been responsible for processing and analyzing the large volume of detailed data produced by the PIV, PLIF, and Mie scattering measurements.

Plans for Next Period

The objective of the blowoff task in year 2 is to measure detailed operational data near the blowoff limits of a swirl combustor that mimics OEM hardware. The combustor, used in year 1 of this program, is a swirl-stabilized spray combustor, which is configured similarly to the referee rig, but without dome cooling and liner-cooling flows. The benefits of this task will be threefold. The first benefit of this task will be the measurement of detailed boundary conditions and validation data that are critical to a successful modeling effort. These measurements will be selected collaboratively with Area 4 after their year 1 simulation attempt, in order to support their refinement and validation cycle. For example, this effort will likely involve a detailed spray characterization using PDPA. The second benefit of this task is exploratory refinement of detailed diagnostics and best practices, which can be rapidly explored on the simplified Area 3 rig, and then fed forward to the referee rig. The third benefit of this task is the capability to rapidly measure a wealth of screening data, in order to probe alternate conditions (i.e., temperatures, pressures, and injector geometries) for key fuel sensitivities. The work plan for this task will begin with detailed analysis of the PIV, spray, and OH PLIF data from year 1. The plan will also execute additional detailed diagnostic campaigns, to be designed in close collaboration with Tonghun Lee and Area 4. Finally, the work plan will include additional screening with the air blast injector. Screening conditions will be selected collaboratively with the OEMs, Area 1, and Area 6. Collaboration with Area 6 will ensure overlap at one or more nominal pressure and temperature conditions (as in year 1), while leveraging their sub-atmospheric/low temperature capability and our high pressure/high temperature capability to search for coupled fuel/pressure/temperature trends. For example, between the two teams, we can perform screening over a broad range of pressures to confidently answer the question: "How does pressure couple with fuel composition to influence flame shape and blowoff?" While the key figure of merit and primary focus of this task is blowoff, the detailed diagnostics will help complement the blowoff work by studying fuel effects on flame shape over a range of pressures, as flame shape has important influences on combustor operational characteristics. In coordinating discussions with Prof. Hanson's group at Stanford, they have agreed to obtain data at the same range of pressures as this task.

Blowoff sets important operational limits on a combustor system – for a flame to exist inside the combustor requires low velocity regions where the flame can anchor and subsequently spread to the rest of the system. While blowoff is intrinsically a system-dependent phenomenon, blowoff measurements provide key input needed for modeling blowout, as well as for correctly designing the blowoff measurement test approach and interpreting blowoff data. In particular, we propose *to focus on the dynamics of a spray flame in a high shear flow, and characterize the onset of local extinction as well as final blowoff*. As detailed in [2], blowoff is preceded by a process involving two key steps: (1) local extinction of the flame, with growth in the size and frequency of extinction events as the blowoff boundary is approached; and (2) large scale fluid mechanic alterations as the fundamental hydrodynamic stability character of the flow is altered due to the significant disruption induced by the first stage. This review [2] also noted that Damköhler number correlations of the form $Da=\tau_{flow}/\tau_{chem}$ did a reasonable job in capturing fuel composition impacts on blowoff – however, they emphasized that the reason that these correlations work is because blowoff boundaries are ultimately correlated with the onset of local extinction.

With this in mind, this task will specifically focus on obtaining model validation data and demonstrating methods for characterizing and understanding blowoff boundaries, flowfields, and flame dynamics in a configuration that captures the key physics that combustion models must capture – high shear, swirling, two-phase flows. These data will be measured in a much simpler, more easily modeled configuration than the referee rig's (e.g., without dome and wall cooling flows). This will also allow the diagnostic methods and fundamental fuel sensitivities to be better characterized. The diagnostic and data analysis approaches can then be reliably transitioned to the referee rig. They will be obtained in an existing liquid-fueled, high pressure, swirl combustor, developed under funding from Pratt & Whitney [4, 5]. We are currently partnering with Prof. Suresh Menon on a related project in this facility, in which he has performed simulations of the facility using gaseous fuel and have developed extensive experience in closely working with modelers in obtaining the data needed for model validation [3] and determining the controlling processes through data analysis and comparison with detailed kinetic calculations. Our partnership with Suresh Menon during year 1 of this program has also generated a mesh of the rig, a preliminary simulation of the liquid fueled system, and has helped demonstrate the challenging boundary condition and validation data that are needed for a liquid fueled simulation.



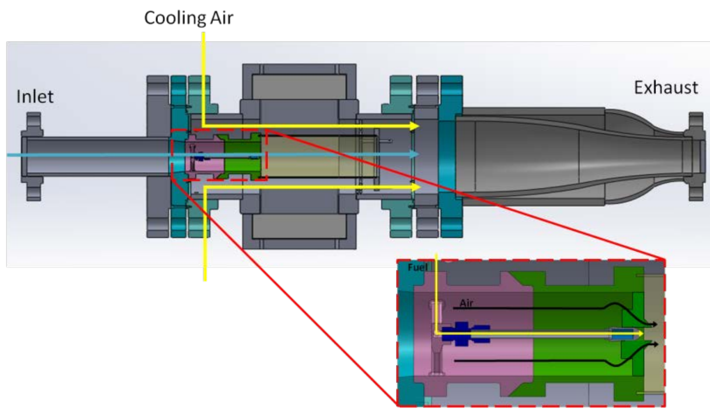


Figure 6. High shear swirl combustor, showing a) pressure vessel instrumented for high speed stereo PIV and OH PLIF, and b) a cross section with generic swirler holder/injector for illustrative purposes

Citations

[1] Won, S. H., Sun, W., and Ju, Y., 2010, "Kinetic Effects of Toluene Blending on the Extinction Limit of N-Decane Diffusion Flames," Combustion and Flame, 157, pp. 411-420.
[2] Shanbhogue, S. J., Husain, S., and Lieuwen, T., 2009, "Lean Blowoff of Bluff Body Stabilized Flames: Scaling and Dynamics," Progress in Energy and Combustion Science, 35, pp. 98-120.
[3] Chterev, I., Foley, C. W., Foti, D., Kostka, S., Caswell, A. W., Jiang, N., Lynch, A., Noble, D. R., Menon, S., Seitzman, J. M., and Lieuwen, T. C., 2014, "Flame and Flow Topologies in an Annular Swirling Flow," Combustion Science and Technology, 186, pp. 1041-1074.

