Spray Characteristics of a Hybrid Airblast Pressure-Swirl Atomizer at Cold Start Conditions using Phase Doppler Anemometry

D.Shin*, A. J. Bokhart†, N. S. Rodrigues‡, P. E. Sojka§, J. P. Gore¶, R. P. Lucht‖
School of Aeronautics and Astronautics, Purdue University, West Lafayette, USA
shin206@purdue.edu and lucht@purdue.edu

Abstract

There has been an increased interest in alternative avaiation fuels to reduce pollutant emissions to mitigate climate change and diversify the fuel. The presented work examines the spray characteristics of two aviation fuels and one fuel candidate as part of a larger effort by the National Jet Fuel Combustion Program (NJFCP). A hybrid airblast pressure-swirl atomizer was used to investigate the spray characteristics of Jet-A (A-2), JP-5 (A-3), and a JP-5/farnesane blend (C-3) at cold start conditions: ambient gas pressure P_{vessel} = 1.01 bar, fuel temperature T_{fuel} = 239 K, and atomizing gas temperature T_{gas} = 239 K. The pressure drop across the swirler of the atomizer ($\Delta P/P$) was varied in order to investigate the effect on the spray characteristics. Phase Doppler anemometry (PDA) was used to measure the drop size and drop velocity of the spray at multiple axial locations downstream of the swirler exit plane. The spray was measured as far as 30 mm from the centerline of the spray in 5 mm increments and in both radial directions. The D_{10}, D_{32}, and MMD were used as representative diameters to characterize the mean drop size. The mean axial drop velocity with its root-mean square was used to characterize drop velocity. The investigation showed the D_{10}, D_{32}, and MMD decreased with increases in $\Delta P/P$ for all fuels. It was observed that no significant variations occured among the test fuels in D_{32}, MMD, and U_z comparisons. Spray measurements at cold start conditions were compared with the measurements from a previous investigation at lean blowout(LBO) conditions.

Introduction

Fuels derived from sources alternative to petroleum are of interest to the aviation industry. Alternative fuels diversify the energy supply, provide low-cost fuel alternatives, and mitigate climate change [1][2]. Current research efforts in this area are focused on drop-in fuels that can be integrated into existing infrastructure and gas turbine engines without requiring significant modification. These fuels must perform to the same standards as fuels currently used in industry to avoid degradation in the margins of safety, operability, performance, and durability[2]. The requirements for the commercial use of alternative fuels has resulted in an extensive certification process outlined in ASTM D4054[2]. Atomization is an important aspect of the combustion process in gas turbine engines and is one of the physical processes evaluated when considering alternative aviation fuels for commercial use due to its effects on combustion efficiency and pollutant emissions[3][5].

The temperature of the fuel is considered for alternative fuels undergoing certification, because the physical properties of the fuel such as liquid viscosity and liquid-gas surface tension vary with temperature. Liquid-gas surface tension and liquid viscosity values increase as temperature decreases. Rizkalla and Lefebvre [4] showed that increases in surface tension and viscosity of the fuel produced larger mean diameter sizes. Wang and Lefebvre [6] demonstrated that increasing fuel temperature resulted in smaller mean drop sizes. The fuel Sasol FSJF was the first alternative jet fuel approved for commercial use after it underwent extensive testing including at cold start conditions[7].

The representative diameter that was used to characterize the spray is the Sauter mean diameter(D_{32}). The D_{32} is a fifth order mean that represents the ratio of drop volume to drop surface area. It is a diameter characteristic commonly used for comparisons in mass transfer and reaction applications such as gas turbine engines[3][8].

This study was performed as part of the National Jet Fuels Combustion Program (NJFCP) which is studying alternative and standard aviation fuels with the intention of streamlining the certification process of alternative

*Corresponding author, shin206@purdue.edu
†Corresponding author, abokhart@purdue.edu
‡Corresponding author, rodri190@purdue.edu
§Corresponding author, sojka@ecn.purdue.edu
¶Corresponding author, gore@purdue.edu
‖Corresponding author, lucht@purdue.edu

fuels[2]. This investigation was performed to provide detailed mean drop size measurements of standard aviation fuels and alternative blend fuels sprays from a hybrid airblast pressure-swirl atomizer at cold start conditions. A phase Doppler anemometry system was used to provide spatially resolved measurements along the radial location(r) for drop size and drop axial velocity(U_z).

