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, 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
- Task(s):
- The tasks to be performed in Year 1 are listed below:

  Quarter 1
  1. Collaborate with area 4 and 6 groups for development of experimental test matrix for Year 1
  2. Obtain heat exchanger and cyclone separator for AGTC test rig for operation with heated nitrogen
  3. Install reference nozzles in AGTC and RTS test rigs
  4. Design of SAE J2715 Standards based laser spray patternator tests for measurement of drop and ligament size distributions and liquid surface area to volume ratios

  Quarter 2
  1. Exploratory/shakedown tests of RTS rig
  2. Exploratory/shakedown test of AGTC rig
  3. Share initial test data with area 4 and 6 groups
  4. Assist Ihme group with mesh generation for RTS and AGTC rigs
  5. Design laser extinction tomography tests
  6. Perform screening study for several fuels of potential interest at a limited number of operating conditions

  Quarter 3
  1. Perform experiments on refined test matrix for first reference fuel: Schlieren in RTS test rig, Mie scattering and fuel PLIF in AGTC test rig
  2. Communicate results to Prof. Ihme, Area #4 researchers, and Area #6 researchers

  Quarter 4
  1. Perform experiments on refined test matrix for second and third reference fuels: Schlieren/PDPA in RTS test rig, Mie scattering and fuel PLIF in AGTC test rig
  2. Comparisons of simulation results against complementary measurements (PLIF, Mie, Schlieren)
  3. Aid model development by quantitative comparisons between the laser sheet spray patternator and tomography data

Project Funding Level

The funding level from FAA was $250,000 for Year 1. 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.

Co-PI Dr. Carson Slabaugh, Senior Research Engineer in Mechanical Engineering is responsible for directly managing facility operations.

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

PhD students Robert Zhang and Rohan Gejji are primarily responsible for getting the fuel cart and optical patternator back into operating condition. Rohan Gejji is also helping with getting the Rules and Tools Spray (RTS) test rig back into operation. PhD student Timo Buschhagen and MS student Andrew Bokhart are responsible for performing the PDPA measurements and for getting the RTS test rig back into operation.

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.

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

Purdue University

Objective(s)

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 proposed, with Matthias Ihme at Stanford, a joint experimental and modeling effort to achieve these objectives. The experimental tasks were performed at Purdue

University and the modeling tasks were performed by Prof. Matthias Ihme's group at Stanford University. Purdue University has very capable test rig facilities for measuring spray characteristics over very wide ranges of fuel pressure, swirler air pressure drop, inlet air temperature, and fuel temperature. The experimental diagnostics that were applied were phase Doppler particle anemometry (PDPA), high-frame-rate video imaging, and optical patternation. 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 also provide detailed transient measurements of and visualization of breakup length for specifying the initial plane for detailed numerical simulations of mixing and combustion processes. The high speed imaging data will include detailed information related to ligament size, breakup length, and oscillation modes and frequencies to support progress towards predictive modelling.

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 (-40°F to 600°F).

Milestone(s)

The major milestones that have accomplished so far during Year 1 of the project are:

1. Screening of candidate alternative fuels using optical patternation and PDPA.
2. PDPA measurements of JP8 pilot only fuel flow, no gas flow across swirler for comparison with LES spray modeling by Dr. Matthias Ihme's group at Stanford University.
3. Acquired PDPA data over a significant range of test matrix for comparison with spray correlations developed by Dr. Nader Rizk. Studied effects of fuel type, fuel temperature, fuel nozzle pressure, swirler location, radial location, and axial location.

Major Accomplishments

During the first year, optical patternation, high-speed video imaging with backlighting, and PDPA were all applied to the study of sprays. Figure 1 shows the atmospheric pressure spray rig and the PDPA system. Some representative PDPA experimental results are shown in Figure 2. In Figure 2, the SMD is plotted as a function of radial distance at two different axial locations for 3 different aviation fuels selected by the NJFCP team for comparison: A2 (POSF-10325, "average JetA"), C1 (POSF-11498, Gevo ATJ "low cetane"), and C5 (POSF 12345 "flat boiling"). The upper and lower data sets were acquired for pilot-only fuel flow at axial locations of 1″ and 2″ downstream of the nozzle exit. Both sets of data were collected for a fuel pressure of 75 psig flowing through the pilot injector at a nominal flow rate of 34 lbm/hr. Nitrogen flows through the nozzle swirler, the pressure drop across the swirler is 2%. It can be seen from Fig. 2 that the drops are smaller for the C5 fuel, and that the SMD distributions for A2 and C1 much more similar, especially for the plane 2″ downstream of the nozzle exit.

