Project 029(A) National Jet Fuels Combustion Program – Area #5: Atomization Test and Models

Purdue University

Project Lead Investigator

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University Participants

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- P.I.(s): Robert P. Lucht, Jay P. Gore, Paul E. Sojka, and Scott E. Meyer
- FAA Award Number: COE-2014-29A , 401321
- Period of Performance: 10/1/2016-9/30/2017
- Tasks:
  1. Obtain PDA data across one plane in the VAPS test rig operated with the Referee Rig nozzle and for numerous fuels at near-lean blowout (LBO) conditions and for cold fuel/cold air flow conditions approximating ground light off (GLO) and high-altitude relight (HAR) conditions
  2. Extend PDA measurements to obtain data across multiple planes for evaluation of Detailed Combustor Simulations (DeCS) by Suresh Menon, Vaidya Sankaran, and Matthias Ihme,
  3. Obtain PDA and/or Malvern measurements for selected operating conditions either in the VAPS test rig to provide data for the spray correlation analysis of Nader Rizk,
  4. Perform PDA measurements for fuel blends including Fuel X and/or another blend designed for testing differences in atomization characteristics to examine the sensitivity of correlations and computations to changes in fuel properties,
  5. Ensure quality of data with repetition tests at Purdue and comparisons with spray measurements at P&W, UDRI/AFRL, and UIUC.

Project Funding Level

The funding level from the FAA was $250,000 for Year 3. Purdue University provided cost sharing funds in the amount of $250,000.

Investigation Team

PI Dr. Robert Lucht, Bailey Distinguished Professor of Mechanical Engineering is responsible for the oversight of the entire project here at Purdue University. He is also responsible for mentoring one of the graduate students, coordinating activities with Stanford and will work with all parties for appropriate results and reporting as required.

Co-PI Dr. Jay Gore, Reilly Professor of Mechanical works closely with the PI for all deliverables of Purdue University, and also oversees the work performed by one of the graduate students that he is mentoring.

Co-PI Dr. Paul Sojka, Professor of Mechanical Engineering is responsible for mentoring one of the graduate student and is responsible for supervising the PDPA measurements.

Co-PI Scott Meyer, Managing Director of the Maurice J. Zucrow Laboratories is responsible for coordinating facility upgrades and for facility design reviews.

Senior Research Scientist Dr. Sameer V. Naik is responsible for direct supervision of the two graduate students involved in the project.

Graduate students Andrew Bokhart and Daniel Shin are responsible for performing the PDPA measurements and for modifying the RTS test rig for operation at near-lean-blow-out (LBO) conditions.

Project Overview

The objectives of this task as stated in the Invitation for ASCENT COE Notice of Intent (COE-2014-29) are to "measure the spray characteristics of the nozzles used in the Referee Combustor used in Area 6 tests and to develop models for characterizing the atomization and vaporization of the reference fuels." We are the experimental part of a joint experimental and modeling effort to achieve these objectives. The experimental tasks will be performed at Purdue University and the modeling tasks will be performed by Prof. Matthias Ihme's group at Stanford University, Prof. Suresh Menon's group at Georgia Tech, and by Vaidya Sankaran at UTRC. Nader Rizk will also develop spray correlations based on our measurements.

Purdue University has very capable test rig facilities for measuring spray characteristics over very wide ranges of pressure, inlet air temperature, and fuel temperature. The experimental diagnostics that are applied include both phase Doppler anemometry (PDA) as well as high-frame-rate shadowgraphy. The atomization and spray dynamics for multiple reference and candidate alternative fuels have been characterized for the referee rig nozzle operated at near lean blowout (LBO) conditions. In the future these same sorts of measurements will be performed for many of these same fuels at operating conditions characteristic of ground lightoff (GLO) and high-altitude relight (HAR).

Task #1: National Jet Fuels Combustion Program Area #5 - Measurement of Spray Characteristics at Near Lean Blowout and Chilled Fuel Conditions

Purdue University

Objective(s)

The objectives of this research program are to visualize and measure the characteristics including drop size distributions, axial, and radial velocity components of the sprays generated by a nozzle being used in the Referee combustor rig in the Area 6 tests. The resulting data will be used for the development of spray correlations by consultant Nader Rizk and for the purpose of submodel development for detailed computer simulations being performed by Matthias Ihme (Stanford University), Suresh Menon (Georgia Tech), and Vaidya Sankaran (UTRC). The experimental tasks are performed at Purdue University and the resulting data will be shared with FAA team members developing modeling, simulations, and engineering correlation based tools.

The upgraded Variable Ambient Pressure Spray (VAPS) test rig at Purdue University is used for measuring spray characteristics over the ranges of pressure, inlet air temperature, and fuel temperature. Our work during the first year allowed us to identify the challenges associated with making reliable and repeatable spray measurements while keeping the windows of the rig clean. Phase Doppler Anemometry (PDA) has emerged as a technique of choice for obtaining fundamental drop size distribution and axial and radial velocity data for comparison with numerical simulations. The VAPS facility has been upgraded to allow us to test over the entire range of fuel and air temperatures and air pressures of interest. We will be able to directly compare reacting and non-reacting spray data by collaborating with the UIUC/UDRI/AFRL Area 6 team.