Experimental Apparatus

Atomizer

The hybrid airblast pressure-swirl atomizer used in this investigation was manufactured by Parker-Hannifin. The atomizer consisted of two components: the fuel injector and the gas swirler. The atomizer was assembled such that the fuel injector was housed within the gas swirler at a position recessed from the swirler exit along the centerline. The fuel injector had two types of injection orifices that can be operated separately: the pilot and the main. The pilot orifice was comprised of a single orifice at the centerline of the injector and was the exit of the pressure-swirl component of the hybrid design. The main was comprised of multiple orifices that injected fuel tangentially onto a prefilming surface on the interior of the gas swirler. This injector design produced hollow cone sprays. The detail description and design of this atomizer can be found in Mansour et al.[9].

Test Rig

The investigation was performed in the Purdue Variable Ambient Pressure Spray (VAPS) rig which consisted of two major components: the airbox assembly and the pressure vessel. The airbox assembly was a length of pipe on which the hybrid airblast pressure-swirl atomizer was mounted. The airbox was placed within the pressure vessel and allowed a pressurized atomizing gaseous flow through the pipe to be isolated from the vessel to create a pressure difference across the gas swirler. Nitrogen was used for all gaseous flows in this study to prevent the formation of combustible mixtures. A liquid nitrogen flow was injected into the gaseous nitrogen airbox flow to chill the atomizing gas flow to 239 K. 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 flow lines is shown in Fig 1.

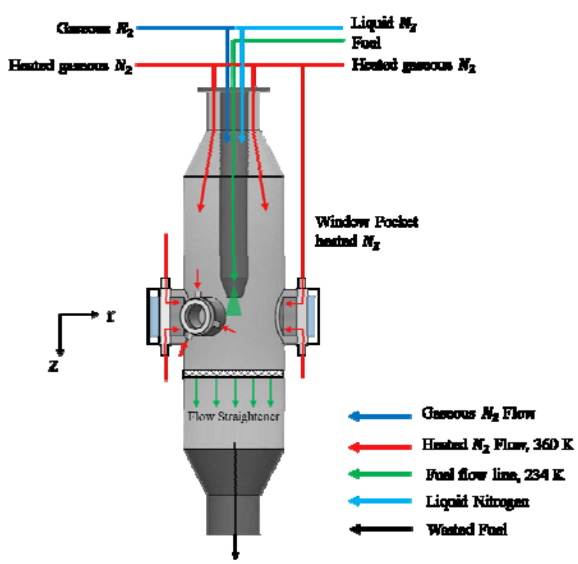


Figure 1: Diagram of the VAPS pressure vessel with four nitrogen flows used for atomization of the fuel, the prevention of fuel recirculation, the pressurization of the vessel, and chilling the atomization flows. The red lines indicate the vessel and window purge flows. The blue line indicates the atomizing flows. The light blue line indicates the liquid nitrogen flow. The green lines denote the fuel. The black line denote the exhaust flows.

The pressure within the VAPS rig was controlled using a back pressure valve downstream of the test section. In this study, however, the vessel pressure remained at approximately standard atmospheric pressure. Four windows, whose centerlines were on the same horizontal plane, allowed access to the interior of the vessel test section for laser diagnostic measurements. Two windows had a diameter of 127 mm (5 inches) and were located directly across from one another. The other two windows had a diameter of 76.2 mm (3 inches) and were located on either side of one of the 127 mm windows at angles of 60 °. Two heated nitrogen flows were introduced to the vessel to mitigate fuel recirculation: the sweeping flow and the window purge flow. The sweeping flow entered the test section from the top of the vessel to direct the fuel spray toward the vessel exit. The window purge flow introduced a nitrogen flow within the window cavities to mitigate the collection of fuel drops on the window interiors to prevent obscuration for laser diagnostic measurements.

A chiller and heat transfer fluid was used to chill the fuel to the desired fuel temperature. The fuel supply line passed through two heat exchangers and traveled along a jacketed fuel line in which the heat transfer fluid was circulated. The chiller could chill the heat transfer fluid to a temperature within the range of -80 °C to -10 °C with ±0.1 °C control stability.

