Project 029 National Jet Fuels Combustion Program, Area #5: Atomization Test and Models

Purdue University, Stanford University

Project Lead Investigator

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University Participants

- P.I.(s): Robert P. Lucht, Jay P. Gore, Carson D. Slabaugh, Paul E. Sojka, and Scott E. Meyer
- FAA Award Number: **COE-2014-29A** , 401321
- Period of Performance: 12/1/2015-11/30/2015
- The experimental tasks to be performed in Year 2 are listed below:

Quarter 1

1. Collaborate with area 4 and 6 groups, and with the Area 5 subcommittee, for development of experimental test matrix for Year 2.
2. Install heat exchangers and cyclone separator for RTS test rig for operation at subatmospheric pressure.
3. Perform extensive characterization of Nozzle B sprays for LBO and other conditions in the RTS test rig using PDPA and high-speed backlit video imaging.
4. Share boundary, initial and operating conditions and resulting experimental data with Ihme and Menon groups.
5. Design system for mixing of liquid and gaseous nitrogen to produce gaseous nitrogen at temperatures down to 230 K.

Quarter 2

1. Exploratory/shakedown testing of the AGTC test rig.
2. Continue extensive characterization of Nozzle B sprays for LBO and other conditions in the RTS test rig using PDPA and high-speed backlit video imaging.
3. Perform characterization of selected Nozzle B spray conditions for LBO conditions in the AGTC test rig using Mie scattering and fuel PLIF imaging.
4. Share boundary, initial and operating conditions and resulting experimental data with Ihme and Menon groups.
5. Fabricate and test system for mixing of liquid and gaseous nitrogen to produce gaseous nitrogen at temperatures down to 230 K.

Quarter 3

1. Perform extensive characterization of Nozzle B sprays for GLO and other conditions in the RTS test rig using PDPA and high-speed backlit video imaging.
2. Perform characterization of selected Nozzle B spray conditions for GLO and other conditions in the AGTC test rig using Mie scattering and fuel PLIF imaging.
3. Install Nozzle A in RTS test rig and perform measurements for selected LBO conditions.
4. Share boundary, initial and operating conditions and resulting experimental data with Ihme and Menon groups.

Quarter 4

1. Continue extensive characterization of Nozzle B sprays for GLO conditions in the RTS test rig using PDPA and high-speed backlit video imaging.
2. Continue characterization of selected Nozzle B spray conditions for GLO and LBO conditions in the AGTC test rig using Mie scattering and fuel PLIF imaging.
3. Install Nozzle A in RTS test rig and perform measurements for selected GLO conditions.
4. Share boundary, initial and operating conditions and resulting experimental data with Ihme and Menon groups.

- P.I.(s): Matthias Ihme
- FAA Award Number: **COE-2014-29B**
- Period of Performance: 12/1/2015-11/30/2016
- The experimental tasks to be performed in Year 2 are listed below:
- The computational modeling tasks to be performed in Year 2 are listed below:
  1. Perform detailed LS/VOF simulations to validate multiphase modeling tools for airblast conditions
  2. Compare simulation results against measurements from PDPA provided by Purdue and UDRI
  3. Analyze correlations for SMD, breakup-length, and droplet distribution using high-fidelity simulation results from LS/VOF computations; identify correlations between droplet distribution and LBO-conditions (coordination with Nader Rizk)
  4. Perform detailed simulations and validation on nozzle A; compare model results with experiments; evaluate effects of different nozzle geometries (nozzle A vs. nozzle B) on ignition and LBO characteristics

Project Funding Level

The funding level from FAA was $250,000 to Purdue University for Year 2. Purdue University provided cost sharing funds in the amount of $250,000.
The funding level from FAA was $40,000 to Stanford University for Year 2. Purdue University provided cost sharing funds in the amount of $40,000.

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.

PI Dr. Matthias Ihme is responsible for the oversight of the computational modeling effort at Stanford University. He is also responsible for supervising the post-doctoral and graduate students at Stanford, coordinating activities with Purdue and UDRI and will work with all parties for appropriate results and reporting as required.

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 propose 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. The modeling tasks are described in a separate proposal but a specific task will involve rendering of modeling results in the form of measurable and important quantities including liquid surface area density and discrete probability density functions of liquid ligament and drop sizes.

Purdue University has two 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 will be applied will include both well-established diagnostics such as phase Doppler particle anemometry (PDPA) as well as advanced high-frame-rate simultaneous Mie scattering and fuel planar laser-induced fluorescence (PLIF). Recently commercialized and SAE J2715 standards based techniques for liquid surface area density and drop size probability density functions will be utilized by renting patternator equipment from a Purdue Technology Center small business. These tests will help us qualify the nozzles to be installed in the high-pressure rigs. The atomization and spray dynamics of the three reference fuels and referee rig nozzle configurations will be performed in both of our spray rig facilities. These facilities will allow us to test over the entire range of fuel and air temperatures and air pressures of interest. In one of the test rigs we will be able to directly compare reacting and non-reacting flow cases.

The objectives of the computational research are the development and validation of modeling capabilities for the prediction of primary and secondary breakup of liquid fuel under consideration of multicomponent fuel effects. These modeling efforts will be accompanied by validation against measurements from the complementary experimental effort that is conducted at Purdue University.

Task: COE-2014-29A: National Jet Fuels Combustion Program – Area #5: Atomization Tests and Models

Purdue University

Objective(s)

The objectives of this proposal 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 and for a nozzle with the design made available by the Pratt & Whitney (P&W) and Georgia Tech teams. 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 will be performed at Purdue University and the resulting data will be shared with FAA team members developing modeling, simulations, and engineering correlation based tools. We will develop methods to compare the spray properties under non-reacting flow conditions and those under combustor flow conditions.

The upgraded RTS test facility at Purdue University will be used for measuring spray characteristics over the ranges of pressure, inlet air temperature, and fuel temperature for two different spray nozzles. Our work during the first year and up to this point in the second 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 particle anemometry (PDPA) 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 atomization and spray dynamics of the three reference fuels and two nozzle configurations will be measured in the Purdue Rules and Tools Spray (RTS) test rig. This facility will be further 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 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 vapors and breakdown components from the liquid fuels critically affects the ignition, flame-stabilization, and pollutant formation processes. The focus during the rest of Year 2 and Year 3 activities will be on obtaining data for extension of long-standing Rizk correlations to include effects of fuel properties and the effects of the non-reacting (RTS rig) and reacting (referee rig) at AFRL and/or the Advanced Gas Turbine Combustor (AGTC) rig at Purdue.

