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

Purdue University

Project Lead Investigator

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- FAA Award Number: COE-2014-29A , 401321
- Period of Performance: 10/1/2017-9/30/2018
- Tasks:

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

Project Funding Level

The funding level from the FAA was $150,000 for Year 4. Purdue University provided cost sharing funds in the amount of $150,000.

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 oversees the work performed by one of the graduate students that he is mentoring. 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 responsible for mentoring one of the graduate students 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 two graduate students involved in the experimental portion of 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) and cold start conditions.

Project Overview

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

Purdue University has very capable test rig facilities for measuring spray characteristics over very wide ranges of pressure, inlet air temperature, and fuel temperature. The experimental diagnostics that are applied include both phase Doppler anemometry (PDA) as well as high-frame-rate shadowgraphy. The atomization and spray dynamics for multiple reference and candidate alternative fuels have been characterized for the referee rig nozzle operated at near lean blowout (LBO) conditions. In the future these same sorts of measurements will be performed for many of these same fuels at operating conditions characteristic of high-altitude relight (HAR). A new fuel, IH2, has been added to the test matrix and will be investigated at LBO and cold start conditions.

Task 1- Measurement of Spray Characteristics at Near Lean Blowout and Chilled Fuel Conditions

Purdue University

Objective(s)

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

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

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

The project objectives are summarized as:

(a) Obtain PDA data across one plane in the VAPS test rig operated with the Referee Rig nozzle and for numerous fuels at near-lean blowout (LBO) conditions and for cold fuel/cold air flow conditions approximating ground light off (GLO) and high-altitude relight (HAR) conditions

(b) Extend PDA measurements to obtain data across multiple planes for evaluation of Detailed Combustor Simulations (DeCS) by Suresh Menon, Vaidya Sankaran, and Matthias Ihme,
(c) Obtain PDA measurements for selected operating conditions either in the VAPS test rig to provide data for the spray correlation analysis of Nader Rizk,
(d) Perform PDA measurements for fuel blends including Fuel X and/or another blend designed for testing differences in atomization characteristics to examine the sensitivity of correlations and computations to changes in fuel properties,
(e) Ensure quality of data with repetition tests at Purdue and comparisons with spray measurements at P&W, UDRI/AFRL, and UIUC.

Research Approach

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

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

Liquid fuels can be supplied to the test rigs by multiple systems. A facility-integrated system draws fuel from one of two certified flame-shield fuel containments for testing standard aviation fuels as well as other alternative blends. A mobile fuel 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 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 30 kg/hr, supplied to the control circuits at a 10 MPa regulated line pressure. The mobile fuel system was built with two onboard heat exchangers and a chilling unit controls the temperature of the fuel over a range of 193 K to 263 K (-80 ºC to -10 ˚C).

Milestone(s)

The tasks that were performed in FY2018 are listed below:

Quarter 1

1. Performed PDA measurements for chilled fuel/nitrogen conditions for A2, A3, and C3 fuels after installation of system to inject liquid nitrogen into the gaseous nitrogen airbox flow. Measurements were performed for A2, A3, and C3 fuels at -30F fuel temperature and -30F nitrogen airbox temperature.
2. Performed PDA measurements for chilled fuel/nitrogen conditions for A1, A2, A3, C1 and C7 fuels after Installation of system to inject liquid nitrogen into the gaseous nitrogen airbox flow. The test matrix was provided by the Area 6 group based on their ignition measurements. The conditions provided were conditions where the probability of ignition was 5%.
3. Developed computational methodology based on CONVERGE code for LBO predictions in referee combustor for a given fuel. CFD model utilizes the on fly automatic mesh generation and adaptive mesh refinement techniques. All tiny effusion holes on the liners are resolved and gridded in this methodology.
4. Performed non reacting RANS and LES simulations to estimate the flow splits for swirler passages (radial, inner axial, outer axial and swirler cooling slot), primary and secondary dilution holes, and effusion holes. Both and RANS and LES results compared with experimental data.
5. Reacting LES Simulations were performed using finite rate chemistry solver (laminar closure for sub-grid scale turbulent chemistry interactions) and compact kinetic models for A-2 and C-1 fuels.
6. PhD student Veeraraghava Raju Hasti presented two papers at the 2018 SciTech meeting (1. Assessment of turbulent combustion models with automatic meshing and AMR for Volvo bluff body flame 2. Evaluation

of LES methodology based on automatic meshing and AMR for capturing the turbulent flame structures with CO2 addition (0%, 5% and 10%)).

Quarter 2

1. Performed PDA measurements for high ambient pressure conditions for A2. Measurements were performed for A2 fuel at 45 F fuel temperature and 45 F nitrogen airbox temperature at vessel pressure of 1, 2, 5, and 7 bar.
2. Began the process of moving the VAPS test rig and PDA system to a test cell in the new High Pressure Combustion Laboratory.
3. Began the process of designing a new stand for the VAPS rig system in the new facility.
4. MS students Andrew Bokhart and Daniel Shin co-authored a paper for the 2018 AIAA SciTech Meeting. Daniel Shin presented the work at 2018 AIAA SciTech.
5. Reacting LES Simulations were performed using finite rate chemistry solver (laminar closure for sub-grid scale turbulent chemistry interactions) and HyChem mechanisms (detailed, skeletal and reduced version) for A-2 and C-1 fuels. Skeletal mechanism showed the correct trends for both fuels where as detailed and reduced mechanisms showed opposite trends with multi-zone finite rate chemistry model.
5. PhD student Veeraraghava Raju Hasti drafted 3 AIAA JPC papers – 1. Non reacting flow-splits 2. LBO computation with Compact kinetic models 3. Flame structure evaluation and key markers identification during LBO for both A-2 and C-1 fuels.

Quarter 3

1. A new stand design for the VAPS rig system was developed to accommodate to the new facility. A new stand frame that will support the pressure vessel was redesigned. A Linos structure for PDA system was designed for the VAPS test rig. This structure will also allow other measurement techniques such as SLIPI, holography, etc.
2. Began the process of expanding the data acquisition and control system (DACS) in new test facility for VAPS test rig. Working in progress counting channels, cables, instrumentations, hardware, etc.
3. Worked on editing and revising AIAA book chapter describing the NJFCP program.
4. Graduate students Daniel Shin and Andrew Bokhart co-authored a paper for the ICLASS 2018 and submitted the abstract for 2019 AIAA Sci-Tech. Daniel Shin presented the measurements at Cold Start Condition in the ICLASS 2018 conference.
5. Collected spray boundary conditions for cold start ignition LES simulations
6. Graduate student Veeraraghava Raju Hasti presented 3 papers at the AIAA JPC meeting and also delivered training on LBO computation using CONVERGE CFD tool organized by the Convergent Science for OEMs and Gas turbine community at the JPC 2018.
7. Developed a conjugate heat transfer methodology based LES simulations to account for heat losses through liner walls on the flame structure and LBO limits for referee combustor
8. Abstract on LBO mechanism submitted and accepted for presentation at the 71st APS division of fluid dynamics annual meeting.

Quarter 4

1. New stand design for VAPS test rig has been developed and fabricated. Frames were welded/assembled together and moved in a new test cell.
2. Expansion on data acquisition & control system (DACS) for the VAPS test rig in a new test cell has been initiated. Assembling and installing parts for additional DACS components in a new test cell is still in progress.
3. Previous fuel line design on a mobile fuel system damaged the flowmeter. Modification on fuel line on a mobile fuel system has been done, and a new flowmeter will be installed.
4. Facility fluid supply lines for the atomizing flow, vessel flow, purge, and pilot in a new test cell have been specified and are under modification.
5. AIAA Sci-Tech 2019 abstract for the cold start condition measurement has been accepted.
6. Attended and presented the work at NJFCP mid-year meeting hosted by GE at Cincinnati, Ohio.
7. Graduate student Hasti Veeraraghava Raju edited the 3 JPC papers for submission to AIAA journal and AIAA Journal of Propulsion and Power

8. Evaluated the Flamelet Generated Manifold combustion model with diffusion flamelet for C-1 fuel with compact kinetic mechanism to compute the LBO. This model show blow-out for C-1 fuel at global equivalence ratio of 0.084 and experimentally measured global equivalence ratio at the blow-out is 0.0869.
9. Implemented Partially Stirred Reactor (PaSR) combustion model in CONVERGE code to account for sub-grid scale turbulence-chemistry interactions for LBO simulations.
10. LBO mechanism identified based on LES simulations and presented this work at the 71st APS division of fluid dynamics annual meeting in Atlanta, Georgia, USA.

Major Accomplishments

Experimental Contribution

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 characteristics at cold start conditions are presented in the rest of this section. The Purdue Variable Ambient Pressure Spray (VAPS) test rig is discussed along with modifications needed for the cold start measurements. A generic hybrid airblast pressure-swirl injector is used and we have investigated the spray characteristics of three different fuels. The spray data was provided to Dr. Nadar Rizk for developing correlations as well as to modelers for computational models of the combustion process in a Referee rig developed by the NJFCP team.

Experimental Systems

Purdue Variable Ambient Pressure Spray (VAPS) rig is consisted of two major components: the airbox assembly and the pressure vessel. The airbox is a length of pipe on which the hybrid airblast pressure-swirl atomizer was mounted. The airbox is placed within the pressure vessel. This allows a pressurized atomizing gaseous flow through the airbox to be isolated from the vessel to create a pressure difference across the gas swirler. Nitrogen is used for all gaseous flows in this investigation to prevent the formation of combustible mixtures. A liquid nitrogen flow is injected into the gaseous nitrogen airbox flow to chill the atomizing gas flow to 239 K for cold start condition measurements. The airbox assembly was capable of vertical translation allowing measurements at multiple locations downstream of the injector. A diagram of the VAPS rig with all the fuel/gas flows is shown in Figure 1.

The pressure vessel houses the airbox and injector assemblies and allows the variation of different ambient pressure into which the fuel is being injected. The vessel is rated to withstand 4.14 MPa (600 psi) at 648.9°C (1200°F). The pressure within the vessel is controlled by a butterfly valve downstream of the test section which can be partially closed to increase pressure and opened to vent pressure or operate at ambient pressures. For this study, the vessel pressure remained at approximately standard atmospheric pressure. The vessel has four windows in the same horizontal plane, which allow laser diagnostic measurements to be performed within the test section. Two windows have a diameter of 127 mm (5 inches) and the other two windows have a diameter of 76.2 mm (3 inches). The 76.2 mm windows are both at a 60° angle from one of the 127 mm windows, with one of the 76.2 mm windows located on either side of the 127 mm window. Two heated nitrogen flows enters the vessel to mitigate fuel recirculation and collection of fuel drops on the windows: the sweeping flow and the window purge flow. These two flow are also used to build pressure within the vessel. A diagram depicting these two nitrogen flows as well as the airbox co-flow is shown in Figure 1(a) and a picture of the VAPS vessel is shown in Figure 1(b).

The mobile fuel system uses an IMO CIG Lip Seal and Weep Hole Design gear pump, which is used to supply pressurized fuel to the injector mounted on the airbox. The mobile fuel system also uses a chiller unit with two heat exchangers to chill the fuel to the desired fuel temperature. The fuel supply line passes through two heat exchangers and travels along a jacketed fuel line in which the heat transfer fluid is circulated. The chiller unit can chill the heat transfer fluid to a temperature within the range of -80 °C to -10 °C with ±0.1 °C control stability.

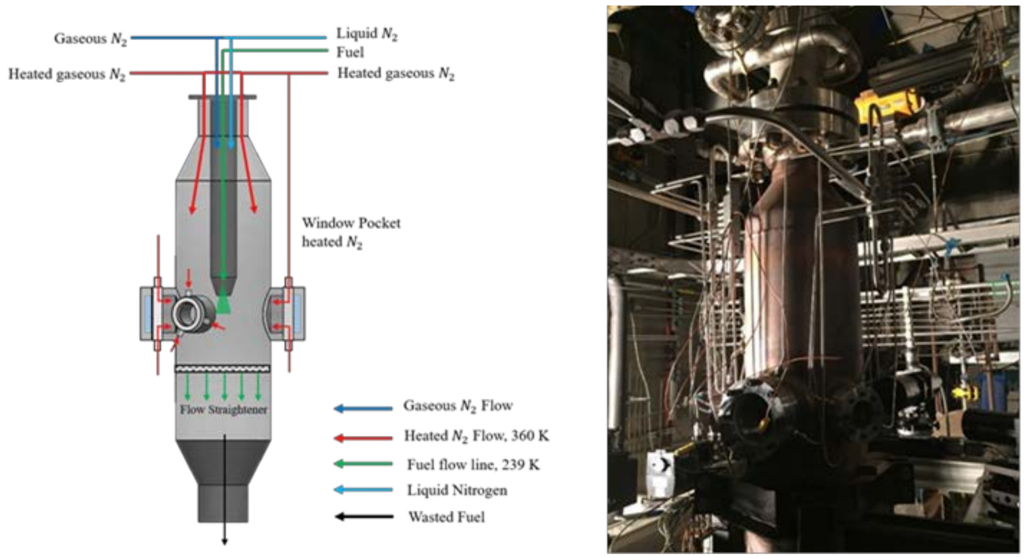

Figure 1. Schematic diagram and photograph of the Variable Ambient Pressure Spray (VAPS) test rig.

