Experimental investigation on spray characteristics of Jet A-1 and alternative aviation fuels

Manish Kumar¹, Srinibas Karmakar¹, Sonu Kumar² and Saptarshi Basu²,³

Abstract
Potential alternative fuels that can mitigate environmental pollution from gas turbine engines (due to steep growth in the aviation sector globally) are getting significant attention. Spray behavior plays a significant role in influencing the combustion performance of such alternative fuels. In the present study, spray characteristics of Kerosene-based fuel (Jet A-1) and alternative aviation fuels such as butyl butyrate, butanol, and their blends with Jet A-1 are investigated using an airblast atomizer under different atomizing air-to-fuel ratios. Phase Doppler Interferometry has been employed to obtain the droplet size and velocity distribution of various fuels. A high-speed shadowgraphy technique has also been adopted to make a comparison of ligament breakup characteristics and droplet formation of these alternative biofuels with that of Jet A-1. An effort is made to understand how the variation in fuel properties (mainly viscosity) influences atomization. Due to the higher viscosity of butanol, the SMD is higher, and the droplet formation seems to be delayed compared to Jet A-1. In contrast, the lower viscosity of butyl butyrate promotes faster droplet formation. The effects of the blending of these biofuels with Jet A-1 on atomization characteristics are also compared with that of Jet A-1.

Keywords
Alternative fuels, atomization, spray sheet, ligament, breakup mechanism, Sauter mean diameter

Date received: 18 November 2020; accepted: 24 March 2021

I. Introduction
Aviation industries are facing considerable challenges due to pollutant emissions and limited sources of fossil fuels. Multiple potential fuel options can be one of the best ways to overcome issues like increasing the price of fuel, supply of energy, energy certainty, climate change, and emissions.¹² Due to all these concerns, the aviation sector has prompted the search for renewable, efficient, and non-polluting alternative aviation fuels.³ During the last decades, researchers have taken a significant interest in alternative aviation fuel. The selection criteria of these fuels depend entirely on their properties, combustion, and emission characteristics under operational conditions. Gas turbine combustor, in general, is a swirl stabilized spray combustion system, and the performance of the spray combustion majorly depends on the efficient atomization of liquid fuel.⁴ The atomization characteristics of fuel are important for gas turbine applications to decide combustion stability and exhaust emission signatures. In the atomization process surface area of fuel increases, which gives a better environment for fuel-air interaction, and due to that air-fuel mixing gets improved.⁵ Usually, two phases are involved in the atomization process: 1st phase is primary atomization and 2nd phase is secondary atomization. In the 1st phase atomization process, the liquid jet breaks into

¹Department of Aerospace Engineering, Indian Institute of Technology Kharagpur, Kharagpur, India
²Interdisciplinary Centre for Energy Research, Indian Institute of Science, Bangalore, India
³Department of Mechanical Engineering, Indian Institute of Science, Bangalore, India

Corresponding author:
Srinibas Karmakar, Department of Aerospace Engineering, Indian Institute of Technology Kharagpur, Kharagpur, Kharagpur Technology PO., Paschim Medinipur, West Bengal, India.
Email: skarmakar@aero.iitkgp.ernet.in
sheets, ligaments, and larger droplets, while these ligaments/droplets are further subdivided into sub-droplets in the secondary atomization process.\(^5\) Due to the complex process of atomization and its impact on the combustion process, it is important to investigate spray characteristics for any new aviation fuel.

For spray analysis, Phase Doppler Particle Analyzer (PDPA) technique is the most commonly used diagnostic tool. Jedelsky et al.\(^6\) and Guerrassi & Champoussin\(^7\) with the help of PDPA measurements in atmospheric environments, observed that the droplet Sauter mean diameter (SMD) decreases with the increase of radial distance from the central axis. It is noted that for dense spray, PDPA is doubted to be suitable due to the multi-scattering effect. The droplet sphericity hypothesis is another significant limitation of the PDPA technique. Jet breakup in airblast atomizers has been investigated by many researchers\(^8\)--\(^11\) and image-based analysis has emerged as another method to examine the sprays.\(^12\) The major attraction of this method lies in its ability to examine the morphology of the liquid element quantitatively. The exploration of drop disintegration inflowing air has a long history. This break-up process has been investigated both theoretically and experimentally since Lefebvre.\(^3\)--\(^5\)\(^,\)\(^13\)--\(^15\) These developed theories are quite helpful in understanding the spray characteristics of new fuels. A comprehensive study of jet disintegration was performed by Krzywoblocki.\(^16\) Castleman\(^17\) stated that the aerodynamic interaction between liquid and air leads to unstable wave development on the liquid surface, which causes atomization. Three modes of liquid sheet disintegration, i.e., rim, wave, and perforated sheet, were defined by Fraser et al.\(^18\) According to them, holes appear in the sheet. These holes grow rapidly and produce irregular ligaments, a process that leads to the formation of different shapes and sizes of droplets. Using a photographic technique, Dombrowski and Fraser\(^19\) provided insight into liquid sheet breakup. They concluded that the viscosity and surface tension oppose the disruption of the liquid sheet, while density has a minor effect. Dombrowski and Johns\(^20\) stated that liquid/air interaction produces a wake, which destabilizes the spray sheet, causing its disintegration. Later, Rizk and Lefebvre\(^21\) provided a similar explanation. According to these authors, an escalation in air velocity generates liquid sheet breakup into ligaments near the nozzle. These ligaments are thin and small; they split into tiny droplets. Willert et al.\(^22\) carried out a time-resolved break-up process of liquid in an air blast atomizer and measured the mean droplet diameter using high-speed shadowgraphy techniques. Sivakumar et al.\(^23\) analyzed the atomization characteristic like atomized flow number, liquid sheet disintegration length, the cone angle of spray, and the droplet size of fuel using a simplex swirl atomizer in a spray test facility. The data were compared with the data obtained from the model on liquid film breakup.\(^24\) The atomization characteristics of fuel, such as droplet diameter, play an important role in combustion performance.\(^25\)