The project objectives are summarized as:

(a) Obtain PDPA data across one plane in the Rules and Tools Spray (RTS) rig operated with the Referee Rig nozzle and the P&W nozzle,
(b) Extend PDPA measurements to obtain data across multiple planes for evaluation of Detailed Combustor Simulations (DeCS) by Suresh Menon, Vaidya Sankaran, and Matthias Ihme,
(c) Obtain PDPA and/or Malvern measurements for selected operating conditions either in the RTS test rig or at atmospheric pressure to provide data for the spray correlation analysis of Nader Rizk,
(d) Perform PDPA 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,
(f) Compare spray data under non-reacting flow conditions of the Rules and Tools Spray test rig with those under reacting flow conditions from the Referee Rig at AFRL and/or the Advanced Gas Turbine Combustor (AGTC) rig at Purdue.

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 has been 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 Rules and Tools spray (RTS) test rig which will allow measurements under high and low pressure conditions relevant to the aviation applications and is 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 PDPA drop size and velocity measurements. 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 is 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 (-40ºF to 600ºF).

Milestone(s)

The major milestones that have accomplished so far during Year 2 of the project are:

1. Modification of the RTS test rig for measurements at near LBO conditions. This was a very significant effort that was complicated by condensation of fuel on the inside of the windows and liquid water or ice on the outside of the

windows. The LBO test matrix was developed in coordination with Nader Rizk. The LBO test conditions that were investigated are shown below:

Table 1. of LBO test conditions.

Injector	OP	ΔP/P [%]	Fuel Flow Rate [lbm/hr]	Fuel Temp. [°F]	ΔP_{pilot} [psia]	Vessel Press. [psia]	Vessel Temp. [°F]
100% Pilot	1	2.00	20.00	120	25	30	250
	2	4.00	20.00	120	25	30	250
	3	6.00	20.00	120	25	30	250
	4	2.00	28.28	120	50	30	250
	5	2.00	34.64	120	75	30	250
	6	3.00	20.00	120	25	30	250
	7	3.00	28.28	120	50	30	250
	8	3.00	34.64	120	75	30	250

2. PDPA measurements of A2, C1, and C5 fuels at the test conditions in Table 1. Comparison of our measurements for a non-reacting spray with measurements by UDRI/UIUC for a reacting spray conditions. Sent detailed PDPA data to Dr. Vaidya Sankaran at UTRC for comparison with his spray calculations.
3. High-speed imaging of sprays at LBO conditions to assess spray geometry and aid in the definition of spray angle.
4. Investigated filming on the inner surface of the inner swirler of the nozzle. Established that the pilot spray was impacting this surface.

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 conditions are presented in the rest of this section. The Purdue Rules and Tools Spray (RTS) test rig is discussed along with modifications needed for the LBO measurements. A generic hybrid air blast injector is used and we have investigated the spray characteristics for three different fuels. The spray data are being used as initial conditions for computational models of the combustion process in a Referee rig developed by the NJFCP team.

Experimental Systems

The rules and tools (RTS) test rig is shown in a photograph in Fig. 1 and in a schematic diagram in Fig. 2. The RTS test rig consists of two major sub-assemblies: a vertically-actuated air-box assembly and an optically-accessible pressure vessel. The air-box assembly houses the injector and (optional) swirler components. This assembly can be operated independently from the pressure vessel for atmospheric-pressure testing utilizing diagnostics requiring unrestricted optical access such as patternation. The injector assembly can be traversed vertically, with precise control, relative to supply manifolds. This design feature supports the application of point diagnostics over a grid of measurement locations with varying distances from the nozzle exit.

Pressure modulation of test conditions is achieved by installing the complete air-box assembly into the pressure vessel. The pressure vessel was originally designed for a study of spray behavior under super-critical conditions and has demonstrated sustained operation at quiescent flow pressures and temperatures up to 4 MPa and 900 K. Optical access is achieved through four windows for high-speed video, Schlieren, Malvern and PDPA measurements. Two of the windows are located on opposite sides of the vessel to achieve a clear line of sight, supporting Schlieren and other line-of-sight measurements. The other two windows are located 30 degrees from the line of sight optical axis with a 60 degree included angle. A sweeping flow, within the vessel, helps to prevent window fouling by the ejected spray.

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 and for running alternative fuel blends. The fuel cart has 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 to control the temperature of the fuel over a range from 233 K to 600 K (-40˚F to 620˚F).

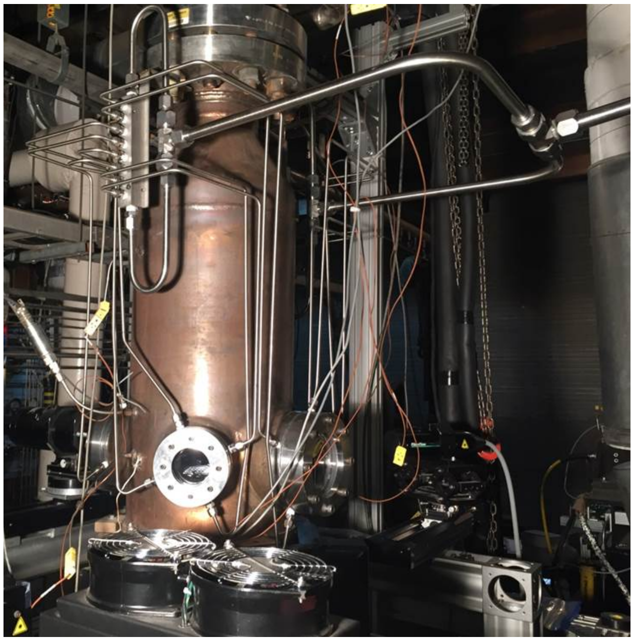


Figure 1. Photograph of the RTS test rig.

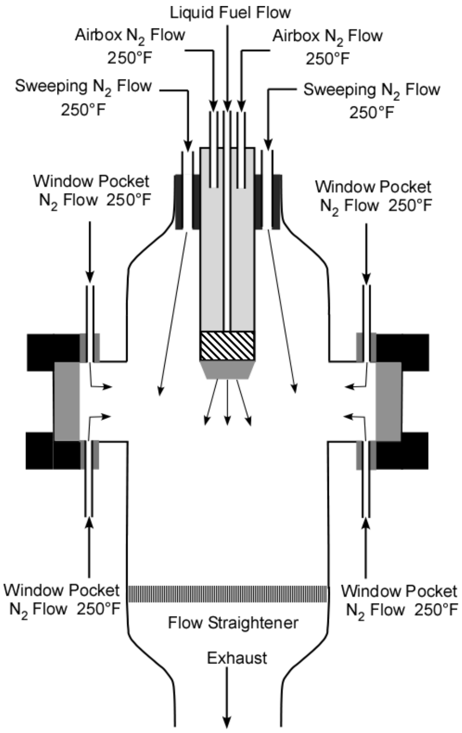


Figure 2. Schematic diagram of the RTS test rig.