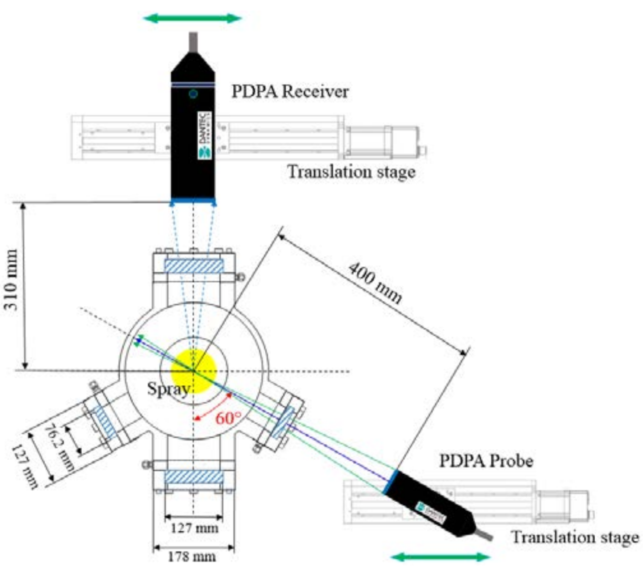

Figure 2. PDA measurement system for the VAPS test rig.

There are two independently controlled and metered fuel lines, which are used to supply fuel to the pilot and main orifices on a hybrid airblast pressure-swirl atomizer. The schematic of this hybrid airblast pressure-swirl atomizer is provided in 3. The atomizer consists of two parts: the fuel injector and gas swirler. The atomizer is assembled such that the fuel injector is housed within the gas swirler. The fuel injector has two types of injection orifices that can be operated separately: the pilot and the main. The pilot orifice is comprised of a single orifice at the centerline of the injector and performs as a pressure swirler of the hybrid design. The main is comprised of multiple orifices that injects fuel tangentially onto a prefilming surface on the interior of the gas swirler. The resulted spray of this hybrid atomizer is a hollow cone spray.

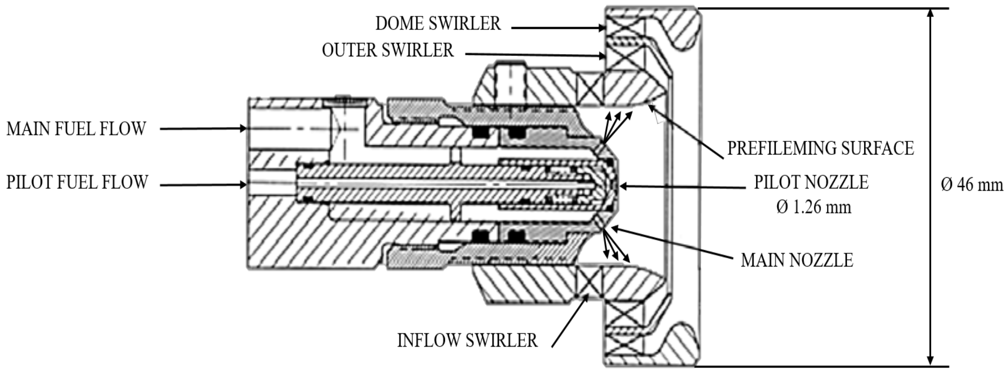

Figure 3. Schematic of the hybrid airblast pressure-swirl atomizer

The fuel sprays are characterized using a DANTEC Dynamics phase Doppler anemometry (PDA) system which measured a variety of mean diameter statistics and a component of drop velocity. The receiving probe and the transmitter probe are aligned at a scattering angle of 60˚ due to the orientation of the windows on the vessel. The alignment of the PDA system relative to the VAPS vessel is shown in Figure2. The PDA probe and receiver optics are mounted on Zaber translation stages to move the system to measurement locations throughout the spray along the horizontal axis. The center of the spray on the horizontal axis is defined as the zero location for the radial locations. Measurements are taken between ±30 mm from the center of the spray with increments of 5 mm and 20,000 samples at each radial location.

Experimental Results: PDA Measurements

Spray measurements at cold start operating conditions have been performed in the VAPS rig for three different fuels: A-2, A-3, and C-3. The cold start operating conditions are at an ambient pressure of 1 bar (15.4 psia), an air box nitrogen temperature of 239 K (-30^{0}F), a pilot fuel temperature of 239 K (-30^{0}F), a pilot fuel mass flow rate of 9.22 kg/hr (20 lb/hr), and a pressure drop (ΔP/P) of 2, 3, and 4 % across the swirler. All three fuels were investigated at three different axial distance downstream from the exit of swirler: 12.7 mm (0.5 inch), 25.4 mm (1 inch), and 38.1 mm (1.5 inch). Figure 4 shows the D_{32} and U_z measurements for C-3 fuel at 25.4 mm measurement plane. The distribution shows that the symmetry of the spray produced by the hybrid atomizer for this study is preserved at cold start conditions, similar to the previous lean blowout (LBO) investigation using the same injector.

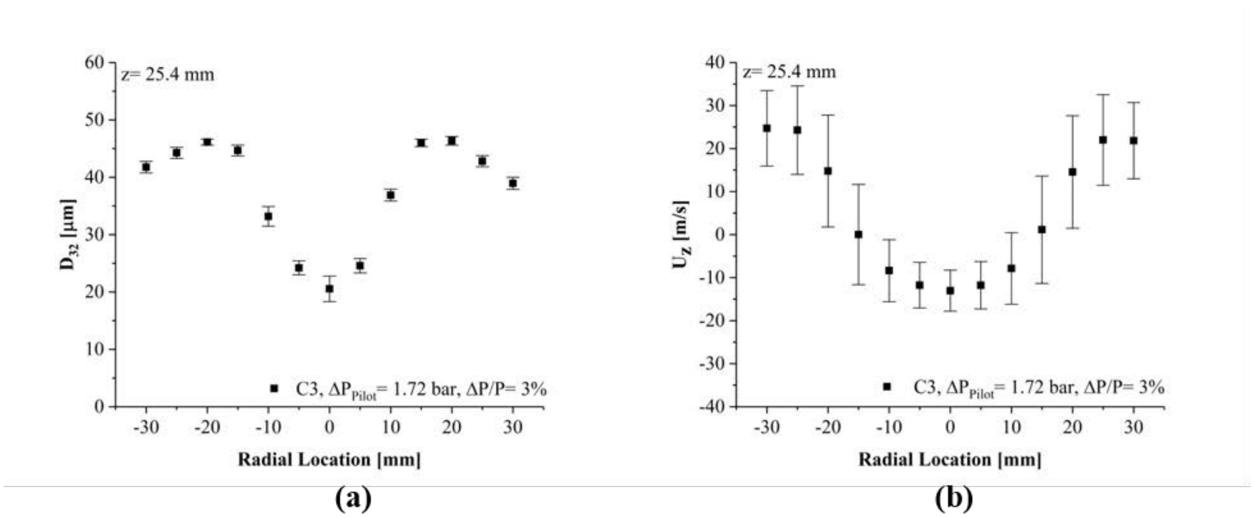

Figure 4. D_{32} and U_z distributions for C-3 with ΔP/P =3 %, T_{fuel} = 238 K, T_{gas} = 238 K at 25.4 mm measurement plane. Vertical bars on velocity represent RMS.

The D_{32} and U_z distributions for C-3 at 12.7 mm, 25.4 mm, and 38.1 mm measurement planes are shown in Figure 5. The minimum values of all of these distributions remained at the center of the spray (r = 0 mm) for all three planes investigated, but the peaks of the distributions shifted away from the center of the spray toward the edge of the spray as the axial distance from the injector increased. These observations demonstrated that as the spray travels downstream from the injector the largest drops continued to maintain their trajectories and spread radially outward.

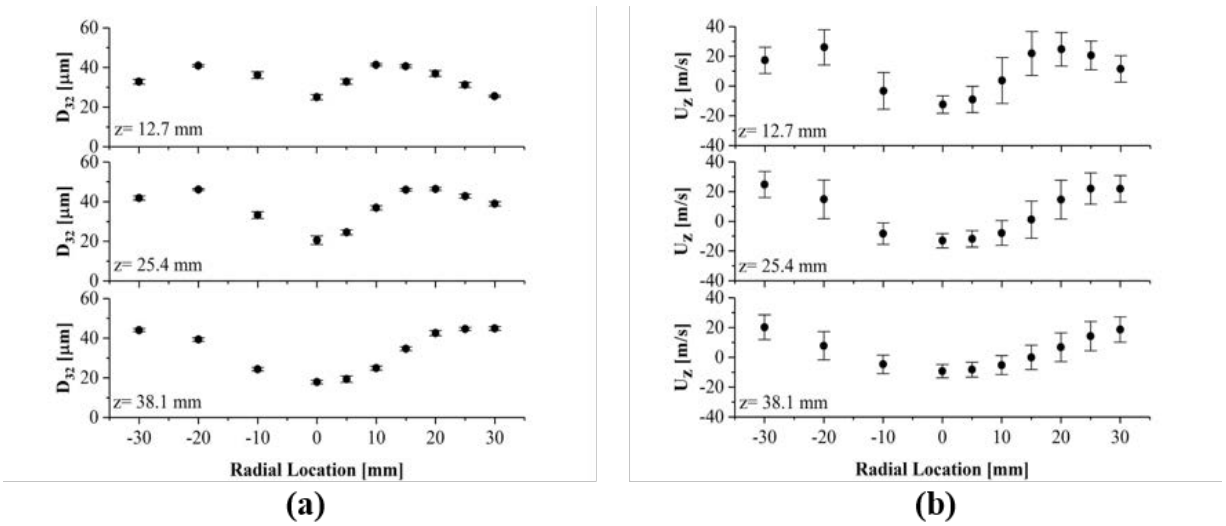

Figure 5. Comparisons of D_{32} and U_z distributions for C-3 at different measurement planes at ΔP/P =3 %, T_{fuel} = 238 K, T_{gas} = 238 K at 25.4 mm measurement plane. Vertical bars on velocity represent RMS.

The effect of pressure drop across the swirler (ΔP/P) on the D_{32} and U_z was observed to be significant for the A-2, A-3, and C-3 fuels. Figures 6 to 8 show the comparisons of D_{32} and U_z distributions at three different pressure drops of 2, 3, and 4% for A-2, A-3, and C-3. It was observed that a decrease in D_{32} with increases in ΔP/P at all radial locations. The U_z comparisons at different ΔP/P values for the A-2 fuel are shown in Figure 6(b). The magnitude of drop velocities increased as ΔP/P increased due to the larger inertia imparted by the greater gas flow.

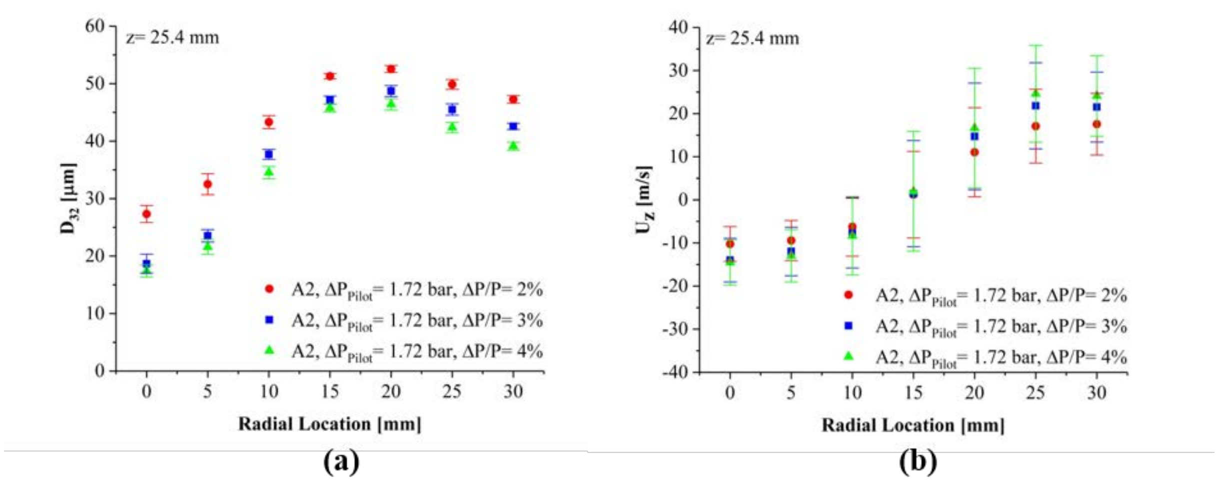

Figure 6. Comparisons of D_{32} and U_z distributions for A-2 when ΔP/P = 2, 3, 4 %, T_{fuel} = 238 K, and T_{gas} = 238 K at 25.4 mm measurement plane. Vertical bars on velocity represent RMS.