Task 2. Ignition

Georgia Institute of Technology

Objective(s)

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

Research Approach

The objective of this task is to measure the forced ignition probability of various fuels under experimentally repeatable, engine-relevant, and readily modeled conditions (i.e., well defined boundary conditions and a computationally tractable flowfield). The benefit of this task is that it can quickly determine if candidate fuels have different forced ignition response over a wide range of conditions. Simultaneously, this task is measuring the characteristics of the flow field and the spark discharge as inputs for ignition models. Measurements of the probability of successful ignition, and the space-time evolution of the ignition kernel and flame ball, will serve as benchmarks for ignition models and their inherent kinetic models.

Forced ignition in an engine combustor is deemed successful if the spark kernel(s) lead to the *initiation* and *stabilization* of a self-sustained flame. For many aircraft engines, the fuel-air ratio at the igniter location can be outside the flammability limits (e.g., much leaner). It is important to emphasize that the <u>fuel sensitivity of forced ignition can differ substantively from its autoignition sensitivity</u>. For example, autoignition delay times are generally a weak function of fuel/air ratio, while the probability of successful forced ignition is a strong function of fuel/air ratio [6] and fuel composition [7]. To understand forced ignition, one must differentiate between the three things that must occur to achieve a self-sustained flame: (1)

initiation of a reacting fuel-air ignition kernel, (2) transition of the kernel to a self-sustained reaction front, and (3) stabilization of the flame [8]. These three processes involve different physical mechanisms and success in one of them does not imply success in other. The third process (3) is perhaps most dependent on the combustor configuration, and so we will specifically focus on the first two processes, which strongly couple turbulence to the chemical kinetics and diffusive characteristics of the fuel to provide the most elemental data for model validation of fuel effects. In addition there is some overlap with the other tasks, as process (2) is closely related to the mixtures S_T value, focused on in Task 3, and process (3) relates to flame stabilization/extinction in shear layers -the focus of Task 1.

With this in mind, this task is utilizing an existing forced ignition facility, developed in partnership with Pratt & Whitney, to measure ignition probabilities of stratified fuel-air mixtures in a 10-50 m/s flow, and which employs a typical aircraft engine sunken fire igniter [6]. The facility has been utilized this year to test vaporized liquid fuels in order to particularly focus on kinetic effects, and in following years will be utilized to test atomized liquid fuels (using results from Area 5 to inform the test matrix, particularly with regards to spray distribution). This task is investigating the sensitivity of successful ignition to the fuel composition at a range of fuel-air ratios, velocities, fuel and air temperatures and stratification gradients. The facility is designed to isolate the interaction of fuel chemistry with the rapid entrainment associated with a pulsed, plasma kernel ejected into a well-characterized, nearly uniform velocity cross-flow. Thus the measurements obtained in the facility are discriminating fuel effects on the ignition process and are providing useful model validation data. Kernel/flame ball evolution is being characterized with high speed Schlieren and emission (chemiluminescence) imaging; additionaly CH PLIF imaging is planned at a later time. However, the primary measurement used to discriminate fuel effects and to validate models is a measurement of the ignition probability for a fuel at each nominal flow condition, i.e., the fraction of plasma kernels that successfully develop into a self-sustained, propagating flame. This well-characterized experimental facility in a simplified but relevant flow field will be able to validate models developed under Area 4 that focus on ignition (high altitude relight and cold start). This task also aims to model the forced ignition process to improve physical understanding of the role of fuel chemical properties.

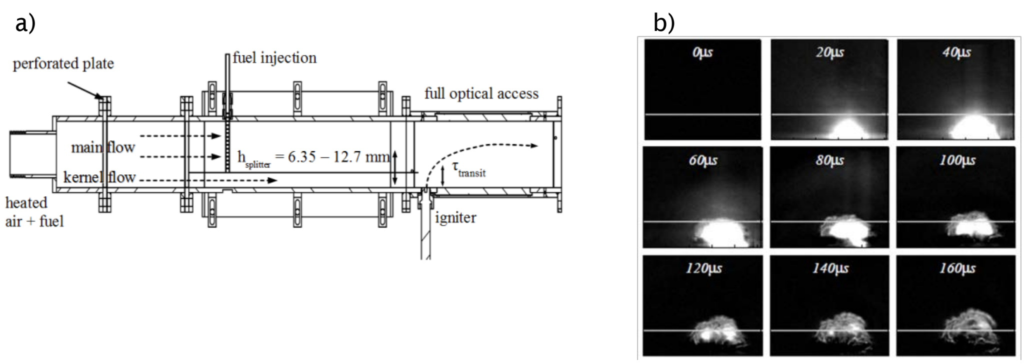


Figure 7. a) Drawing of the ignition rig and b) sequence of Schlieren images of ignition event

Milestone(s)

- Measurements of inflow and igniter boundary conditions. Rig characterization measurements are complete, and more detailed measurements are pending.
- Measurements of ignition probability for full (vaporized) fuel test matrix as function of parameters outlined in proposal. An extensive database of ignition probability data has been completed for all fuels of interest.
- Measured space-time evolution of the ignition kernel and propagating flame front. These measurements are complete and are being analyzed.

Major Accomplishments

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

- The first major accomplishment is a fuel screening dataset. The fuel screening investigated the dependence of ignition probability on equivalence ratio for each fuel. This dependence was demonstrated to be sensitive to fuel composition. A sample of the screening dataset is shown in Figure 8. These results have identified at least one of the fuels as an outlier with respect to the range observed in the A-category fuels.
- One of the detailed measurements performed in this task was high speed chemiluminsecence imaging. Analysis of the chemiluminescence images demonstrated that the time-history of the chemiluminescence of the ignition kernel

and ensuing flame ball is different for different fuels, which is a further demonstration of fuel sensitivity. A sample of the chemiluminescence results is shown in Figure 9.

- Significant progress has been made on a reduced-order ignition model, which encompasses entrainment physics unique to the type of forced ignition systems used in jet engines. Thus the model promises to elucidate the physics that govern the forced ignition process. This modeling effort is illustrated in Figure 10.