We initially tried measurements with a Malvern diffraction particle sizing system in the RTS test rig in collaboration with Andrew Corber from National Research Council (NRC), Canada. For the initial LBO measurements the nitrogen swirler flow was directed to an electric heater, then was mixed into the air box that holds the referee nozzle/swirler assembly. The electric heater is used to heat the air box nitrogen flow so that the temperature is 250˚F at the swirler inlet. For the initial measurements we tried using an unheated sweeping flow of nitrogen. The sweeping flow is intended to keep the fuel droplets from the spray from hitting the windows. However, we observed significant wetting of the inside of the window with fuel, although there were some operating conditions where the fuel on the window was minimal. Moreover, the cold sweeping flow chilled the windows and caused condensation of water vapor on the outside of the windows. Malvern/diffraction measurements are extremely sensitive to window contamination, and we observed artifacts in the acquired data due to window contamination and also due to beam steering resulting from the large temperature difference between the sweeping and the air box nitrogen flows. The sweeping nitrogen flow temperature was about -20˚F as a result of the significant cooling upon expansion from the supply pressure of 6000 psi.

The next step that we took was to install nitrogen purge lines both inside the window in the window flange pocket and then outside the window to flow dry nitrogen over the window surface to prevent condensation of water from the room air. This was not successful, there were some runs where we were able to keep the windows clear but as we tried to increase the chamber pressure to 30 psia and take measurements at LBO conditions significant artifacts in the Malvern measurements occurred, which we now believe are due to beam steering resulting from the temperature gradient between the air box and the sweeping nitrogen flows.

We then decided to heat the sweeping flow by sending it through our natural-gas-fired air heater. This improved the situation but we were still not able to acquire artifact-free Malvern data at LBO conditions, and depending on the particular run conditions we still had problems with fuel condensation on the inside of the window and water condensation on the outside of the window. At this point, the window flange purge flow was unheated and thus entered the pressure vessel at -20˚F. To overcome this, we decided to heat the window purge flow. This required a significant plumbing effort. The window purge flow and the sweeping flow are now obtained from the single exit stream from our natural-gas-fired air heater. Heating both the window purge flow and the sweeping flow solved our window contamination problem. At the same time, we decided to switch from Malvern/Sympatec measurement system to a Phase Doppler particle anemometer (PDPA) system allowing simultaneous measurements of drop size distributions, axial, and radial velocity components. As it turns out, it now appears that the PDA measurements are much easier to implement in the RTS test rig than the Malvern measurements.

Experimental Results: PDPA Measurements

We have successfully performed spray measurements in the RTS test rig at LBO conditions using PDPA and high-speed imaging systems for three different fuels (A2, C1, and C5). The LBO operating conditions are at an ambient pressure of 2.07 bars (30 psia), an air box nitrogen temperature of 394 K (250ºF), a pilot fuel temperature of 322 K (120ºF), a pilot fuel mass flow rate of 9.22 kg/hr (2.56 g/s), and a pressure drop of 3% across the swirler. The geometry of the PDPA measurement system is shown in Fig. 3 for negative and positive radial location along a line through the nozzle centerline. Some of the initial measurements are presented in Figs. 4 and 5. All of the data shown were collected at an axial distance of 25.4 mm from the swirler exit plane. Figure 4 shows the measured Sauter Mean Diameter (SMD) for the three fuels for negative radial locations (referring to Fig. 3) and Fig. 5 shows the axial and radial velocities for both positive and negative radial locations for fuel A2. Our work has included analyzing droplet diameter distribution statistics in terms of the probability of occurrence of different drop sizes that lead to the Sauter Mean Diameter (SMD or D_{32}) depicted in Fig. 4. The SMD is biased by the populations representing larger drops because these evaporate at slower rates than the smaller drops as a result of lower surface area to volume ratios.

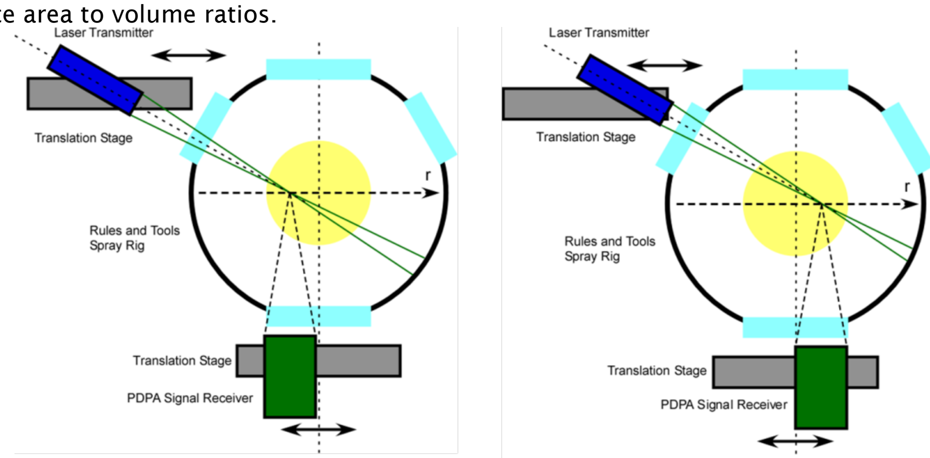


Figure 3. Top view of PDPA measurement geometry.

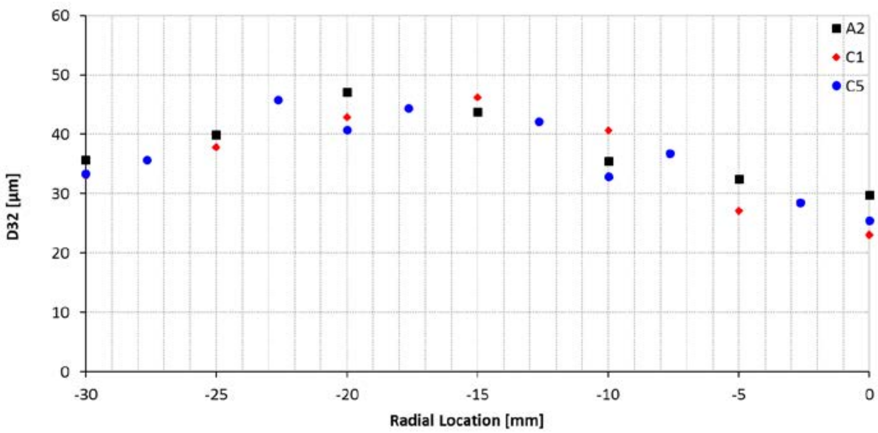


Figure 4. Sauter mean diameter D_{32} as a function of radial position for three different fuels.