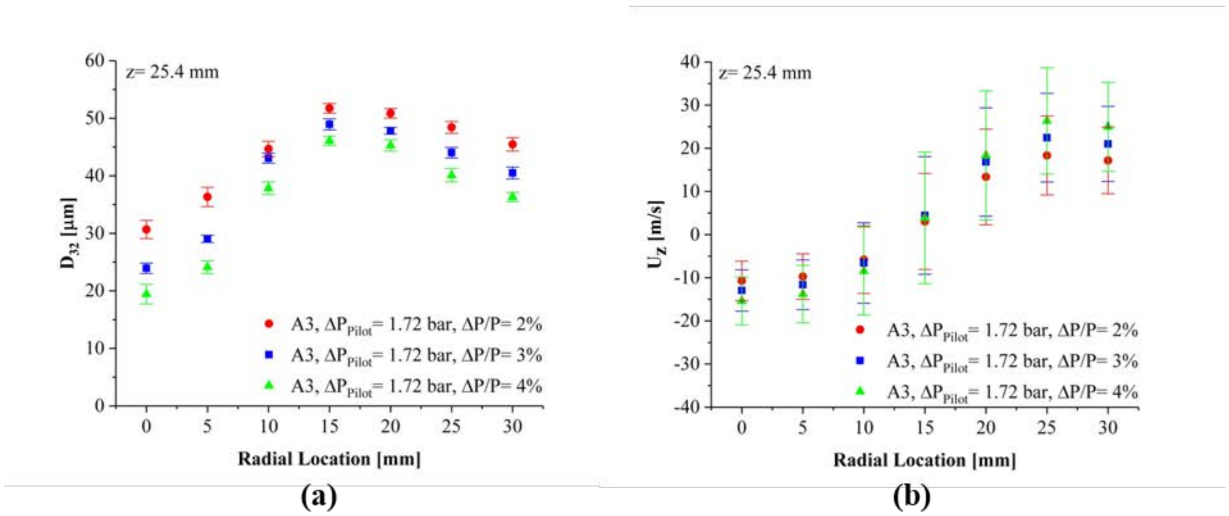

Figure 7. Comparisons of D_{32} and U_z distributions for A-3 when ΔP/P = 2, 3, 4 %, T_{fuel} = 238 K, and T_{gas} = 238 K at 25.4 mm measurement plane. Vertical bars on velocity represent RMS.

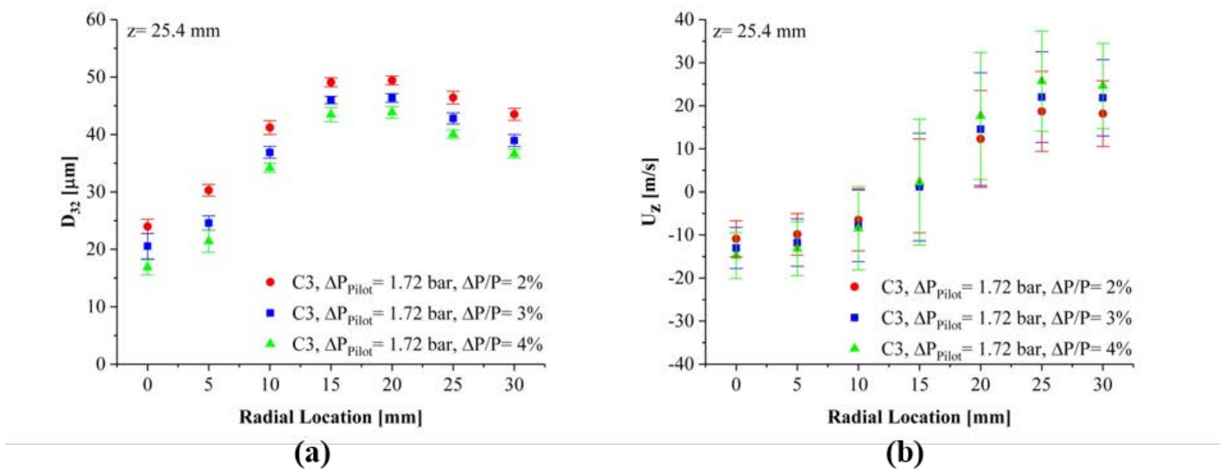

Figure 8. Comparisons of D_{32} and U_z distributions for C-3 when ΔP/P = 2, 3, 4 %, T_{fuel} = 238 K, and T_{gas} = 238 K at 25.4 mm measurement plane. Vertical bars on velocity represent RMS.

The effect of fuel type on D_{32} and U_z was investigated at the cold start conditions on the 25.4 mm measurement plane. The comparisons of D_{32} and U_z for A-2, A-3, and C-3 are shown in Figure 9. The D_{32} comparison showed that A-3 fuel formed the highest D_{32} within the recirculation zone. The U_z measurements showed no significant variations among the fuels. The fuel properties at the cold start conditions did not provide any definitive conclusions regarding observations made about the effect of fuel type.

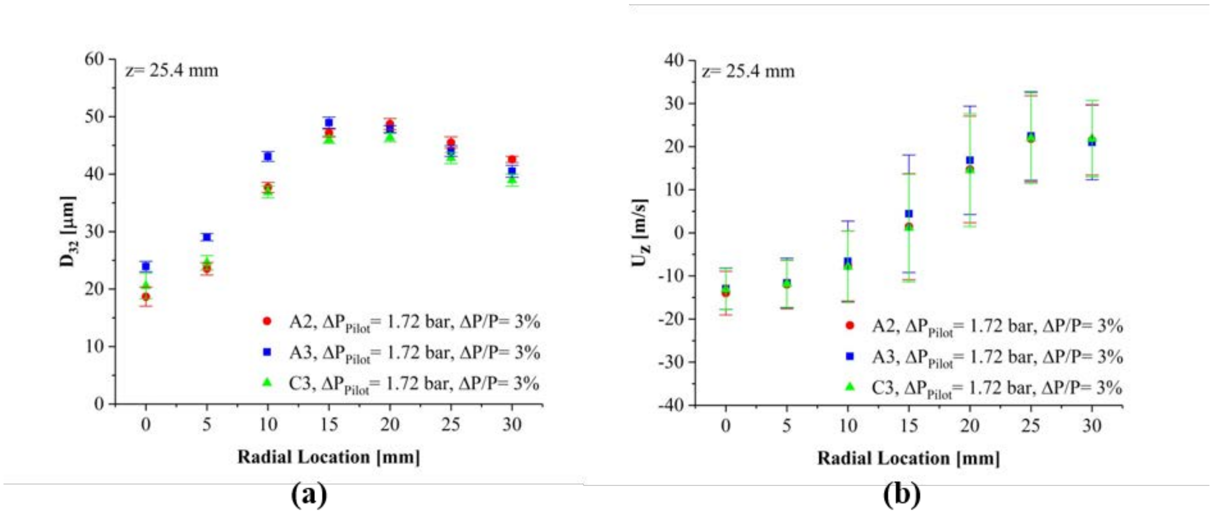

Figure 9. Comparisons of D_{32} and U_z for A-2, A-3, and C-3 when ΔP/P = 2, 3, 4 %, T_{fuel} = 238 K, and T_{gas} = 238 K at 25.4 mm measurement plane. Vertical bars on velocity represent RMS.

The effect of ambient pressure on spray characteristics was also investigated with A-2 fuel in VAPS test rig. The operating conditions for this investigation were ΔP/P =2 %, ΔP_{pilot} = 1.72 bar, T_{fuel} = 278 K, and T_{gas} = 259 K. The ambient pressure was varied to values of 1, 2, 5, and 7 bar, and the measurements were taken at 25.4 mm downstream from the swirler exit. Figure 10 shows the comparisons of D_{32} and U_z for A-2 at different ambient pressures. The observation shows that a decrease in D_{32} with increases in ambient pressures. However, the effect of ambient pressure on the drop size diminished with continuous increase in ambient pressure. The U_z comparison shows that the the drop velocity was not affected significantly by the ambient pressure variation.

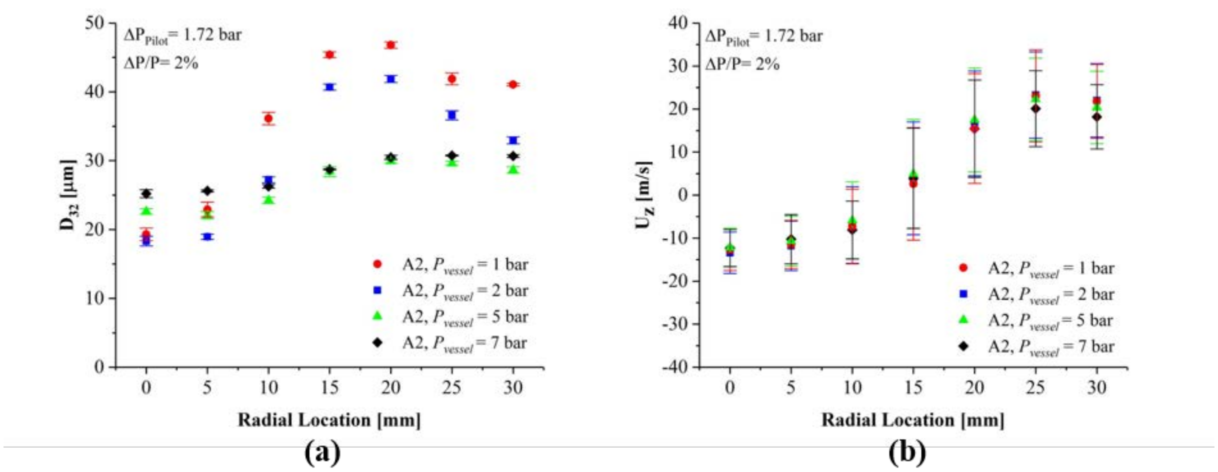

Figure 10. Comparisons of D_{32} and U_z for A-2 at ambient pressure of 1, 2, 5, and 7 bar when ΔP/P = 2 %, T_{fuel} = 278 K, and T_{gas} = 259 K at 25.4 mm measurement plane. Vertical bars on velocity represent RMS.

Computational Contribution

The following section describes the computational efforts for predicting the fuel sensitivity to LBO in referee combustor. The CFD model developed for LBO calculations is shown in Figure 11. Flow through all passages including tiny effusion holes on the liners is resolved in this CFD model. The computational grid for flow simulations with all passages open is shown in

Figure 11. The grid is locally refined in the regions with the steepest gradients in the domain while leaving the grid relatively coarse in sections with weaker gradients using adaptive mesh refinement (AMR).

Non-reacting simulations are carried out first for flow rate comparison with experimental data for swirler component-wise passages and all passages in the referee combustor. Reacting flow LES simulations are carried out for referee combustor using a finite volume based compressible flow solver CONVERGE and detailed finite-rate chemistry. The gas phase equations are described with the Eulerian approach and the liquid spray is modeled with discrete injections of droplets in a Lagrangian frame to simulate the liquid fuel spray. The compressible form of the Favre-averaged Navier-Stokes equations after LES decomposition is solved on a non-staggered, collocated computational grid along with the species transport equations, energy equation and the equation of state in the present study. The sub-grid stress tensor, $\tau_{ij} = \bar{\rho}(\widetilde{u_i u_j} - \tilde{u}_i \tilde{u}_j)$ in the momentum equation is modeled using a non-viscosity based one-equation sub-grid scale model to obtain the closure. The filtered reaction rate in the species transport equation is estimated using the Arrhenius law and assumed well-stirred reactor model for sub-grid level turbulence-chemistry interactions.

The spray boundary conditions (droplet diameter, average velocity, and cone angle) specified at 2 mm from the nozzle exit are obtained from the PDPA measurements (provided details on these measurements in our experimental contribution section) at 25.4 mm from the deflector plate. An ensemble of six ring injectors, each with its own droplet size and velocity distributions, represents the nozzle. Taylor Analogy Secondary Breakup and the dynamic drag models are employed to estimate the secondary breakup and resulting spray droplet dynamics. A droplet dispersion model is used to include the effects of the sub-grid-scale flow field on the discrete parcels. The drop evaporation rates are calculated using the Frossling correlation based on the laminar mass diffusivity of the fuel vapor, a mass transfer number, and a Sherwood number. The prescribed fuel properties are as determined for A-2 and C-1 fuels.

Parts of this work were carried out at Argonne National Laboratory.

CFD Model:

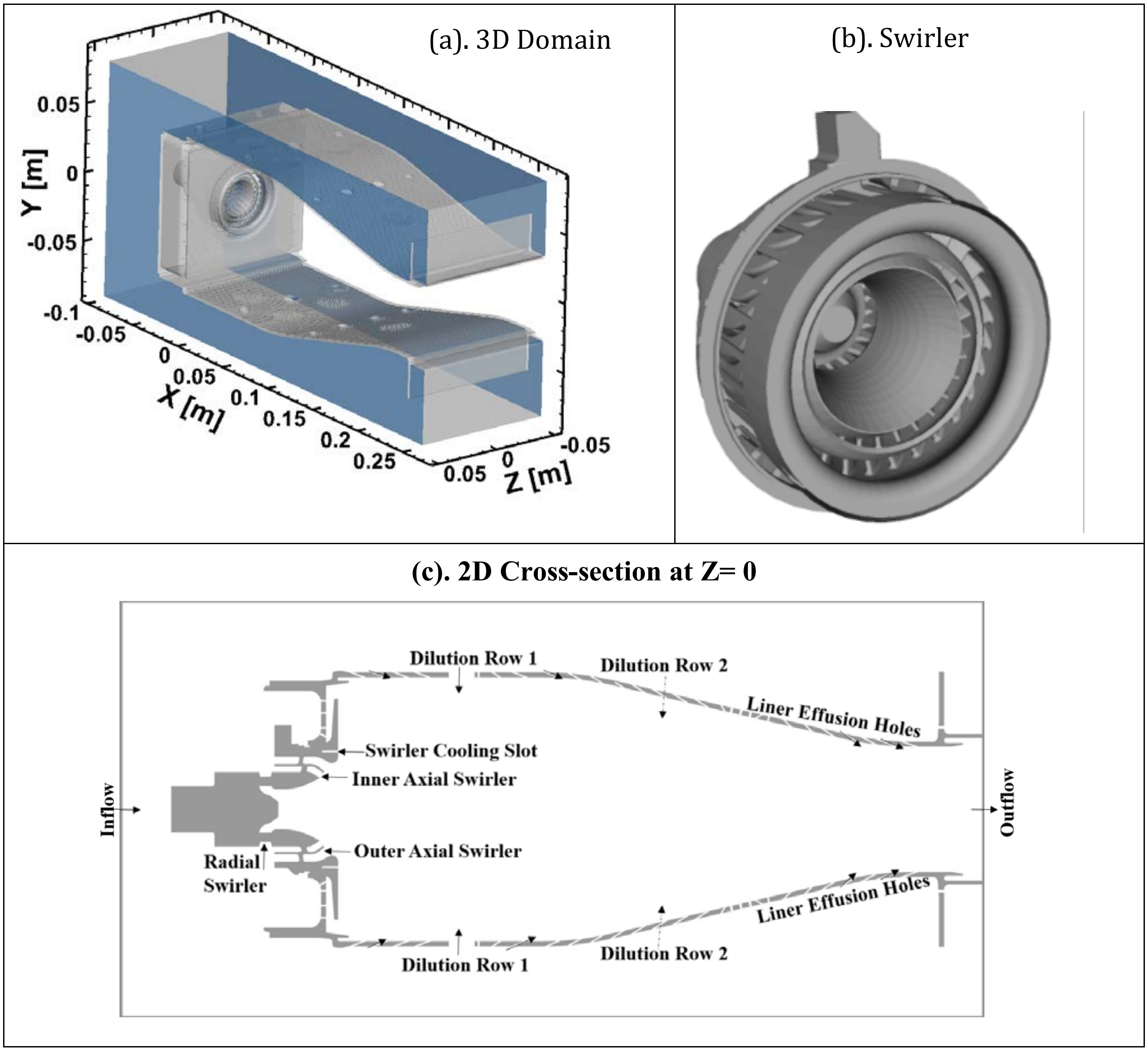

Figure 11. (a) 3D Computational domain (b) magnified view of the 3D swirler (c) magnified the view of the 2D cross-section at Z=0 (mid-plane).

