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

Purdue University

Project Lead Investigator

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University Participants

Purdue University

- PIs: Robert P. Lucht, Jay P. Gore, Paul E. Sojka, and Scott E. Meyer
- FAA Award Number: 13-C-AJFE-PU, Amendments: 27, 28, 30
- Period of Performance: October 1, 2019 to September 30, 2020
- Tasks:
    1. Obtain phase Doppler anemometry (PDA), Mie scattering, and fuel laser-induced fluorescence data in the variable ambient pressure spray (VAPS) test rig operated with the referee rig nozzle for numerous fuels under near-lean blowout (LBO) conditions and under cold fuel/cold air flow conditions approximating ground light-off (GLO) and high-altitude relight (HAR) conditions.
    2. Perform computational fluid dynamics (CFD) simulations of the referee rig under near-LBO and LBO conditions for different fuels.

Project Funding Level

No additional funding was executed in the period of performance A no-cost extension was awarded through December 19, 2020.

Investigation Team

- PI Dr. Robert Lucht, Bailey Distinguished Professor of Mechanical Engineering, is responsible for overseeing the project at Purdue University. He is also responsible for mentoring one of the graduate students, coordinating activities with Stanford, working with all parties for appropriate results, and reporting results as required.
- Co-PI Dr. Jay P. Gore, Reilly Professor of Mechanical Engineering, works closely with the PI and oversees the work performed by one of the graduate students. He is also responsible for interacting with the CFD groups to suggest comparisons with experiments and with results of an adaptive grid solver.
- Co-PI Dr. Paul Sojka, Professor of Mechanical Engineering, is mentoring one of the graduate students and is responsible for supervising the spray measurements.
- Co-PI Scott Meyer, Managing Director of Maurice J. Zucrow Laboratories, is responsible for coordinating facility upgrades and for performing facility design reviews.
- Graduate Student (until December 2019) and Research Assistant Professor now, Hasti Veeraraghava Raju has conducted simulations with an adaptive grid solver and has performed comparisons with experimental results and results from the other CFD groups.
- Graduate student Daniel Shin is responsible for performing the PDA measurements and for modifying the VAPS test rig for operation under near-LBO and cold start conditions.

- Graduate student Neil Rodrigues contributes to the project by providing advice for the PDA measurements and technical editing.

Project Overview

The objectives of this project, 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 conducting experiments within the joint experimental and modeling effort. The experimental tasks are being performed at Purdue University, and the modeling tasks are being performed by Prof. Matthias Ihme's group at Stanford University, Prof. Suresh Menon's group at Georgia Tech, and Vaidya Sankaran's group at United Technologies Research Center (UTRC). Nader Rizk is developing spray correlations based on the measurements.

Purdue University has highly capable test facilities for measuring spray characteristics over wide ranges of pressure, air temperature, and fuel temperature. The experimental diagnostics applied in this project include PDA and high-frame-rate shadowgraphy. The atomization and spray dynamics for multiple reference and candidate alternative fuels have been characterized for the referee rig nozzle operating under near-LBO conditions. In the future, measurements will be performed for these fuels under operating conditions characteristic of HAR. A new fuel, IH^2 (Shell CPK-0), has been added to the test matrix and is being investigated under LBO and cold start conditions.

Task 1 – Measurement of Spray Characteristics under Near-Lean-Blowout and High Ambient Pressure Conditions

Purdue University

Objectives

The objectives of this Task are to visualize and measure the characteristics, including drop size distributions and axial velocity components, of sprays generated by a nozzle in the Referee Combustor in the Area 6 tests. The resulting data are being applied by Nader Rizk to develop spray correlations and by Matthias Ihme (Stanford University), Suresh Menon (Georgia Tech), and Vaidya Sankaran (UTRC) to develop a sub-model for detailed computer simulations. The spray data are being shared with the FAA National Jet Fuel Combustion Program (FAA-NJFCP) team members for their interpretation and for the development of modeling, simulation, and engineering correlation-based tools.

An upgraded VAPS test rig at Purdue University is utilized to measure spray characteristics over a range of pressures, atomizing gas temperatures, and fuel temperatures. Our work has led to the identification of challenges associated with performing reliable and reproducible spray measurements while keeping the windows of the apparatus clean. PDA has emerged as the technique of choice for obtaining drop size distribution and axial velocity data for comparison with numerical simulations. The VAPS facility was upgraded to support experiments over the entire range of fuel/air temperatures and pressures of interest and to enable planar spray measurement. We have compared reacting and nonreacting spray data by collaborating with the University of Illinois Urbana Champaign (UIUC), University of Dayton Research Institute (UDRI), and Air Force Research Laboratory (AFRL) Area 6 team.

The experimental data have supported the continued development and evaluation of engineering spray correlations, including the dependence of the Sauter mean diameter, spray cone angle, and particle number density per unit volume on the fuel properties at the fuel and air temperatures of interest. The experimental data provide detailed statistical measurements for comparison with high-fidelity numerical simulations of mixing and combustion processes. The predicted spatial distribution of the liquid fuel and of the 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 follows:

1. Obtain PDA data across different planes in the VAPS test rig operating with the referee rig nozzle for numerous fuels under near-LBO conditions and under cold fuel/cold air flow conditions approximating GLO and HAR conditions.
2. Provide data to the research groups of Suresh Menon, Vaidya Sankaran, Matthias Ihme, and Jay P. Gore for simulations.

3. Conduct PDA measurements for selected operating conditions in the VAPS test rig to provide data for the spray correlation analysis of Nader Rizk.
4. Ensure data quality through repeated tests at Purdue and through comparisons with spray measurements at Pratt & Whitney, UDRI/AFRL, and UIUC.

Research Approach

The Purdue University VAPS test rig facility is designed to measure spray characteristics over wide ranges of pressure, atomizing gas temperature, and fuel temperature. 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 to test standard aviation fuels as well as alternative blends. A mobile fuel system, 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 supplying alternative fuel blends. Both systems were designed with two independently controlled and metered circuits to supply fuel to the pilot and main injector channels of the test injector. The mass flow rates of both fuel 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 by a sensor immediately upstream of the fuel control circuits. High-pressure gear pumps provide fuel at rates of up to 30 kg/hr, which is supplied to the control circuits at a regulated line pressure of 10 MPa. The mobile fuel system was built with two onboard heat exchangers, and a chilling unit controls the fuel temperature over a range of 193–263 K (-80 °C to -10 °C).