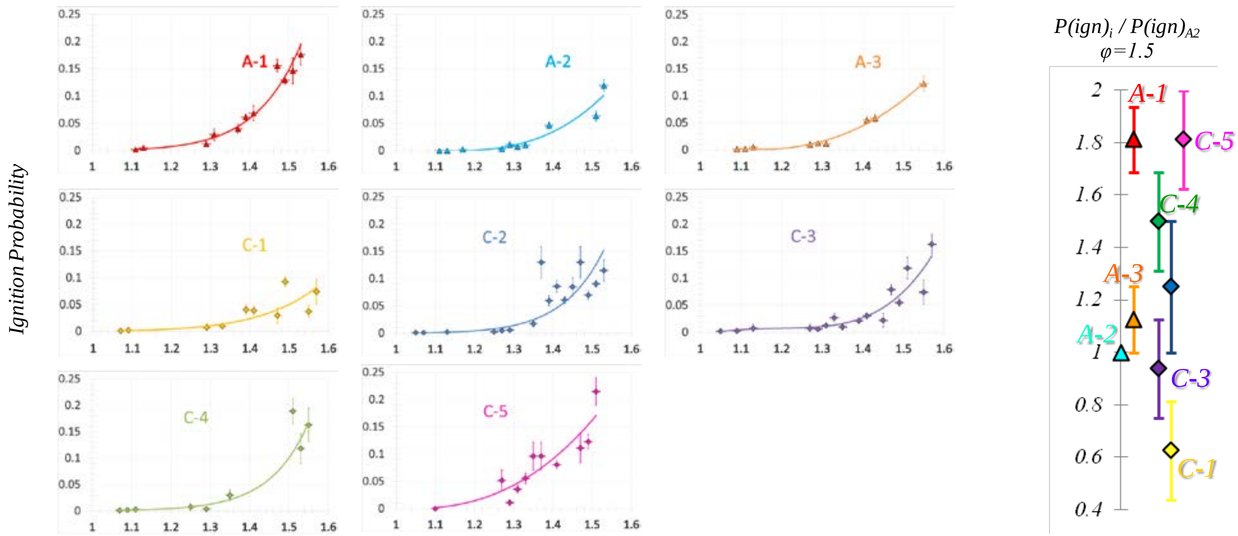


Figure 8. Sample ignition screening data, showing a) ignition probability vs equivalence ratio, and b) ignition probability relative to A2 at an equivalence ratio of 1.5

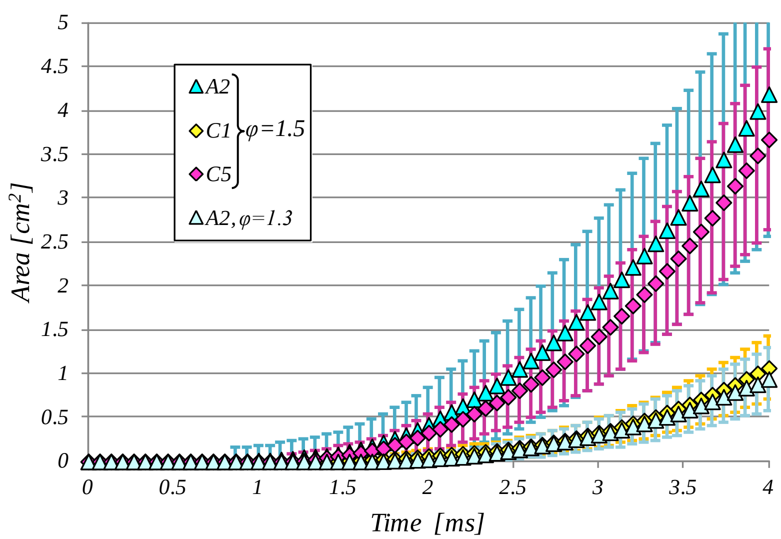


Figure 9. Further demonstration of fuel-effects through chemiluminescence data

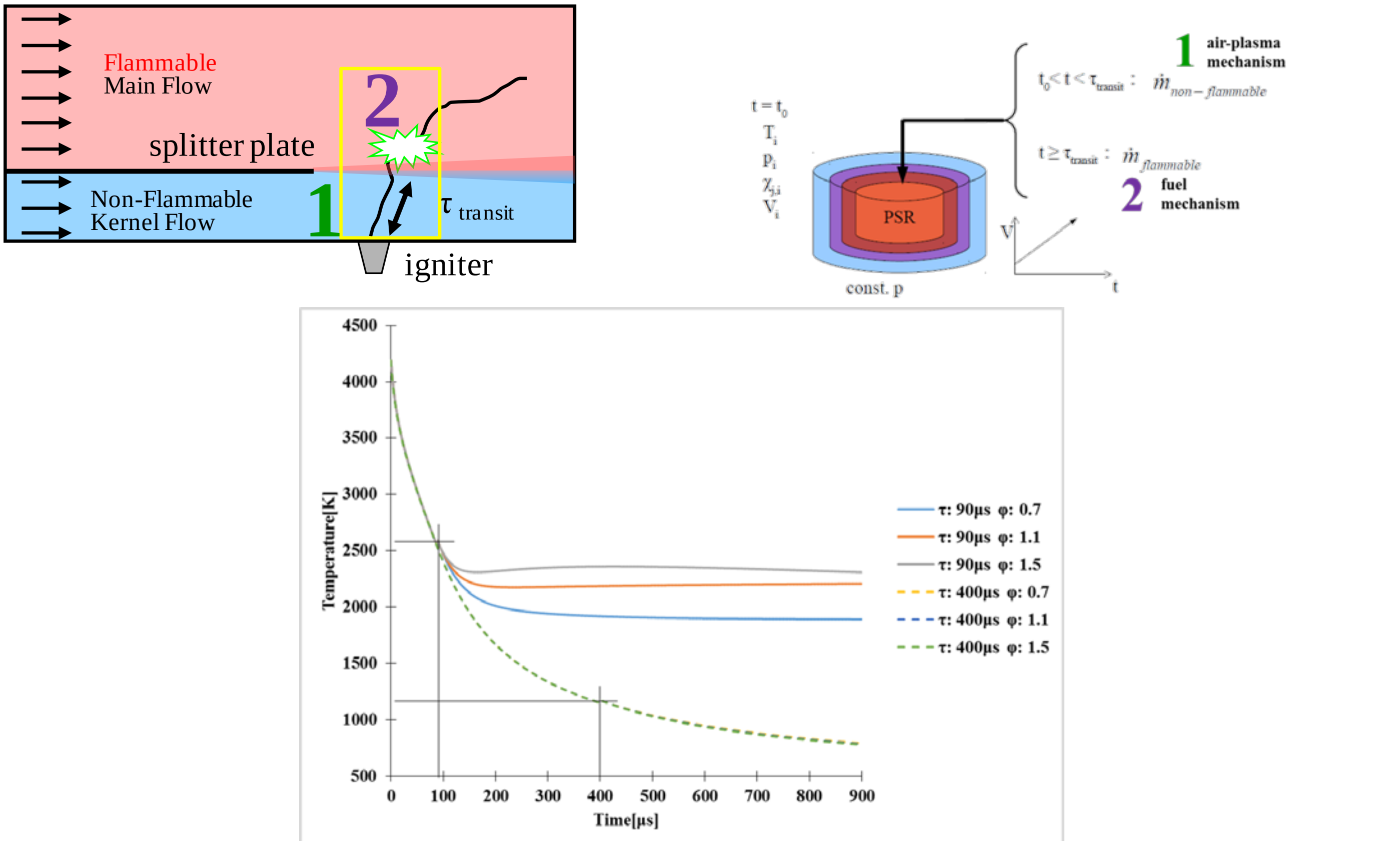


Figure 10. Illustration of ignition modeling effort

Publications
None published to date.