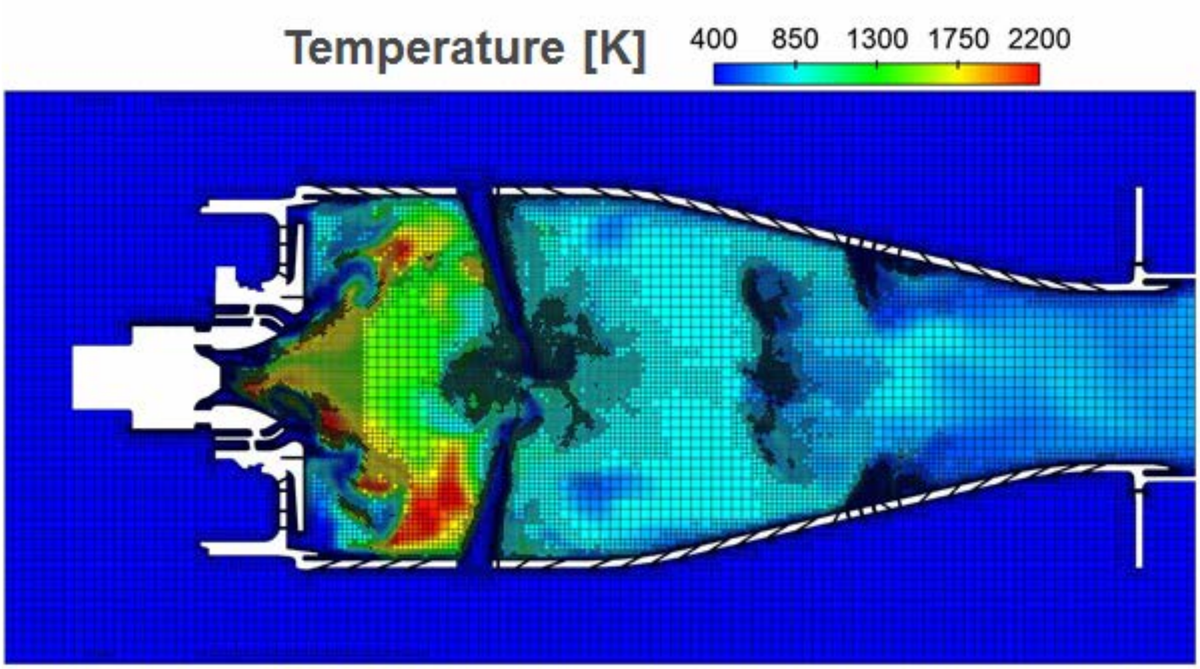

Figure 12. Computational grid with AMR on mid-plane of the referee combustor for a reacting case and colored with temperature contours

Non-reacting swirler component-wise flow splits study (one passage open at a time)

For the component-wise flow split study, a comparison between the experimental and computed results is shown in Figure 13. Computed results are in excellent agreement with experimental data for outer axial, inner axial and radial swirlers. Both RANS and LES underestimate (by about 22%) the order of magnitude smaller swirler cooling flow. However, both computational models capture the flow splits contributing to over 95% of the total flow accurately.

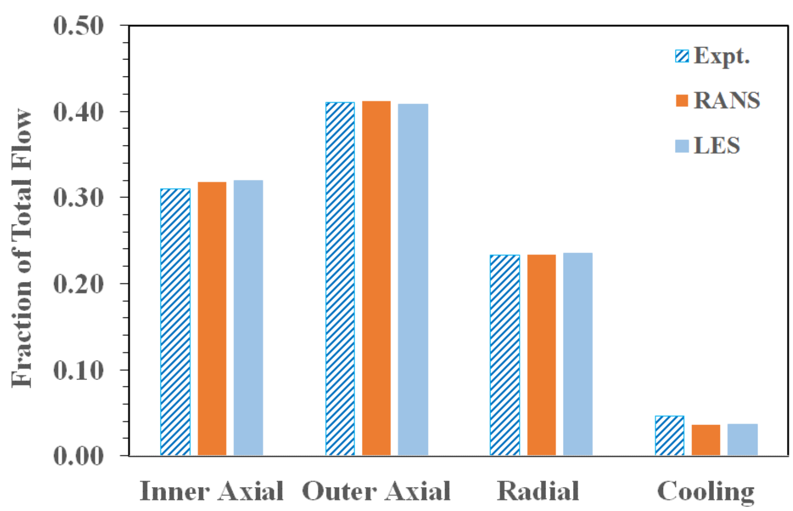

Figure 13. Comparison of component-wise flow splits for swirler passages for 10 million cells.

Non-reacting flow with all combustor passages open at the same time

RANS model is evaluated for a total cell count of 10 million with a maximum cell size 3 mm and a minimum cell size of 0.375 mm. The LES model is evaluated for a total cell count of 10 million and a total cell count of 21 million. The LES results for the two different meshes show grid convergence for flow splits. Both RANS and LES estimate similar flow splits for total swirler, total dilution and total effusion flow and comparison with experimental data and previous literature is shown in Table 4 and bar chart in Figure 14. Total swirler flow is overestimated by 19% with the coarse mesh and by 17.6% with the fine mesh; total dilution flow is overestimated by 14% with the coarse mesh and 9% with the fine mesh, and total effusion flow underestimated by 11.7% with coarse mesh and 10.6% with fine mesh. The differences between experiments and computations can be attributed to the interactions between the flows from multiple passages, numerical errors

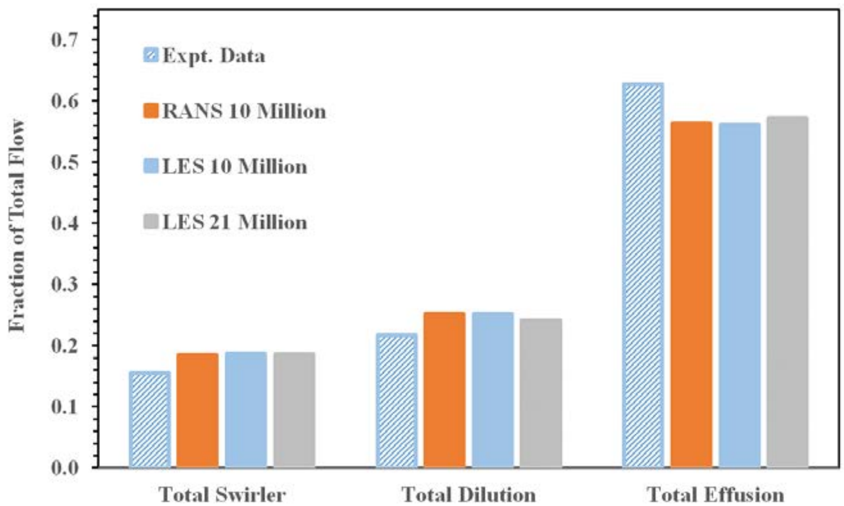

Figure 14. Comparison of combustor flow splits.

Non-reacting primary zone flow field

The mean velocity magnitudes on the XY-plane at Z=0 are shown in Figure 15. Air flows through all swirler passages interact resulting in a radially outward airflow entering the combustor. The primary dilution holes result in the highest velocities and their impingement leads to local flow reversals in this cross section. Bending of the cross jets in the stream wise direction is observed. However, the dilution jets have a high enough momentum to impinge upon each other. A relatively low velocity region exists beyond the cross flow jets and the primary zone. Flow is accelerated as it passes through the convergent section. The flows from the effusion holes form a film on the liner walls and pass along the wall. While the overall flow field seen in Figure 8 is highly symmetric around the X-axis, small dis-symmetries observed in the experiments are also captured in the results of the simulations. For example, the measured angles of the cross-jets are 13 and 14 degrees while the computed angles of the cross-jets are 12 and 13 degrees, respectively. While these comparisons are encouraging, more quantitative measurements of velocities and other detailed flow features are awaited for comparison with the LES results.

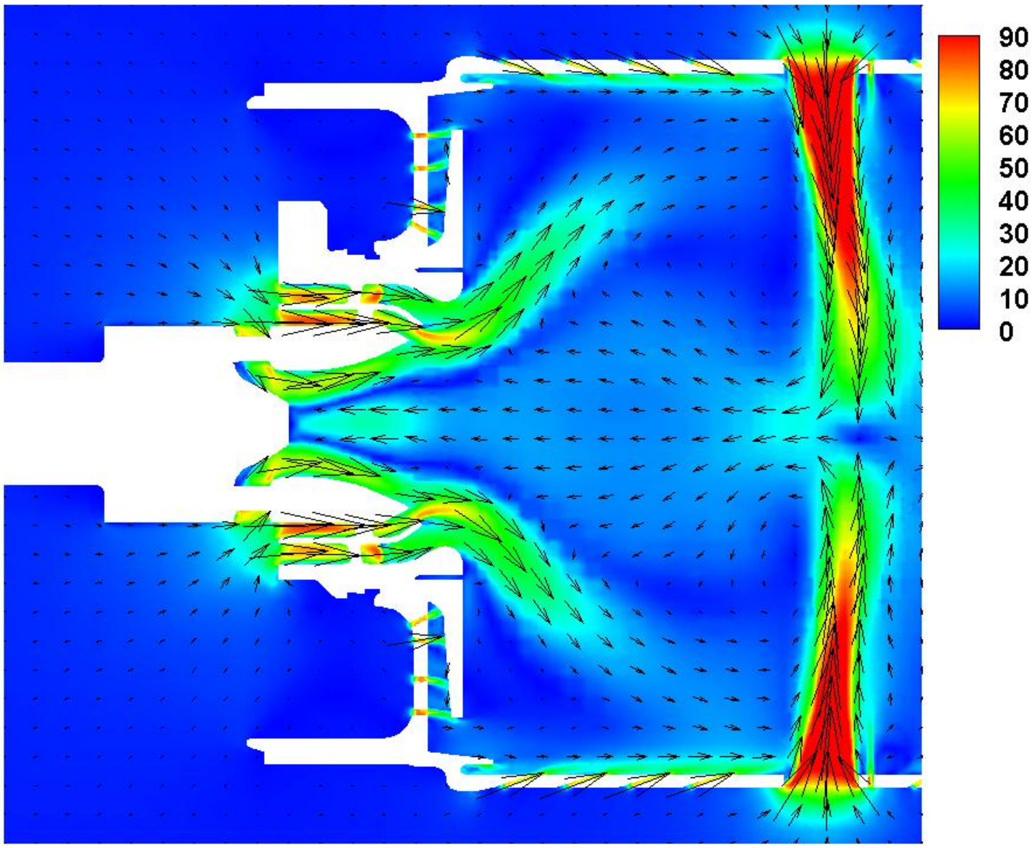

Figure 15. LES time-averaged velocity magnitude (m/s) on mid-plane with velocity vectors for 10 million cells (all passages open).

LBO LES Simulations

LBO Approach

LES simulations are carried out at a global equivalence ratio of 0.096, which was experimentally found to produce stable combustion. From this condition, the fuel flow rate is reduced in a gradual stepwise manner with larger time steps first and progressively reduced flow rate reduction steps as evidence of impending blowout behavior is approached as shown in Figure 16. The simulations are run with a fixed global equivalence ratio for at least two flow-through times, estimated to be approximately 30 ms. The fixed equivalence ratio is maintained beyond 30 ms, if a quasi-steady heat release rate is not reached during either of those limits. Heat release rate is used as a criterion for identifying the lean blowout. The global equivalence ratio steps resulting from this process are plotted as a function of time in Figure 16 for fuel A-2 on the left-hand side and fuel C-1 on the right-hand side. Experimental data shown as red filled circles indicate that the C-1 fuel shown on the right-hand frame blows out at higher equivalence ratio than for the A-1 fuel (left-hand frame).