Milestones

The milestones for the work performed in FY2020 are listed below:

Quarter 1

1. New window on the pressure vessel of the VAPS test rig was added to enable planar laser-induced fluorescence (PLIF), structured laser illumination planar imaging (SLIPI), and particle image velocimetry (PIV) measurements of the spray.
2. First shake down test was done in upgraded VAPS test rig with modified fuel supply system.
3. First PLIF measurement was performed using 266 nm excitation wavelength at 10 Hz.
4. The work accepted by the American Institute of Aeronautics and Astronautics (AIAA) *Journal of Propulsion and Power* was published in press.
5. Revised the spray book chapter.

Quarter 2

1. No experimental work had been done in this period due to nationwide shutdown by COVID-19.
2. A phenomenological three-step atomization model for the hybrid pressure-swirl air blast atomizer was developed to predict the drop size at LBO and cold start conditions.
3. Continued work on the book chapter revision.

Quarter 3

1. Simultaneous PLIF and Mie scattering measurements were performed high ambient pressure LBO conditions for A-2 and C-5 using 266 nm excitation wavelength at 10 Hz.
2. Cone angle estimation and liquid and vapor discrimination analysis were completed using previously obtained PLIF and Mie images.
3. The laser head for the PDA system at Purdue had failed, therefore an equivalent laser head was borrowed from UIUC and was successfully integrated with the PDA system at Purdue.
4. Continued revising the AIAA volume book chapter on sprays.

Quarter 4

1. The laser head from UIUC was integrated to PDA system and the laser alignment was re-done.
2. The drop size and drop velocity measurement was performed using PDA system at LBO and high ambient pressure conditions with 1, 2, 5, and 9.5 bar for A-2 and C-5.
3. Data processing is in progress.
4. Completed spray book chapter 5.

Major Accomplishments

Experimental contributions

The work described in this section is a part of the Purdue contribution to a larger FAA-funded effort, the NJFCP. The major objective of the experimental work at Purdue was to measure 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 LBO and GLO conditions.

These measurements were successfully performed last year using a PDA, which provided single-point measurements of the spray. This year, two-dimensional (2D) planar imaging measurements were completed for A-2 and C-5 fuels for a more detailed investigation of the spray. Simultaneous PLIF and Mie imaging were performed in the upgraded VAPS test rig at high ambient pressure and LBO conditions. The PDA measurements were also performed at the same operating conditions as the PLIF and Mie scattering measurements. The remainder of this section presents the results of PLIF and Mie imaging and PDA measurements.

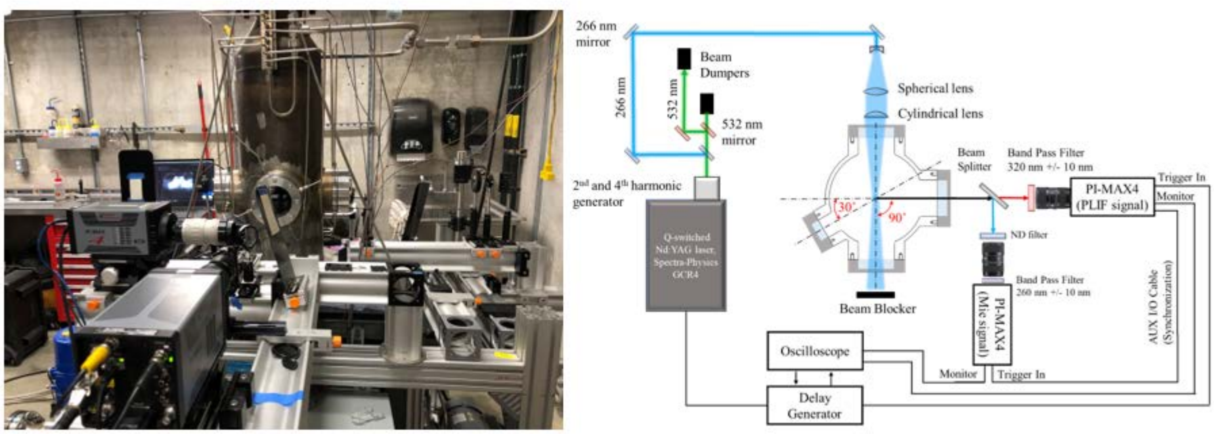
Experimental systems

The Purdue VAPS test rig comprises two major components: the airbox assembly and the pressure vessel. The airbox assembly is a length of pipe in which the hybrid air-blast pressure-swirl atomizer is mounted. The airbox is placed within the pressure vessel, which allows a pressurized atomizing gaseous flow through the airbox to be isolated from the vessel to create a pressure difference across the gas swirler. The pressure vessel is rated to withstand 4.14 MPa (600 psi) at 650 °C (1200 °F).

A new 127 mm window was added to the pressure vessel so that three 127 mm windows are oriented at a 90° angle each other and a 72.6 mm is oriented at a 60° angle from one of the 127 mm windows. With this new window system, Simultaneous PLIF and Mie imaging measurement was performed at LBO and high ambient pressure conditions (1, 2, 5, and 9.5 bar) for A-2 and C-5 fuels to provide a 2D representation of the spray. Figure 1 shows the image of simultaneous PLIF and Mie imaging measurement system in upgraded VAPS test rig. A 266 nm excitation wavelength laser beam was expanded into a 40 mm of sheet in height and illuminated a plane of the spray. Two synchronized intensified charge-coupled device (ICCD) cameras were used to obtain simultaneous PLIF and Mie images of the spray at 5 Hz with the laser power of approximately 70 mJ per pulse.

The laser head used for the PDA system at Purdue died due to old age. Another compatible laser head was borrowed from UIUC and was integrated to the existing PDA system at Purdue. Figure 2 shows the schematic diagram of the PDA system around upgraded VAPS test rig. The window modification on the pressure vessel allowed us to set the PDA transmitter and receiver probes at a 30° of scattering angle, which was suggested to get a strong signal from the forward scattering when the droplets passes through the probe volume.

(b)



(a)

Figure 1. (a) Photographs of simultaneous PLIF and Mie imaging measurement system in VAPS test rig. (b) Schematic diagram of simultaneous PLIF and Mie system around the VAPS rig.