The experimental data will support continued development and evaluation of engineering spray correlations including the dependence of Sauter Mean Diameter (SMD), spray cone angle, and particle number density per unit volume on the fuel properties at fuel and air temperatures of interest. The experimental data will provide detailed statistical measurements for comparisons with high-fidelity numerical simulations of mixing and combustion processes. The prediction of the spatial distribution of the liquid fuel and resulting vapor and breakdown components from the liquid fuels critically affects the ignition, flame-stabilization, and pollutant formation processes.

The project objectives are summarized as:

(a) Obtain PDA data across one plane in the VAPS test rig operated with the Referee Rig nozzle and for numerous fuels at near-lean blowout (LBO) conditions and for cold fuel/cold air flow conditions approximating ground light off (GLO) and high-altitude relight (HAR) conditions
(b) Extend PDA measurements to obtain data across multiple planes for evaluation of Detailed Combustor Simulations (DeCS) by Suresh Menon, Vaidya Sankaran, and Matthias Ihme,
(c) Obtain PDA and/or Malvern measurements for selected operating conditions either in the VAPS test rig to provide data for the spray correlation analysis of Nader Rizk,
(d) Perform PDA measurements for fuel blends including Fuel X and/or another blend designed for testing differences in atomization characteristics to examine the sensitivity of correlations and computations to changes in fuel properties,
(e) Ensure quality of data with repetition tests at Purdue and comparisons with spray measurements at P&W, UDRI/AFRL, and UIUC.

Research Approach

The Purdue University test rig facilities are designed for measuring spray characteristics over very wide ranges of pressure, inlet air temperature, and fuel temperature. An atmospheric pressure spray test rig facility was extensively used in year 1 of the project to establish the differences in spray properties of the different fuels at multiple fuel temperatures, fuel pressures, and swirler pressure drops. The second facility is the VAPS test rig which allows measurements under high and low pressure conditions relevant to the aviation applications and was being reactivated during the last part of year 1 activities and the first part of year 2 activities.

The operating system for the atmospheric pressure spray facility and the instrument positioning and atomization systems have been upgraded over the first year to allow high repeatability for PDA drop size and velocity measurements. The PDA system itself was repaired and refurbished near the end of Year 2, beginning of Year 3. A high speed camera with backlighting has yielded significant insights into the structure of the liquid fuels flowing out of the nozzle with and without the swirling co-flow through the injector. An optical patternator was also used for rapid analysis of spray distribution patterns.

Liquid fuels can be supplied to the test rigs by multiple systems. A facility-integrated system draws fuel from one of two certified flame-shield fuel containments for testing standard aviation fuels as well as other alternative blends. A mobile fuel cart, developed under the combustion rules and tools (CRATCAF) program and redeployed during the first year of the NJFCP program is being utilized for further control of additional injector circuits or for running alternative fuel blends. Both systems were designed with two independently controlled and metered circuits to supply fuel to pilot and main injector channels of the test injector. The mass flow rates of both supplies are measured with Micro Motion Elite® Coriolis flow meters. A nitrogen sparge and blanket ullage system is used to reduce the dissolved oxygen content of the fuel, which is monitored with a sensor just upstream of the fuel control circuits. High pressure gear pumps provide fuel at up to 300 kg/hr, supplied to the control circuits at a 10 MPa regulated line pressure. The mobile fuel cart was built with two onboard heat exchangers and a chilling unit controls the temperature of the fuel over a range of 233 K to 600 K (-40°F to 600°F).

Milestone(s)

The tasks that were performed in FY2017 are listed below:

Quarter 1

1. Collaborated with area 4 and 6 groups, and with the Area 5 subcommittee, for development of experimental test matrix for FY2017.
2. Returned Dantec PDA system to Denmark for repair and refurbishment.
3. Designed system for mixing of liquid and gaseous nitrogen to produce gaseous nitrogen at temperatures down to 230 K.

Quarter 2

1. Received the refurbished fiber-based color separator from Dantec and installed it in the PDA system. We then demonstrated excellent performance of the PDA system in the 1D PDA configuration.
2. Presented AIAA SciTech Conference paper describing the PDA spray measurements for near LBO conditions at the AIAA SciTech Conference in Grapevine, TX, 9-13 January 2017.
3. Performed extensive 1D PDA measurements of droplet size and axial velocity for A2 and C1 fuels over a wide range of near-LBO operating conditions.
4. Tested successfully operation of the variable ambient pressure spray (VAPS) test rig for low fuel temperatures of -30F.

Quarter 3

1. Continued 1-D fiber PDA measurements of droplet size and axial velocity over a wide range of near-LBO conditions for A2, C1, and C5 fuels. Performed repeatability tests, especially for A2 at near-LBO conditions. In particular, the pressure drop across the swirler and the pilot fuel pressure drop were varied over significant ranges.
2. Performed 1-D fiber PDA measurements of droplet size and axial velocity over a wide range of near-LBO conditions for the Fuel-X fuels C7, C8, and C9.
3. Performed PDA measurements of droplet size and axial velocity for A2, A3, and C3 fuels over a wide range of operating conditions with fuel temperatures of -30F, airbox nitrogen temperature of 40F, and at an absolute pressure of 15 psia.
4. Hosted the NJFCP Midyear Meeting on 19-23 June, 2017.