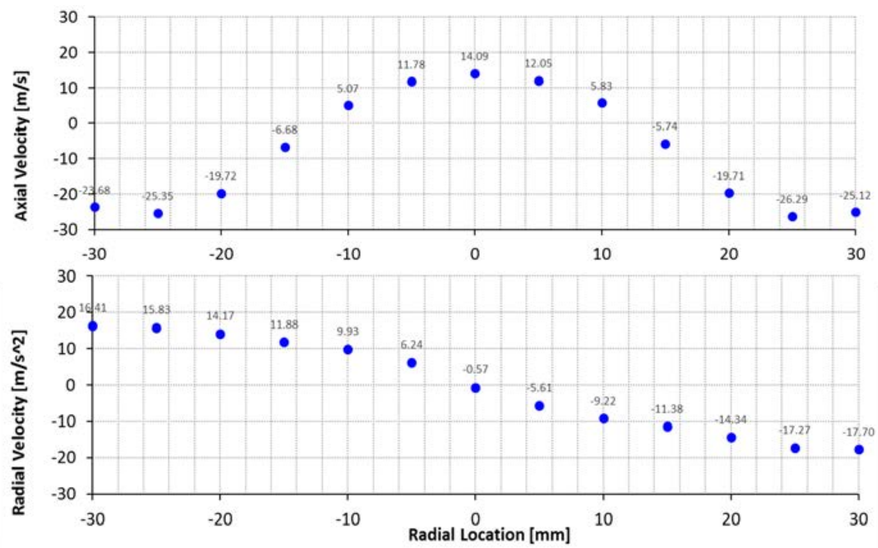


Figure 5. Axial and radial velocities for fuel A2 as a function of radial position. Note the central recirculation zone from -12 mm to +12 mm positive axial velocities (towards the nozzle).

Experimental Results: Spray Geometry

The cone angle is defined in this study as the angle between two straight lines that represent the fuel cone geometry. The lines are drawn from the injector orifice to some specified distance from the nozzle exit so that the edges of the spray cone are determined. The full cone angles 0.5 inches away from the nozzle exit were measured for C-1, C-5, and A-2 with varied differential pressure and fuel flow rate. A simple image processing has been performed on the high speed images in order to determine the spray cone angles. A background image and 5823 high speed spray images were obtained for each test case. These images were averaged and the background was subtracted from the averaged image. Figure 6 shows the average shadowgraph image of an A-2 spray at OP 1 and the modified image after the subtraction of the background.

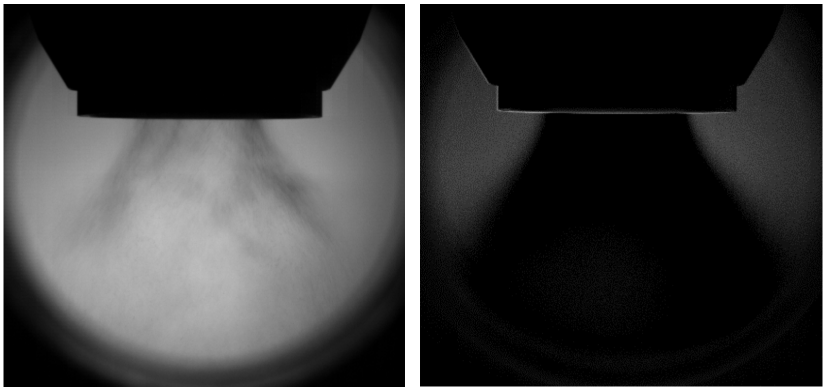


Figure 6. Shadowgraph image of A-2 spray at OP 1 (Left). Spray image with the background subtracted (Right).

In order to define the spray edge from the background subtracted image, the pixels that fit within a specific intensity limit are masked in different colors. The intensity in a grayscale image is a value between 0 to 1. The pixel intensity values near the spray edge were determined to be between 0.025 to 0.043. These intensity limits are divided into three smaller limits and masked in yellow, red, and blue as shown in Figure 7b. By accessing the coordinates of selected pixels along the spray edge, a linear regression fit was applied with the location of the injector orifice fixed within the regression. The location of the injector orifice is marked as a green circle in Fig. 7c and Fig. 7d.

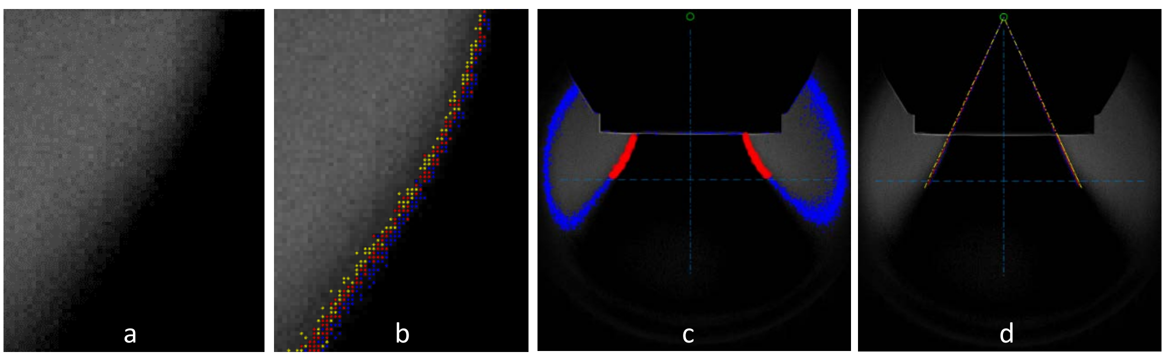
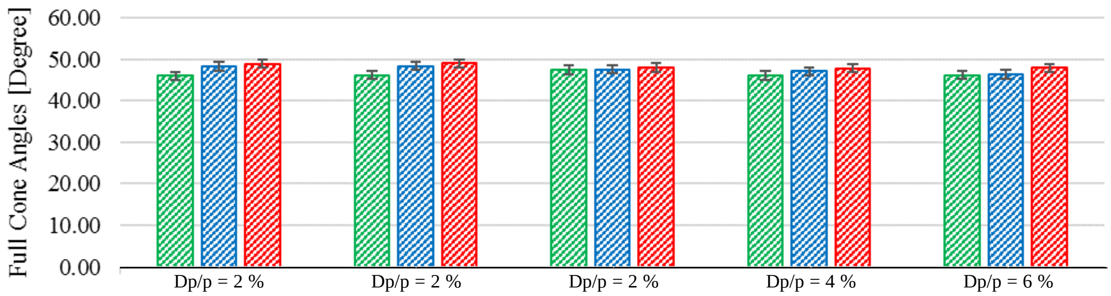


Figure 7. a) Edge of the spray in grayscale image. b) Applied three different masks on the pixels in spray edge. c) Selected masked pixels on the edge of the spray are shown in red. d) Linear regression fit is obtained using the selected pixels and a fixed point at the injector orifice.