Phase Doppler Anemometry

The fuel sprays were characterized using a DANTEC Dynamics phase Doppler anemometry (PDA) system which measured a variety of mean diameter statistics and a component of drop velocity. Detailed discussion of the theory behind PDA measurements can be found in Albrecht et al.[10]. The receiving probe and the transmitter probe were 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 Fig.2. The transmitter probe and the receiving probe were mounted on two separate Zaber translation stages to move the PDA system to measurement locations throughout the spray. PDA measurements were taken between ±30 mm from the center of the spray. The system was constrained to these locations because at locations greater than ±30 mm the laser exiting the transmitter probe would be partially obscured by the mounting flange for the 76.2 mm window. The PDA was moved in increments of 5 mm and 20,000 samples were recorded at each measurement location for all operating conditions investigated. The uncertainties of the D_{32} and U_z measurements were determined from 10 repeated measurements at individual radial locations in the spray. The D_{32} uncertainties throughout the radial locations varied from 1.8% to 6.5%. The uncertainties for the U_z measurements varied from 2.8% to 4.8% throughout the spray.

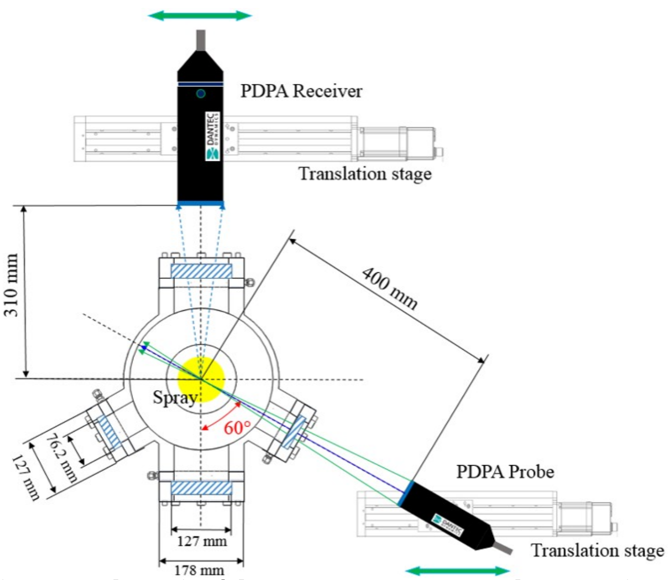


Figure 2: Schematic of the PDA system set-up on the VAPS rig

Fuels

The fuels investigated in this study were selected from a group of standard aviation fuels and alternative candidate fuels used for NJFCP research. The three fuels investigated in this study were Jet-A, JP-5, and a blend of JP-5 and farnesane. The NJFCP assigned all fuels used in the program code names to simplify identification among the programs participants. Jet-A, JP-5, and the farnesane blend were assigned the codes A-2, A-3, and C-3 respectively. All fuels in this study were selected by the NJFCP and Jet-A (A-2) was selected as a reference fuel. The physical properties of each fuel are presented in Table 1. Each property was estimated using curve fits based on data provided by the Air Force Research Laboratory (AFRL) to determine the values at the cold start condition.

Table 1: Fuel Properties

Fuel Property	A-2	A-3	C-3
μ [$kg/m.s$]	0.0055	0.0086	0.012
σ [N/m]	0.031	0.032	0.030
ρ [kg/m^3]	838	862	842

Operating Conditions

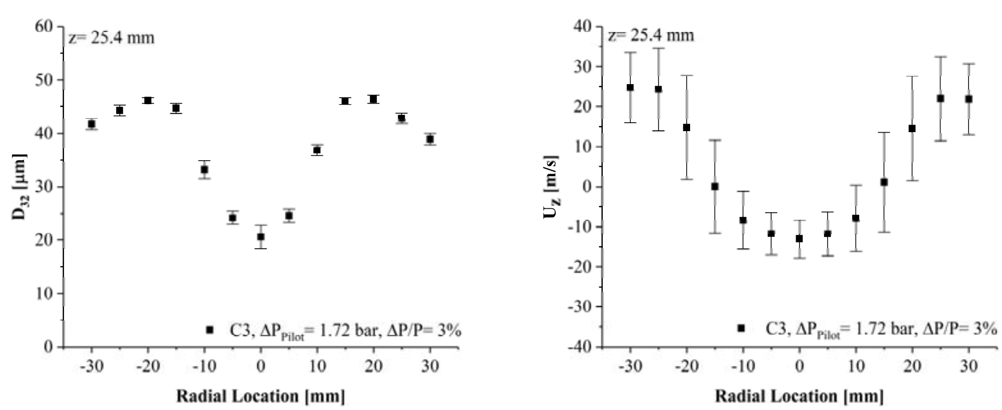
This study focused on the characteristics of the fuel sprays produced by the hybrid atomizer operating at cold start conditions. The vessel pressure was set to ambient conditions, 1.01 bar (14.5 psia) with uncertainty of 0.3%. The fuel temperature and atomizing nitrogen temperature were set to 239 K (-30 °F) with uncertainties of 0.6% and 0.8% respectively for the cold start investigation. The fuel injection pressure differential (ΔP_{pilot}) was held at 1.72 bar (25 psid) with uncertainty of 3.2% for all conditions investigated. The ΔP_{pilot} was defined as the pressure difference between the fuel line upstream of the injector assembly and the vessel pressure. The varied operational parameter was the pressure drop across the gas swirler ($\Delta P/P$). The pressure drop was quantified as the percent difference between the upstream and downstream pressures of the gas swirler. The $\Delta P/P$ was investigated at values of 2, 3, and 4 % with uncertainty of 4.0% for three axial distances downstream from the swirler exit: 12.7 mm, 25.4 mm, and 38.1 mm (0.5 inch, 1 inch, and 1.5 inch). These locations were defined as measurement planes (z) for the study. The pilot injector of the hybrid airblast pressure-swirl atomizer was the only component of the fuel injector used in this investigation.