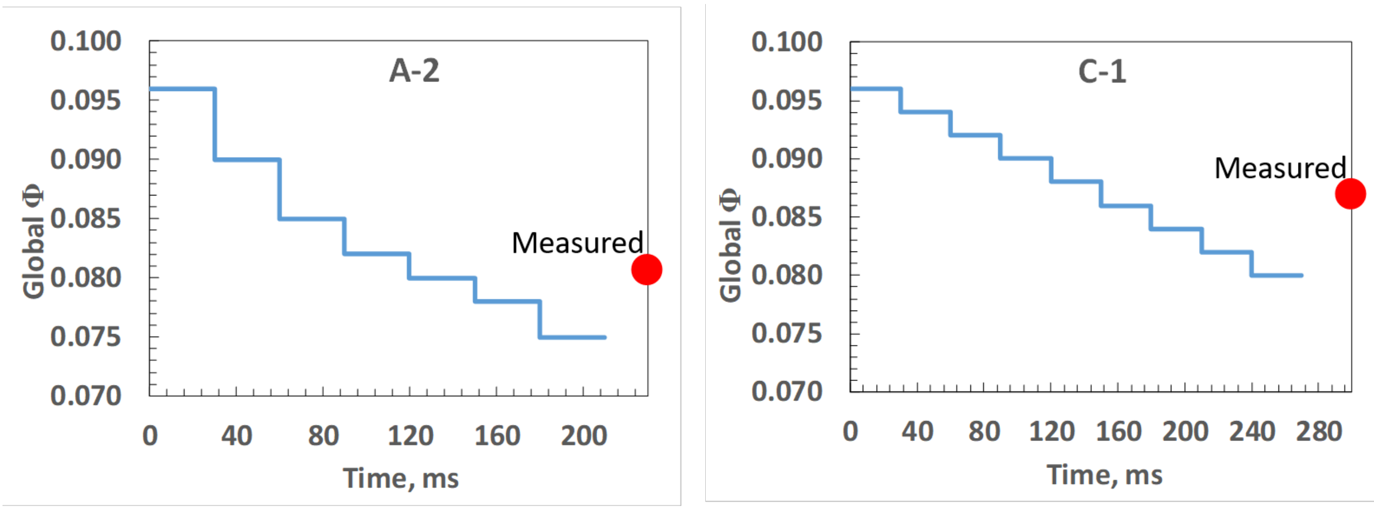

Figure 16. Staged fuel ramp down approach for LBO prediction. The red dot represents the measured lean blowout global equivalence ratio

Reacting spray comparison

Spray statistics were collected using LES calculations at a stable operating point are over a period equal to two flow-through times. The averaging process over two flow-through times is started after the flame and heat release rate reached a quasi-steady state. Figure 17 shows the experimental and predicted statistics of droplets at four axial stations as a function of radial distance. The fuel spray exhibits a pattern with smaller diameter droplets near the hollow cone surface 10mm downstream of the nozzle exit. This distribution widens in the radial direction as we go towards the downstream locations with larger droplets towards the center and vice-versa. The model is able to satisfactorily capture this trend for both the fuels. Better agreement with experiments is observed for the downstream locations. Axial and radial velocities increase away from the center and then decrease again with increasing spray cone angle. These trends are accurately captured for the near-nozzle regions as well as in downstream regions for both fuels. Overall, the Lagrangian spray setup is able to accurately capture the spray breakup and evaporation.

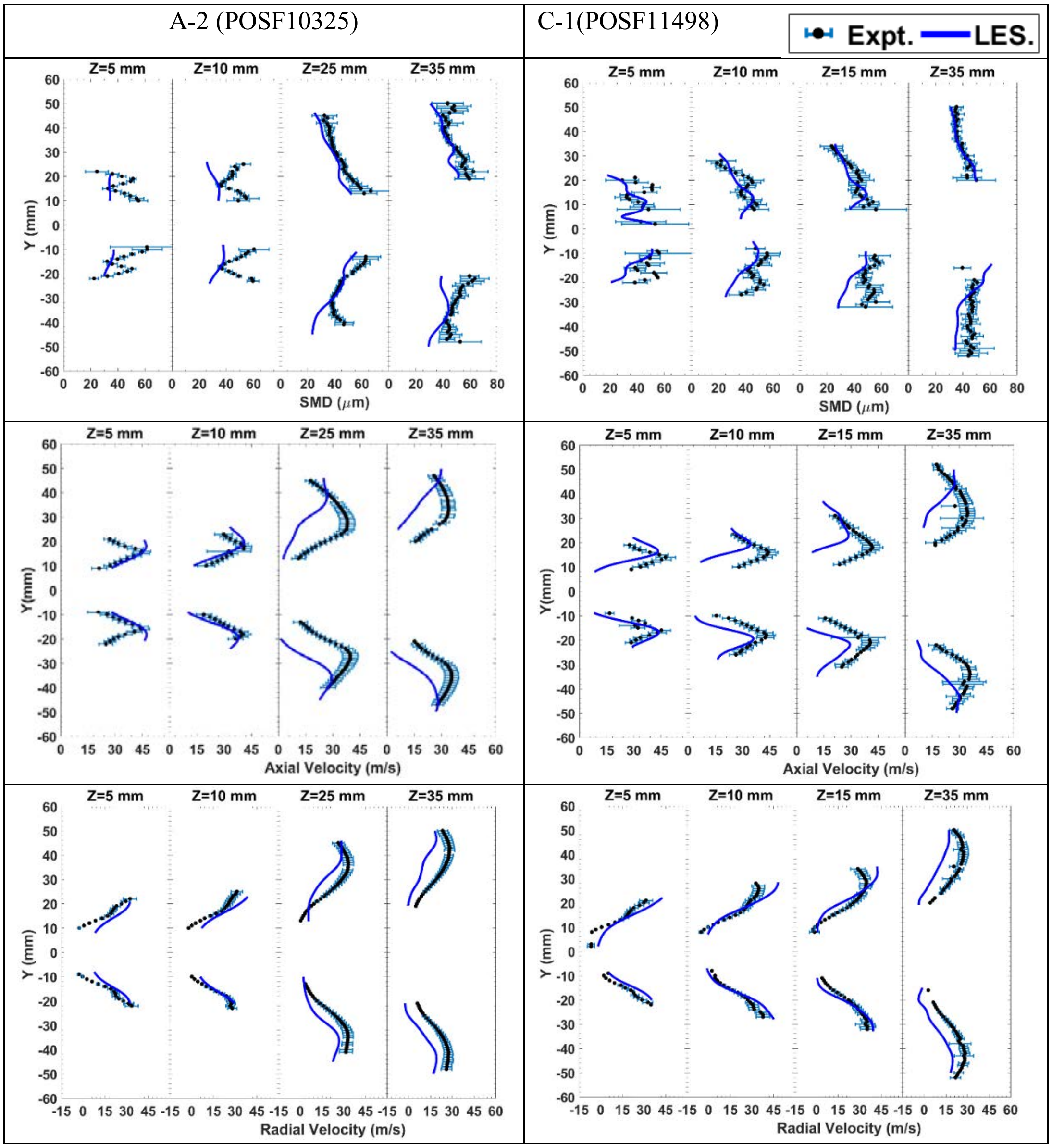

Figure 17. Spray statistics comparison with PDPA data[9] for a stable flame case at $\phi = 0.096$

Flame shape comparison

The OH* chemiluminescence data from UIUC experiments is utilized to compare the line of sight averaged OH mass fraction from LES simulations. They are reported for detailed, skeletal, reduced and compact mechanisms in Figure 18 alongside experimentally observed OH* chemiluminescence. The results from the detailed, the skeletal and the reduced mechanisms are qualitatively similar. The experimental data (OH* chemiluminescence) and the results of the detailed mechanism calculations (OH) show a similar spread in radial and axial directions. It must be noted these comparisons are qualitative in nature. The experimental images are based on false color and do not indicate a quantitative measurement of the OH field. The horizontal position of 0 mm corresponds to the deflector plate. OH formation marks the high temperature heat release regions, which extends 50 mm downstream of the deflector plate and also corresponds to the downstream location of first row of dilution holes. This is the flame stabilization region of the swirl-stabilized flame. It exhibits a truncated cone shape with high regions of OH/heat release corresponding to the cone angle of the hollow spray cone. This indicates strong burning and heat release near the spray cone surface downstream of the swirl cup. The A-2 fuel exhibits a higher degree of asymmetry in OH* for this configuration and measurements. These regions of intense heat release are captured qualitatively by all the four chemistry mechanisms.

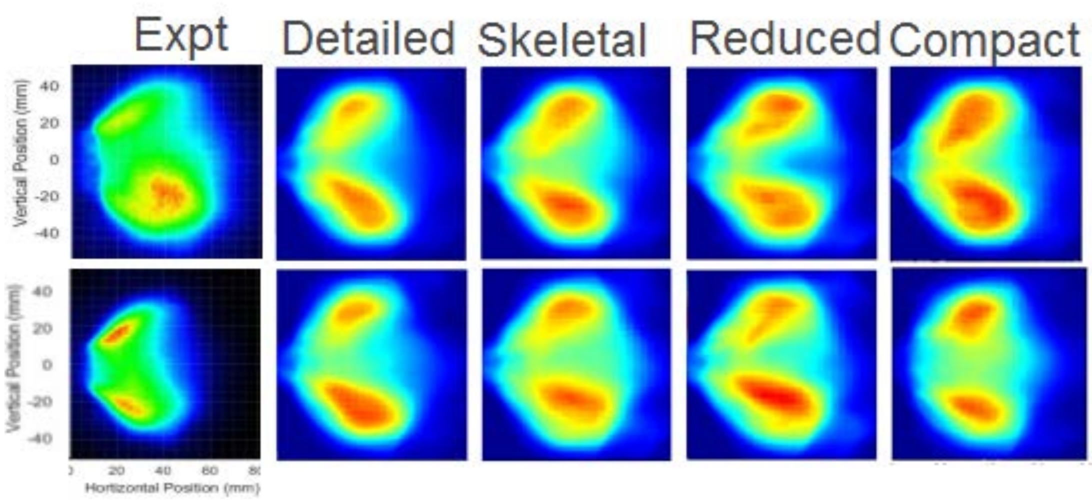

Figure 18. Line of Sight averaged mass fraction of OH from LES compared with experimental OH* from chemiluminescence.

<u>**Heat release rate**</u>
The evolution of heat release rates for each equivalence ratio and the two different fuels with compact and HyChem skeletal mechanism shown in Figure 19. The flame is observed to be stable for the first couple of milliseconds; this is followed by a steady decrease and eventually by a sharp drop in heat release rate for both A-2 and C-1 fuels. The heat release rates are allowed to reach a steady state before the next step down.

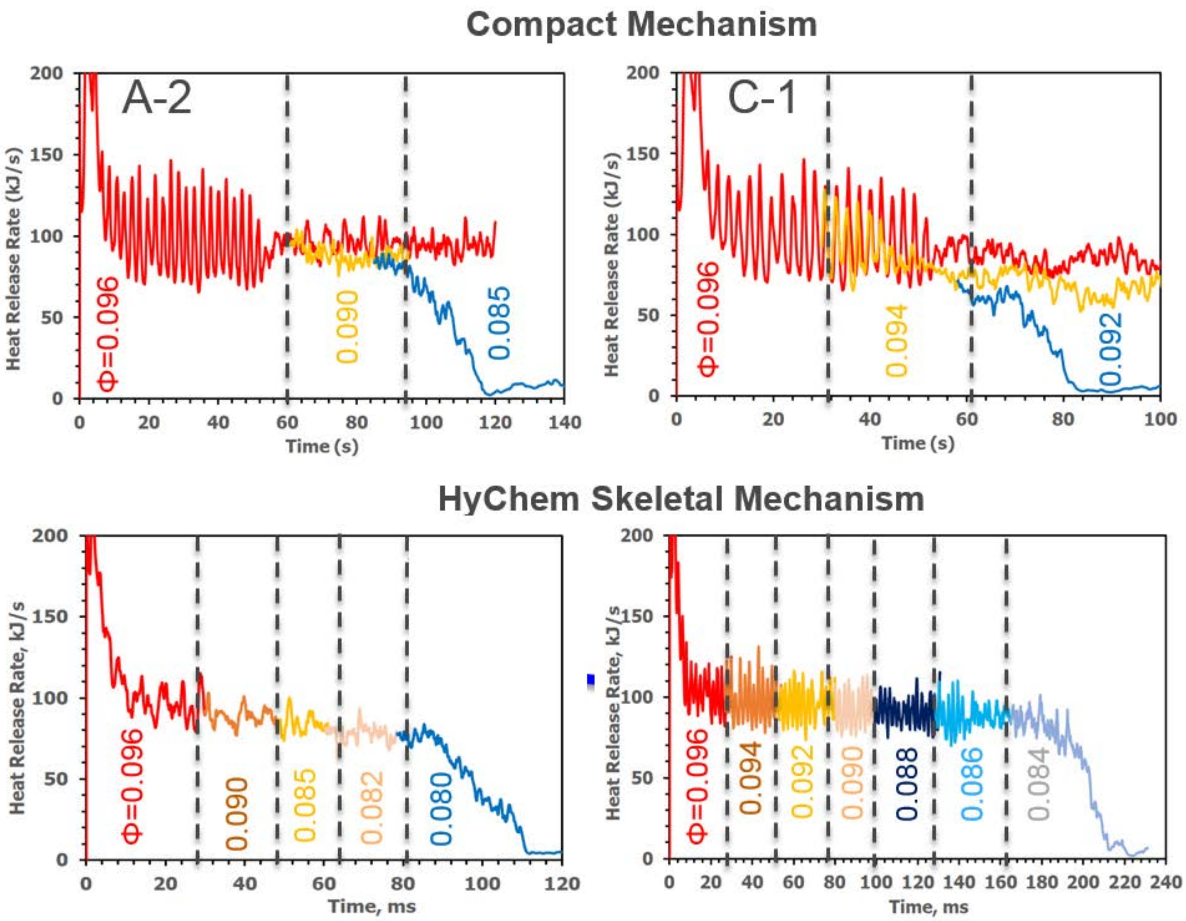

Figure 19. Heat release rate

Lean blowout equivalence ratio comparison

The LBO trends for both fuels are summarized and compared against experiments in Figure 20. C-1 blows-out at a significantly higher equivalence ratio compared to A-2 in the experiments. This LBO dependence on the fuel physical and chemical properties is very complex. The simulations are able to capture qualitatively the trend in LBO for each fuel as well as their relative behaviors with compact and HyChem skeletal mechanism.