We have completed a significant number of PDPA measurements examining the effects of fuel temperature, fuel nozzle pressure, pressure drop for the gas flow across the swirler, and axial location. Of these effects, the pressure drop across the swirler has the most dramatic effect on the SMD distribution.

Another key finding during the year 1 work involved the significant deterioration of atomization quality with fuel temperature. This is an expected result but with the differences in the temperature dependence of fuel properties between the aviation fuels it is a key effect that must be studied. For example, the backlit images from amongst the videos taken for C1 fuel show that the drop size significantly increases and the drop number density significantly decreases as the temperature is reduced from T=50ºF to T=0ºF while maintaining a fixed pressure drop of 50 psi across the nozzle and a fixed nitrogen pressure drop of 2 % across the air box. Recent studies at fuel temperatures down to -30 °F show even more deterioration in spray quality.

Flow visualization and PDPA measurements for many representative operating conditions have been completed and are being checked for repeatability, uncertainty and effects of optics are being documented and shared with the NJFCP community. These interactions will continue through the remainder of the year 1 project period. The results are being used for comparison with both advanced LES simulations of spray breakup and atomization (Ihme group at Stanford, Menon group at Georgia Tech) and also for comparison with correlation equations for parameterization of spray properties (Dr. Nader Rizk, formerly of Rolls Royce).

In addition to drop sizes and number densities velocities in the axial and radial directions are key variables that affect the fuel vaporization and fuel air mixing resulting in very significant impact on lean blowout, cold start ignition and high altitude relight conditions. The PDPA provides measurements of two important components of the liquid velocity simultaneously with drop sizes and drop diameters.

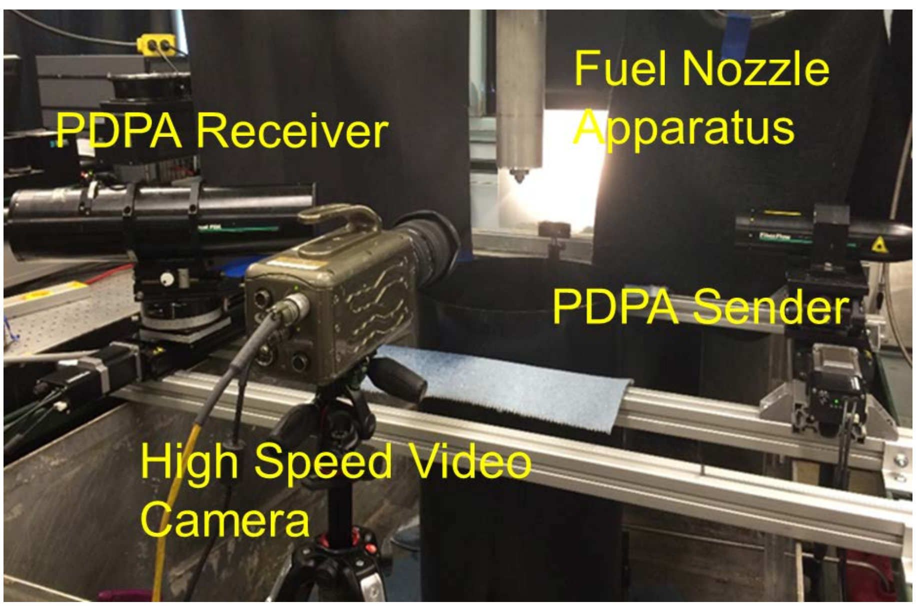

Figure 1. Photograph of the atmospheric pressure spray rig, the PDPA system, and the high speed video camera.