At present, biofuel with properties similar to Jet A-1 can be a good candidate as an alternative fuel for the aviation sector to overcome fuel-related challenges.\(^26\) Ethanol, a member of biofuels, is widely used in many countries for S.I. (spark ignition) engines as a petrol-ethanol mixture. Higher heat values, higher flash points, lower hygroscopic and lower vapor pressures are some of the properties that make n-butanol more suitable for alternative aviation fuel than ethanol.\(^27\) Butyl butyrate is another potential type of biofuel that can satisfy the chemical property requirement of alternative aviation fuel.

The objective of the present study is to investigate the spray characteristics of butyl butyrate, butanol, and their blends with Jet A-1 and compare them with that of neat Jet A-1. The fuel properties such as surface tension and viscosity play an important role in the spray characteristics of liquid fuel. The surface tension of the biofuels tested in the present study is almost similar to that of Jet A-1. Therefore, the present investigation primarily focuses on the effect of viscosity variation (among pure fuels and blends with Jet A-1) on the spray characteristics such as cone angle, spray tip penetration length, droplet diameter and velocity distribution, and breakup characteristics of spray sheet and ligaments. Phase Doppler interferometry (PDI) has been employed to extract information on droplet diameter and velocity distribution whereas a high-speed shadowgraphy system has been used to obtain the spray cone angle and spray tip penetration length. The specific purpose of using the high-speed shadowgraphy technique in this work is to understand how the variation in viscosity of various fuels influences the sheet and ligament breakup and droplet formation.

2. Experimental approach

Two experimental approaches have been adopted to investigate the spray characteristics: (1) PDI measurements and (2) high-speed shadowgraphy. These two methods have been used to provide complementary information for the present study. A spray test rig is designed and developed and this test rig has been used for both PDI measurement and high-speed shadowgraphy. An airblast atomizer (Delavan SN type 30610-1) has been used to investigate the atomization characteristics. The schematic of the PDI setup is shown in Figure 1(a), the locations of PDI measurement are presented in Figure 1(b) and the internal structure of the spray nozzle is shown in Figure 1(c). A high-speed shadowgraphy system is also used to characterize the spray, which is shown in Figure 2. Both these spray setups have some common components, such as 1) fuel line, 2) atomizing airline,
Figure 1. (a) Schematic diagram of PDI system. (b) Locations representation of PDI measurement. (c) Internal details of airblast atomizer (dimensions are in mm).

Figure 2. Schematic diagram of the high-speed shadowgraphy image acquisition system for spray.
(3) atomizer and its adapter, (4) fuel and air flowmeter/controller, and (5) supporting table and stand. Atomizing air and fuel are supplied through two different concentric tubes. A rotameter is used to precisely meter the fuel supplied from the fuel tank to the atomizer. To make uniform delivery of fuel during the experiments, liquid fuel is pressurized inside the fuel tank using N₂ gas. Using ALICAT Scientific mass flow controller (MCR-m50 SLPM-TFT), the atomizing air flow rate is monitored and regulated.

### 2.1 Operating conditions

The nomenclature and composition of different fuel blends tested in this study are provided in Table 1.

**Table 1. Composition and nomenclature of the fuel.**

| Composition of fuel (volume basis) | Designated nomenclature |
|-----------------------------------|--------------------------|
| 100% pure Jet A-1                 | Jet A-1                  |
| 10% pure butanol, 90% pure Jet A-1| B1J9                     |
| 10% pure butyl butyrate, 90% pure Jet A-1 | BB1J9               |
| 50% pure butanol, 50% pure Jet A-1 | BSJ5                    |
| 50% pure butyl butyrate, 50% pure Jet A-1 | BB5J5               |
| 100% pure butanol                  | Butanol                  |
| 100% pure butyl butyrate           | BB                       |

The atomizing air and fuels are supplied at room temperature of 293 K at three constant atomizing air to fuel ratios (AFR), i.e., 1.1, 1.5, and 2. The operating parameters of the present investigation are tabulated in Table 2. All the runs have been conducted at similar ambient conditions. The fuel orifice diameter (0.5 mm) and the coaxial air orifice diameter (1.73 mm) of the nozzle as shown in Figure 1(c) are considered as characteristic lengths for the calculation of the Reynolds number for fuel and air flows respectively. The dynamic viscosity values of fuel and air at 20°C were used. The effective areas of the fuel and air orifices are used to estimate the average velocities of fuel and air at the exit of the nozzle. The flow parameters at the nozzle exit are tabulated in Table 3.

**Table 2. Operating conditions used for this study.**

| Fuel                | Jet A-1 | B1J9 | BB1J9 | BSJ5 | BB5J5 | Butanol | BB |
|---------------------|---------|------|-------|------|-------|---------|-----|
| Fuel flow rate (ml/min) (constant for all three operating conditions) | 13 | 13 | 12.9 | 13 | 12.6 | 13.1 | 12.3 |
| Operating condition 1 | 11 | | | | | | |
| Operating condition 2 | 14 | | | | | | |
| Operating condition 3 | 18 | | | | | | |