The resulting cone angles calculated between the two linear regression lines for each test are shown in Fig. 8 for A-2, C-1, and C-5. The full cone angles obtained from each fuel are between 46.05 ° and 49.05° with the uncertainty within ±0.33° and ±1.65°. The results show that the effect of pressure drop and fuel flow rate on the cone angles is minimal and the change in cone angles is within the margin of experimental uncertainty. It is also shown that the fuel type has a minimal effect on the cone angles and it is negligible.



	Dp/p = 2 % FFR = 20 lbm/hr		Dp/p = 2 % FFR = 28.28 lbm/hr		Dp/p = 2 % FFR = 34.64 lbm/hr		Dp/p = 4 % FFR = 20 lbm/hr		Dp/p = 6 % FFR = 20 lbm/hr	
	Cone Angle	Uncertainty	Cone Angle	Uncertainty	Cone Angle	Uncertainty	Cone Angle	Uncertainty	Cone Angle	Uncertainty
C-1	46.05°	±1.16°	46.16°	±0.64°	47.47°	±0.86°	46.11°	±1.65°	46.19°	±1.51°
A-2	48.32°	±0.55°	48.40°	±0.48°	47.60°	±0.41°	47.13°	±0.91°	46.33°	±0.56°
C-5	48.91°	±1.02°	49.05°	±0.76°	48.03°	±0.46°	47.82°	±0.63°	47.95°	±0.33°

Figure 8. Bar graph of full cone angles comparison for A-2, C-1, and C-5 under pressure drop variation and fuel flow rate variation.

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, to be presented at the 2017 AIAA SciTech Meeting, Grapevine, TX, 8-13 January 2017.

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 2016 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, to be presented at the 2017 AIAA SciTech Meeting, Grapevine, TX, 8-13 January 2017.

Awards

None.

Student Involvement

PhD 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 Timo Buschhagen and Rohan Gejji assist with the project when their expertise is required.

Plans for Next Period

The Year 3 deliverables for Area #5 are as follows:

1. Early in Year 3 we will modify the variable-ambient-pressure RTS test rig (brought back online by us during Year 2) for measurements with chilled fuel and chilled nitrogen swirler flow. We will perform PDPA measurements for low-pressure

high-altitude relight (HAR) conditions with fuel temperatures down to -30˚F. An ejector will be installed on the RTS rig for sub atmospheric pressure conditions. A heat exchanger for the nitrogen will be installed so that we can run with nitrogen at temperatures below room temperature as well as at temperatures up to 350˚F. The RTS spray rig will be suitable for measurements with both heated fuel and chilled fuel. In the RTS spray rig, the diagnostics will include PDPA, Malvern SMD, and high-speed video with backlighting. The RTS test rig will be used for extensive testing guided by a test matrix provided by Nader Rizk for HAR conditions for the selected category A and category C fuels. Ground Lift Off (GLO) measurements will be performed in an atmospheric-pressure spray rig with cold fuel and cold nitrogen for Nozzle B. Measurements will be performed for selected category A and C fuels and the experiments will be guided using a test matrix supplied by Nader Rizk.

2. Spray measurements will be performed near LBO conditions for Configuration 2 in which the main fuel circuit for Nozzle B will be activated. Spray measurements for GLO conditions will also be performed for the Pratt and Whitney swirler/fuel nozzles that are the subject of measurements at LBO conditions in Year 2.
3. We will develop research transition and implementation plan as well as share data and results with other area research teams on a timely basis as applicable and/or as directed by the Steering Committee (Purdue, Stanford, Georgia Tech, and industry partners). We will coordinate closely with Area 6 as their testing capabilities expand in the rest of Year 2. We will share data and get input from Suresh Menon in addition to the input we have been receiving from Matthias Ihme on cases of particular interest and regarding additional measurements needed for characterization of boundary conditions for CFD model validation and calibration.

The tasks to be performed in Year 3 are listed below:

Quarter 1

1. Collaborate with Area 4 and Area 6 members, and with the Area 5 subcommittee, for development of experimental test matrix for Year 3.
2. Install heat exchangers and cyclone separator for Rules and Tools (RTS) test rig for operation at sub-atmospheric pressure.
3. Perform initial spray measurements with Nozzle B for high-altitude relight (HAR) conditions in the RTS test rig and for Ground Lift Off (GLO) conditions in an atmospheric-pressure rig using PDPA and high-speed backlit video imaging.
4. Share boundary, initial, and operating conditions and resulting experimental data with correlations and modeling team (Rizk, Ihme, Menon, and Sankaran).
5. Design a system for mixing of liquid and gaseous nitrogen to produce gaseous nitrogen at temperatures down to 230 K.
6. Perform spray measurements for Nozzle B in Configuration 2 (main fuel circuit activated) near LBO conditions.

Quarter 2

1. Continue extensive characterization of sprays with Nozzle B for HAR conditions in the RTS test rig and for GLO conditions in an atmospheric-pressure rig using Phase Doppler Particle Analyzer (PDPA) and high-speed backlit video imaging.
2. Share boundary, initial, and operating conditions and resulting experimental data with correlations and modeling team (Rizk, Ihme, Menon, and Sankaran).
3. Fabricate and test the system for mixing of liquid and gaseous nitrogen to produce gaseous nitrogen at temperatures down to 230 K.
4. Continue spray measurements for Nozzle B in Configuration 2 (main fuel circuit activated) near LBO conditions.