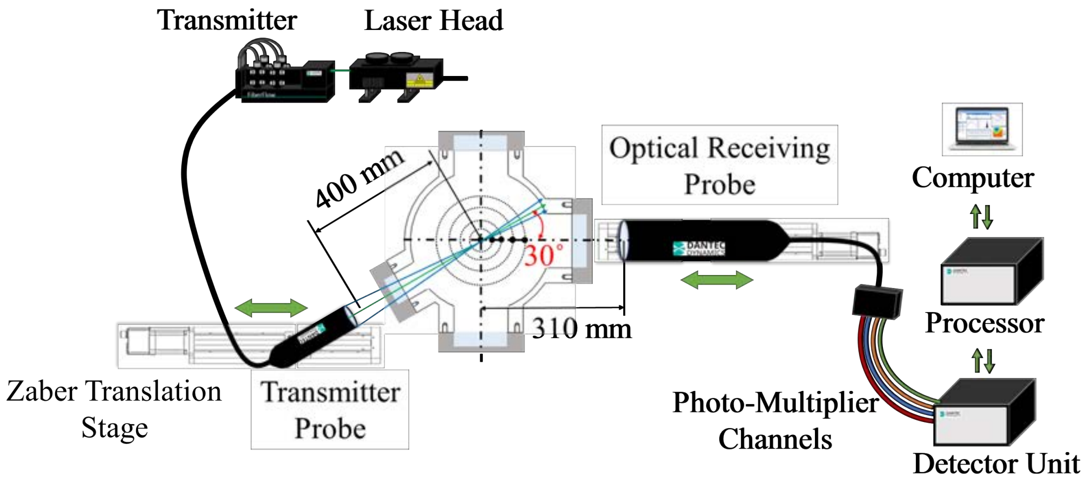


Figure 2. Schematic diagram of PDA system in upgraded VAPS rig.

Results from PLIF/Mie imaging and PDA measurements

Both PLIF/Mie and PDA measurements were performed at T_{fuel} = 328K, T_{airbox} = 394K, $\Delta P/P$ = 3%, $\Delta Ppilot$ = 1.72 bar, and $\dot{m}_{fuel} = 2.52\ g/s$ for A-2 and C-5 fuels. The operating condition with ambient pressure of 2 bar case is corresponding to the near-LBO conditions.

The drop size and drop velocity were measured using PDA measurement system at LBO and high ambient pressure conditions (1, 2, 3, 4, 5, and 9.5 bar) for A-2 and C-5 fuels. Some 20,000 samples were recorded within ±30 mm from the center of the spray at increments of 5 mm. Figure 3 shows the comparison of D32 and axial velocity (Uz) at different ambient pressure conditions. A decrease in D32 was observed with increases in ambient pressure. Higher ambient gas density with an increase in pressure caused the drag force on a droplet to increase. This resulted in smaller droplet diameter with increasing ambient pressure. The significant reduction in D32 was observed from 1 bar to 2 bar. However, minimal decrease in D32 was observed with further increase in ambient pressure beyond 5 bar. This indicated that the effect of ambient pressure on the drop size diminished with further increasing in ambient pressure. Similar trends were observed for both A-2 and C-5 fuels.

No significant variations were observed in axial velocity at different ambient pressures for most radial locations within the spray. However, at near the spray edge (r=30mm), the drop axial velocity decreased with ambient pressures as the droplet encountered higher drag force due to higher ambient pressure.

Figure 4 shows the instantaneous and averaged PLIF and Mie images at different ambient pressure conditions: 1, 2, 5, and 9.5 bar. The hollow-cone spray structure was observed from both PLIF and Mie images. At lower ambient pressure, it can be seen that the larger droplets were presented from both PLIF and Mie images. The cone angle estimation was done using a Sobel edge detection technique using averaged Mie images at different ambient pressure conditions. The ambient pressure had minimal effect on the spray cone angle as shown in Fig. 5. The LIF/Mie drop sizing analysis was also performed at different ambient pressures to predict D32 of the entire spray as shown in Fig 6. The drop size measurements by PDA at measurement plane of 12.7 and 25.4 mm were used to calibrate the LIF/Mie ratio with measured D32 values. The percentage difference between the predicted D32 and measured D32 were found to be within 17% for ambient pressure of the 1-bar case and 19% for ambient pressure of the 5-bar case.