**Table 3. Flow parameters at the nozzle exit.**

| Gas-phase (air) | Atomising air-to-fuel ratio (AFR) | 1.1 | 1.5 | 2.0 |
|-----------------|-----------------------------------|-----|-----|-----|
| 1. $V_{\text{jet}}$ (m/s) | 70.82 | 90.14 | 115.90 |
| 2. $m_\text{g}$ (g/s) | 0.20 | 0.25 | 0.33 |
| 3. $Re_a$ | 8305 | 10,570 | 13,590 |

| Liquid phase (fuel) | Fuels/Parameters | Jet A-1 | B1J9 | BB1J9 | BSJ5 | BB5J5 | Butanol | BB |
|---------------------|-----------------|---------|------|-------|------|-------|---------|-----|
| 1. $V_{\text{f_jet}}$ (m/s) | 1.10 | 1.10 | 1.09 | 1.10 | 1.07 | 1.11 | 1.04 |
| 2. $m_\text{f}$ (g/s) | 0.17 | 0.17 | 0.17 | 0.17 | 0.17 | 0.17 | 0.17 |
| 3. $Re_f$ | 234.89 | 227.5 | 248.06 | 201.8 | 322.24 | 178.09 | 519.2 |
| 4. $We_{\text{f_jet}}$ | 63.88 | 64.08 | 61.39 | 65.33 | 61.16 | 65.30 | 61.42 |
80% across all the measurements. The PDI measurements are carried out at locations 05 to 65 mm below the nozzle tip with a gap of 15 mm between two rows in the axial direction and a gap of 5 mm along the radial direction between two locations in each row (as shown in Figure 1). Considering the symmetrical nature of the spray around the central axis, the PDI measurements are conducted in one-half of the spray only. The axial and radial distributions of SMD are obtained for three different air to fuel ratios, as mentioned above. The maximum uncertainty in the SMD measurement is determined based on the repeated sets of data and was found as approximately ±5% whereas at least ±2% uncertainty is present in the fuel flowrate.

Information on spray sheet breakup, ligament length, and droplet formation is obtained from the high-speed shadowgraphy technique. Most repetitive and in-focus structures are considered for the analysis. 500 images have been analyzed taking a time step between two images as approximately 170 μs. The high-speed shadowgraphy setup consists of a high-speed camera (Model Phantom V7.3), high-intensity LED light, and a computer. Camera settings for close-up imaging are the following: (i) spatial resolution: 256*256 pixels, (ii) exposure time: 27 μs, and (iii) frame rate: 35,087 fps. On the other hand, the following parameters are used for full-field imaging: (i) spatial resolution: 800*600 pixels, (ii) exposure time: 27 μs, and (iii) frame rate: 6568 fps. The set of recorded raw images was processed and analyzed using image processing software (Image-Pro). The uncertainty of sheet, ligament, and droplet measurement is in the range of about 2–3% which is determined from the repeated runs.

3. Results and discussion

3.1 Characterization of tested fuel properties

Density, surface tension, and viscosity of pure fuels and their blends are measured at room temperature using a Redwood viscometer, Ohaus instruments (Adventurer Analytical), and ring Tensiometer (type K6) respectively. The measured values of fuel properties are tabulated in Table 4. The surface tension of the tested fuel does not have any appreciable variation. In the investigation, it has been found that the density of Jet A-1 and butanol are almost identical, while is slightly lower than that of butyl butyrate. The viscosity of butanol is comparatively higher than Jet A-1 whereas the viscosity of butyl butyrate is much lower than that of Jet A-1. The measured fuel properties of the tested fuels are in good agreement with the literature. These properties for the case of blends are almost according to their volumetric loading of pure fuels. Surface tension is almost identical for the tested fuel blends, but there is a significant difference in viscosity. These properties were measured once again after one month, and no appreciable variation was observed compared to the earlier data.

3.2 Comparison of spray structures

Fully developed solid cone sprays are observed for all fuel samples at three air to fuel ratio conditions (i.e., 1.1, 1.5, and 2.0). The maximum distance of spray or the distance covered by the fuel droplets in quiescent air is the penetration length of the spray.28,29 The angle between the tangents on the spray envelope is defined as the spray cone angle, which is often used in spray analysis. Many researchers have observed that the fuel properties like surface tension, viscosity, density, etc. have effects on the spray penetration length and spray cone angle.28,30 The objective of this section of the analysis is to examine the spray penetration length and spray cone angle of the tested fuels. The tip penetration length has been calculated manually (i.e. by placing tissue paper at different locations downstream of the spray). Later, using the image-based method, the intensity of the location at which the tip penetration of the spray (manually) obtained has been taken as the reference intensity, and with the help of Image-J software, the spray tip penetration length is measured from the upstream of the spray to the downstream. This process is adopted for all fuels. From Figure 3(b), it is observed that the length of spray penetration is minimum for butyl butyrate and maximum for butanol. In contrast, the spray cone angle is the lowest for butanol and the highest for butyl butyrate as presented in Figure 3(a). Many researchers have found in their investigation that the viscosity and density of the fuel affect the penetration length of spray5 because the viscous nature of fuel assists longer spray penetration length.31 Similarly, the viscosity of fuel resists the expansion of spray.32 In the case of blended fuel, the variation has been seen in the spray cone angle and penetration length corresponding to the loading of pure fuel. It is also observed that the rise in the

**Table 4.** Experimental physical properties of fuel blends.

| Properties/Fuel | Density\(^{a}\) (kg/m\(^3\)) | Viscosity\(^{a}\) (mPa·s) | Surface tension\(^{a}\) (mN/m) |
|----------------|-------------------------------|--------------------------|-----------------------------|
| Jet A-1        | 817                           | 1.92                     | 26.5                        |
| Butanol        | 810                           | 2.53                     | 26.1                        |
| Butyl butyrate | 861                           | 0.866                    | 26                           |
| BJ9            | 816.5                         | 1.981                    | 26.4                        |
| BB1J9          | 821.5                         | 1.814                    | 27.3                        |
| BS5J5          | 813.5                         | 2.225                    | 25.8                        |
| BBS5J5         | 839                           | 1.393                    | 26.7                        |

\(^{a}\)Laboratory analysis.
atomizing air flow rate increases the length of spray penetration and reduces the spray cone angle slightly. Many researchers\textsuperscript{33,34} have found a similar trend in their studies.