Quarter 3

1. Continue extensive characterization of sprays with Nozzle B for HAR conditions in the RTS test rig and for GLO conditions in an atmospheric-pressure rig using Phase Doppler Particle Analyzer (PDPA) and high-speed backlit video imaging.
2. Share boundary, initial, and operating conditions and resulting experimental data with correlations and modeling team (Rizk, Ihme, Menon, and Sankaran).
3. Exploratory/shakedown testing of the Advanced Gas Turbine Combustor (AGTC) test rig.
4. Install the P&W swirler and fuel nozzles or another nozzle of interest and perform measurements in the AGTC for selected GLO conditions.

Quarter 4

1. Continue extensive characterization of sprays with Nozzle B for HAR conditions in the RTS test rig and for GLO conditions using Phase Doppler Particle Analyzer (PDPA) and high-speed backlit video imaging.
2. Continue characterization of selected sprays with Nozzle B for LBO conditions in the AGTC test rig using Mie scattering and fuel PLIF imaging.
3. Perform measurements for selected GLO conditions with the P&W swirler and fuel nozzles or another nozzle of interest.
4. Share boundary, initial, and operating conditions and resulting experimental data with correlations and modeling team (Rizk, Ihme, Menon, and Sankaran).

Task: COE-2014-29B: National Jet Fuels Combustion Program – Area #5: Atomization Tests and Models

Stanford University

Objective(s)

The objectives of the computational research are the development and validation of modeling capabilities for the prediction of primary and secondary breakup of liquid fuel under consideration of multicomponent fuel effects. These modeling efforts will be accompanied by validation against measurements from the complementary experimental effort that is conducted at Purdue University.

Research Approach

The objective of this study is to use a LES approach in conjunction with an unstructured Volume-of-Fluid (VoF)/Lagrangian-spray (LSP) framework to conduct high-fidelity simulations of the breakup and atomization processes in a realistic gas- turbine hybrid air blast atomizer. Conditions corresponding to lean blowout are considered in this study to assess the capabilities of the current model under very low liquid Webber number. Simulation results for pilot injection with POSF 10264 Cat-A1 fuel are presented. Fuel droplet statistics are compared to available experimental data measured utilizing phase Doppler particle analyzer (PDPA) systems.

Experimental Setup

Measurements of a Parker-Hannifin hybrid airblast injector that were performed at Purdue University for different aviation fuels and operating conditions. Argon ion laser (488 nm and 514.5 nm) was used with a 400 nm transmitter focal length and a 310 nm receiver focal length. Extinction tomographic measurements using an optical patternator were used to measure the liquid surface area per unit volume. The experimental setup is shown in Figure 9. The hybrid atomizer consists of a low flow number (FN = 4) pressure swirl pilot nozzle and a circuit of five main injectors at a flow number of 15. The hybrid air blast atomizer takes advantage of both the pressure swirl injector at low fuel-flow rates and air blast atomization at high fuel flows. The atomizer has a 90 degree spray angle. The target condition considered in this study is of 100% pilot injection with the PSOF 10264 Cat-A1 fuel at ambient conditions. The fuel pressure drop is 25.4 psi with a mass flow rate of 20.15 lb/hr, and the ambient conditions are 14.7 psi and 60 F. This fuel pressure drop and mass flow rate correspond to the lean blowout conditions where the fuel spray has a very low liquid Webber number.

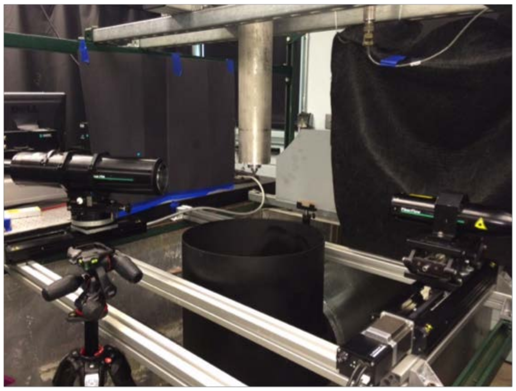


Figure 9: Experimental Setup

Numerical Solver

In this study, a VoF-method coupled with a LSP-framework is adopted. The incompressible Navier-Stokes equations for immiscible, two-phase flows are solved to describe the flow field. Density and viscosity are assumed to be constant within each phase, and can be expressed as a function of the volume of fluid. The Piecewise-Linear Interface Calculation (PLIC) scheme is adopted, which has advantages in conserving the mass and constructing monotone advection schemes. The overall VoF-scheme is geometric and unsplit, enforcing exact mass conservation on unstructured grids. The VoF-method is coupled to the LSP-framework to describe the secondary breakup dynamics, which cannot be fully resolved using available computational resources. The Lagrangian particle method is applicable to droplets with small local Weber numbers in the subsequent breakup and atomization processes. In this manner, the primary breakup and the subsequent atomization can be modeled efficiently. The subgrid stresses in the LES-approach were described using a Vreman model. For the LSP-method, the liquid droplet motion is simulated using the Basset-Boussinesq-Oseen (BBO) equation with shear force, Basset force and added mass neglected. The secondary breakupof Lagrangian particles into smaller drops, which was shown to be important, is modeled by a stochastic breakup model.

Geometry and Mesh Generation

The computational domain is shown in Figure 10 with zoomed view of the near nozzle region. To provide an accurate description of the primary break-up dynamics and cone-angle, a portion of the injector nozzle is included. All the geometry used in the simulation is the same as the geometry provided by Parker-Hannifin. The injector nozzle has three feeding slots, which serve as inlet boundary conditions in the simulation. According to the mass flow rate in the experiments, the inlet velocity at each feeding slot is set to 12.4 m/s. A swirl chamber is located upstream of the discharge orifice. The discharge orifice of the pilot injector has a diameter of $D = 1.31$ mm, and the feeding slots have diameters of 0.33 mm. The computational domain is described by a cylinder with 300D diameter and 150D height. The geometry of the air-box and the center-cap used to install the injector are also included in the computational domain to have a better description of the recirculation region outside the injector. No-slip boundary conditions are applied to the walls inside the pilot injector, the walls of the air-box, and the upper face of the cylinder. Convective outflow boundary conditions are applied at all other walls of the cylinder.