Quarter 4

1. Continued 1-D fiber PDA measurements of droplet size and axial velocity over a wide range of near-LBO conditions for A2, C1, and C5 fuels. Performed numerous repeatability tests, for near-LBO conditions. Characterized the uncertainties associated with our measurements of droplet size (Sauter mean diameter) and axial velocity.
2. Performed PDA measurements for near-LBO conditions at planes both closer and further way from the nozzle exit than the 1-inch plane for which we have taken most of our measurements. These measurements will be of great interest to the modelers, including Vaidya Sankaran of UTRC, who is working on a detailed spray model and is using our measured downstream conditions to project back up to the nozzle exit.
3. Installed a liquid nitrogen line for injection of liquid nitrogen into the supply line for our airbox flow.

Major Accomplishments

The work described in this section is a part of the Purdue contributions to the larger FAA-funded effort, the National Jet Fuels Combustion Program (NJFCP). The major objective of the work at Purdue is to perform measurements of spray properties (droplet size, droplet velocity, spray cone angle) for a variety of jet fuels and candidate jet fuels under a wide range of conditions, including lean blowout (LBO), Ground Lift Off (GLO), and high altitude relight (HAR). Representative measurements of spray properties for LBO and chilled fuel conditions are presented in the rest of this section. The Purdue Variable Ambient Pressure Spray (VAPS) test rig is discussed along with modifications needed for the LBO measurements. A generic hybrid airblast pressure-swirl injector is used and we have investigated the spray characteristics of eight different fuels. The spray data is being used as initial conditions for computational models of the combustion process in a Referee rig developed by the NJFCP team.

Experimental Systems

The Purdue Variable Ambient Pressure Spray (VAPS) rig has three main components: the airbox assembly, the pressure vessel, and the fuel cart. The airbox assembly includes a length of pipe which is housed within the vessel. The hybrid pressure swirl airblast atomizer assembly is mounted on one end of the pipe and nitrogen enters through the other end. The airbox isolates the nitrogen flow traveling through the swirler from the flow within the vessel, allowing the creation of a higher pressure environment within the airbox compared to the pressure of the vessel. The airbox allows a pressure differential to be created across the swirler component of the injector, which results in the airblast component of the atomization process to occur. The airbox can be vertically traversed to allow spray measurements at different distances from the injector exit.

The vessel houses the airbox and injector assemblies and allows the variation of different ambient pressure into which the fuel is being injected. The vessel is rated to withstand 4.14 MPa (600 psi) at 648.9°C (1200°F). The pressure within the vessel is controlled by a butterfly valve downstream of the test section which can be partially closed to increase pressure and opened to vent pressure or operate at ambient pressures. The vessel has four windows in the same horizontal plane, which allows laser diagnostic measurements to be performed within the test section. Two windows have a diameter of 127 mm (5 inches) and the other two windows have a diameter of 76.2 mm (3 inches). The 76.2 mm windows are both at a 60° angle from one of the 127 mm windows, with one of the 76.2 mm windows located on either side of the 127 mm window. There are two nitrogen flows entering the vessel: the sweeping flow and the window purge flow. These two flows are supplied by the same regulated line, which is split with one line going to the top of the vessel for the sweeping flow and the other traveling to two manifolds that supply the window purge flow. The purpose of these flows is to mitigate the recirculation and collection of fuel drops and vapors on the vessel windows, and thereby avoid obscuration for laser diagnostic measurements. These two flow are also used to build pressure within the vessel. A diagram depicting these two nitrogen flows as well as the airbox co-flow is shown in Fig. 1(a) and a picture of the VAPS vessel is shown in Fig. 1(b).

The fuel cart is a mobile fuel supply system that was designed for the Combustion Rules and Tools (CRATCAF) program. The fuel cart uses an IMO CIG Lip Seal and Weep Hole Design gear pump, which is used to supply pressurized fuel to the injector mounted on the airbox. There are two independently controlled and metered fuel lines on the fuel cart, which are used to supply fuel to the pilot and main orifices on the pressure swirl injector in the hybrid design.

The measurement system used in this study is a DANTEC DANAMICS Phase Doppler Particle Anemometry (PDPA). The alignment of the system relative to the VAPS vessel is shown in Fig. 2. The PDPA probe and receiver are mounted on Zaber translation stages to move the system to measurement locations throughout the spray along the horizontal axis shown in Fig. 2. The center of the spray on the horizontal axis is defined as the zero location for the radial locations. Positive radial locations denote locations on the left side of spray in Fig. 2 while negative radial locations denote locations on the right side. The positive and negative definitions for the radial locations was a result of the values communicated to the Zaber stages. Positive inputs moved the PDPA system to the left away from the motor while negative inputs moved the system to the right toward the motor. Measurements were taken along the negative radial locations for all conditions.