The PDI measurements provide detailed information about the droplet size, velocity, droplet angle of trajectory, local number density, and volume flux. High-speed imaging is required for obtaining information on the liquid breakup of the spray sheet and ligament formation, droplet formation, and qualitative visualization of the spray formation. The average velocity of air near the tip of the nozzle, for AFR 1.1, 1.5, 2.0 are 70, 90, 115 m/s respectively. The Reynolds number for air flow is directly influenced by the change in AFR. As AFR increases, $Re_a$ increases, and its effect on the atomization characteristics can be observed (from coarser to a fine spray as evident from Figure 4). However, the presence of fine droplets in the case of butyl butyrate is more dominant compared to other counterparts, whereas more number of coarse droplets can be observed for the butanol case. It shows that butanol has poor atomization quality due to the higher viscosity and has coarser droplets. Butanol/\textit{Jet A-1} blends (particularly higher butanol content case- B5J5) show a similar trend according to loading of butanol, whereas for the case of butyl butyrate blends, the spray mist increases with the loading of butyl butyrate. One trend is common to all the fuel samples is the presence of fine droplets in the central area and bigger blobs of fuel near the spray periphery. It is to be noticed that the distribution of the fuel in the entire spray becomes more uniform as the air to fuel ratio increases from 1.1 to 1.5 and 2. The droplet size of butanol reduces for higher atomizing air to fuel ratios (such as for AFR = 2), which is evident in Figure 4. The fineness of the spray increases with an increase in the Reynolds number of the atomizing air flow.

### 3.3 Droplet size (Sauter mean diameter $D_{32}$) distribution

PDI technique has been employed to characterize the droplets present in the spray for all the test samples. The radial distribution of the droplet size ($D_{32}$) at different downstream locations of $z = 5, 20, 35, 50, \text{ and } 65$ mm are presented in Figure 5 for three atomizing air to fuel ratios. The droplet Sauter mean diameter, ($D_{32}$), rises monotonically from the injector centreline toward the edge of the spray for all the test conditions, whereas it decreases axially. The primary atomization phenomenon occurs mainly in air-fuel interaction where droplets are generated by shear action. The Delavan SN type (30610-1) atomizer creates swirling flow and due to that compared to smaller droplets, larger droplets are centrifuged outward. An increase in the atomizing air to fuel ratio decreases the overall droplet SMD significantly, and it is common for all the tested fuels. The decrease in droplet size ($D_{32}$) may be due to a rise in relative velocity, which increases the instability on the surface of the liquid. Bayvel and Orzechowski\textsuperscript{35} suggest that the relative velocity is amenable for the break-up of liquid into droplets through self-excitation pulsations. From Figure 5, it can be seen that butanol has the highest SMD among tested fuels, whereas it is the lowest for butyl butyrate. The SMD distribution of Jet...
Jet A-1 is almost identical to that of butanol and the blends have followed the trend according to loading. This trend is similar for all the atomizing air to fuel ratios. It is because there is a minor variation in the physical properties (such as surface tension and viscosity) of Jet A-1, butanol, and their blends.

In contrast, the viscosity of butyl butyrate is approximately $\frac{2}{3}$ of that of butanol. It can be concluded that the reason for the variation in Sauter mean diameter may be due to the fuel viscosity because the viscous nature of the fluid opposes the atomization process.\footnote{Rizk and Lefebvre\cite{Rizk1984} were obtained using line of sight measurements with the ensemble light scattering method. They used a plain-jet atomizer and tested with a liquid such as gas oil, kerosene, and blended fuel to establish the SMD correlation expressed as}

$$\frac{D_{32}}{d_0} = 0.48 \left( \frac{\sigma_I}{\rho_A U_R d_0} \right) \left( 1 + \frac{1}{AFR} \right)^{0.4} + 0.15 \left( \frac{\mu_f^2}{\rho_L d_0} \right)^{0.5} + \left( 1 + \frac{1}{AFR} \right)$$ (1)

The SMD values calculated using empirical relations are presented in Figure 6, and they are compared with the corresponding experimental values. This shows an acceptable agreement with a 10% deviation between the experimental and theoretical data. The correlation over-predicts the measurement for AFR = 1.1 and under-predicts for the AFR = 1.5 and 2.0. A similar prediction was reported previously by Chong et al.\footnote{Chong et al.\cite{Chong2003}}

3.4 Droplet local mean velocity distribution

The local mean velocity of the droplet is measured in the same way as SMD has been measured, shown in Figure 7. The local velocity distribution of the droplets for all the test samples is plotted in Figure 7. The abscissa denotes radial positions, where $r = 0$ is
The mean velocity of the droplets is higher at the central zone of the jet and decreases with the radial distance away from the centreline due to momentum transfer with the surrounding air. On the other hand, as the axial distance from the atomizer outlet escalates, momentum interchange with the surrounding air decreases the velocity of droplets. The increase in droplet mean velocities is observed with an increase in the air to fuel ratio. It is mainly due to the more energy delivered by the momentum of airflow and smaller droplet size. From Figure 7, it can be seen that the fuel properties have an almost

Figure 6. Average SMD using PDI technique and their comparison with established analytical formula.

Figure 7. Droplet axial velocity distribution of pure fuel at three atomizing air to fuel ratios (a) 1.1, (b) 1.5, and (c) 2.0.
negligible effect on the droplet velocity profile. The velocity profile is almost similar for all the tested fuel samples. The atomizing air also influences the tangential and radial velocity components, which were not considered in the present investigation.