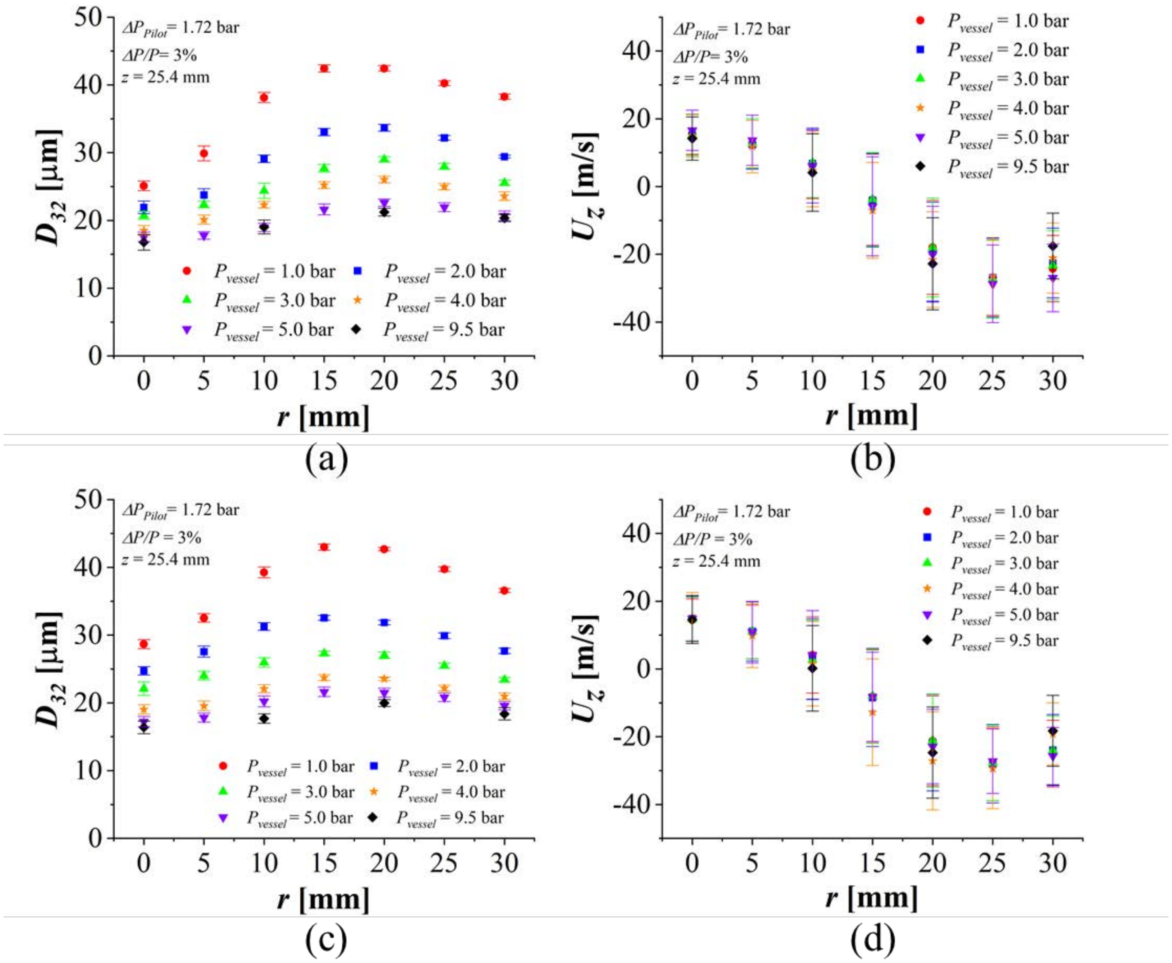


Figure 3. D32 and axial velocity at different ambient pressures of 1, 2, 3, 4, 5, and 9.5 bar, T_{fuel} = 328K, and T_{airbox} = 394 K for A-2 and C-5 fuels. (a) D32 comparison for A-2 fuel. (b) Axial velocity comparison for A-2 fuel. (c) D32 comparison for C-5 fuel. (d) Axial velocity comparison for C-5 fuel.

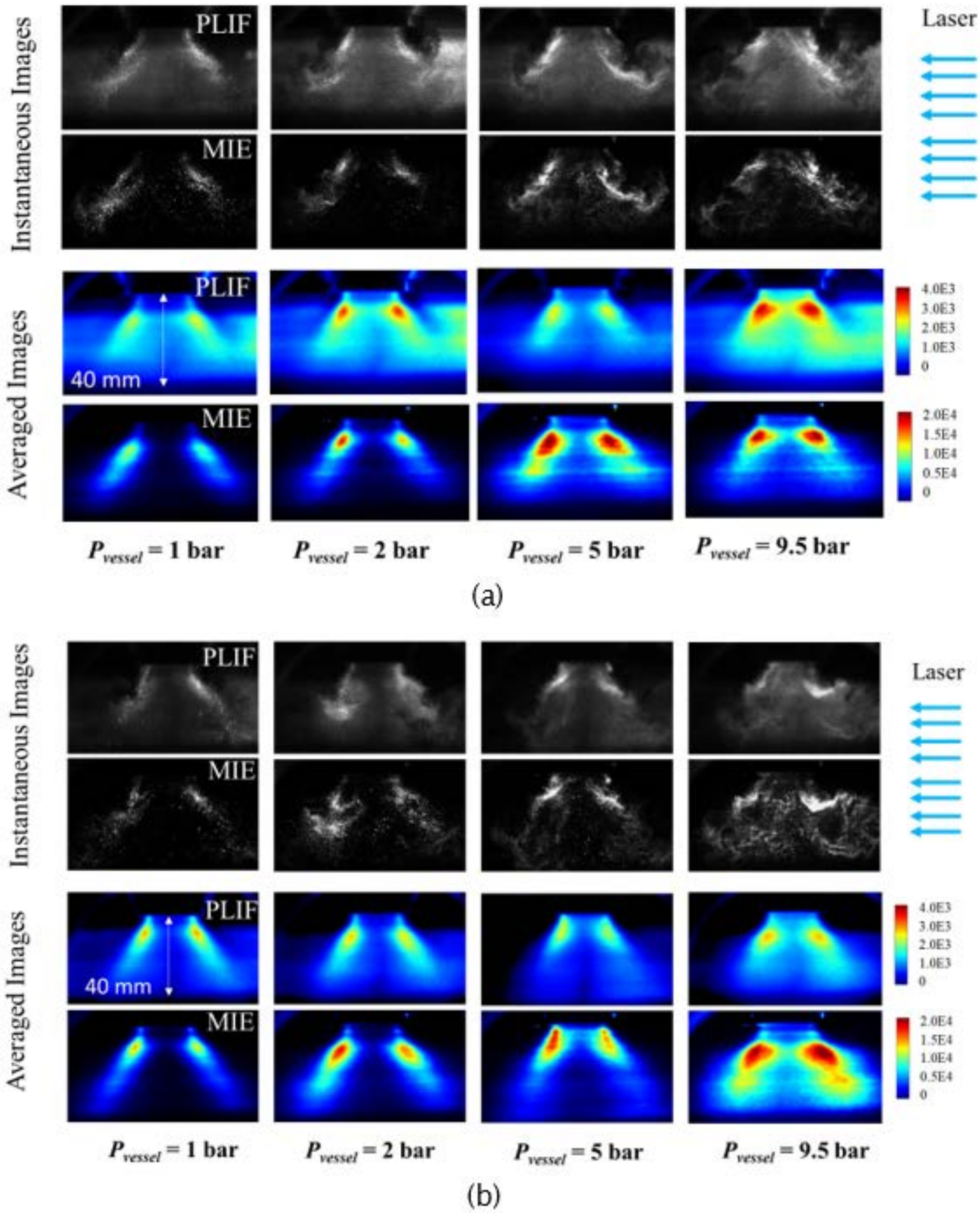


Figure 4. Instantaneous and averaged images of PLIF and Mie measurements at ambient pressures of 1, 2, 5, and 9.5 bar. The 2-bar case is corresponding to the LBO condition. (a) A-2 fuel. (b) C-5 fuel.