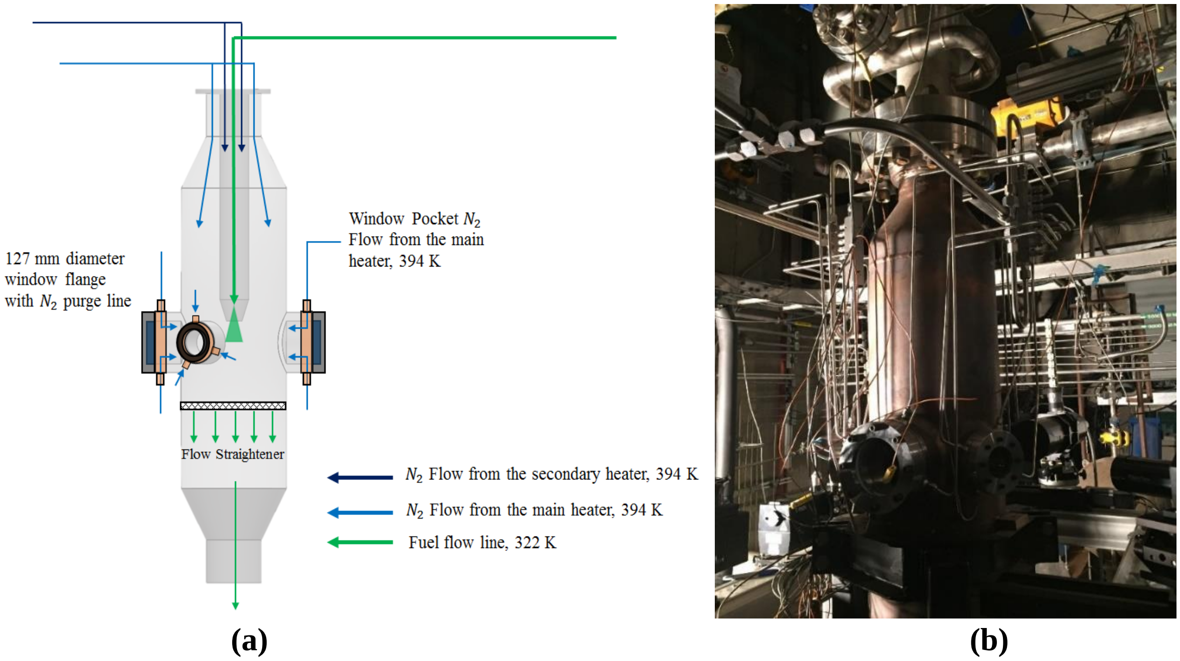


Figure 1: (a) diagram showing the three nitrogen flows within the VAPS vessel, (b) image of the VAPS rig

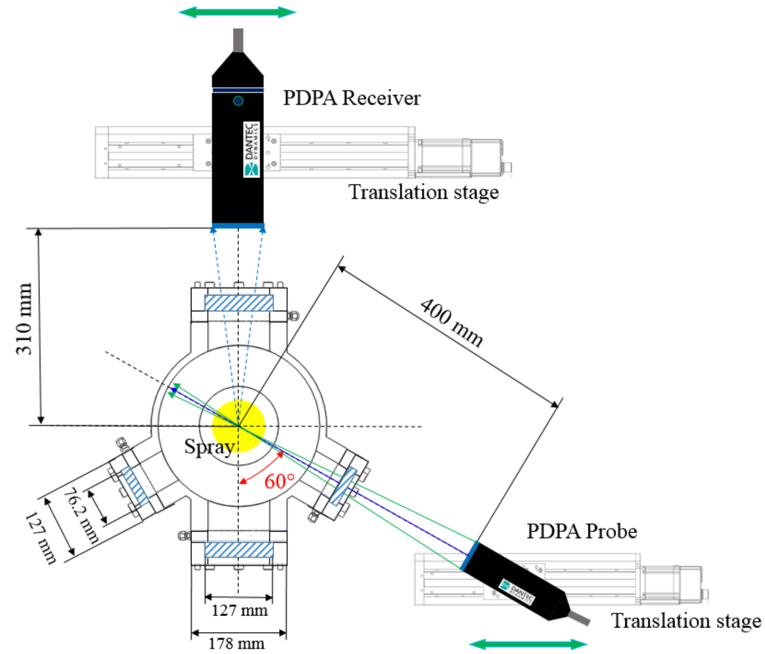
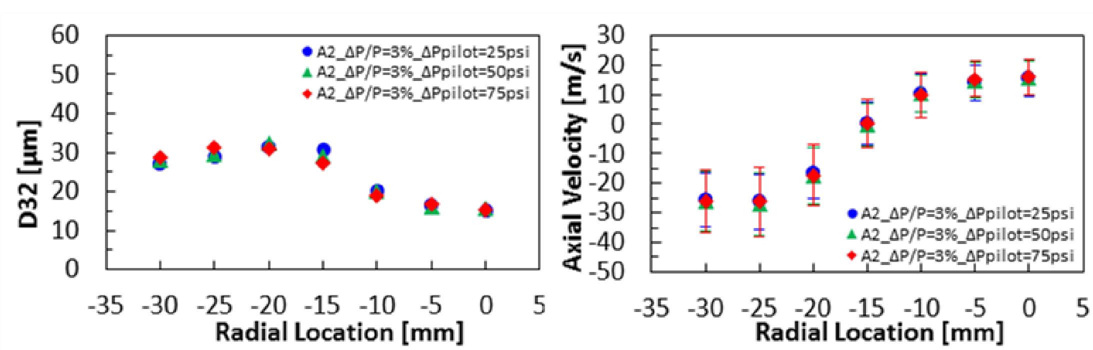