The liquid-air (two-phase flow) interaction can be explained by Stokes number

\[
Stokes\, number\, (Stk) = \frac{\rho_l d_p^2 \Delta \bar{v}}{18 \mu_g L}
\]

where \(\rho_l\) is the droplet density, \(\Delta \bar{v}\) is the difference in mean air jet velocity and the mean velocity of the droplets, \(\mu_g\) is the air dynamic viscosity. The characteristic length \((L)\) is the distance from the breakup position to the inspected point. The Cunningham correction factor \(C_c\) is 1 for the present case. The Stokes number calculated at 1.1 AFR for Jet A-1, butanol, and butyl butyrate and it increases with droplet size. Generally, droplets with \(Stk \ll 1\) follow the airflow truly. Therefore, the droplet size \(<5\) \(\mu m\) was used to deliver an estimate of the local airflow velocity. Liquid droplets in the size of 15–25 \(\mu m\) with \(Stk \sim 2\) are somewhat influenced by airflow, whereas the larger droplets (60–90 \(\mu m\)) with \(Stk \gg 34\) moves almost ballistically.

Figure 8 displays the droplet velocity variation with the SMD for three different atomizing air to fuel ratios at axial locations of 20 and 50 mm along the centreline of the spray. At AFR = 1.1, relatively lower axial velocity is associated with larger droplets. This is evident at both the axial locations presented. On the other hand, at larger atomizing air to fuel ratios (for instance AFR = 2), a higher fraction of small droplets are formed and the associated mean axial velocity of the droplets appears to be comparatively higher.

### 3.5 Breakup characteristics of spray sheet

Investigation of spray break-up using the high-speed shadowgraphy technique is an important method to see the effect of fuel properties with different operating conditions during the atomization process. Under the optical limit, this technique can be used to gain an understanding of spray sheet formation and break-up, ligament dynamics, droplet formation, and the morphology of droplets during atomization. This helps to make different types of correlations with atomization parameters and with the help of these correlations, the reliability and safety of aircraft engines can be enhanced. The primary atomization is strongly dependent on the liquid jet Weber number

\[
We_{\text{jet}} = \frac{\rho_l v_{\text{jet}}^2 d_0}{\sigma_l}
\]

where \(d_0\) is the nozzle orifice diameter and \(v_{\text{jet}}\) is the jet velocity (i.e., fuel velocity), \(\sigma_l\) is the surface tension of fuel. The jet Weber has been calculated for all the test samples and it is less than 100. If the jet Weber number is low, the surface tension forces hinder the development of a new surface area, which prevents the liquid sheet breakup. Conversely, at a high Weber number, the breakup occurs due to the inertial forces. In that, the inertial force completely dominates over the surface tension force, which tears the liquid sheet into ligaments and droplets. According to the fuel properties (such as viscosity, surface tension, and density), liquid spray sheet formation takes place near the tip of the nozzle and subsequently breaks into many pieces due to instability. Centrifugal and inertia forces are involved in the deformation and disintegration of the spray sheet in small fragments, while the other two forces such as viscous and surface tension act in contrast. The formation process of spray sheets, ligaments, and drops, is shown in Figures 9-11. The entire breakup mechanism (such as the fragmentation of the spray sheet into ligaments and droplets, the formation of droplets from the ligaments) is nearly identical for all tested specimens.

Study of liquid sheet appearance and their breakup supports understanding the ligament characteristics, and the development of drops. Images of spray sheets for all the fuels have been presented in Figure 12. The visualization of the spray sheet was only possible for
low AFR i.e. 1.1. This is mainly due to the low atomizing air velocity. The variation in the length of the spray sheet is not very major, except for butyl butyrate and butanol, as shown in Figure 13. Surface tension is almost the same for all fuels. Hence these differences are possible because of variation in viscosity. Generally, surface tension and viscosity decrease the tendency of the jet/sheet to disintegrate, which is accounted for by the Ohnesorge number (i.e., the ratio of viscous to surface tension forces).

\[ Oh = \mu_l / \sqrt{\sigma \rho_l d^*} \]

where \( \rho_l \), \( \mu_l \), \( \sigma \), and \( d^* \) are the liquid density, viscosity, surface tension, and characteristics length (nozzle orifice diameter), respectively. Ohnesorge number affects the spray sheet breakup process.\(^{40}\) Since the Ohnesorge number is large for butanol, their coarse droplets go for secondary atomization whereas for the case of butyl butyrate mostly the atomization occurs near the tip of the nozzle and can be seen in Figures 10 and 11.

At high AFRs (air to fuel ratios) i.e. 1.5 and 2, the spray sheet was not visible. This could probably be due to very short spray sheets formed for high atomizing air velocity, which was not captured by the camera. From Figure 13, it can be observed that as the viscosity increases, the length of the spray sheet increases. In the process of atomization, ligaments are formed from the spray sheet and subsequently break to generate droplets.\(^{10}\) Along with this break-up regime, it can also be noticed that the spray sheet itself pinches off from the nozzle tip and undergoes secondary atomization, as shown in Figure 11. In this regime of atomization, the complete disintegration time of the spray sheet has been presented in Figure 11 for the butyl butyrate, Jet A-1, and butanol at 1.1 AFR. As can be seen in Figure 11, the broken spray sheet of butyl butyrate is fragmented into various droplets near the nozzle tip, but for the case of butanol, this phenomenon occurs.
Figure 10. Spray sheet fragmentation of pure fuel with increasing Ohnesorge number near the nozzle tip.