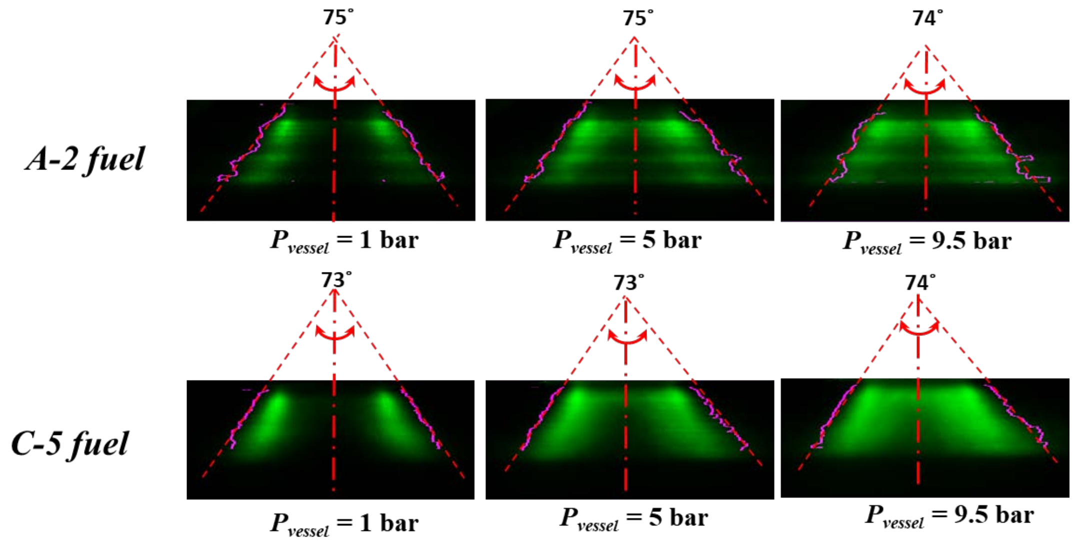
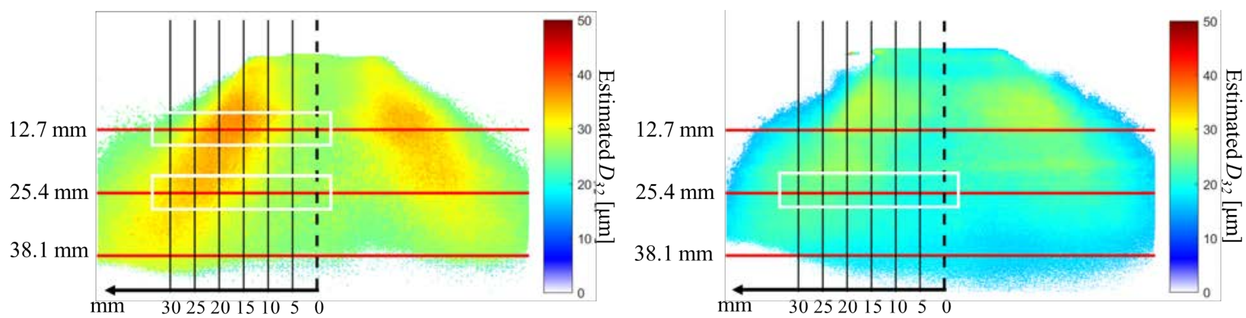


Figure 5. Cone angle comparison for A-2 and C-5 at different ambient pressures.



(a) Predicted D32 map at 1 bar.

(b) Predicted D32 map at 5 bar.

Figure 6. D32 map resulted from LIF/Mie ratio drop sizing.

Task 2 – CFD Simulations of the Referee Rig Under Near-LBO and LBO Conditions

Milestones

The milestones for the work performed in FY2020 are listed below:

Quarter 1

1. Updated the CFD model for domain sensitivity studies and performed non-reacting simulations.

Quarter 2

1. Updated the CFD model for domain sensitivity studies and performed non-reacting simulations.

Quarter 3

1. Analyzed the non-reacting large eddy simulations (LES) results to understand the impact of plenum size on the combustor flow field.
2. Contributed to the CFD modeling and simulations section of the AIAA volume book chapter on CFD.

Quarter 4

1. Completed the Purdue section on LBO modeling in the CFD book chapter.

Major Accomplishments

Domain sensitivity study

The reacting LES simulations reported in the previous year were performed with a reduced plenum size and excluded bypass air passages near the combustor exit. During 2019, we initiated efforts to model the actual size of the plenum in the rig hardware and included all bypass air passages near the combustor exit. The reduced and actual plenum domains are compared in Figure 7. A domain sensitivity study was performed under non-reacting conditions and LES simulations were completed during the 4th quarter of 2019. A detailed investigation of the results in the first quarter of 2020 revealed that we had failed to include a few effusion holes on the liners in the 2019 CFD model. We have now updated the CFD model to include all of the liner effusion holes. Revised non-reacting LES simulations have been completed in the first quarter of 2020 with the actual plenum size, all combustor passages, and the full rig inlet air flow rate of 391.4 g/s at the computational domain inlet.

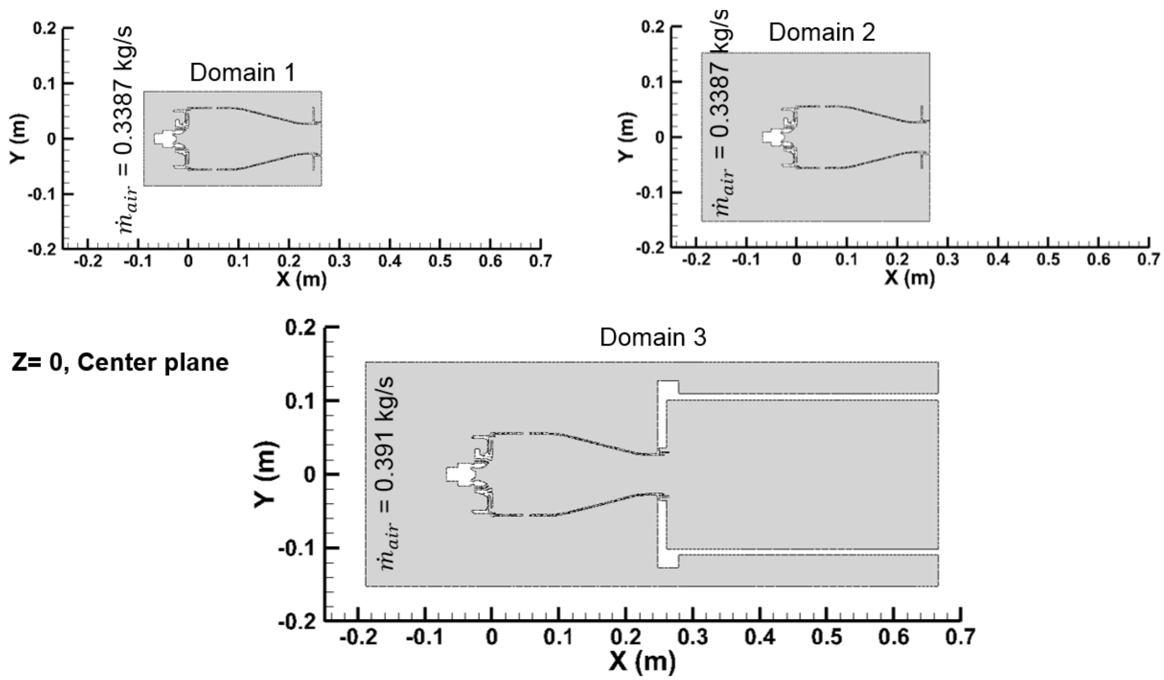


Figure 7. Comparison of computational domains at the Z=0 center plane for the three computational domains.

Combustor aft effusion holes are not included in domains 1 and 2. The flow-splits are compared in Table 1. The combustor aft effusion holes account for a total air flow rate of 52.9 g/s. This air flow rate is excluded in the CFD simulations for domains 1 and 2. An air mass flow rate of 338.5 g/s is specified at the inlet for the domain 1 and 2 CFD simulations. An air mass flow rate of 391.4 g/s is specified for domain 3 since it includes all the effusion holes, including those at the combustor aft end. In addition, the flow rates are increased by 4.9% and 2.5% for the first row of dilution holes and the second row of dilution holes, respectively, for domain 3. In order to maintain the total mass flow rate of air at 391.4 g/s, the swirler flow is decreased by 1.6%.