Results and Discussion

Spatially-resolved drop diameters and velocities

The standard aviation and alternative fuel sprays investigated in this study were characterized using D_{32} and U_z as shown in Fig.3 for the C-3 fuel on the 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 [11]. The observation of continued symmetry using this atomizer at cold start conditions resulted in some of the analyses presented in this study only containing measurements along the positive radial locations to conserve time and resources.

The D_{32} distribution in Fig.3 shows a region of small diameter value at and near the center of the spray (r = 0 mm). The drop size increases as the radial locations(r) approach the edges of the spray reaching peaks at between $\pm$15 mm and $\pm$25 mm depending on the statistic being observed. The drop size distribution then demonstrate a decrease in drop size as radial location reaches the edge of the spray at $\pm$30 mm.

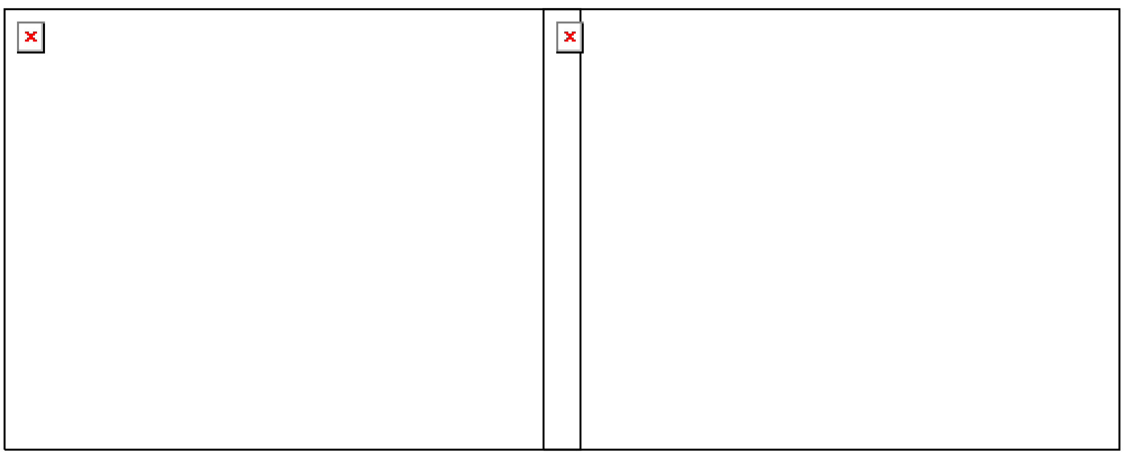


(a) Comparison for D_{32} at $\Delta P/P$ = 3% (b) Comparison for U_z at $\Delta P/P$ = 3%

Figure 3: Drop diameters and drop velocities distributions for C-3 at $\Delta P/P$ = 3 %, T_{fuel}=238 K, T_{gas}=238 K, at z = 25.4 mm