Figure 11. Secondary atomization process near the tip of the nozzle with increasing Ohnesorge number near the nozzle tip.
slightly away from the nozzle tip. This may be mainly due to variation in Ohnesorge number, as discussed earlier. One more thing to notice is that the size of the butanol detached spray sheet is much larger than the butyl butyrate detached spray sheet. It is all mainly due to the difference in the viscosity of tested fuels. Overall, the viscosity of butanol is the highest among the tested fuels, which resists the spray sheet from break-up and hence delays the ligament formation.

3.6 Ligament and droplet characteristics

Figure 9 shows the sheet breakup and formation of ligaments. It can be seen that due to the interaction of fuel/air, waves are generated on the surface of the spray sheet and this wave causes instability on the spray sheet surface which disintegrates this fuel spray sheet into many fragments. The liquid filaments attached to the liquid bulk are considered as a ligament. The most common factor in the process of ligament formation is the effect of relative motion between the liquid sheet and air. The distance between the free ends of the liquid filament to the fixed end is considered as the length of the ligament ($L_l$). The average diameter across the length is considered as a ligament diameter ($\xi$). Typically, two types of ligament development are observed. The primary (first generation) ligaments that form near the nozzle tip are almost
identical. Figures 10 and 11. In secondary (second generation) ligaments, the liquid bulk separates from the nozzle tip and the ligament is formed away from the nozzle tip due to the high flow rate which can be seen in Figures 10 and 11. In the present investigation, it has been found that the spray sheet immediately disintegrates into several small tiny fragments (sizes are in micron) at a high air-to-fuel ratio (mainly AFR = 2.0). Mostly, the spray ligaments are formed near the tip of the nozzle. Figure 14 shows the ligament fragmentation into droplets, and this break-up mechanism is common for almost all the test samples. From Figure 15 it can be grasped that in the case of butyl butyrate the average ligament length is minimal, while for butanol it is highest. Such kind of trend is also observed for the ligament diameter, as evident in Figure 15, which is mostly because of the difference in the viscosity of fuels. The effect on the length and diameter of the ligament due to the difference in viscosity of the fuel is also observed by Dombrowski et al.\textsuperscript{20} The length and diameter of the ligaments decrease with an increase in the atomizing air to fuel ratio, as shown in Figure 15, and this trend is common for the entire test samples. It could all be due to atomizing air velocity, which affects the ligament size and breakup.\textsuperscript{42} The effect of fuel properties on ligament size appears to be more dominant at low atomizing air to fuel ratio.

The average ligament growth rate has been calculated from the time-sequence images of ligaments and plotted in Figure 16. The subsequent growth of the ligament obeys the dynamics, i.e., the air velocity stretches the ligament crest from the liquid bulk by elongating it and maintaining its azimuthal regularity. Therefore, the ligament starts growing.\textsuperscript{15} Among the tested fuel samples, the growth rate of the ligament length is the highest for butyl butyrate and the lowest for butanol, as evident from Figure 16. The ligament growth rate of Jet A-1 is lying between the butyl butyrate and butanol, whereas the biofuel’s blends have shown the characteristics according to their loading. Overall it can be concluded that the viscous nature of fuel decreases the ligament growth rate, which delays the pinch-off of the droplets as is observed in Figure 17. The development rate of the ligament is increased with atomizing air to fuel ratio because interference forces or aerodynamic forces have increased due to higher

\textbf{Figure 14.} Spray ligament break-up and droplets formation during atomization near the nozzle tip.
atomizing air flow rate, and it is common for all the tested samples.

Air velocity causes the oscillation of liquid ligaments in the radial direction, which generates instability in the ligaments, and it disintegrates into several blobs, which form fine droplets, as presented in Figure 14. According to Lefebvre and Mc Donell, droplet diameter ($D_d$) mostly be influenced by the initial thickness of the liquid sheet, the relative velocity of the surrounding gas, and the physical properties of the liquid. In the current investigation, the pinch-off time has been calculated whereas the diameter of the droplets has been measured just after the break-up near the tip of the nozzle. From Figure 17, It can be noticed that butyl butyrate has a lower droplet diameter than butanol, and it is mainly due to differences in ligament characteristics. The thin ligament of butyl butyrate processes the low scale diameter of droplets while the thicker and elongated ligament of butanol counteracts breakup, this causes the establishment of larger diameter droplets. With increasing atomizing air to fuel ratio, the droplet diameter decreases, and this trend has been observed for all the test samples. Atomizing air to fuel ratio affects the drop size formation and its distribution.

Droplet pinch-off time has been calculated using the relation $\sqrt{\frac{\rho g^2}{\pi}}$ which is given by Marmottant & Villermaux. All the parameters used for this calculation have been found experimentally. Droplet pinch-off time decreases with increasing AFR. This is mainly due to the aerodynamic forces, which increase the
instability and leads to the early disintegration of ligaments. In terms of fuel property, butanol has a higher droplet pinch-off time than the other counterparts and lowest for the butyl butyrate. As it is evident, the ligament growth rate of butyl butyrate is the maximum, which means that it will break quickly, whereas the growth rate of the butanol's ligament is the lowest due to its viscous nature, which causes a longer pinch-off time. Other counterparts of the test samples have their droplet pinch-off times fall in between, as evident in Figure 17. In almost every case, the diameter of the droplets is higher than the diameter of the ligament, as seen in Figure 18. As long as the ligament is with liquid bulk, it expands due to air interference, which causes capillary instability and sinus wave formation. Eventually, the liquid ligament takes shape like several attached blobs as shown in Figure 14. When two liquid blobs $d_1$ and $d_2$ of two different sizes ($d_1 < d_2$) are connected, the smaller blob ($d_1$) has a higher-pressure difference. Due to this pressure
difference, the blobs get into the form of a bigger blob and detach from the ligament.\textsuperscript{11,45} This is the reason that the final droplet size is higher than the ligament diameter ($n$) just after it gets released from the liquid bulk.