Figure 2: PDPA alignment relative to the VAPS test rig

Experimental Results: PDPA Measurements

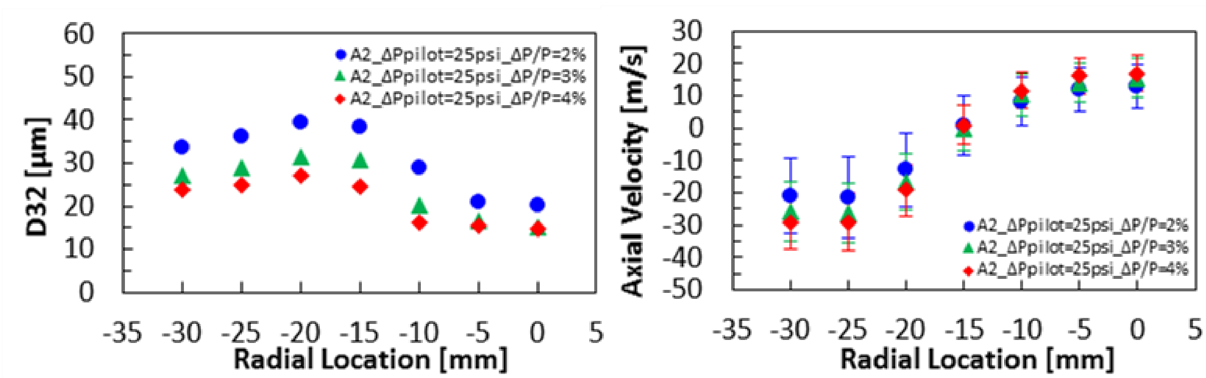
Spray measurements at LBO operating conditions have been performed in the VAPS rig for six different fuels: A-2, C-1, C-5, C-7, C-8, and C-9. The LBO operating conditions are at an ambient pressure of 2.07 bars (30 psia), an air box nitrogen temperature of 394 K (250^{0}F), a pilot fuel temperature of 322 K (120^{0}F), a pilot fuel mass flow rate of 9.22 kg/hr (2.56 g/s), and a pressure drop of 3% across the swirler. All six fuels were investigated at a distance of 25.4 mm (1 inch) downstream from the exit of the injector swirler. Figure 3a shows the comparison of the D_{32} measurements for all six fuels while Figure 3b shows a comparison of the measured axial velocities for each fuel.



(a) **(b)**

Figure 3: D_{32} and axial velocity for A-2 at near LBO condition with varied ΔP_{pilot}. Vertical bars on velocity represent RMS.

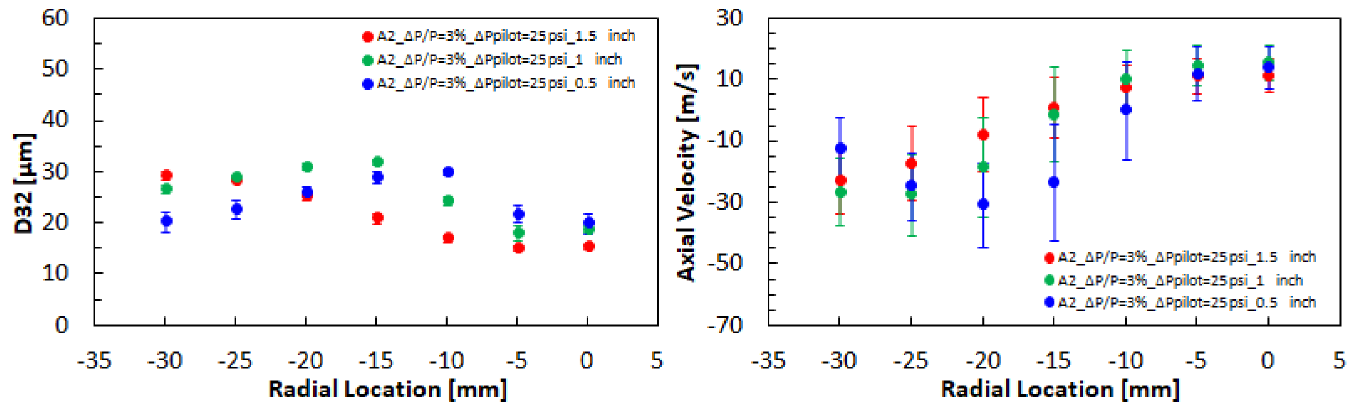
The injection pressure differential (ΔP_{pilot}) was varied for investigations of A-2, C-1, and C-5 at LBO conditions on the 25.4 mm plane. Injection pressure differentials investigated were: 25, 50, and 75 psid. Figure 4a shows the comparison of D_{32} measurements for A-2 for each injection pressure differential investigated while Fig 4b shows the axial velocity comparison. The pressure drop ($\Delta P/P$) was varied for each of the six fuels studied at LBO conditions on the 25.4 mm plane. The pressure drops investigated were: 2, 3, and 4%. Figure 4a show the comparison of D_{32} measurements for A-2 for each pressure drop investigated while Fig. 4b shows the axial velocity comparison.