The region of smaller drop sizes in the D_{32} distribution was attributed to a recirculation zone in the hollow portion of the conical spray produced by the hybrid atomizer. The entrainment of the ambient nitrogen within the hollow cone by the mixture of high velocity fuel and nitrogen exiting the injector produced a low pressure region within the hollow cone of the spray. This low pressure region caused some gas to recirculate back into the hollow region of the spray. Smaller droplets that did not possess the momentum to maintain their trajectories recirculated with this gas into the hollow cone. The recirculation of these smaller drops resulted in the smaller D_{32} regions observed in the distribution. This observation was supported by the U_z distribution in Fig.3(b). The U_z values measured at and near the center of the spray were observed to be negative while radial locations greater than $\pm$10 mm showed positive U_z measurements. Positive U_z values indicated that the fuel and nitrogen mixture was traveling away from the injector while negative U_z values represented flow that was traveling towards the injector. The recirculation zone or hollow cone of the spray was determined to include any radial locations for which the U_z was measured to be negative while radial locations with measurements of positive U_z were determined to be part of the fuel cone of the spray. The distributions provided in Fig.3 demonstrate an increase in values to a peak that was then followed by a decrease as the radial location approached the edge of the spray at $\pm$30 mm. This observation was attributed to the entrainment of the ambient nitrogen by the fast moving fuel and nitrogen mixture at the edge of the spray, similar to the observation made within the recirculation zone.

The D_{32} and U_z distributions for C-3 were investigated on all three measurement planes used in this study: 12.7 mm, 25.4 mm, and 38.1 mm. The comparisons of D_{32} on all three planes were presented in Fig.4(a). 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 measurement range as the axial distance from the injector increased. The D_{32} distribution showed an initial peak at radial locations $\pm$10 mm on the 12.7 mm plane. This shifted to $\pm$20 mm on the 25.4 mm plane and then $\pm$30 mm on the 38.1 mm plane. These observations demonstrated that as the spray travels downstream from the injector the largest drops continue to maintain their trajectories and spread radially outward.

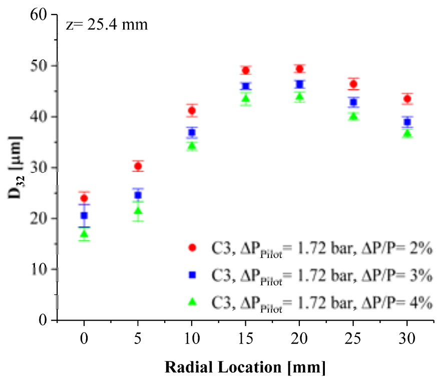


(a) Comparison for D_{32} at z = 12.7 mm, 25.4 mm, 38.1 mm (b) Comparison for U_z at z = 12.7 mm, 25.4 mm, 38.1 mm

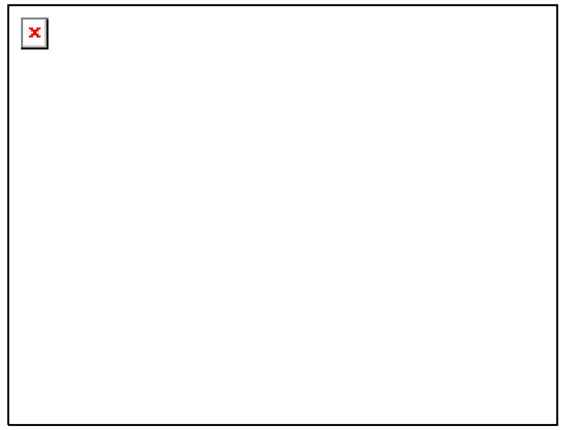
Figure 4: Comparisons of drop diameters and drop velocities for C-3 at different measurement planes at $\Delta P/P$ = 3 %, T_{fuel}=238 K, and T_{gas}=238 K

Effect of Pressure Drop across the swirler

The effect of pressure drop across the swirler ($\Delta P/P$) on the D_{32} and U_z was observed to be significant for the A-2, A-3, and C-3 fuels. Figure 5 and Fig.6 show a decrease in D_{32} with increases in $\Delta P/P$ at all radial locations. The $\Delta P/P$ represents the velocity of the atomizing gas used by the airblast component of the hybrid atomizer. Thus, higher $\Delta P/P$ resulted in increased atomizing gas velocity, which increased the relative velocity between the injected fuel drops and atomizing gas flow. This resulted in the formation of smaller drop diameters due to the greater inertial and aerodynamic forces compared to the restorative force of the fuel surface tension and damping the effect of viscosity. Decreases in D_{32} with increases in $\Delta P/P$ from 2% to 4% at individual measurement locations was observed to be similar for all three fuels with $\pm$1 μm variation. The U_z comparisons at different $\Delta P/P$ values for the C-3 fuel are shown in Fig.5(b). The magnitude of drop velocities increased as $\Delta P/P$ increased due to the larger inertia imparted by the greater gas flow. No significant variation was observed in U_z distribution at r = 15 mm. This observation was attributed to the transition of the spray from the hollow cone to the fuel cone, where the mean drop velocity is approximately zero. This location was defined as the shear layer. Similar trends were observed for A-2 and A-3 as shown in Fig.6 and Fig.7.