Outreach Efforts
We are presenting one poster at the UTSR workshop, and writing one conference paper to be presented at the ASME Turbo Expo 2016 conference.

Awards
None

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

Plans for Next Period

The objective of this task in the second year is to measure the spark ignition probability of various fuels under experimentally repeatable, engine-relevant, and readily modellable conditions. The benefit of this task is that it can quickly determine the forced ignition response over a wide range of conditions and fuels. This capability was successfully demonstrated during the first year of the program. During the second year, the ignition facility will be expanded to accommodate more realistic conditions, with the most important change being addition of a pressure-atomizer to produce two-phase flows. While the year 1 data focused solely on chemical effects, measurements of ignition probability for a fuel spray will include the fuel's physical property dependencies, such as boiling range and viscosity. For the non-prevaporized fuels, we will also extend the range of fuel and air temperatures investigated in year 1 (T>380°F) to lower values (within the limits of achieving ignition). A liquid chiller system will be added to reach low fuel temperatures; the minimum air temperature from our non-preheated supply will be limited by seasonal variations, although we speculate that the limit of zero ignition probability will be the lower limit on the air temperature. Similarly, the pressure atomizer will be chosen to target a specific fuel droplet size range. The specific temperature range and targeted droplet size will be collaboratively selected in close-collaboration with the OEMs, in order to answer the question "How closely do the lessons learned to-date about fuel sensitivity carry over to high altitude re-light conditions where forced ignition is difficult?" In addition to ignition probabilities, this task will measure the characteristics of the flow field and the spark discharge as inputs for ignition models. Measurements of the probability of successful ignition, and the space-time evolution of the ignition kernel and flame ball, will serve as benchmarks for ignition models and their inherent kinetic models. For example, we anticipate employing a new high-speed CH PLIF measurement approach developed by Tonghun Lee at UI for characterizing the ignition kernel's reaction zone development and its conversion to a propagating turbulent flame. The operating conditions will also be coordinated with the Area 1 team. In coordinating discussions with Prof. Hanson's group at Stanford, they have agreed to obtain data at the same conditions examined in this task.

Forced ignition in an engine combustor is deemed successful if the spark kernel(s) lead to the *initiation* and *stabilization* of a self-sustained flame. For many aircraft engines, the fuel-air ratio at the igniter location can be outside the flammability limits (e.g., much leaner). It is important to emphasize that the <u>fuel sensitivity of forced ignition can differ substantively from its autoignition sensitivity</u>. For example, autoignition delay times are generally a weak function of fuel/air ratio, while the probability of successful forced ignition is a strong function of fuel/air ratio [6] and fuel composition [7]. To understand forced ignition, one must differentiate between the three things that must occur to achieve a self-sustained flame: (1) initiation of a reacting fuel-air ignition kernel, (2) transition of the kernel to a self-sustained reaction front, and (3) stabilization of the flame [8]. These three processes involve different physical mechanisms and success in one of them does not imply success in other. The third process (3) is perhaps most dependent on the combustor configuration, and so we will specifically focus on the first two processes, which strongly couple turbulence to the chemical kinetics and diffusive characteristics of the fuel to provide the most elemental data for model validation of fuel effects. In addition there is some overlap with the other tasks, as process (2) is closely related to the mixtures S_T value, focused on in Task 3, and process (3) relates to flame stabilization/extinction in shear layers -the focus of Task 1.

With this in mind, this task will utilize an existing forced ignition facility, developed in partnership with Pratt & Whitney, to measure ignition probabilities of stratified fuel-air mixtures in a 10-50 m/s flow, and which employs a typical aircraft engine sunken fire igniter [6]. The facility will be utilized in year 1 of this work to test vaporized liquid fuels in order to particularly focus on kinetic effects, and in following years to test atomized liquid fuels (using results from Area 5 to inform the test matrix, particularly with regards to spray distribution). The proposed program will investigate the sensitivity of successful ignition to the fuel composition at a range of fuel-air ratios, velocities, fuel and air temperatures and stratification gradients. The facility is designed to isolate the interaction of fuel chemistry with the rapid entrainment associated with a pulsed, plasma kernel ejected into a well-characterized, nearly uniform velocity cross-flow. Thus the measurements obtained in the facility should be able to discriminate any fuel effects on the ignition process and provide useful model validation data. This well-characterized experimental facility in a simplified but relevant flow field will be able to validate models developed under Area 4 that focus on ignition (high altitude relight and cold start), as well as providing useful support for chemical mechanism reduction approaches under Areas 2 and 4.

Citations

[4] Rosfjord, T., and Cohen, J., 1990, "Air and Spray Patterns Produced by Gas Turbine High-Shear Nozzle/Swirler Assemblies," AIAA 90-0465.

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

Task 3. Turbulent Flame Speed

Oregon State University

Objective(s)

This task has two objectives. These objectives focus on the turbulent flame speed, which is a critical parameter in many turbulent combustion closure models used by modelers, and which has a major influence on all combustion figures of merit. The first objective of this task is to measure and demonstrate the sensitivity of the turbulent flame speed to fuel composition, for a range of conventional jet fuels as well as fuels with varying physical and kinetic properties. The second objective is to build a database of turbulent flame speeds for pre-vaporized jet fuels. A third, tangential objective of this task is to elucidate the fundamental physics that drive the observed fuel sensitivities.