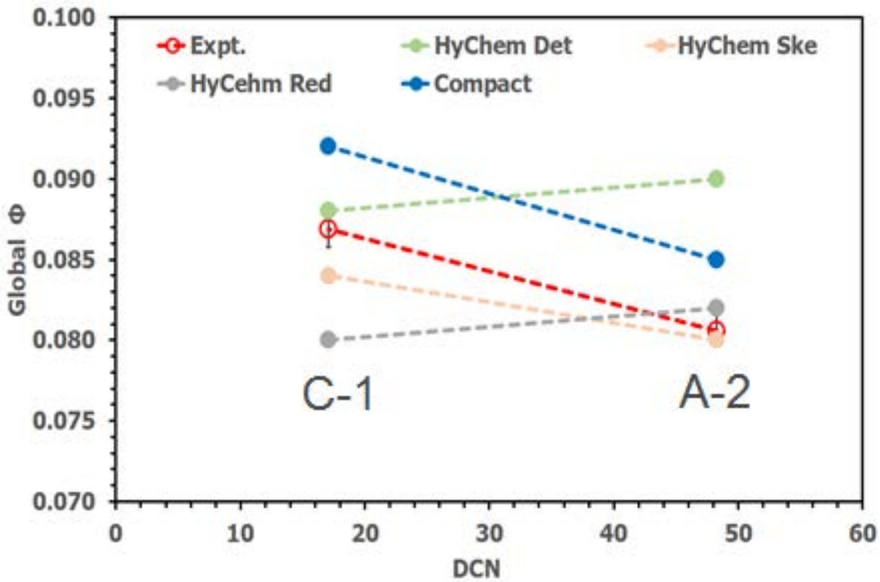

Figure 20. LBO Equivalence ratio comparison between LES and experiments

<u>Flame structure during LBO</u>

LES results from the HyChem skeletal mechanism are chosen for understanding the flame extinction process during the LBO for both A-2 and C-1 fuels. A qualitative analysis of the flame during LBO is presented in Figure 21. Instantaneous temperature contour plots at the combustor mid-plane are shown on the left for both fuels and corresponding formaldehyde mass fractions are shown on the right. The primary recirculation zone corresponds to the region of intense heat release rate. These regions correspond to the high OH formation regions described in the previous section. For A-2 fuel, after the final step-down, at an equivalence ratio of 0.080, a lifted flame is observed to stabilize inside the swirler cup region between the 0 to 5 ms window. Formaldehyde is observed to form very close to the nozzle tip and follows the spray regions. It gets oxidized to form the high-temperature regions. As time progresses, the flame stabilization point starts to move in the axial direction and a remarkable shift in the CH_2O regions is observed away from the nozzle tip. Finally, by 15 ms, the heat release in the primary recirculation region decreases considerably with a considerable shift of CH_2O formation in the downstream regions. Finally, the flame is observed to blowout by 25 ms. A similar trend is observed for the C-1 fuel, however, at a much higher global equivalence ratio of 0.084. The C-1 fuel has significantly higher CH_2O formation even at 0 ms and this will be analyzed further in the next section. From these plots, it can be summarized that overall the flame is observed to shift downstream as we approach LBO along with a downstream movement of intermediate species. The reduction of heat release rates and overall temperatures lead to a partial oxidation of these intermediate species which shows up as a corresponding downstream shift in the contour plots.

To understand the flame stabilization and key factors governing LBO limits, species formation in the mixture fraction space analyzed in the primary zone of the combustor. These are reported in Figure 22. The aim is to identify key markers or events that are universal in nature, with respect to different fuels.

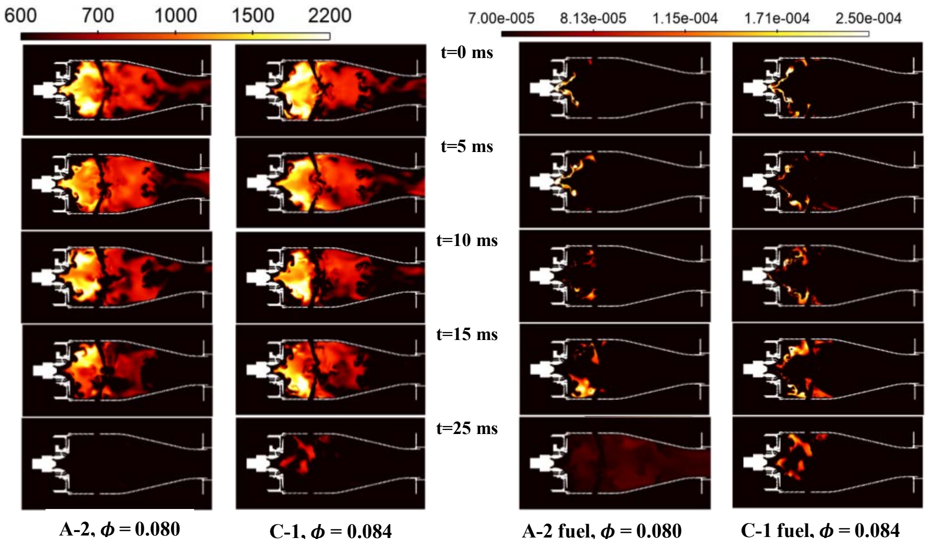

Figure 21. Instantaneous temperature [K] contour plots (left) at the combustor mid-plane and formaldehyde mass fractions (right) for A-2 and C-1 fuel during LBO.

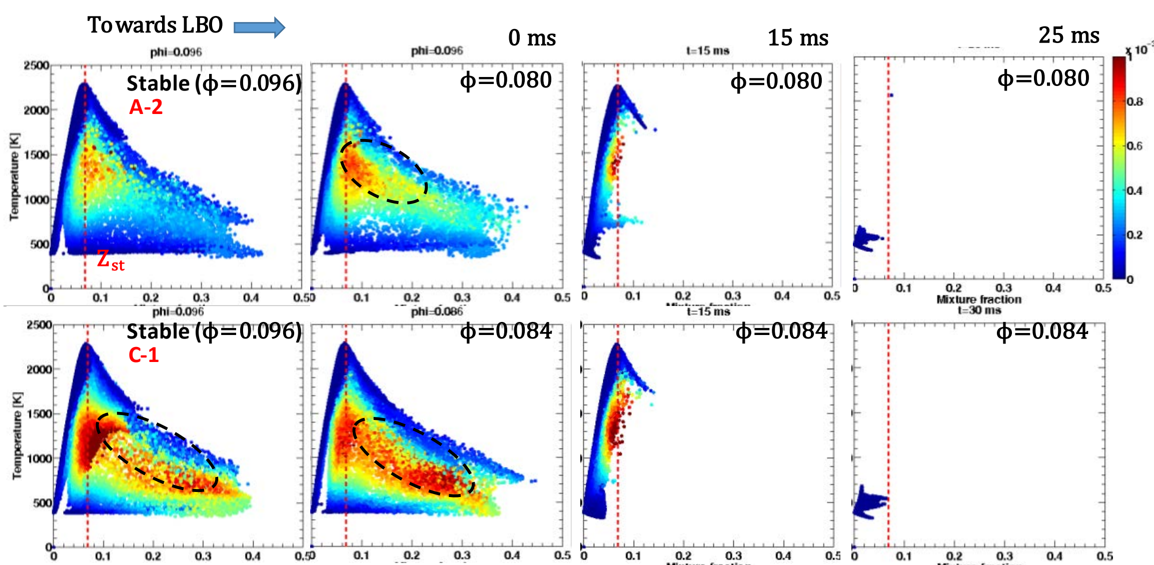

Figure 22. Temperature versus mixture fraction scatterplots for A-2 fuel (top) and C-1 fuel (bottom) sampled from the primary zone. Colored with CH2O mass fraction

The intermediate radical OH is formed in the high-temperature stoichiometric regions and does not shift with lower global equivalence ratios as shown in Figure 23. This study showed that the trend of increasing concentrations of intermediate species in rich regions is an important marker during the LBO process.

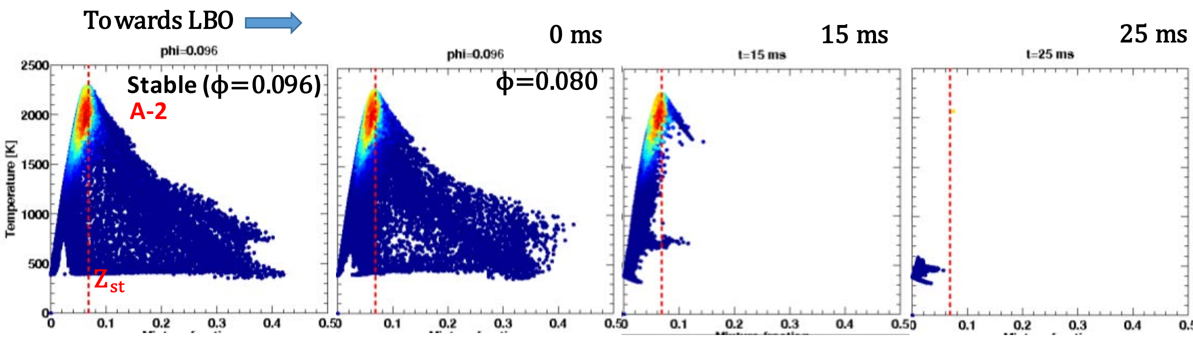

Figure 23. Temperature versus mixture fraction scatterplots for A-2 fuel sampled from the primary zone. Colored with OH mass fraction.

Temperatures from the primary zone (upstream of the primary dilution holes) are isolated from the 3-D CFD domain and further filtered based on their axial velocities. The computational cells that have axial velocities in the negative direction are selected for analysis. As this is a non-uniform grid, these points are weighted with their respective cell volumes. These set of points represent the recirculating fluid that flows from the high temperature regions towards the base of the flame. Statistical analysis is carried out by generating a probability density function of the temperature distribution of these points. The temperature distribution of the recirculation zone shows a non-uniform, multi-modal distribution with a peak in the 500 K zone and major part of the distribution spread in the range of 1500 K – 2300 K. This indicates that high temperatures are a major part of the recirculation zone and these play a significant role in stabilizing the flame. The reduced fuel flow rates corresponding to stable operation condition also exhibit a similar distribution; however, the distributions show more bias towards the low temperatures. At the blowout equivalence ratio, the distribution is observed to have shifted significantly. The second peak of the bimodal distribution corresponding to the high temperature region is now at a significantly lower temperature compared to the previous equivalence ratios. As the flame finally approaches LBO, we observe that this distribution shifts towards the low temperature region and merges into a delta PDF type of distribution. Thus, it is observed that, as the flame blows out, the recirculation zone cools down due to the decrease in overall heat release rates. This causes lower evaporation rates and further triggers a reduction in heat release leading to a cyclic process. This weakening of the recirculation zone is a key marker of flame stability. A significant shift in the PDF distribution of temperatures of the recirculating fluid can be marker for the start of LBO. This is demonstrated for both fuels A-2 and C-1 in Figure 24.

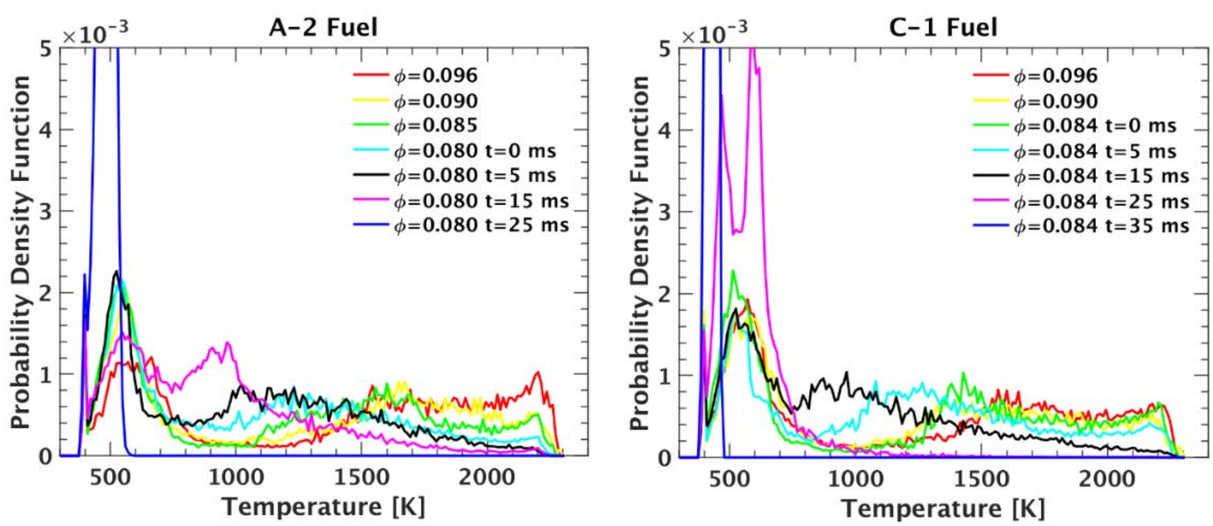

Figure 24. Probability density function of the temperatures of the recirculating gases in the primary zone for A-2 fuel (left) and C-1 fuel (right).