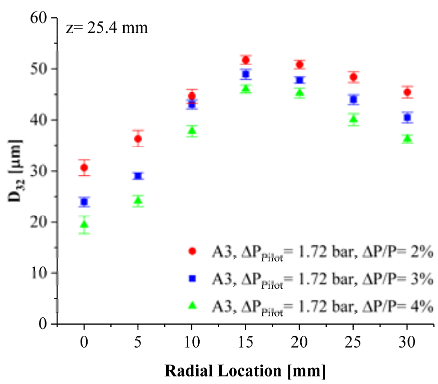


(a) Comparison for D_{32} at $\Delta P/P$ = 2, 3, 4 %

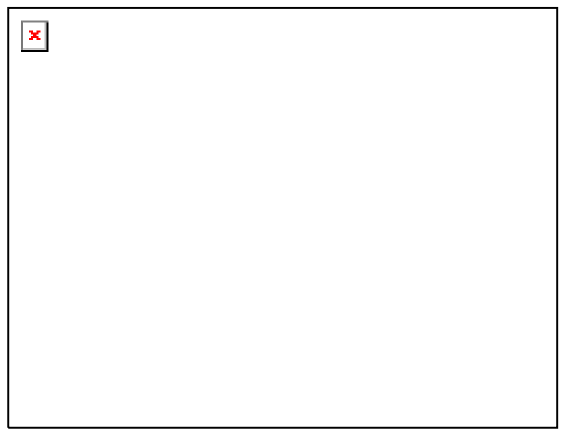


(b) Comparison for U_z at $\Delta P/P$ = 2, 3, 4 %

Figure 5: Comparisons of drop diameters and drop velocities for C-3 when $\Delta P/P$ = 2, 3, 4 %, T_{fuel}=238 K, and T_{gas}=238 K on the 25.4 mm plane

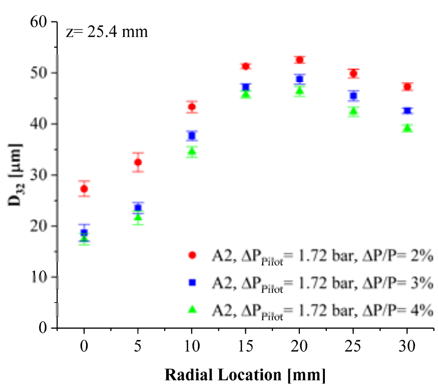


(a) Comparison for D_{32} at $\Delta P/P$ = 2, 3, 4 %

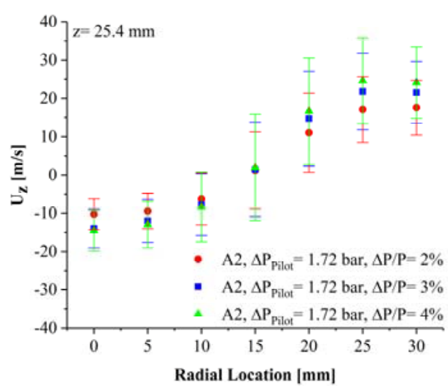


(b) Comparison for U_z at $\Delta P/P$ = 2, 3, 4 %

Figure 6: Comparisons of drop diameters and drop velocities for A-3 when $\Delta P/P$ = 2, 3, 4 %, T_{fuel}=238 K, and T_{gas}=238 K on the 25.4 mm plane



(a) Comparison for D_{32} at $\Delta P/P$ = 2, 3, 4 %



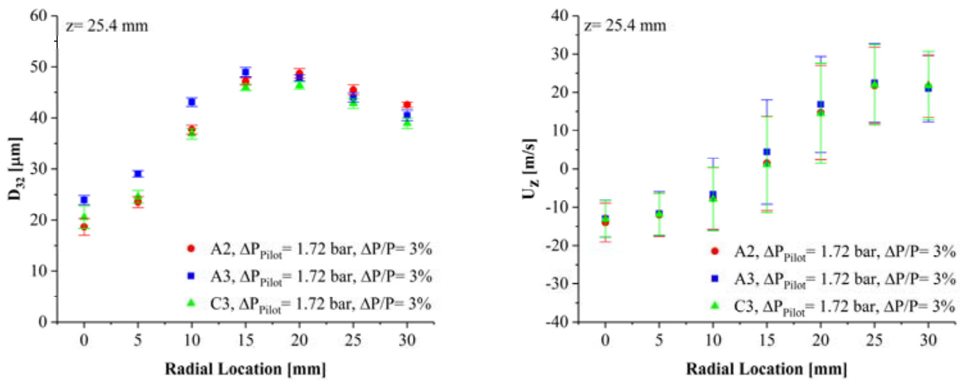
(b) Comparison for U_z at $\Delta P/P$ = 2, 3, 4 %