(a) **(b)**

Figure 4: D_{32} and axial velocity for A-2 at near LBO condition with varied $\Delta P/P$. Vertical bars on velocity represent RMS

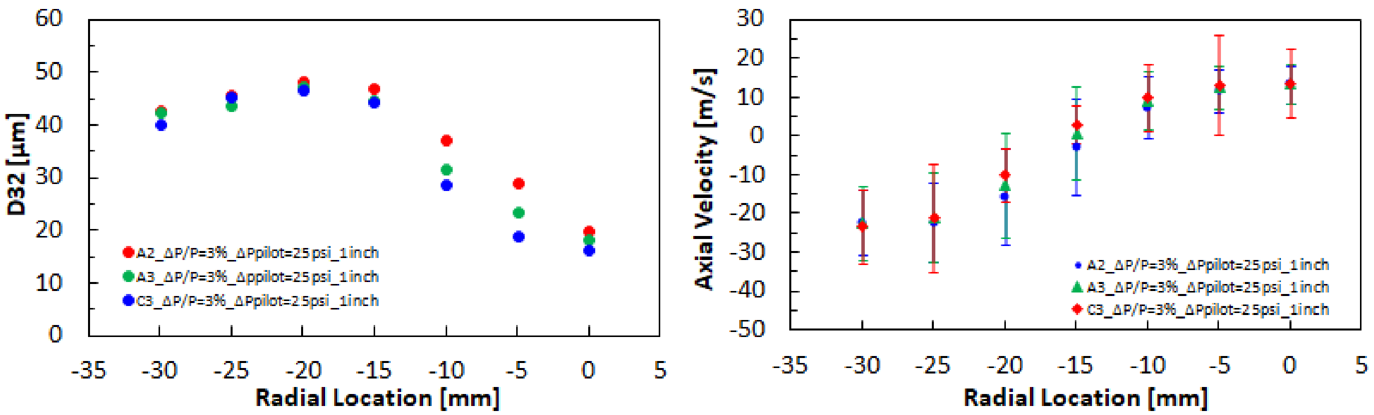
A-2, C-1, and C-5 were also investigated at different distances away from the injector exit. The measurement planes investigated were 12.7, 25.4, and 38.1 mm (0.5,1.0, and 1.5 inches). Investigations of pressure drop variations (2, 3, and 4%) were performed for all three fuels at each of the three measurement planes. The injection pressure variation (25, 50, and 75 psid) has only been additionally investigated for C-1 on the 38.1 mm plane. Figure 5a shows the comparison of D_{32} measurements for A-2 at multiple measurement planes while Fig. 5b shows the axial velocity comparison.



(a) **(b)**

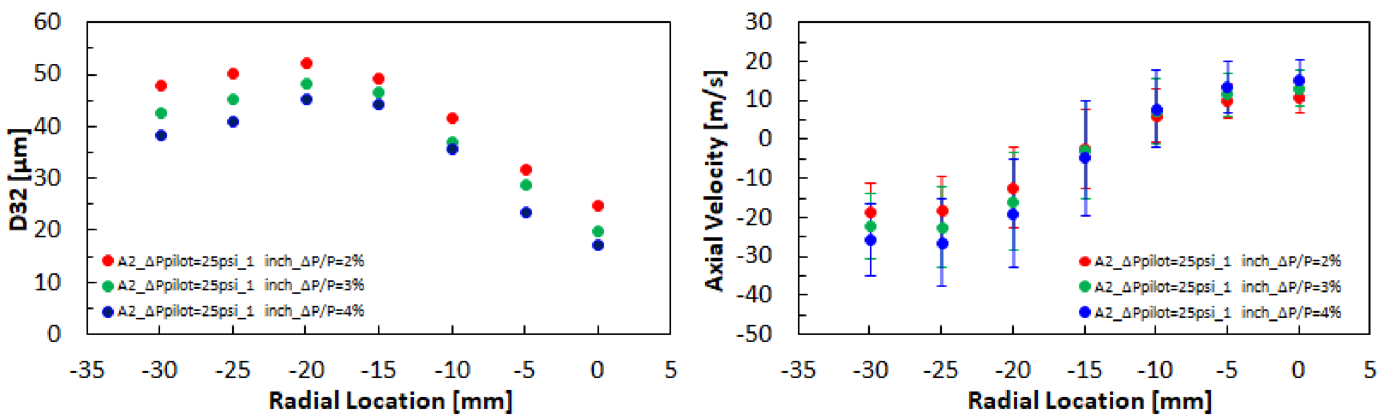
Figure 5: D_{32} and axial velocity for A-2 at near LBO condition for different measurement planes. Vertical bars on the D_{32} plot represents uncertainty from repeatability standard deviation. Vertical bars on velocity represent RMS.