Results and Discussion

The simulation was first performed without LSP model. Once the flow-field is statistically stationary with regard to the VoF field, the LSP was activated for the modeling of the subsequent secondary breakup and atomization processes. Figure 11 displays representative simulation results for two different view angles. The iso-surface of the VoF-interface is shown in green, displaying the liquid sheet and the liquid ligaments. Lagrangian particles are shown in blue and the size of the particles are scaled by the droplet diameters. It can be seen that the liquid fuel is discharged from the nozzle exit in the form of a conical hollow liquid sheet due to the swirl provided by the atomizer. As the liquid sheet expands, perforations are formed and the liquid sheet deforms into liquid ligaments. At these low Weber number, the main mechanism for the break-up of the liquid fuel spray is the hydrodynamic instability within the liquid sheet rather than external aerodynamic forces. This is also found in the current study that there is little interaction between the liquid sheet and the surrounding air and the turbulence level is low in the velocity field. Finally, the liquid ligaments further break up and disintegrate into fuel droplets, which are represented as Lagrangian particles in the simulation. The operating conditions are representative of lean blowout conditions. As consequence, the primary breakup of the fuel droplets do not experience a secondary break-up because the shear forces between the fuel droplet and air is so small that the local droplet Weber number is on the order of unity. The numerical simulation qualitatively captures essential features of the breakup and atomization processes for the pilot pressure-swirl atomizer under the conditions considered, demonstrating the capabilities of the current modeling technique.

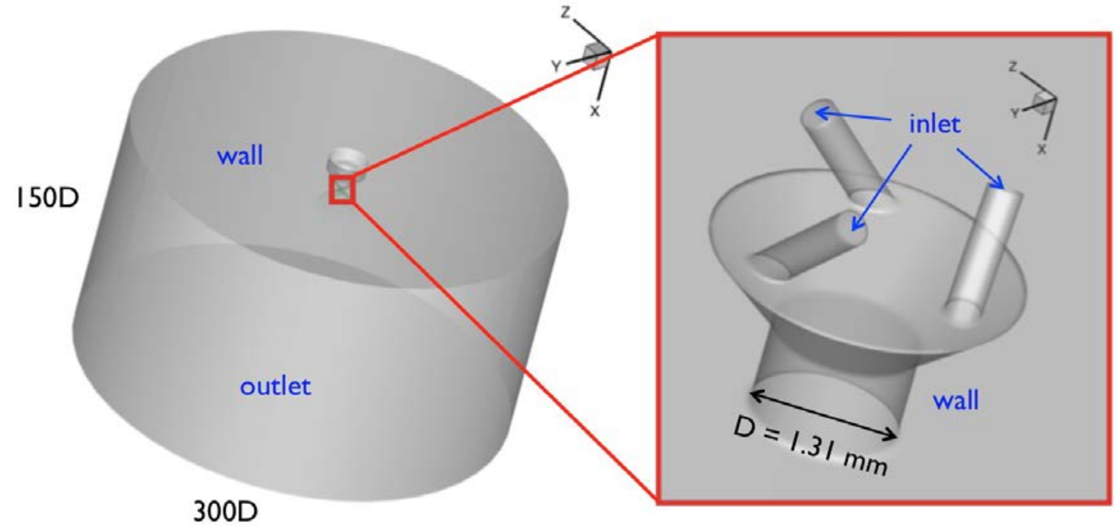


Figure 10: Computation domain and boundary conditions. Left: Shows the whole computational domain and the right gure shows zoom-in view of the injector nozzle region.

Figure 12 shows simulation results and experimental results next to each other for comparison. The instantaneous experimental image was taken from high-speed camera. The simulation results show a VOF iso-surface, augmented with Lagrangian particles scaled by droplet size. From this figure, it can be seen that the spray angle predicted by the numerical simulation is about 90 degree which is in good agreement with experiment. However, the breakup length predicted by the simulation is shorter than the experiment. The early breakup in the simulation is believed to be due to the stringent mesh resolution requirement needed for this low Weber number conditions. The liquid sheet thickness right before breakup can be as thin as 4 μm while the minimum resolution of the computational mesh is about 26 μm. To resolve the thin liquid sheet, typically at least 4-6 grid points are needed. Moreover, the low Weber number condition also yields a long liquid sheet that requires resolution. All these restrictions introduce signifant challenging mesh resolution requirements which are beyond our current available computational resources.

Figure 13 shows the fuel droplet statistics collected from the simulation at the measurement plane which is 20 mm below the nozzle exit. Figure 13(a) shows the droplet size distribution at the measurement plane along with the log-normal and Rosin-Rammler fit to the simulation results. It can be seen that the droplet distribution seems more like a log-normal distribution and has a peak at slightly below 100 μm. Figures 13(b) to 13(d) show simulation results of the droplet SMD and droplet velocities at the measurement plane in comparison with the experimental measurements. The simulation results are averaged in both time and azimuthal direction and then binned at different radial distances to collect the statistics. The correlation for SMD is also shown in Fig. 13(b) for comparison. In the center of hollow cone (radial distance ~ 5 mm), no droplets were found in the simulation due to the short runtime and therefore zero values are plotted in all three figures, while in the experiment droplets were collected by the PDPA system. As can be seen in Fig. 13(b), the simulation results show good agreement in the droplet size with experiment with a slightly underprediction. Both the experiment and simulation show higher SMD compared to the value predicted by the correlation. Results for the droplet axial and radial velocities also show that simulation results are in good agreement with the experimental measurements.

Figure 11: Representative simulation results. The iso-surface of VoF variable = 0:5 is shown in green and the Lagrangian particles is shown as blue spheres whose size is scaled based on the droplet diamter.