Research Approach

Methodology

Turbulent flames are generated using a vaporizer and burner based on designs developed by the Air Force Research Lab and Lieuwen and colleagues. The experimental setup consists of fuel and air metering systems that deliver jet fuel and air to the burner. Fuel is vaporized using a series of heaters, and elevated to a temperature of 200 °C. The air/fuel mixture is flowed through an adjustable turbulent generator which generates turbulent fluctuations ranging from 10 to 20% of the bulk flow velocity. Turbulence intensity (TI) is independent of bulk flow velocity. A premixed methane pilot flame is used for ignition. Fuel and air flow rates for the jet flame are metered to a precision of 0.5% and 2% of set-point value, respectively.

Data is collected for each jet fuel variant over $5{,}000 \leq Re \leq 10{,}000$, $0.8 \leq \Phi \leq 1.15$, and $10\% \leq TI \leq 20\%$. Measurements are taken using a 16-bit intensified charge-coupled device (ICCD) camera with a 1024 x 1024 pixel resolution and a 25 mm, f/4.0, UV camera lens. For each flow condition (Re, Φ, TI), data is collected over a 3 minute period at 2 Hz.

Data Analysis

Image processing to determine the average flame sheet from the measurements was completed using the technique developed by Venkateswaran et al. and is summarized here. The line-of-sight images are time-averaged, the background is subtracted, and the image is cropped to include only the flame. The image is then checked for axis-symmetry, straightened, and filtered using a 2-D median filter with a kernel less than 2% of the burner diameter, as seen in Figure 11 (b) and (c). A 3 point Abel deconvolution is applied and the resulting axial distribution of the centerline intensity is fit to a Gaussian curve. The maximum intensity location is determined. This allows the leading edge of the time averaged flame-brush to be determined. This point is the most probable location of

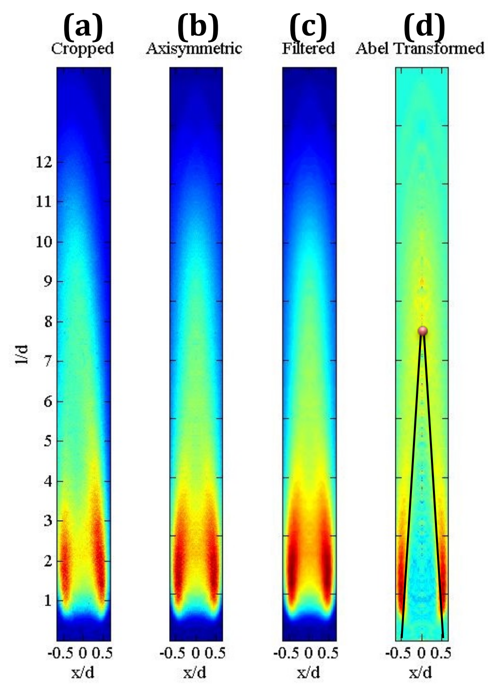


Figure 11. Step-by-step summary of image processing approach:(a) time-averaged, background subtracted and cropped (b) Axisymmetric (c) 2-D median filtered (d) Abel transform with ⟨c⟩=0.5 contour drawn.

the flame brush, and is defined as the $\langle c \rangle = 0.5$ progress variable contour and corresponds to the location of maximum intensity, see Figure 11 (d) [1]. The estimated uncertainty in this process is 1%-2% [1].

Milestone(s)

- Building burner and experimental arrangement for turbulent flame speed measurements of large hydrocarbon fuels.
- Measurements of turbulent flame speeds for a suite of fuels.

Major Accomplishments

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

- A burner for measuring turbulent flame speeds of large hydrocarbon fuels has been built and is operational. The combined vaporizer and burner system is one of just a few such systems in the world. The system has the flexibility to vary the Reynolds number, equivalence ratio, and turbulence intensity of the flame. A picture of the system is shown in Figure 14 (b).
- Turbulent flame (consumption) speeds have been measured for multiple fuels, with detailed measurements collected for two fuels at varying Reynolds numbers, equivalence ratios, and turbulence conditions. These are some of the only such data in the world reported for these types of fuels. Figure 12 shown below shows representative data.