Table 1. Comparison of Flow Splits

	Exp (g/s)	Domain 1 Non-Reacting (g/s)	Domain 1 Reacting A2-0.096 (g/s)	Domain 2 Non-Reacting (g/s)	Domain 3 Non-Reacting (g/s)
Dilution Row 1	39.5	45.22	46.3	47.03	47.45
Dilution Row 2	45.4	50.01	52.4	50.57	51.27
Total swirler	60.7	75.37	72.9	73.12	74.17
Radial swirler	14.3	15.56	14.7	15.68	15.34
Axial int. swirler	18.9	25.18	23.8	23.92	24.93
Axial ext. swirler	24.6	32.37	31.9	31.3	31.64
Swirler cooling	2.9	2.25	2.3	2.22	2.24
Effusive plate	245.4	167.66	166.7	164.82	210
Total (sum)	391	338.26	338.3	335.54	382.89

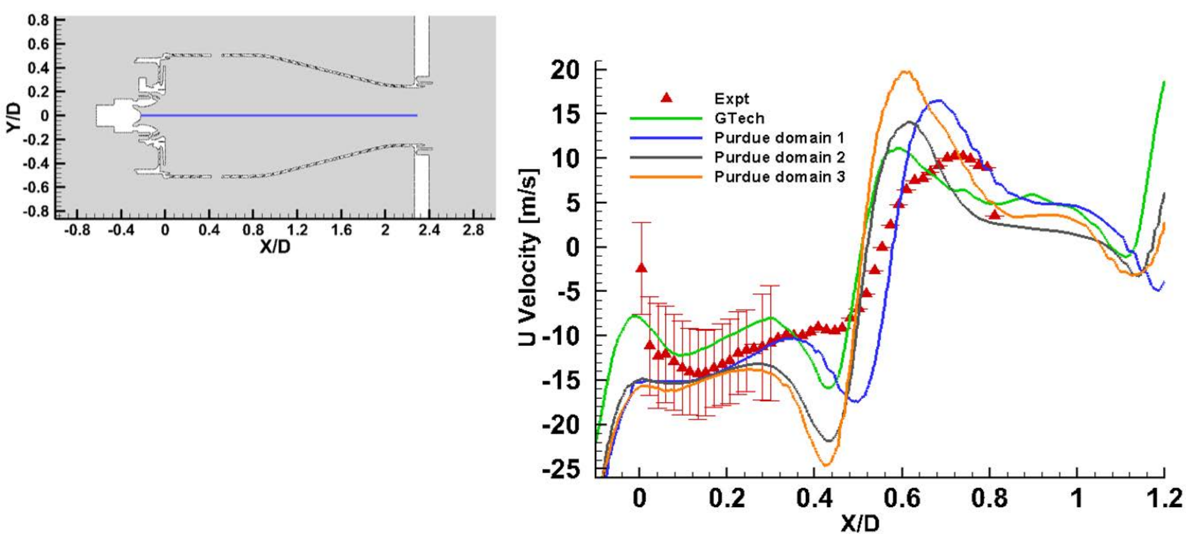


Figure 8. Comparison of the measurements of the mean axial velocity with results of the Georgia Tech (GTech) computations and the Convex-PU computations with three computational domains.

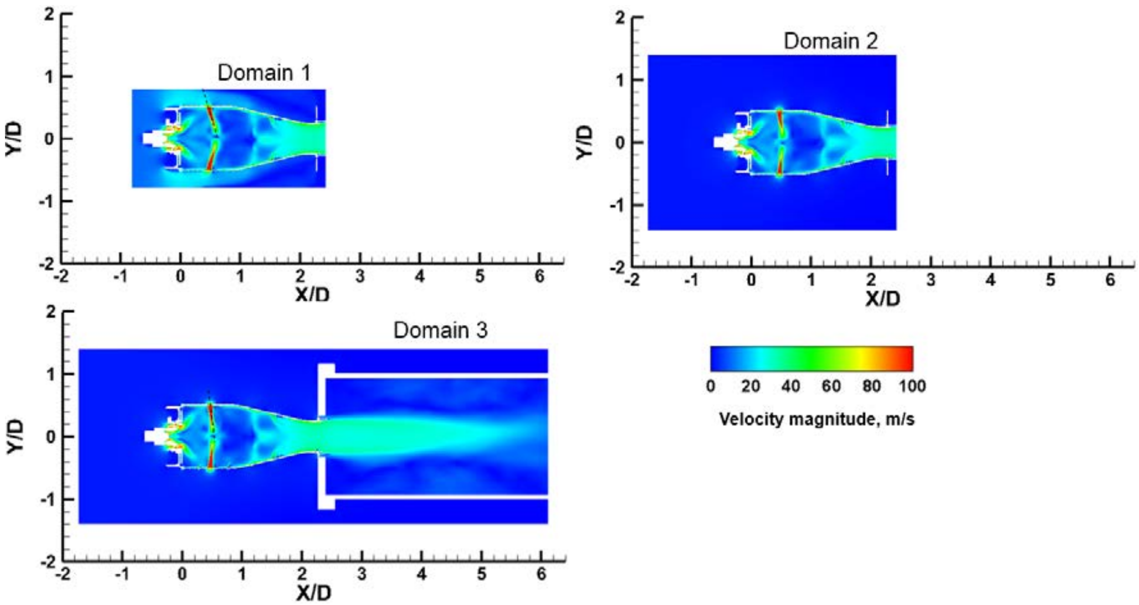


Figure 9. Comparison of velocity magnitude on the middle plain (Z =0) of the combustor.

The measurements of mean axial velocity along the centerline of the combustor and the results of the Argonne National Laboratory-Purdue University (ANL-PU) computations using the three domains and the Georgia Tech computations are compared in Figure 8. The contour plots for the velocity magnitude on the middle plane of the combustor (Z=0) are compared in Figure 9. For domain 1, the dilution jets in the first row enter the combustor with a higher velocity because of the smaller width of the annulus and therefore show an 8° greater angle. The results also show that the domain size does not have a significant effect on the flow patterns and velocity magnitudes in the critical primary flame stabilization zone. This zone is dominated by the swirling flow.