Mesh resolution sensitivity to LBO computations

We have carried out a study to understand the effect of mesh resolution on the computed LBO equivalence ratio for C-1 fuel with Won-Dryer compact mechanism.

Table 1. Details of the minimum mesh resolution for establishing a mesh independent solution with a base size of 3 mm

Total Cells (Millions)	10	25
Adaptive Mesh Refinement Level	3	4
Min.Cell Size, mm	0.375	0.1875

Volume integrated heat release rate is compared for different mesh resolutions in Figure 25. We noticed stable heat release rate for both mesh resolutions at the near LBO condition showing stable flame corresponding to global equivalence ratio of 0.094 and then decrease in heat release rate due to flame extinction at 0.092 for both mesh resolutions. It is noted from this study that minimum mesh resolution of 0.375 mm and 0.1875 mm considered in this study yielded the same LBO global equivalence ratio.

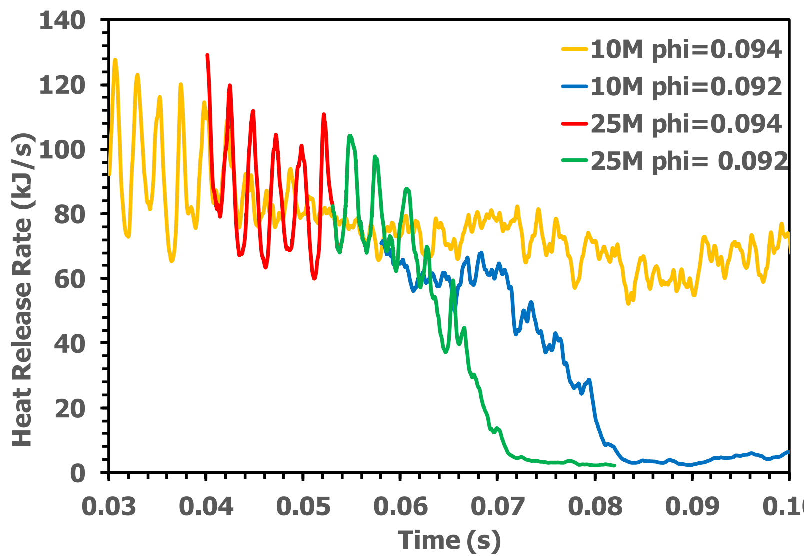

Figure 25. Heat release rate for the LBO study with two different mesh resolution (C1 fuel with compact mechanism)

Implementation of sub-grid scale combustion model in CONVERGE CFD code to account for sub-grid scale turbulence chemistry interactions for Referee rig LBO simulations. Work in progress

The LBO simulations done so far, for A-2 and C-1 fuels with different kinetic models (detailed, skeletal and reduced) and Won-Dryer compact mechanism used laminar chemistry model and ignored the sub-grid scale interactions between combustion and turbulence. We have made efforts during the reporting period to include these SGS TCI using Partially Stirred Reactor (PaSR) model. Many researchers, for treating the SGS TCI with Finite Rate Chemistry approach successfully, use this model.

Favre filtered species transport equation:

$$\frac{\partial \bar{\rho}\,\widetilde{Y_m}}{\partial t} + \frac{\partial \bar{\rho}\tilde{u}_j\widetilde{Y_m}}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\bar{\rho}(D + D_t)\frac{\partial \widetilde{Y_m}}{\partial x_j}\right) + \bar{\dot{\omega}}_m\,, \quad m = 1,2,3\,\ldots\ldots, n \qquad (3)$$

In laminar chemistry model, the filtered reaction rate $\bar{\dot{\omega}}_m$ in the above equation is computed using the Arrhenius law and resolved flow field. In PaSR model, the filtered reaction rate term computed using Arrhenius law is scaled to account for sub-grid scale turbulence chemistry interactions by computing the chemical and mixing time scales.

$$\overline{\dot{\omega}_\iota\,(\rho,\, Y_\iota,\, T)} \approx k\ \dot{\omega}_\iota\,(\bar{\rho},\, \widetilde{Y}_\iota,\, \widetilde{T})$$

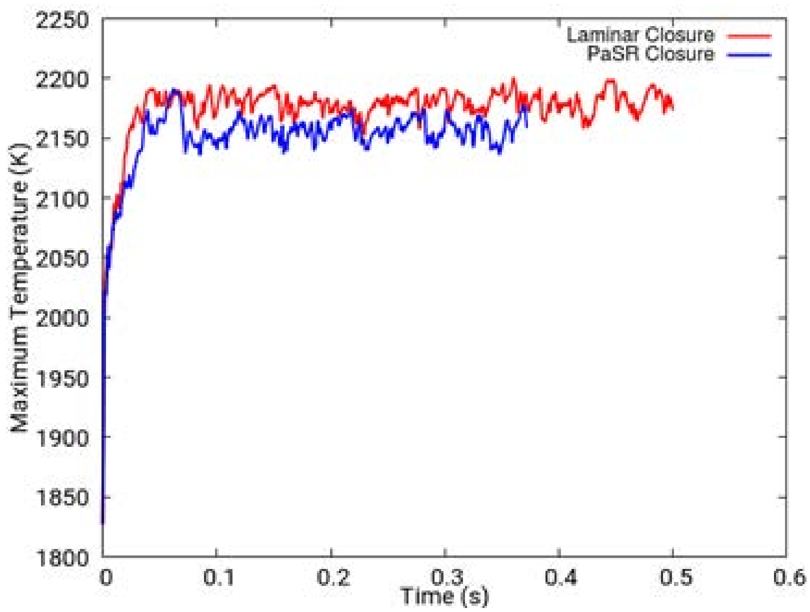

Figure 26. Global maximum Temperature comparison for Sandia Flame D LES simulations

Where k is known as reacting volume fraction and is computed as $k = \frac{\tau_c}{\tau_m + \tau_c}$, τ_c is chemical time scale and τ_m is mixing time scale. More details on this model can be found in the literature [1-7].

This model implementation is tested for Sandia flame D, computed global maximum temperature with, and without SGS TCI effect with LES turbulence model is shown in Figure 26.

Conjugate Heat Transfer model developed for Referee combustor to study the effect of heat losses across the combustor liners on flame structure and LBO. Work in progress. Conjugate heat transfer model developed for a realistic gas turbine combustor (Referee) under reacting conditions in order to understand the effect of heat loss through liners walls on the flame stabilization and lean blowout (LBO) as shown in Figure 27.

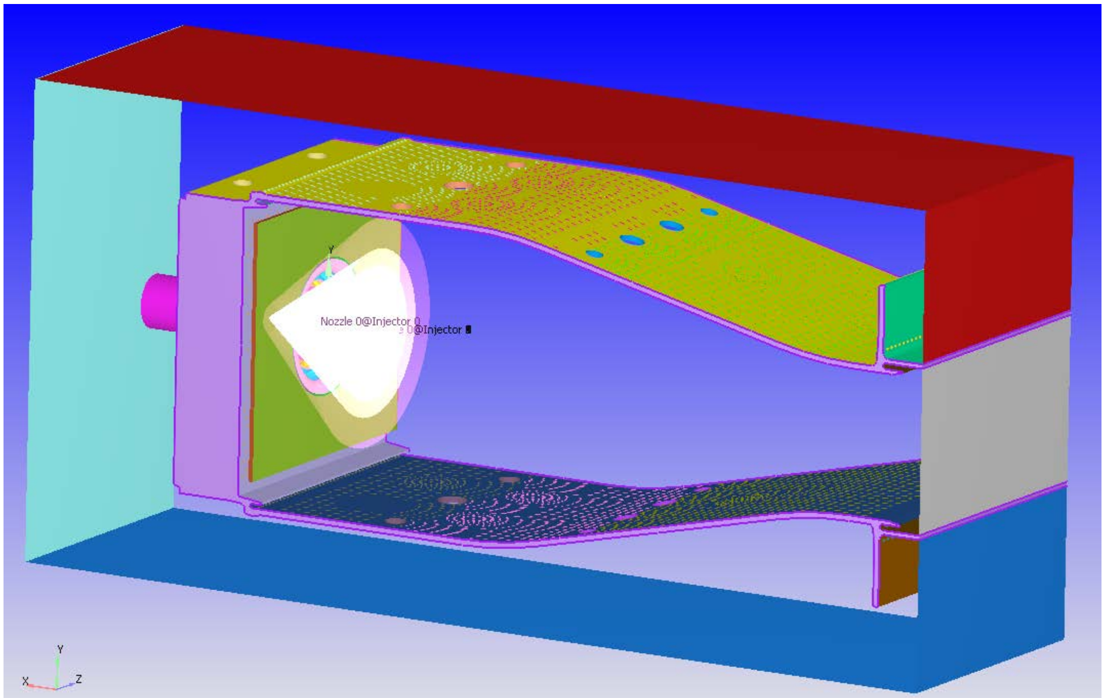

Figure 27. Fluid-solid domain of referee combustor for conjugate heat transfer analysis

Gas turbine combustors under engine relevant high-pressure conditions have high rate of heat transfer to the liner walls through convection and radiation. Combustor liner walls are heated through radiation and convection from the flame on the hot side and are cooled through convection to the cold air in the annulus and radiation to the outer casing. Thermal conduction along the liner wall also contributes to the distribution of heat flux and wall temperature. Transient three dimensional solid-fluid fully coupled numerical simulations will be performed to account for the effects of spatio-temporal variations of temperature of hot gases in the combustor on the rate of heat transfer to the combustor liner. The coupled simulations facilitate an accurate estimation of liner temperature distribution and heat losses and the subsequent effect on the flame stabilization and lean blowout process. The computational domain consists of a combustor fitted with a hybrid airblast swirler, dilution holes and a large number of liner effusion cooling holes. Automatic mesh generation with fixed embedding and adaptive mesh refinement are employed to generate an optimized mesh distribution on the fly for accurately resolving the flow field along with a reduction in computational time. The dynamic structure sub-grid scale turbulence model is utilized for LES computation. Combustion is modeled using finite rate detailed chemistry using the HyChem skeletal mechanism consisting of 41 species and 202 reactions for a conventional petroleum derived fuel (denoted as A-2). Flame radiation is not considered in the present study. The computed LBO equivalence ratio for A-2 fuel with wall temperature predicted using the conjugate heat transfer model without radiation model will be compared with that assessed using an adiabatic wall condition. The computed liner temperature distribution with conjugate transfer model will also be compared against the experimental data at near-blowout but stable flame condition. Conjugate heat transfer methodology developed for practical combustors in the present work can contribute to improvements in component life by optimizing liner-cooling schemes. Future work will involve incorporating the flame radiation in the calculations.

Assessment of Flamelet approach with adaptive mesh refinement for LBO calculations. Work in progress

Flamelet Generated Manifold approach under adaptive mesh refinement framework is currently being assessed for LBO predictions. C-1 fuel with Won-Dryer compact mechanism is chosen for this study. Currently simulations are in progress for global equivalence ratio of 0.086 with stable flame at this condition. Experimental data for C-1 fuel show LBO at 0.087.The finite rate chemistry model with Won-Dryer mechanism computed LBO at 0.092. We will continue to decrease the fuel flow rate with FGM model to assess its capability to capture flame extinction processes.