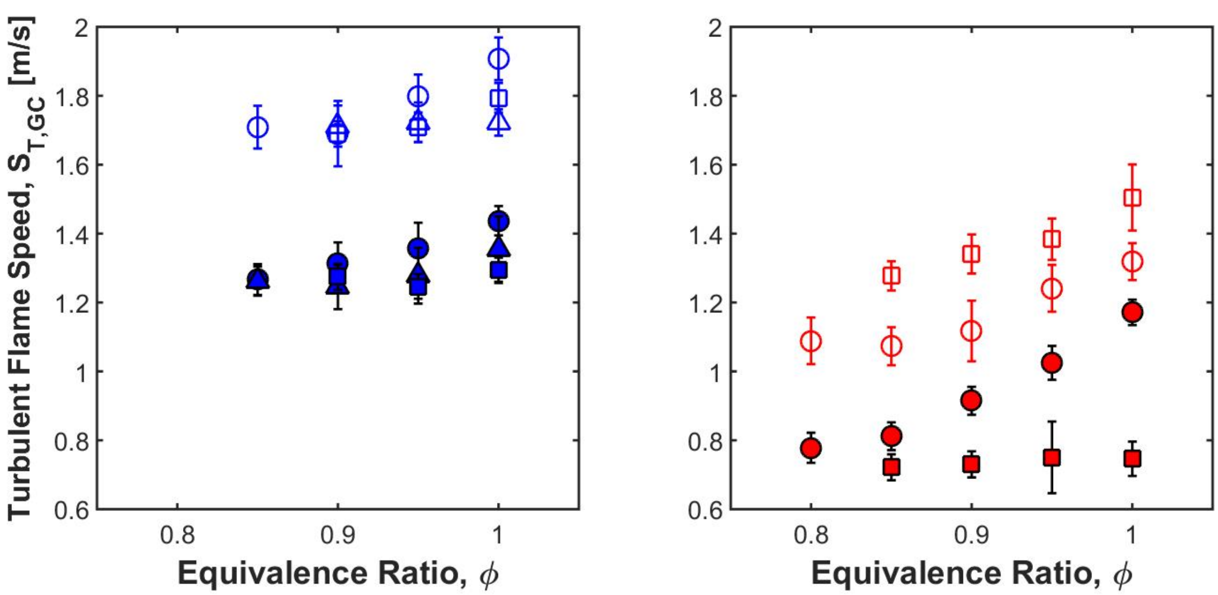


Figure 12. Sample turbulent flame speed data

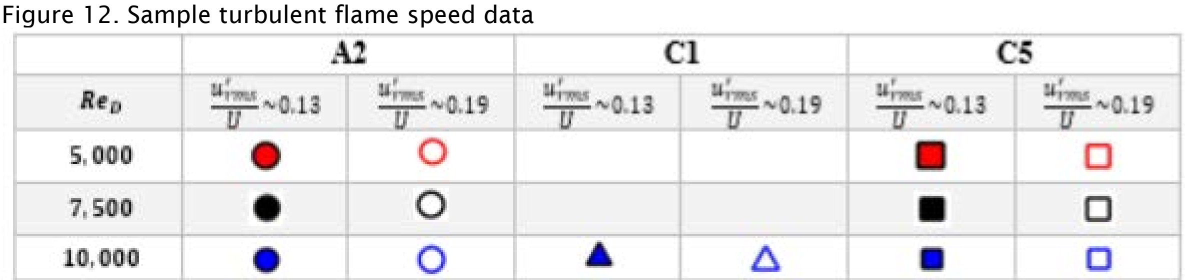


Figure 13. Legend for Figure 12

Publications

From Funding

- *Effects of Fuel Chemistry and Turbulence Intensity on Turbulent Consumption Speed for Large Hydrocarbon Fuels*, Aaron J. Fillo, David L. Blunck, Western States Combustion Institute, Fall 2015

Related

- *Effect of Turbulent Fluctuations on Radiation Emissions from a Premixed Flame*, J. Bonebrake, A. J. Fillo, D. Blunck, Western States Section Combustion Institute, 2015
- *Radiation Characteristics of Turbulent Diffusion Flames Burning Alternative Aviation Fuels,* E. Zeuthen, D. Blunck, "," *9th US Combustion Meeting*, Cincinnati, OH (2015).

Outreach Efforts

None

Awards

None

Student Involvement

- Aaron Fillo, a PhD student, took the lead in designing and building the experimental arrangement for the turbulent flame speed burner. He has then lead efforts to measure and analyze data. He has subsequently received an NSF Graduate Fellowship and will work tangentially on this project to analyze results and further investigate scientific phenomena.
- Jonathan Bonebrake, MS student, is currently leading efforts to collect and analyze data. Moreover, he is responsible for analyzing the turbulent flow conditions at the exit of the burner.
- Multiple undergraduate 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.
- The burner developed as part of this project is being used for a graduate level measurement and instrumentation course. This is a significant benefit to the students by providing a practical system to use.

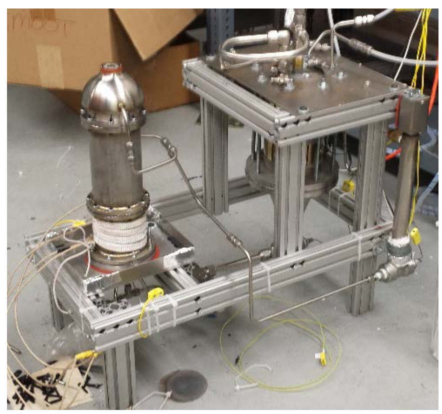
Plans for Next Period

For the second year of this program, we propose extending the tasks from year 1 to more severe/extreme conditions. These tasks address the figures of merit and most critical challenges associated with advanced combustion model development: (1) flame stabilization, extinction, and blow-off in gas-turbine realistic flow fields and (3) turbulent flame speeds. The task is designed toward addressing critical gaps associated with both objectives of the larger program, namely an improved combustor rig evaluation process for ASTM D4054 and validated models for combustor evaluation. The study will leverage existing facilities and infrastructure that were developed and demonstrated in year 1 of the current effort. The proposed plan for year 2 will continue to search for fuel sensitivities at other conditions that are expected to stress-test the combustion models and fuels.

The turbulent flame speed has significant influence on essentially all important combustor operational and emissions metrics including propagation of flames during combustor light-off, blow-off, and combustion instability. The objective of this task is to quantify the turbulent flame speed, S_T, of conventional and alternative jet fuels at varying pressures and preheat temperatures. This has three significant benefits. First, this work would be useful to help identify chemistry effects of jet fuels that should be captured in the modeling efforts of other groups (Area 4) and OEMs. Second, turbulent flame speed measurements may offer a metric for screening the significance of fuel chemistry of alternative fuels. Third, the turbulent flame speed database can be helpful to Area 4, where LES models often use flamelet approaches that require turbulent flame speed closures. Hence, inaccuracies in turbulent flame speeds of jet fuels (which have not been well characterized for aviation fuels) bias the combustion models. This task will leverage the existing turbulent flame speed facility at OSU, developed in collaboration with GT during year 1 of this program. Year 2 data at OSU will focus on sub-atmospheric pressure conditions (e.g., 1/3 atm), which match that under Task 2 and which will be matched by Prof. Hanson's group in Area 1.

We will leverage our extensive experience in obtaining these types of measurements to meet the objectives with the OSU facility. Over the last six years, we (the joint OSU and GT team) have extensively utilized a benchmark high pressure facility for characterizing fuel composition influences of synthesis gas fuels on S_T. We have collected data at pressures up to 20 atm and velocities of 70 m/s at very high turbulence intensities (u'/u_o values up to 30%) [9]. We have shown that different fuels with identical laminar unstretched flame speeds can have S_T values that differ by 400% at high turbulence intensities (e.g., see data in [10]). These variations can be correlated with the reactants sensitivity to high levels of stretch, and so this effort will closely coordinate with Areas 1 and 2 to communicate the Area 3 test conditions. Such S_T measurements are useful discriminators of fuel composition influences – indeed, detailed kinetic calculations show that the maximum stretched laminar flame speed (shown to be a good correlating parameter for fuel influences on the turbulent flame speed) for the three prevaporized category A fuels varies by 50%. The extension of this task to low pressures will help assess the significance of low temperature chemistry, and develop general methodologies for collecting flame speed measurements at subatmospheric conditions.