Publications

Peer-reviewed journal publications

V. R. Hasti, R. P. Lucht, and J. P. Gore, "Large Eddy Simulation of Hydrogen Piloted CH_4/Air Premixed Combustion with CO_2 Dilution," *Journal of the Energy Institute* **93**, 1099-1109 (2020). DOI: 10.1016/j.joei.2019.10.004

D. Shin, A. J. Bokhart, N. S. Rodrigues, P. E. Sojka, J. P. Gore, and R. P. Lucht, "An Experimental Investigation of Spray Characteristics of Alternative Aviation Fuels Using a Hybrid Pressure Swirl Airblast Atomizer at Lean Blowout Conditions," *Journal of Propulsion and Power* **36**, 323-334 (2020). DOI: 10.2514/1.B37712

Published conference proceedings

Bokhart, J.A., Shin, D., Gejji, R., Buschhagen, T., Naik, S.V., Lucht, R.P., Gore, J.P., Sojka, P.E., & Meyer, S.E. (2017). Spray measurements at elevated pressures and temperatures using phase doppler anemometry. Presented at the 2017 AIAA SciTech Meeting, Grapevine, TX. Paper Number AIAA-2017-0828.

Buschhagen, T., Zhang, R.Z., Naik, S.V., Slabaugh, C.D., Meyer, S.E., Gore, J.P., & Lucht, R.P. (2016). Effect of aviation fuel type and fuel injection conditions on non-reacting spray characteristics of hybrid air blast fuel injector. Presented at 2016 AIAA SciTech Meeting, San Diego, CA. Paper Number AIAA 2016-1154.

Hasti, V.R., Liu, S., Kumar, G., & Gore, J.P. (2018). Comparison of premixed flamelet generated manifold model and thickened flame model for bluff body stabilized turbulent premixed flame. 2018 AIAA Aerospace Sciences Meeting, AIAA SciTech Forum, (AIAA 2018-0150)

Hasti, V.R., Kundu, P., Kumar, G., Drennan, S.A., Som, S., & Gore, J.P. (2018). A numerical study of flame characteristics during lean blow-out in a gas turbine combustor. 2018 Joint Propulsion Conference, AIAA Propulsion and Energy Forum, (AIAA 2018-4955)

Hasti, V.R., Kundu, P., Kumar, G., Drennan, S.A., Som, S., & Gore, J.P. (2018). Numerical simulation of flow distribution in a realistic gas turbine combustor. 2018 Joint Propulsion Conference, AIAA Propulsion and Energy Forum, (AIAA 2018-4956)

Hasti, V.R., Kundu, P., Kumar, G., Drennan, S.A., Som, S., Won, S.H., Dryer, F.L., & Gore, J.P. (2018). Lean blow-out (LBO) computations in a gas turbine combustor. 2018 Joint Propulsion Conference, AIAA Propulsion and Energy Forum, (AIAA 2018-4958)

May, P.C., Nik, M.B., Carbajal, S.E., Naik, S., Gore, J.P., Lucht, R.P., & Ihme, M. (2016). Large-eddy simulations of fuel injection and atomization of a hybrid air-blast atomizer. Presented at the 2016 AIAA SciTech Meeting, San Diego, CA. Paper Number AIAA 2016-1393.

Shin, D., Bokhart, J.A., Rodrigues, N.S., Lucht, R.P., Gore, J.P., Sojka, P.E., & Meyer, S.E. (2018). Spray characteristics at lean blowout and cold start conditions using phase doppler anemometry. Presented at the 2018 AIAA SciTech Meeting, Kissimmee, Florida.

Shin, D., Bokhart, J.A., Rodrigues, N.S., Naik, S.V., Lucht, R.P., Gore, J.P., Sojka, P.E., & Meyer, S.E. (2018). Spray characteristics of a hybrid airblast pressure-swirl atomizer at cold start conditions using phase doppler anemometry. Presented at ICLASS 2018 14th Triennial International Conference on Liquid Atomization and Spray Systems, Chicago, Illinois.

Shin, D., Bokhart, J.A., Rodrigues, N.S., Sojka, P., Gore, J.P., & Lucht, R.P. (2019). Experimental study of spray characteristics at cold start and elevated ambient pressure using hybrid airblast pressure-swirl atomizer. Presented at 2019 AIAA SciTech Meeting, San Diego, CA. Paper Number AIAA 2019-1737.

Outreach Efforts

N/A

Awards

- Veeraraghava Raju Hasti received the Outstanding Research Award from the College of Engineering, Purdue University, May 2020.
- Veeraraghava Raju Hasti served as the subject matter expert and global judge for the NASA Space Apps COVID-19 Challenge Competition, May 2020.
- Veeraraghava Raju Hasti received the 2019 Gordon C. Oates Air Breathing Propulsion Graduate Award from the AIAA Foundation. The AIAA Foundation presents this award to a graduate student performing excellent research in air and space science.
- Veeraraghava Raju Hasti received the Computational Interdisciplinary Graduate Program's Bilsland Dissertation Fellowship from Purdue University in 2019.
- Veeraraghava Raju Hasti received the Outstanding Graduate Student Mentor award from Purdue University in May 2019.
- Veeraraghava Raju Hasti received the Outstanding Service award from the College of Engineering, Purdue University in May 2019.
- Veeraraghava Raju Hasti won 1st prize (best poster) under the 100 Years Category in the Sustainable Economy and Planet Poster Competition for PhD Students, Ideas Festival, 150 Years Celebrations at Purdue University for his poster presentation entitled "Quantum Computers on Artificial Intelligence: Automatic and Adaptive Solutions," given February 6, 2019.
- Veeraraghava Raju Hasti delivered an invited talk entitled "Computational methodology for biofuel performance assessment" at the Spring CIGP Symposium, Purdue University, April 17, 2019.
- Veeraraghava Raju Hasti and Jay P. Gore delivered a keynote speech entitled "Computational Study of Fuel Effects on Lean Blow-Out in a Realistic Gas Turbine Combustor" at the Modeling and Simulation of Turbulent Mixing and Reaction: For Power, Energy and Flight, April 12–13, 2019.
- Veeraraghava Raju Hasti was elected as Chair for the Membership Committee of the Gas Turbine Engines Technical Committee (GTE TC), AIAA, August 2019.
- Veeraraghava Raju Hasti delivered an invited talk entitled "Computational Methodology for Biofuel Performance Prediction" at the Academic Research Colloquium, University of Dayton, September 10–12, 2019.
- Veeraraghava Raju Hasti successfully defended his PhD dissertation on October 30, 2019.
- Veeraraghava Raju Hasti served as a Global Ambassador following selection by the Purdue Graduate School for interactions with prospective international students on November 8, 2019.