Figure 7: Comparisons of drop diameters and drop velocities for A-2 when $\Delta P/P$ = 2, 3, 4 %, T_{fuel}=238 K, and T_{gas}=238 K on the 25.4 mm plane

Effect of Fuel Types

The effect of fuel type on D_{32} and U_Z was investigated at the cold start condition on the 25.4 mm measurement plane. The comparisons of D_{32} and axial velocity for A-2, A-3, and C-3 are shown in Fig.8. The D_{32} comparison showed that A-3 fuel formed the highest D_{32}. The U_z measurements also showed no significant variations among the fuels.

The fuel properties at the cold start condition in Table1 did not provide any definitive conclusions regarding observations made about the effect of fuel. No significant difference in the surface tension was found for all fuels with a range from 0.030 N/m to 0.032 N/m. The C-3 fuel was found to have the highest viscosity, which should lead to the formation of larger drop sizes in the spray. The investigation, however, showed that C-3 formed the lowest D_{32} outside of the recirculation zone compared to the other two fuels. Larger D_{32} variations were observed within the recirculation zone between the A-2 and A-3 fuels with variations within ±6μm. The D_{32} variations at each radial location outside of the recirculation zone were observed to be within ±2μm. The physical properties used in this investigation have significant uncertainties due to the estimations performed to obtain the values at test condition. Accurate measurements of the physical properties of the fuels at the cold start conditions would alleviate concerns regarding uncertainty and lead to more accurate conclusions regarding the effect of fuel type on the spray.

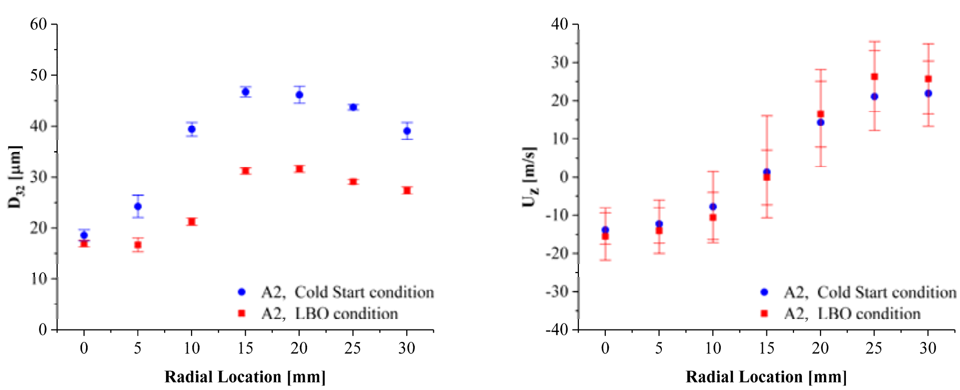


(a) Fuel Type Comparison for D_{32} at $\Delta P/P$ = 3% (b) Fuel Type Comparison for U_z at $\Delta P/P$ = 3%

Figure 8: Comparisons of fuel type at $\Delta P/P$ =3%, T_{fuel}=238 K, and T_{gas}=238 K on the 25.4 mm plane

Comparisons of drop diameters and velocities at Cold Start and Lean Blowout Conditions

The spray characteristics of the A-2 fuel at lean blowout(LBO) conditions and at cold start conditions were compared. The LBO meausrements were obtained in a previous investigation by Bokhart et al.[11]. The LBO condition was defined as T_{fuel}=322 K, T_{gas}=394 K, and P_{vessel}=2.03 bar while the cold start condition was defined as T_{fuel}=239 K, T_{gas}=239 K, and P_{vessel}=1.01 bar. The comparisons of D_{32} and U_z at those two conditions with $\Delta P/P$ = 3% and ΔP_{pilot} = 1.72 bar on 25.4 mm measurement plane are shown in Fig.9.