This focuses on similar measurements for prevaporized fuels of interest, in order to particularly focus on kinetic effects and not incorporate additional spray physics. As such, this work will be closely coupled with measurements and analysis in Areas 1 and 2. Validation of turbulent combustion models in Area 4 may take the form of comparisons of predicting turbulent flame speeds with our measurements.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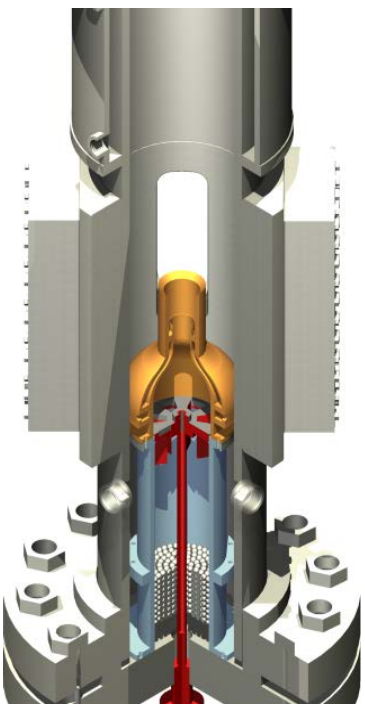
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Figure 14. a) Drawing of nozzle inserted into a pressure vessel, and b) photograph of OSU facility designed and built during year 1.

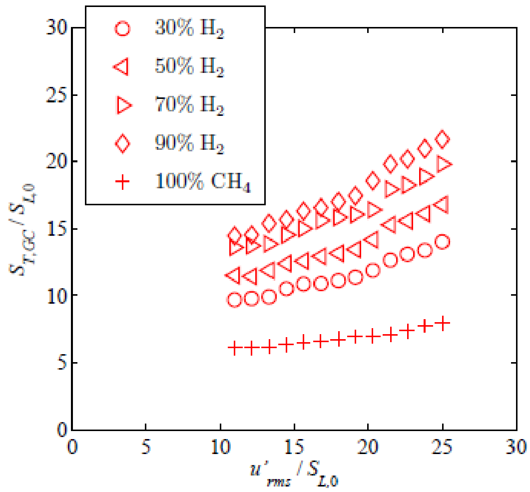

Figure 15. Measured dependence of turbulent flame speed of various fuel blends having identical laminar, unstretched flame speeds, SLo (done by adjusting stoichiometry of each mixture) upon turbulence intensity at a mean velocity of 50 m/s. Note the variation of almost 400%, purely due to fuel effects. As explained in the main text, this fuel effect can be correlated with the maximum stretched laminar flame speed. Similar data in this facility has been obtained at pressures up to 20 atm.

Citations

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

2 Venkateswaran, P., et al., *Pressure and fuel effects on turbulent consumption speeds of H2/CO blends.* Proceedings of the Combustion Institute, 2012. **34**: p. 1527-1535.

3Venkateswaran, P., et al., *Turbulent Consumption Speeds of High Hydrogen Content Fuels From 1-20 atm*, in *Journal of Engineering for Gas Turbines and Power*. 2014.

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

University of Illinois at Urbana-Champaign

Objective(s)

The objectives are to work with Georgia Tech in their advanced combustor experiments and achieve the following four goals:

- Evaluate the experimental combustor setup and operating conditions for laser diagnostics
- Design laser and optical diagnostics setup and oversee data acquisition process
- Participate in fuel screening process for optimizing experimental design
- Analyze data and pass on structured information to modeling groups in combustion program

Research Approach

Diagnostics Optimization and Setup

The main goal here is the development of multi-phase 2D diagnostics using Planar Laser Induced Fluorescence (PLIF) and Particle Imaging Velocimetry (PIV) to understand the blowoff development at the boundaries and flame dynamics in the GATech high shear and high pressure combustor. The goal will be to apply two simultaneous measurements from high speed PLIF, PIV, and chemiluminescence. In both PLIF and PIV, we will look to obtain quantitative and spatially resolved data. We will configure and set up the laser and optical diagnostics equipment around the high shear combustor at GATech with remote access and control, possibly with beam relay from an adjoining room due to vibration and thermal loading issues. For the high speed PLIF measurements, we plan to pump a high speed dye laser (Credo, Sirah) with a high speed diode pumped Nd:YAG (Edgewave) for generation of the UV light. We anticipate that the frame rate will be in the 5 to 10 kHz range. Energy per laser pulse at these conditions maybe small (20 μJ/pulse) and light collection from the PLIF will be enhanced using a f/1.8 UV lens. For the PIV measurements, we will use a stereo PIV system to ensure that we can collect velocity information in all three spatial coordinates.

Quantification of the LIF Signal

To ensure that the signal is fully quantified, we set out to build and calibrate a small scale flat flame burner for use in the GATech test rig. The combustor will be fully calibrated at Illinois using a combination of laser absorption and multi-line nitric oxide LIF thermometry. By calibrating the intensity of the setup with the flat flame combustor, we can assess first order values for concentration of radical concentrations in the flame. We were also required to address the issue of fuel PLIF as a significant interference source in our measurements. In order to account for the fuel PLIF, a two camera PLIF system with a multi-filter setup was used to selectively control the level of both the OH LIF signal and fuel LIF. The two images then can be used to isolate the OH LIF signal.

Milestone(s)

Proposed (3 Month): At the 3 month mark, we will conclude the analysis of the experimental setup and should be close to finishing the design of the laser and diagnostics setup.
Achieved: design of the laser setup complete and fabrication of calibration torch started.

Proposed (6 Month): At the 6 month mark, we should be finalizing the experimental setup and getting ready to actually deploy measurements in Task 1 of the proposal. Fuel screening will be conducted during this phase.
Achieved: Most of experimental setup complete. Calibration torch completed and initial quantification of radicals complete.

Proposed (9 Month): At the 9 month mark, we should be almost complete with the initial shakedown of the tests in Task 1 and making changes to optimize the experimental setup. Send preliminary test guidelines and results of the fuel screening studies (sensitivity to fuel characteristics) to the modeling groups.
Achieved: First test run at GATech for simultaneous PLIF and PIV successfully complete and results analyzed. Laser and optical setup successfully implemented and tested. Identified key problems such as fuel PLIF. Main measurement campaign set for last quarter.

Proposed (12 Month): At the 12 month mark, we should have completed an initial set of data for tasks outline in the proposal. We should be planning for additional measurements in the next phase of the combustion program.
Achieved: Major three week campaign completed at GATech for two of the test fuels. Experiments included two camera PLIF and stereo PLIF over a wide range of test conditions. Data analysis started. Fuel PLIF isolated using two camera PLIF setup with differing detection bandwidth.

Major Accomplishments

The main accomplishment of year 1 in this project was that we were able to assemble the laser system around the test rig at GATech and accomplish the task of simultaneous stereo PIV and two camera PLIF. The schematic of the experimental setup is shown in Figure 16.