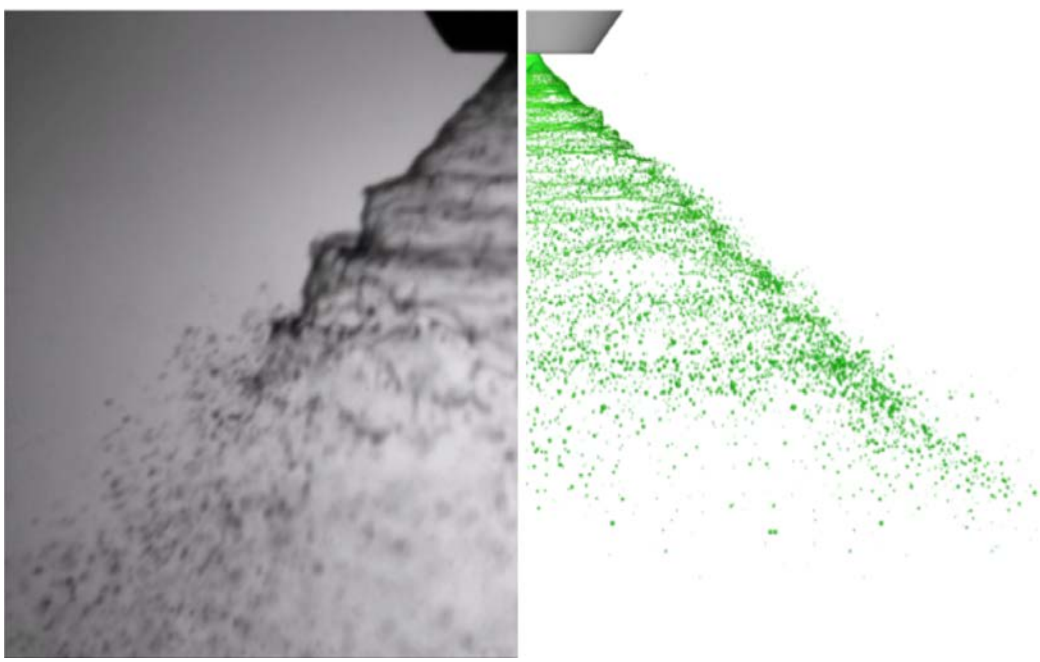
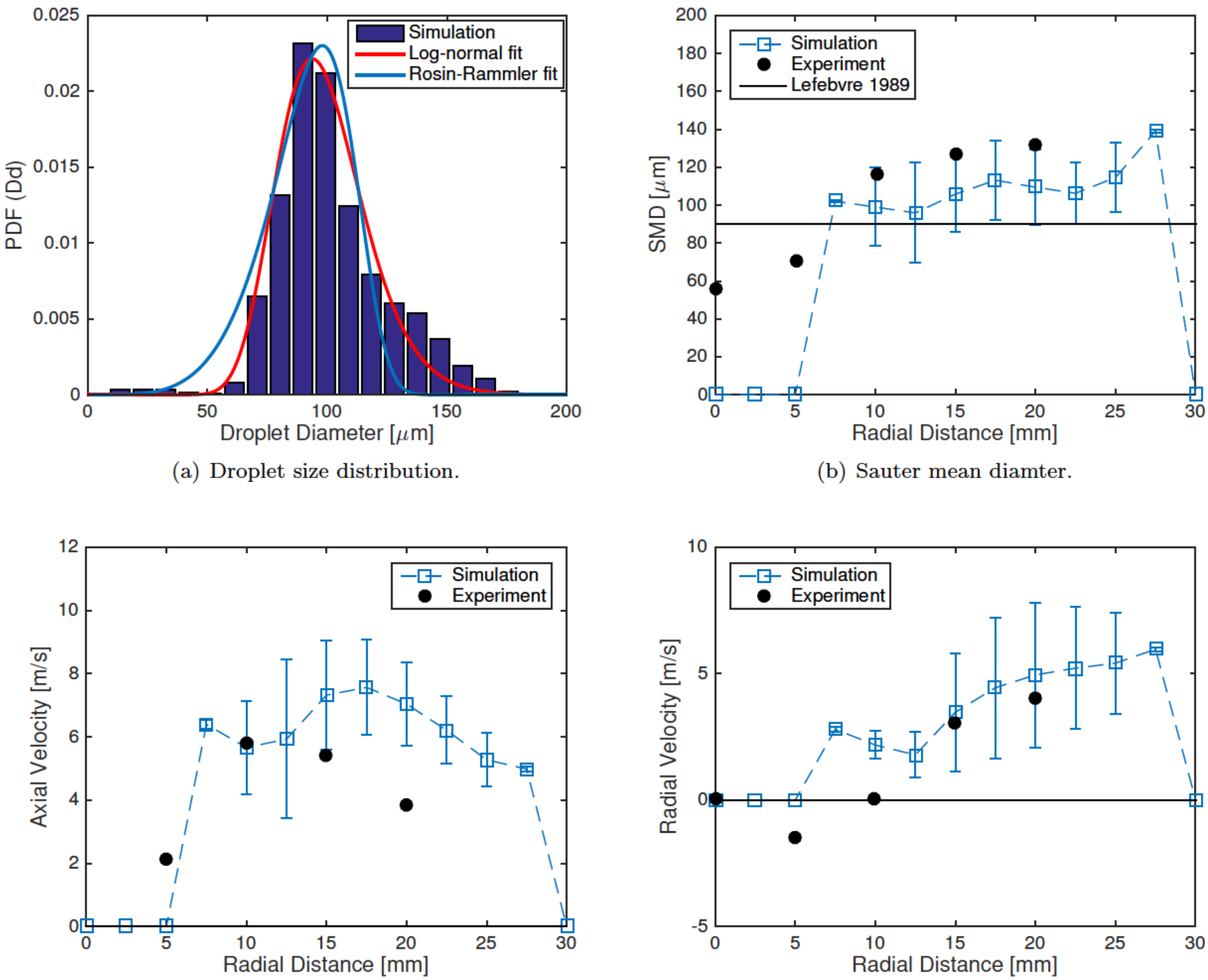


Figure 12: Comparison between numerical simulation and experiment. The image on the left was taken by high-speed camera in the experiment. Simulation results of iso-surface = 0:5 and Lagrangian particles scaled by droplet size are both colored in green shown on the right.



(a) Droplet size distribution.

(b) Sauter mean diamter.

(c) Droplet axial velocity.

(d) Droplet radial velocity.

Figure 13: Statistics of fuel droplet at measurement plane x = 20 mm downstream the nozzle exit. Log-normal and Rosin-Rammler distributions are used to t the simulation results of the droplet diameters. Simulation results at the measurement plane are averaged in both time and azimuthal direction and then binned at dierent radial locations. One standard deviation is shown for the error bar of the simulation results.

Publications

- "High-Fidelity Simulations of Fuel Injection and Atomization of a Hybrid Air-Blast Atomizer," P. C. Ma, 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.
- "Large-Eddy Simulations of Fuel Effect on Gas Turbine Lean Blow-out," L. Esclapez, P. C. Ma, E. Mayhew, R. Xy, S. Stouffer, T. Lee, H. Wang, and M. Ihme, presented at the 2017 AIAA SciTech Meeting, Grapevine, CA, 9-13 January 2017, Paper Number AIAA 2017-1955.
- "The role of preferential evaporation on the ignition of multicomponent fuels in a homogeneous spray/air mixture." Stagni, A., Esclapez, L., Govindaraju, P., Cuoci, A., Faravelli, T., and Ihme, M., Proceedings of the Combustion Institute, 2016, in press.
- "Group contribution method for multicomponent evaluation with application to transportation fuels." Govindaraju, P. B. and Ihme, M., International Journal of Heat and Mass Transfer, 2016, 102, 833-845.

Awards

None.

Student Involvement

PhD students Peter Ma and Pavan Govindaraju and post-doctoral fellow Lucas Esclapez are primarily responsible for the simulations and development of multicomponent evaporation models.