(a) Cold Start and LBO comparison for D_{32} at z = 25.4 mm (b) Cold Start and LBO comparison for U_z at z = 25.4 mm

Figure 9: Comparisons of drop diameters and drop velocities for A-2 at Cold Start and LBO conditions. Cold Start : $\Delta P/P$ = 3%, T_{fuel}=T_{gas}=238 K. LBO : $\Delta P/P$ = 3%, T_{fuel}=322 K, and T_{gas}=394 K

The comparison of the D_{32} measurements showed that the drop sizes at the cold start conditions were significantly larger than the drop sizes at the LBO conditions. This observation was attributed to the increased surface tension, viscosity, and density of the fuel at chilled conditions. The increase in these physical properties increased the drop reformation energy, which resulted in the formation of larger drop diameters. The LBO conditions also had an increased vessel pressure compared to the cold start conditions. Wang and Lefebvre [12] investigated the effect of ambient pressure on mean drop size from pressure-swirl atomizers. They observed an initial increase in drop size to a maximum value followed by a gradual decrease as ambient pressure was increased. Detailed investigation regarding the effect of ambient pressure on the hybrid atomizer used in this study is necessary to determine its significance to the observations made.

Summary and Conclusions

An investigation of spray characteristics of standard and alternative aviation fuels was performed at cold start conditions using a hybrid airblast pressure-swirl atomzier. The pressure differential across the gas swirler of the atomizer ($\Delta P/P$) and the axial distance downstream of the injector exit were varied. The investigation of the effect of $\Delta P/P$ with the standard aviation fuels(A-2 and A-3) found that increasing the pressure differential resulted in a decrease in mean drop sizes and an increase in axial velocity magnitudes. The alternative aviation fuel (C-3) also showed the similar trends as the standard fuels. The investigation of multiple measurement planes showed that as the spray travels downstream away from the exit of the injector, the largest drops maintained their trajectories and continued to spread radially. The three fuels investigated in this study were compared to determine any differences between the standard and alternative fuels. Larger D_{32} variation was observed among the fuels, especially between A-2 and A-3, within the recirculation zone. The variations in D_{32} outside of the recirculation zone, however, were observed to be minimal. A comparison between measurements at LBO and cold start conditions was performed. It was observed that the mean drop sizes at LBO conditions were smaller than those at the cold start conditions. In order to determine the significance of different operating parameters for each condition, further investigation is necessary.

Acknowledgements

This research was funded by the United States Federal Aviation Administration (FAA) Office of Environment and Energy as a part of the ASCENT Project 29a under FAA Award Number 13-C-AJFE-PU-005. The test matrix used for the Cold Start conditions was provided courtesy of project consultant Dr. Nadar Rizk. The authors thank Scott Meyer, Rohan Gejii, and Andrew Pratt for their assistance with facility and technical issues.

References

[1] Hileman, J. I., and Stratton, R. W., *Transport Policy* 34:52-62 (2014).
[2] Colket, M., Heyne, J., Rumizen, M., Gupta, M., Edwards, T., Roquemore, W. M., Andac, G., Boehm, R., Lovett, J., Williams, R., Condevaux, J., Turner, D., Rizk, N., Tishkoff, J., Li, C., Moder, J., Friend, D., and Sankaran, V., *AIAA Journal* 55-4:1087-1104 (2017).
[3] Lefebvre, A. H., *Atomization and Sprays*, Hemisphere Publishing Corporation, 1989.
[4] Rizkalla, A. A., and Lefebvre, A. H., *Journal of Engineering for Power* 97-2:173-177 (1975).
[5] Lefebvre, A. H., *Journal of Engineering for Gas Turbines and Power* 117:617-654 (1995).
[6] Wang, X. F., and Lefebvre, A. H., *Journal of Propulsion and Power* 4-3:222-227 (1988).
[7] Moses, C. A., and Roets, P. N. J., *Journal of Engineering for Gas Turbines and Power* 131:041502-1-041502-17 (2009).
[8] Mugele, R. A., and Evans, H. D., *Industrial and Engineering Chemistry* 43-6:1317-1324 (1951).
[9] Mansour, A., Benjamin, M., Burke, T., Odar, A., and Savel, B., *US Patent 6,547,163* (2003).
[10] Albrecht, H. E., Borys, M., Damaschke, N., and Tropea, C., *Laser Doppler and Phase Doppler Measurement Techniques* Springer-Verlag Berlin Heidelberg, 2003.
[11] Bokhart, A. J., Shin, D., Rodrigues, N. S., Sojka, P. E., Gore, J. P., and Lucht, R. P., *AIAA SciTech Forum*, Kissimmee, Florida, January 8 - January 12, 2018.
[12] Wang, X. F., and Lefebvre, A. H., *ASME 1987 International Gas Turbine Conference and Exhibition* Anaheim, California, May 31 - June 4, 1987.