Three fuels were chilled to 239 K (-30˚F) and investigated in the VAPS test rig. The three fuels were: A-2, A-3, and C-3. The pressure drop ($\Delta P/P$) and injection pressure differential (ΔP_{pilot}) were varied using the same values as the LBO investigation. All measurements for the chilled fuel conditions were performed at the 25.4 mm (1 inch) plane. The nominal operating conditions for the chilled investigation are an ambient pressure of 1.01 bars (14.7 psia), an air box nitrogen temperature of 279 K (42^{0}F), a pilot fuel temperature of 239 K (-30^{0}F), a pilot fuel mass flow rate of 9.22 kg/hr (2.56 g/s), and a pressure drop of 3% across the swirler. Figure 6a shows the D_{32} comparison of all three fuels at the nominal operating condition while Fig. 6b shows the axial velocity comparison. Figure 7a shows the D_{32} comparison for A-2 for an investigation of $\Delta P/P$ variation while Fig. 7b shows the axial velocity comparison. Figure 8a shows the D_{32} comparison for A-2 for the ΔP_{pilot} variation for chilled fuel while Fig. 8b shows the axial velocity comparison.



(a) (b)

Figure 6: D_{32} and axial velocity plots for fuel variation at chilled fuel conditions. Vertical bars on velocity represent RMS



(a) (b)

Figure 7: D_{32} and axial velocity plots for A-2 at chilled fuel condition with varied $\Delta P/P$. Vertical bars on velocity represent RMS

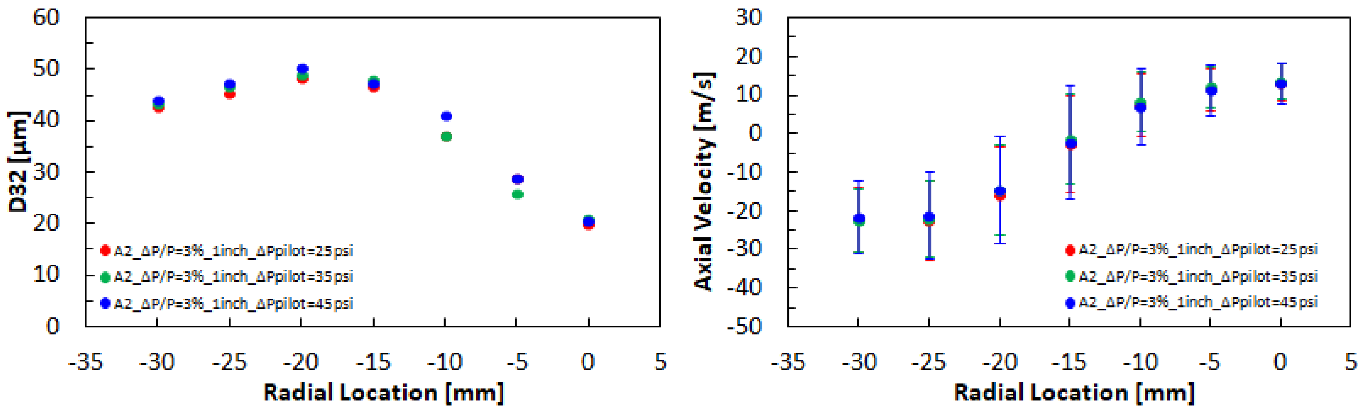


Figure 8: D_{32} and axial velocity plots for A-2 at chilled fuel conditions with varied $\Delta P_{pilot.}$ Vertical bars on velocity represent RMS

Publications

- "Effect of Aviation Fuel Type and Fuel Injection Conditions on Non-Reacting Spray Characteristics of Hybrid Air Blast Fuel Injector," Timo Buschhagen, Robert Z. Zhang, Sameer V. Naik, Carson D. Slabaugh, Scott E. Meyer, Jay P. Gore, and Robert P. Lucht, presented at the 2016 AIAA SciTech Meeting, San Diego, CA, 4-8 January 2016, Paper Number AIAA 2016-1154.
- "Large-Eddy Simulations of Fuel Injection and Atomization of a Hybrid Air-Blast Atomizer," P. C. May, M. B. Nik, S. E. Carbajal, S. Naik, J. P. Gore, R. P. Lucht, and M. Ihme, presented at the 2016 AIAA SciTech Meeting, San Diego, CA, 4-8 January 2016, Paper Number AIAA 2016-1393.
- "Spray Measurements at Elevated Pressures and Temperatures Using Phase Doppler Anemometry," A. J. Bokhart, D. Shin, R. Gejji, T. Buschhagen, S. V. Naik, R. P. Lucht, J. P. Gore, P. E. Sojka, and S. E. Meyer, presented at the 2017 AIAA SciTech Meeting, Grapevine, TX, 8-13 January 2017, Paper Number AIAA-2017-0828,.
- "Spray Characteristics at Lean Blowout and Cold Start Conditions using Phase Doppler Anemometry," A. J. Bokhart, D. Shin, N. Rodrigues, S. V. Naik, R. P. Lucht, J. P. Gore, P. E. Sojka, and S. E. Meyer, to be presented at the 2018 AIAA SciTech Meeting, Kissimmee, Florida, 8-12 January 2018.