Publications

1. "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.
2. "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.
3. "Spray Measurements at Elevated Pressures and Temperatures Using Phase Doppler Anemometry," A. J. Bokhart, D. Shin, R. Gejji, T. Buschhagen, S. V. Naik, R. P. Lucht, J. P. Gore, P. E. Sojka, and S. E. Meyer, presented at the 2017 AIAA SciTech Meeting, Grapevine, TX, 8-13 January 2017, Paper Number AIAA-2017-0828,.
4. "Spray Characteristics at Lean Blowout and Cold Start Conditions using Phase Doppler Anemometry," A. J. Bokhart, D. Shin, N. Rodrigues, S. V. Naik, R. P. Lucht, J. P. Gore, P. E. Sojka, and S. E. Meyer, presented at the 2018 AIAA SciTech Meeting, Kissimmee, Florida, 8-12 January 2018.
5. "Spray Characteristics of a Hybrid Airblast Pressure-Swirl Atomizer at Cold Start Conditions using Phase Doppler Anemometry," Dongyun Shin, D. Shin, A. J. Bokhart, N. Rodrigues, S. V. Naik, R. P. Lucht, J. P. Gore, P. E. Sojka, and S. E. Meyer, presented at ICLASS 2018 14th Triennial International Conference on Liquid Atomization and Spray Systems, Chicago, Illinois, 22-26 July 2018.
6. Veeraraghava Raju Hasti, Prithwish Kundu, Gaurav Kumar, Scott A. Drennan, Sibendu Som, and Jay P. Gore. "A Computational Study of Flame Characteristics in Referee Combustor during Lean Blow-Out", Under preparation for AIAA Journal of Propulsion and Power
7. Veeraraghava Raju Hasti, Prithwish Kundu, Gaurav Kumar, Scott A. Drennan, Sibendu Som, Sang Hee Won, Frederick L. Dryer, and Jay P. Gore. " Computation of Fuel Sensitivity to Lean Blow-Out in a Gas Turbine Combustor", Under preparation for AIAA Journal
8. Veeraraghava Raju Hasti, Prithwish Kundu, Gaurav Kumar, Scott A. Drennan, Sibendu Som, and Jay P. Gore. " Numerical Simulations of Gas Turbine Combustor Flows using Adaptive Mesh Refinement", Under preparation for AIAA Journal of Propulsion and Power
9. Veeraraghava Raju Hasti, Prithwish Kundu, Gaurav Kumar, Scott A. Drennan, Sibendu Som, and Jay P. Gore. "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)
10. Veeraraghava Raju Hasti, Prithwish Kundu, Gaurav Kumar, Scott A. Drennan, Sibendu Som, Sang Hee Won, Frederick L. Dryer, and Jay P. Gore. "Lean blow-out (LBO) computations in a gas turbine combustor", 2018 Joint Propulsion Conference, AIAA Propulsion and Energy Forum, (AIAA 2018-4958)
11. Veeraraghava Raju Hasti, Prithwish Kundu, Gaurav Kumar, Scott A. Drennan, Sibendu Som, and Jay P. Gore. "Numerical Simulation of Flow Distribution in a Realistic Gas Turbine Combustor", 2018 Joint Propulsion Conference, AIAA Propulsion and Energy Forum, (AIAA 2018-4956)
12. Veeraraghava Raju Hasti, Gaurav Kumar, Shuaishuai Liu, Robert P Lucht and Jay P Gore "A Computational Study on H2 Piloted Turbulent Methane / Air Premixed Flame with CO2 Dilution",2018 Spring Technical Meeting, Central States Section of the Combustion Institute, Minneapolis, MN 55455 USA
13. Veeraraghava Raju Hasti, Shuaishuai Liu, Gaurav Kumar, and Jay P. Gore. "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)
14. Veeraraghava Raju Hasti, Gaurav Kumar, Shuaishuai Liu, Robert P. Lucht, and Jay P. Gore. "Large Eddy Simulation of Pilot Stabilized Turbulent Premixed CH4+Air Jet Flames", 2018 AIAA Aerospace Sciences Meeting, AIAA SciTech Forum, (AIAA 2018-0675)
15. Dong Han, Veeraraghava Raju Hasti, Jay P. Gore and Robert P Lucht, "An Experimental and Computational Study of Turbulent Lean Premixed Flames", Propellants and Combustion Session, AIAA Propulsion and Energy 2015 Conference, Orlando, Florida, USA
16. Vikrant Goyal, Veeraraghava Raju Hasti, Jay P. Gore, Hukam C. Mongia, "Detached eddy simulation of turbulent swirl-stabilized flame" 9th U.S. National Combustion Meeting, Central States Section of the Combustion Institute, May 17-20, 2015, Cincinnati, Ohio, USA

Outreach Efforts

1. "Effect of Aviation Fuel Type and Fuel Injection Conditions on Non-Reacting Spray Characteristics of Hybrid Air Blast Fuel Injector," Timo Buschhagen, Robert Z. Zhang, Sameer V. Naik, Carson D. Slabaugh, Scott E. Meyer, Jay P. Gore, and Robert P. Lucht, presented at the 2017 AIAA SciTech Meeting, San Diego, CA, 4-8 January 2016
2. "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.
3. "Spray Measurements at Elevated Pressures and Temperatures Using Phase Doppler Anemometry," A. J. Bokhart, D. Shin, R. Gejji, T. Buschhagen, S. V. Naik, R. P. Lucht, J. P. Gore, P. E. Sojka, and S. E. Meyer, presented at the 2017 AIAA SciTech Meeting, Grapevine, TX, 8-13 January 2017, Paper Number AIAA-2017-0828,
4. "Spray Characteristics at Lean Blowout and Cold Start Conditions using Phase Doppler Anemometry," A. J. Bokhart, D. Shin, N. Rodrigues, S. V. Naik, R. P. Lucht, J. P. Gore, P. E. Sojka, and S. E. Meyer, presented at the 2018 AIAA SciTech Meeting, Kissimmee, Florida, 8-12 January 2018.
5. "Spray Characteristics of a Hybrid Airblast Pressure-Swirl Atomizer at Cold Start Conditions using Phase Doppler Anemometry," Dongyun Shin, D. Shin, A. J. Bokhart, N. Rodrigues, S. V. Naik, R. P. Lucht, J. P. Gore, P. E. Sojka, and S. E. Meyer, presented at ICLASS 2018 14th Triennial International Conference on Liquid Atomization and Spray Systems, Chicago, Illinois, 22-26 July 2018.
6. Veeraraghava Raju Hasti, Prithwish Kundu, Sibendu Som, Robert P. Lucht and Jay P. Gore, "Lean blow-out mechanism in a swirl-stabilized turbulent spray combustion in a realistic gas turbine combustor, Presented at the 71st Annual Meeting of the APS Division of Fluid Dynamics, Sunday–Tuesday, November 18–20, 2018; Atlanta, Georgia, USA
7. Veeraraghava Raju Hasti, Prithwish Kundu, Gaurav Kumar, Scott A Drennan, Sibendu Som and Jay P. Gore, "A computational investigation of lean blow-out in a realistic gas turbine combustor", Poster Presentation, 37th International Symposium on Combustion, 29th July – 3rd August 2018, Dublin, Ireland
8. Veeraraghava Raju Hasti, Gaurav Kumar, Shuaishuai Liu, Robert P. Lucht and Jay P. Gore, "A computational study on turbulent premixed flames with CO2 dilution", Poster Presentation, 37th International Symposium on Combustion, 29th July – 3rd August 2018, Dublin, Ireland
9. Veeraraghava Raju Hasti presented the work on "Computational modeling of fuel effects on engine combustion" at the 2018 Spring Reception Meeting, Office of Interdisciplinary Graduate Programs, Purdue University, West Lafayette, IN, USA
10. Veeraraghava Raju Hasti, Prithwish Kundu, Gaurav Kumar, Scott A. Drennan, Sibendu Som, and Jay P. Gore. "A Numerical Study of Flame Characteristics during Lean Blow-Out in a Gas Turbine Combustor", Presented at the 2018 Joint Propulsion Conference, AIAA Propulsion and Energy Forum, (AIAA 2018-4955)
11. Veeraraghava Raju Hasti, Prithwish Kundu, Gaurav Kumar, Scott A. Drennan, Sibendu Som, Sang Hee Won, Frederick L. Dryer, and Jay P. Gore. "Lean blow-out (LBO) computations in a gas turbine combustor", Presented at the 2018 Joint Propulsion Conference, AIAA Propulsion and Energy Forum, (AIAA 2018-4958)
12. Veeraraghava Raju Hasti, Prithwish Kundu, Gaurav Kumar, Scott A. Drennan, Sibendu Som, and Jay P. Gore. "Numerical Simulation of Flow Distribution in a Realistic Gas Turbine Combustor", Presented at the 2018 Joint Propulsion Conference, AIAA Propulsion and Energy Forum, (AIAA 2018-4956)
13. Veeraraghava Raju Hasti, Shuaishuai Liu, Gaurav Kumar, and Jay P. Gore. "Comparison of Premixed Flamelet Generated Manifold Model and Thickened Flame Model for Bluff Body Stabilized Turbulent Premixed Flame", Presented at the 2018 AIAA Aerospace Sciences Meeting, AIAA SciTech Forum, (AIAA 2018-0150)
14. Veeraraghava Raju Hasti, Gaurav Kumar, Shuaishuai Liu, Robert P. Lucht, and Jay P. Gore. "Large Eddy Simulation of Pilot Stabilized Turbulent Premixed CH4+Air Jet Flames", Presented at the 2018 AIAA Aerospace Sciences Meeting, AIAA SciTech Forum, (AIAA 2018-0675)
15. Dong Han, Veeraraghava Raju Hasti, Jay P. Gore and Robert P Lucht, "An Experimental and Computational Study of Turbulent Lean Premixed Flames", Presented at the Propellants and Combustion Session, AIAA Propulsion and Energy 2015 Conference, Orlando, Florida, USA
16. Vikrant Goyal, Veeraraghava Raju Hasti, Jay P. Gore, Hukam C. Mongia, "Detached eddy simulation of turbulent swirl-stabilized flame" Presented at the 9th U.S. National Combustion Meeting, Central States Section of the Combustion Institute, May 17-20, 2015, Cincinnati, Ohio, USA

Awards

Ph.D. student Veeraraghava Raju Hasti received Research Aide (Jan – Aug 2018) from Argonne National Laboratory, Department of Energy and carried out part of this work at the DOE laboratory.

Student Involvement
Ph.D. student Daniel Shin is primarily responsible for performing the PDA measurements at LBO, HAR/GLO conditions and for upgrading VAPS test rig in a new test cell. PhD students Neil Rodrigues and postdoctoral research associate Rohan Gejji assist with the project when their expertise is required.
Ph.D. student Veeraraghava Raju Hasti is primarily responsible for developing and performing the LES simulations.

Plans for Next Period
The proposed deliverables and tasks for FY2019 are listed below:

Year 5 Deliverables
The Year 5 deliverables for Area #5, Project 29A are as follows:
1. Bring the variable ambient pressure sprays (VAPS) test rig up to operation.
2. Install the ejector on the test rig to verify sub atmospheric operation for the VAPS test rig.
3. Begin measurements with chilled fuel (-30F)/chilled nitrogen (-30F) measurements at sub atmospheric ambient pressure (down to 4 psia), coordinate with Nader Rizk and Area 6 on exact operating conditions to investigate.
4. Begin measurements for a new candidate fuel, IH2, at near lean blowout conditions.
5. Collaborate with Andrew Corber at NRC on SLIPI imaging measurements in the VAPS test rig.
6. Continue interactions with the three CFD groups (Ihme, Vaidya and Menon).
7. Investigate spray structure for sprays with very low levels of pressure drop across the swirler or with the swirler removed.
8. Investigate the structure with the pilot+main spray and/or the main without pilot spray.
9. Computational methodology with sub-grid scale turbulent combustion model to predict fuel sensitivity to LBO
10. Effect of NOx chemistry on LBO mechanism
11. Assessment of flamelet based models for LBO prediction with adaptive mesh refinement
12. Conjugate heat transfer CFD model to study the effect of heat losses through liners on flame structure and LBO
13. Spray boundary condition sensitivity to LBO prediction in the LES computational methodology

The tasks to be performed for FY2019 are listed below:

Quarter 1 FY2019
1. Bring the VAPS test rig back to operational status. Conduct preliminary test to verify that repeatable data can be obtained.
2. Collaborate with Area 4 and Area 6 members, and with the spray subcommittee, for development of experimental test matrix for the remainder of Year 4.
3. Make measurements at near-lean blowout conditions with a new fuel, IH2.
4. Share boundary, initial, and operating conditions and resulting experimental data with correlations and modeling team (Rizk, Ihme, Menon, and Sankaran).
5. Perform LBO LES simulations for A-2 and C-1 fuel with PaSR combustion model with compact kinetic model.
6. Write a journal paper (Fuel) on the LBO mechanism based on the LES simulations with sub-grid combustion model.

Quarter 2 FY2019
1. Collaborate with Area 4 and Area 6 members, and with the spray subcommittee, for development of experimental test matrix for Year 5.
2. Continue extensive characterization of sprays of the new fuel, IH2, with chilled fuel and chilled N_2.
3. Share boundary, initial, and operating conditions and resulting experimental data with correlations and modeling team (Rizk, Ihme, Menon, and Sankaran).
4. Study the effect of NOx chemistry in the compact kinetic model on the flame structure and LBO.
6. Write a journal paper (Combustion and Flame) on the effect of NOx chemistry on the flame structure and LBO.

Quarter 3 FY2019
1. Make the ejector operational on the VAPS test rig for subatmospheric condition test.
2. Perform measurements with chilled fuel and chilled N_2 at subatmospheric pressure.

3. Share boundary, initial, and operating conditions and resulting experimental data with correlations and modeling team (Rizk, Ihme, Menon, and Sankaran).
4. Evaluate and improve the flamelet generated manifold model having the flamelets for the upper burning branch of the S-curve and all the flamelets for the entire S-curve on the LBO predictions.
5. Write a journal paper (Fuel) on the FGM LES based methodology for LBO prediction.

Quarter 4 FY2019

1. Collaborate with Andrew Corber at NRC on SLIPI imaging measurements in the VAPS test rig.
2. Continue extensive investigation on sprays at subatmospheric conditions.
3. Share boundary, initial, and operating conditions and resulting experimental data with correlations and modeling team (Rizk, Ihme, Menon, and Sankaran).
4. Perform LES simulations with conjugate heat transfer (CHT) model and sub-grid combustion model to study the effect of wall boundary condition on the flame structure and LBO.
6. Write a journal paper (International Journal of Heat and Mass Transfer) on the CHT LES based methodology for LBO prediction in a realistic combustor.

Quarter 1 FY2020

1. Investigate spray structure for sprays with very low levels of pressure drop across the swirler or with the swirler removed.
2. Investigate the structure with the pilot+main spray and/or the main without pilot spray.
3. Share boundary, initial, and operating conditions and resulting experimental data with correlations and modeling team (Rizk, Ihme, Menon, and Sankaran).
4. Spray boundary condition sensitivity to LBO prediction in the LES methodology (Collaboration with Vaidya Sankaran, UTRC)
5. Write a journal paper (International Journal of Spray and Combustion Dynamics) on importance of having accurate spray boundary conditions for computational models
6. Identify the gaps if any in the data for detailed spray model validation and work with experimentalists for both non-reacting and reacting spray measurements.