The droplet diameter is examined just after the break-up almost near the tip of the nozzle in the cross-sectional area of 5 square millimeters using high-speed shadowgraphy technique. Hence to get an estimate of the droplet size, the high-speed shadowgraphy technique can be applied. One point we should keep in mind is that the measurement must be performed within the available optical range (i.e. exposure time, resolution, backlight, etc.) and after the depth of field correction. Figure 19 displays that $D_d$ varies almost linearly with the ligament diameter ($n$).

The droplet and ligament diameter are correlated using Pearson correlation coefficients and it is found to be positively correlated (Pearson correlation coefficients for the AFRs 1.1, 1.5, and 2.0 are found as 0.98, 0.98, and 0.99 respectively). The correlation coefficient is considered as a sign of the linear dependency between $\xi$ and $D_d$, which is plotted in Figure 19. The empirical Pearson correlation coefficient\textsuperscript{47} is given as

$$\text{Correl}(D_d, \xi) = \frac{\sum (\xi - \bar{\xi})(D_d - \bar{D}_d)}{\sqrt{\sum (\xi - \bar{\xi})^2 \sum (D_d - \bar{D}_d)^2}}$$

where $D_d$& $\xi$ and are the droplet diameter and ligament diameter and $D_d$ and $\bar{D}_d$ average droplet diameter and ligament diameter respectively. The slopes of all three trend lines are almost the same and they have only different Y-intercepts. It can be interpreted that the droplet diameter relies on the variation in the ligament diameter. It can also be inferred that the higher AFRs favor the formation of thin ligaments which eventually produce smaller droplets.

4. Conclusions

Spray characteristics of Jet A-1, butanol, butyl butyrate, and the blends (biofuel/Jet A-1 mixture) with an inside mix swirl air-blast atomizer were investigated with the help of Phase Doppler Interferometer and high-speed shadowgraphy technique. Experiments were conducted at three different atomizing air to fuel ratios, such as 1.1, 1.5, and 2.0 in atmospheric conditions. The droplet size distribution and velocity profile have been obtained using the PDI technique, whereas the breakup of spray sheet and ligament, droplet pinch-off, and their variations for different fuels at three air to fuel ratios have been examined by a high-speed imaging technique. Under the optical limitation of the imaging technique, the data obtained on droplet size and velocity distribution can be considered complementary to that of the PDI method. However, the information extracted from the high-speed imaging technique on sheet break-up, ligament formation, and its break-up, and morphological changes of droplets may turn out to be important in spray characterization.

Droplet velocity is maximum at the centerline and it decreases radially. The droplet size distribution illustrates that the droplets are smaller in the central zone of the spray, whereas they are comparably larger in the peripheral zone. The size appears to decrease with an escalation in the AFR. Owing to the momentum exchange between droplets and air, the droplet velocities are inversely correlated with size. The overall liquid
breakup mechanism is almost identical for all the tested samples. However, the spray sheets, ligaments, and droplet characteristics are varying according to the properties of fuel as well as atomizing air velocity. The size of spray sheets and ligaments of butyl butyrate is smaller compared to other counterparts. Butyl butyrate shows an early breakup and produces a droplet of small diameter near the tip. Overall, it can be concluded that the viscous property of butanol opposes the atomization, whereas butyl butyrate atomization is efficient. As the atomizing air to fuel ratio increases, the spray sheet length decreases due to the early breakup of ligaments. The mean droplet size profile is in good agreement with data obtained from empirical correlations established for the SMD under the non-reacting condition. Although the atomization is not very efficient in the case of butanol, its other properties (such as the existence of oxygen in the molecule) may favor combustion and emission performance. Hence, these two biofuels should be assessed as potential alternative fuels in light of overall performance characteristics.

Acknowledgements
The authors would like to acknowledge the Indian Institute of Technology Kharagpur (Aerospace Engineering Department) for providing support for this work. The authors would also like to acknowledge the Indian Institute of Science Bengaluru (Mechanical Engineering Department) who provided support to conduct PDPA testing.

Declaration of Conflicting Interests
The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding
The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: The authors would like to address the financial help received from the Science & Engineering Research Board (Sanction Order No. ECR/2016/000142) for conducting this study.