Outreach Efforts

- "Effect of Aviation Fuel Type and Fuel Injection Conditions on Non-Reacting Spray Characteristics of Hybrid Air Blast Fuel Injector," Timo Buschhagen, Robert Z. Zhang, Sameer V. Naik, Carson D. Slabaugh, Scott E. Meyer, Jay P. Gore, and Robert P. Lucht, presented at the 2017 AIAA SciTech Meeting, San Diego, CA, 4-8 January 2016
- "Large-Eddy Simulations of Fuel Injection and Atomization of a Hybrid Air-Blast Atomizer," P. C. May, M. B. Nik, S. E. Carbajal, S. Naik, J. P. Gore, R. P. Lucht, and M. Ihme, presented at the 2016 AIAA SciTech Meeting, San Diego, CA, 4-8 January 2016.
- "Spray Measurements at Elevated Pressures and Temperatures Using Phase Doppler Anemometry," A. J. Bokhart, D. Shin, R. Gejji, T. Buschhagen, S. V. Naik, R. P. Lucht, J. P. Gore, P. E. Sojka, and S. E. Meyer, presented at the 2017 AIAA SciTech Meeting, Grapevine, TX, 8-13 January 2017, Paper Number AIAA-2017-0828,.
- "Spray Characteristics at Lean Blowout and Cold Start Conditions using Phase Doppler Anemometry," A. J. Bokhart, D. Shin, N. Rodrigues, S. V. Naik, R. P. Lucht, J. P. Gore, P. E. Sojka, and S. E. Meyer, to be presented at the 2018 AIAA SciTech Meeting, Kissimmee, Florida, 8-12 January 2018.

Awards
None.

Student Involvement
MS students Andrew Bokhart and Daniel Shin are primarily responsible for performing the PDPA measurements and for modifying the RTS test rig for first LBO and then HAR/GLO measurements. PhD students Neil Rodrigues and Timo Buschhagen and postdoctoral research associate Rohan Gejji assist with the project when their expertise is required.

Plans for Next Period
The proposed deliverables and tasks for FY2018 and Quarter 1 of FY2019 are listed below:

Year 4 Deliverables
The Year 4 deliverables for Area #5, Project 29A are as follows:
1. Move variable ambient pressure spray (VAPS) test rig to the new test facility.
2. Continue measurements with chilled fuel (-30F)/chilled nitrogen (-30F)
3. Make the ejector on the test rig functional; verify subatmospheric operation for the VAPS test rig.
4. Begin measurements with chilled fuel (-30F)/chilled nitrogen (-30F) measurements at subatmospheric ambient pressure (down to 4 psia), coordinate with Nader Rizk and Area 6 on exact operating conditions to investigate.
5. Collaborate with Andrew Corber at NRC on SLIPI imaging measurements in the VAPS test rig.
6. Continue interactions with the three CFD groups (Ihme, Vaidya and Menon).
7. Investigate spray structure for sprays with very low levels of pressure drop across the swirler or with the swirler removed.
8. Investigate the structure with the pilot+main spray and/or the main without pilot spray.

The tasks to be performed for FY2018 and Quarter 1 of FY2019 are listed below:

Quarter 1 FY2018
1. Collaborate with Area 4 and Area 6 members, and with the spray subcommittee, for development of experimental test matrix for the remainder of Year 3.
2. Perform PDPA measurements at near-LBO conditions at axial planes 0.5 in and 1.5 in downstream of the nozzle exit. Continue measurements with chilled fuel.
3. Develop and demonstrate the chilled nitrogen system for obtaining airbox flow temperatures down to -30F. Begin measurements with chilled fuel and chilled nitrogen.
4. Plan the move of the VAPS rig to the new High Pressure Combustion Laboratory.
5. Share boundary, initial, and operating conditions and resulting experimental data with correlations and modeling team (Rizk, Ihme, Menon, and Sankaran).

Quarter 2 FY2018
1. Collaborate with Area 4 and Area 6 members, and with the spray subcommittee, for development of experimental test matrix for Year 4.
2. Move the VAPS rig to the new High Pressure Combustion Laboratory.
3. Make the VAPS test rig operational again.

Quarter 3 FY2018
1. Continue extensive characterization of sprays with chilled fuel and chilled N_2.
2. Share boundary, initial, and operating conditions and resulting experimental data with correlations and modeling team (Rizk, Ihme, Menon, and Sankaran).
3. Make the ejector operational in preparation form subatmospheric operation of the VAPS rig.

Quarter 4 FY2018
1. Collaborate with Andrew Corber at NRC on SLIPI imaging measurements in the VAPS test rig.

2. Perform measurements with chilled fuel and chilled N_2 at subatmospheric pressure.
3. Share boundary, initial, and operating conditions and resulting experimental data with correlations and modeling team (Rizk, Ihme, Menon, and Sankaran).

Quarter 1 FY2019

1. Investigate spray structure for sprays with very low levels of pressure drop across the swirler or with the swirler removed.
2. Investigate the structure with the pilot+main spray and/or the main without pilot spray.
3. Share boundary, initial, and operating conditions and resulting experimental data with correlations and modeling team (Rizk, Ihme, Menon, and Sankaran).