- Veeraraghava Raju Hasti represented Purdue University at the Big Ten Grad Expo on September 22, 2019, following selection by the Office of Interdisciplinary Graduate Programs and Computational Interdisciplinary Graduate Programs. Hasti also served on a Panel at the Big Ten Grad Expo on September 22, 2019.
- Veeraraghava Raju Hasti was invited by the College of Engineering to serve on the Graduate Students Panel on May 21, 2019 to interact with global undergraduate summer interns through the Purdue Undergraduate Research Experience (PURE).
- Veeraraghava Raju Hasti delivered a presentation on computational research opportunities in combustion and energy at the Mechanical Engineering Visitation Program for prospective graduate students on February 14, 2019 at Purdue University.
- Jay P. Gore delivered an invited talk entitled "Radiation Heat Transfer in High Pressure Gas Turbine Combustors" at the United Technologies Research Center (UTRC) Workshop on Combustor–Turbine Wall Heat Transfer Modeling and Prediction, East Hartford, CT, March 11, 2019.
- Jay P. Gore delivered an invited talk entitled "Radiation and Soot Measurements in High Pressure Gas Turbine Combustors" at the United Technologies Research Center (UTRC) Follow-up Meeting for Combustor–Turbine Wall Heat Transfer at the ASME IGTI Conference, Phoenix, AZ, June 16, 2019.

Student Involvement

PhD student Daniel Shin is primarily responsible for performing PDA measurements under LBO and HAR/GLO conditions and for upgrading the VAPS test rig in a new test cell. PhD student Neil Rodrigues and postdoctoral research associate Rohan Gejji assist with the project when their expertise is required. PhD student Veeraraghava Raju Hasti is primarily responsible for developing and performing the LES simulations. Veeraraghava Raju Hasti has graduated and is currently a Research Assistant Professor in the School of Mechanical Engineering at Purdue.

Plans for Next Period

The proposed deliverables and tasks for FY2021 are listed below.

Year-5 deliverables

The year-5 deliverables for Area 5, Project 29A is focused on spray experiments and the deliverables are as follows:

1. Continue revisions and complete the spray section in the AIAA book chapter.
2. Continue interactions with the three CFD groups (Ihme, Vaidya, and Menon).
3. Prepare a journal paper for the measurements at high ambient pressure conditions.
4. Graduate student Daniel Shin will complete his thesis and defend for his Ph.D.

References

Bokhart, A., Shin, D., Gejji, R.M., Sojka, P., Gore, J.P., Lucht, R. P., Naik, S. V., and Buschhagen, T. (2017). Spray measurements at elevated pressures and temperatures using phase doppler anemometry. 55th AIAA Aerospace Sciences Meeting. American Institute of Aeronautics and Astronautics.

Bokhart, A., Shin, D., Rodrigues, N.S., Sojka, P., Gore, J.P., & Lucht, R.P. (2018). Spray characteristics of a hybrid airblast pressure-swirl atomizer at near lean blowout conditions using phase doppler anemometry. American Institute of Aeronautics and Astronautics.

Convergent Science, Inc. (2017). CONVERGE CFD, Version 2.4,. Madison, WI

El-Asrag, H.A., Braun, M., & Masri, A.R. (2016). Large eddy simulations of partially premixed ethanol dilute spray flames using the flamelet generated manifold model. Combustion Theory and Modelling Vol. 20, No. 4, pp. 567-591. doi: 10.1080/13647830.2016.1159732

Elasrag, H. & Li, S. (2018). Investigation of extinction and reignition events using the flamelet generated manifold model. ASME Turbo Expo 2018: Turbomachinery Technical Conference and Exposition. Vol. Volume 4A: Combustion, Fuels, and Emissions.

Giusti, A. & Mastorakos, E. (2017). Detailed chemistry LES/CMC simulation of a swirling ethanol spray flame approaching blow-off. Proceedings of the Combustion Institute Vol. 36, No. 2, pp. 2625-2632. https://doi.org/10.1016/j.proci.2016.06.035

Hasti, V.R., Kundu, P., Kumar, G., Drennan, S.A., Som, S., & Gore, J.P. (2018). A numerical study of flame characteristics during lean blow-out in a gas turbine combustor. 2018 Joint Propulsion Conference, No. AIAA 2018-4955. doi: doi:10.2514/6.2018-4955

Hasti, V.R., Kundu, P., Kumar, G., Drennan, S.A., Som, S., & Gore, J.P. (2018). Numerical simulation of flow distribution in a realistic gas turbine combustor. 2018 Joint Propulsion Conference, No. AIAA 2018-4956. doi: doi:10.2514/6.2018-4956

Hasti, V.R., Kundu, P., Kumar, G., Drennan, S.A., Som, S., Won, S.H., Dryer, F.L., & Gore, J.P. (2018). Lean blow-out (LBO) computations in a gas turbine combustor. 2018 Joint Propulsion Conference, No. AIAA 2018-4958. doi:10.2514/6.2018-4958

Ihme, M., Cha, C.M., & Pitsch, H. (2005). Prediction of local extinction and re-ignition effects in non-premixed turbulent combustion using a flamelet/progress variable approach. Proceedings of the Combustion Institute Vol. 30, No. 1, pp. 793-800. doi: https://doi.org/10.1016/j.proci.2004.08.260

Ihme, M. & Pitsch, H. (2008). Prediction of extinction and reignition in nonpremixed turbulent flames using a flamelet/progress variable model: 1. A priori study and presumed PDF closure. Combustion and Flame Vol. 155, No. 1, pp. 70-89. doi: https://doi.org/10.1016/j.combustflame.2008.04.001

Ma, P.C., Wu, H., Labahn, J.W., Jaravel, T., & Ihme, M. (2019). Analysis of transient blow-out dynamics in a swirl-stabilized combustor using large-eddy simulations. Proceedings of the Combustion Institute Vol. 37, No. 4, pp. 5073-5082. doi: https://doi.org/10.1016/j.proci.2018.06.066

Mayhew, E., Mitsingas, C.M., McGann, B., Hendershott, T., Stouffer, S., Wrzesinski, P., Caswell, A.W., & Lee, T. (2017). Spray characteristics and flame structure of jet a and alternative jet fuels. 55th AIAA Aerospace Sciences Meeting. doi: 10.2514/6.2017-0148

Pomraning, E. & Rutland, C.J. (2002). Dynamic one-equation nonviscosity large-eddy simulation model. AIAA Journal Vol. 40, No. 4, pp. 689-701. doi: 10.2514/2.1701

van Oijen, J.A., Donini, A., Bastiaans, R.J.M., ten Thije Boonkkamp, J.H.M., & de Goey, L.P.H. (2016). State-of-the-art in premixed combustion modeling using flamelet generated manifolds. Progress in Energy and Combustion Science Vol. 57, pp. 30-74. doi: 10.1016/j.pecs.2016.07.001