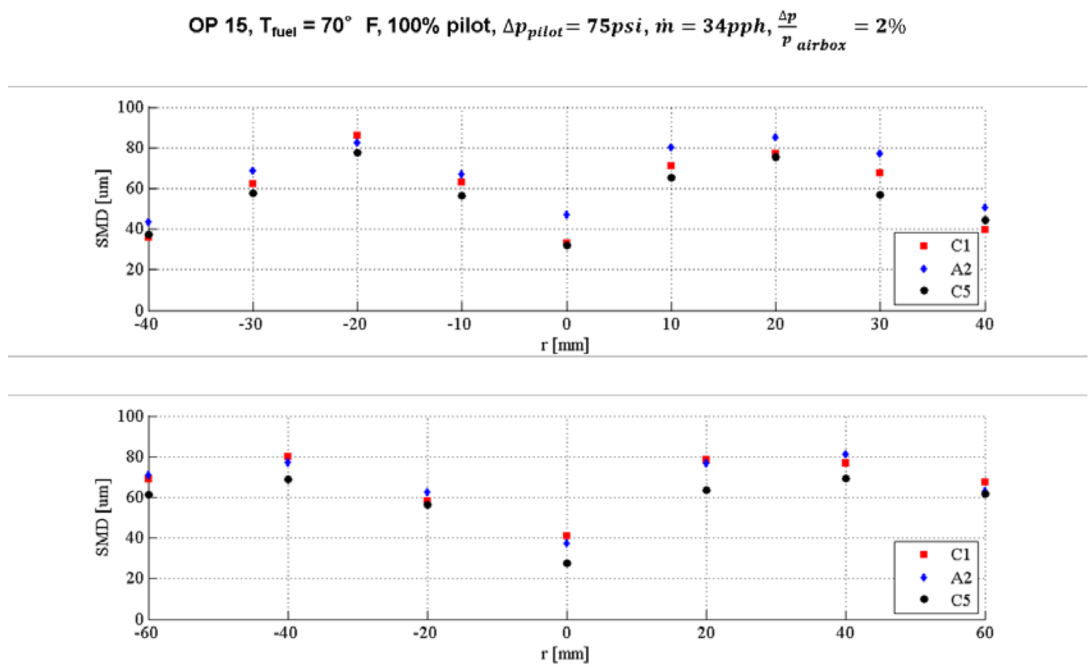

Figure 2. Radial distributions of droplet Sauter Mean Diameter (SMD) at 1″ (upper) and 2″ (lower) axial planes for three different fuels, a pilot pressure of 75 psig, fuel temperature of 70°F, and swirler pressure drop of 2%.

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, to be 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, to be presented at the 2016 AIAA SciTech Meeting, San Diego, CA, 4-8 January 2016.

Outreach Efforts

Same as above.

Awards

None.

Student Involvement

PhD students Robert Zhang and Rohan Gejji are primarily responsible for getting the fuel cart and optical patternator back into operating condition. Rohan Gejji is also helping with getting the Rules and Tools Spray (RTS) test rig back into operation. PhD student Timo Buschhagen and MS student Andrew Bokhart are responsible for performing the PDPA measurements and for getting the RTS test rig back into operation.

Plans for Next Period

Two very capable test facilities at Purdue University for measuring spray characteristics over very wide ranges of pressure, inlet air temperature, and fuel temperature were redeployed for measurements for this project over the first year and are now being extended. Our work during the first year allowed the definition of the locations, the boundary conditions, the operating conditions, and the fuel types for the studies being proposed during this year. Backlit high speed imaging, phase Doppler particle anemometry (PDPA), high-frame-rate simultaneous Mie scattering, and fuel planar laser-induced fluorescence (PLIF) emerged as the techniques for obtaining fundamental data for comparison with the numerical simulations. In addition, commercialized atomizer characterization equipment such as the Malvern particle analyzer and the multiple laser sheet absorption based spray patternator were used in the first year and will be accessed during year 2 when necessary. The atomization and spray dynamics of the three reference fuels and two nozzle configurations corresponding to the referee rig will be performed in both of our spray test 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 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 also provide detailed transient measurements of and visualization of breakup length for specifying the initial plane for detailed numerical simulations of mixing and combustion processes. The high speed imaging data will include detailed information related to ligament size, breakup length, and oscillation modes and frequencies to support progress towards predictive modelling. In addition, the prediction of the spatial distribution of the fuel vapors and breakdown components resulting from the evaporation of the liquid fuels critically affects the ignition, flame-stabilization, and pollutant formation processes. The Purdue facilities are capable of extensions towards detailed species and temperature measurements that would support engineering and detailed scientific simulations based approaches for the description of spray mixing and vaporization as well as gas phase mixing, decomposition and subsequent reactions. The focus during the year 2 activities will be on the transient liquid breakup, spray formation and distribution processes.

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.