ORCID iD
Srinibas Karmakar https://orcid.org/0000-0002-2622-4892

References
1. Govt of USA – Office of Energy Efficiency & Renewable Energy. Alternative aviation fuels: overview of challenges, opportunities, and next steps. Technical report, USA, 2017, n.p. https://doi.org/10.2172/1358063.
2. Demirbas A. Political, economic and environmental impacts of biofuels: a review. Appl Energy 2009; 86: 108–117.
3. Hui X, Kumar K, Sung C-J, et al. Experimental studies on the combustion characteristics of alternative jet fuels. Fuel 2012; 98: 176–182.
4. Jugjai S, Wongpanit N, Laoketkan T, et al. The combustion of liquid fuels using a porous medium. Exp Therm Fluid Sci 2002; 26: 15–23.
5. Lefebvre AH and McDonell VG. Basic Processes in Atomization. Atomization and sprays, 2017.
6. Jedelsky J, Maly M, Pinto del Corral N, et al. Air–liquid interactions in a pressure-swirl spray. Int J Heat Mass Transfer 2018; 121: 788–804.
7. Guerrassi N and Champoussin JC. Droplet sizes and velocities in diesel spray. Entropie 1995; 31: n.p.
8. Lascheras JC, Villernaux E and Hopfinger EJ. Break-up and atomization of a round water jet by a high-speed annular air jet. J Fluid Mech 1998; 357: 351–379.
9. Lascheras JC and Hopfinger EJ. Liquid jet instability and atomization in a coaxial gas stream. Annu Rev Fluid Mech 2000; 32: 275–308.
10. Rajamanickam K and Basu S. Insights into the dynamics of spray–swirl interactions. J Fluid Mech 2017; 810: 82–126.
11. Marmottant P and Villernaux E. On spray formation. J Fluid Mech 2004; 498: 73–111.
12. Lee SY and Kim YD. Sizing of spray particles using image processing technique. KSME Int J 2004; 18: 879–894.
13. Gepperth S, Müller A, Koch R, et al. Ligament and droplet characteristics in prefilming airblast atomization. In: tCLASS 2012, 12th triennial international conference on liquid atomization and spray systems, Heidelberg, Germany, 2–6 September 2012.
14. Warncke K, Gepperth S, Sauer B, et al. Experimental and numerical investigation of the primary breakup of an airblasted liquid sheet. Int J Multiphase Flow 2017; 91: 208–224.
15. Laurila E, Koivisto S, Kankkunen A, et al. Computational and experimental investigation of a swirl nozzle for viscous fluids. Int J Multiph Flow 2020; 128: 103278.
16. Kryzwoblocki MV. Miscellaneous. J Jet Propuls 1956; 26: 760–779.
17. Castleman RA Jr. The mechanism of the atomization accompanying solid injection. NACA report-440, 1932.
18. Fraser RP, Eisenklam P, Dombrowski N, et al. Drop formation from rapidly moving liquid sheets. AICHE J 1962; 8: 672–680.
19. Dombrowski N, Fraser RP and Newitt DM. A photographic investigation into the disintegration of liquid sheets. Philos Trans R Soc London Ser A Math Phys Sci 1954; 247: 101–130.
20. Dombrowski N and Johns WR. The aerodynamic instability and disintegration of viscous liquid sheets. Chem Eng Sci 1963; 18: 203–214.
21. Rizk NK and Lefebvre AH. The influence of liquid film thickness on airblast atomization. J Eng Power 1980; 102: 706–710.
22. Willert C, Freitag S and Hassa C. High-speed imaging of fuel spray using a low-cost illumination source. In: ILASS 2008, Como Lake, Italy, 8–10 September 2008.
23. Sivakumar D, Vankeswaram SK, Sakthikumar R, et al. Analysis on the atomization characteristics of aviation biofuel discharging from simplex swirl atomizer. *Int J Multiph Flow* 2015; 72: 88–96.
24. Carvalho IS and Heitor MV. Liquid film break-up in a model of a prefilming airblast nozzle. *Exp Fluids* 1998; 24: 408–415.
25. Chong CT and Hochgreb S. Effect of atomizing air flow on spray atomization of an internal-mix twin-fluid atomizer. *Atomiz Sprays* 2015; 25: 657–673.
26. Kesime U, Pazouki K, Murphy A, et al. Biofuel as an alternative shipping fuel: technological, environmental and economic assessment. *Sustainable Energy Fuels* 2019; 3: 899–909.
27. Kumar M and Karmakar S. Combustion characteristics of butanol, butyl butyrate, and Jet A-1 in a swirl-stabilized combustor. *Fuel* 2020; 281: 118743.
28. Lee MY, Lee GS, Kim CJ, et al. Macroscopic and microscopic spray characteristics of diesel and gasoline in a constant volume chamber. *Energies* 2018; 11: 2056.
29. Grimaldi C and Postrioti L. Experimental comparison between conventional and bio-derived fuels sprays from a common rail injection system. Technical paper, 2000. https://doi.org/10.4271/2000-01-1252
30. Chang CT and Farrell PV. A study on the effects of fuel viscosity and nozzle geometry on high injection pressure diesel spray characteristics. Technical paper, 1997. https://doi.org/10.4271/970353
31. Wright YM, Margari O-N, Boulouchos K, et al. Experiments and simulations of n-heptane spray auto-ignition in a closed combustion chamber at diesel engine conditions. *Flow Turbul Combust* 2010; 84: 49–78.
32. Bayvel LP and Orzechowski Z. Liquid atomization. Washington, DC: Taylor & Francis, 1993, pp.194–195.
33. Chong CT and Hochgreb S. Effect of atomizing air flow on spray atomization of an internal-mix twin-fluid atomizer. *Atomiz Sprays* 2015; 25: 657–673.
34. Chen SK and Lefebvre AH. Spray cone angles of effervescent atomizers. *Atomiz Sprays* 1994; 4, DOI: 10.1615/AtomizSpr.v4.i3.40
35. Castles RL, Eccles PA, and Wells J. The mechanism of the atomization of liquids. *Bur Stand J Res* 1931; 6: 369.
36. Hinze JO. Fundamentals of the hydrodynamic mechanism of splitting in dispersion processes. *AIChE J* 1955; 1: 289–295.
37. Marmottant P and Villermaux E. Fragmentation of stretched liquid ligaments. *Phys Fluids* 2004; 16: 2732–2741.
38. Swinscow TDV. Statistics at Square One. London: BMJ Publication Group, 1997. Revised by University of Southampton.

### Appendix

#### Notation

- **AFR**: atomizing air fuel ratio
- **$n_a$**: mass flow rate of air
- **$n_f$**: mass flow rate of fuel
- **Oh**: Ohnesorge number
- **PDI**: phase Doppler interferometry
- **PDPA**: phase Doppler particle analyzer
- **Re_a**: Reynolds number (air flow)
- **Re_f**: Reynolds Number (fuel flow)
- **SMD ($D_{32}$)**: Sauter mean diameter
- **Stk**: Stokes number
- **$V_{jet}$**: average velocity of air at the nozzle exit
- **$V_{jet}$**: average velocity of fuel at the nozzle exit
- **We_jet**: Weber number