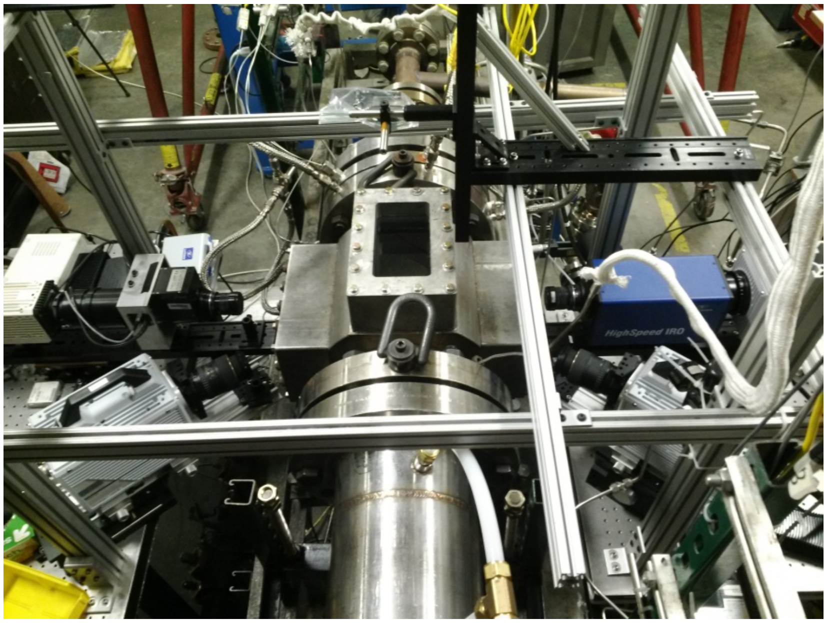

Figure 16. Diagnostics Setup at GATech with Stereo PIV and 2 Camera PLIF (4 high speed cameras + 2 lasers)

Figure 16 shows the experimental setup of the main combustor with the four high speed cameras positioned around it. The laser system, which is composed of a high speed Nd:YAG pumping a tunable high speed dye laser is situated in the adjacent room and the beam is routed to the experimental setup. Prior to reaching the test rig, the beam is expanded into a sheet using a custom set of optics and is routed into the test rig from the top. The beam is about 4 inches in width and about 100μm in thickness. The combustor itself is fully accessible through the top port and two side windows on either side. Prior to the measurements, the Illinois calibration burner is inserted into the chamber and imaging is done with the exact same setup to ensure wavelength position of the laser as well as the intensity of the OH LIF signal, which can later be fully quantified using a spectroscopic model. The laser is tuned to the A-X (1,0) transition of OH at 283nm. For the shakedown of the rig, an air pressure atomizer was used while for the actual tests in August, an air blast atomizer was mainly utilized.

The two cameras on either side at the top are the PLIF detection cameras, which are both intensified. The bottom two cameras at a slight angle are the PIF cameras which are mounted in a scheimpflug setup so as to ensure clear focus across the entire imaging plane. The entire system is synchronized at 5 kHz, which is an adequate repetition rate considering the turbulent intensity of the required flow conditions. The setup was installed and tested during May of 2015 and then the actual full scale measurements of A2, C5 fuels were conducted in August.

In addition to the quantification issue of the LIF signal, it became obvious during the May campaign that fuel PLIF was a major interference source in our measurements. In order to resolve this issue and to isolate the OH PLIF signal, a two camera PLIF setup was utilized with two differing spectral bandpass filters. The difference in the optical bandpass allows the ratio of OH and fuel PLIF to be varied and the strategy is to use one set of images to correct for the fuel PLIF in the other image. An example of this is shown in Figure 17.

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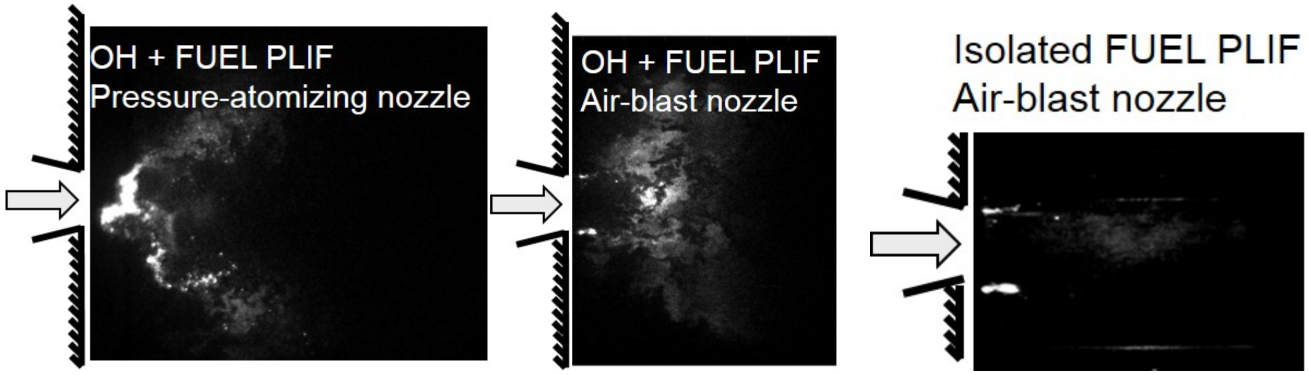

Figure 17. Two camera OH PLIF setup for isolation of fuel PLIF from the images. The image on the very right shows the isolation of the fuel PLIF using the added camera with a wide band-pass filter and suppression of OH PLIF.

Publications
None

Outreach Efforts
None

Awards
None

Student Involvement
Three graduate students (listed above) have participated in this project on a rotational basis to address various aspects of the project. Rajavasanth designed and fabricated the calibration burner used at GATech, and conducted experiments to determine the actual concentration of radical concentrations in the flame. Two other students (Stephen Hammack and Eric Mayhew) made trips to GATech to make test measurements in the high shear combustor. This included assisting in the setup of the laser and optics as well as participating in the actual measurements. The calibration torch as well as other optical and imaging equipment was taken down to GATech for testing.

Plans for Next Period
In year II of the NJFCP, an effort will be made to expand the scope of participation in the GATech combustion tests. This will include measurements over a wider region of test conditions as well as inclusion of more test fuels from the selection made by the PIs. We also anticipate that the measurements will include possibly new diagnostics strategies such as the CH C-X transition to monitor progression of flame front during ignition in the GATech program. Additionally, we will include improvements to the two camera detection method for isolation of fuel PLIF, which would result in enhanced abilities to obtain quantified OH concentrations.