Experimental investigation on the effect of \( n \)-butanol blending on spray characteristics of soybean biodiesel in a common-rail fuel injection system

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**Highlights**

- We investigate the spray characteristics of soybean biodiesel with/without butanol blending.
- The total droplet number slightly decreases from the spray center line to the spray periphery while butanol blending makes the droplets more evenly distributed.
- Butanol addition leads to smaller Sauter Mean Diameter due to reduced viscosity and lower surface tension.

**Abstract**

In this work, the spray and atomization characteristics of neat soybean biodiesel fuel (BD100) and biodiesel/\( n \)-butanol blends (BDB80, 20% of \( n \)-butanol (wt.)), were investigated at room temperature and ambient pressure of 1 and 2 MPa. A high-pressure common-rail injection system was used to generate sprays from an injector (aperture 0.25 mm) at a maximum injection pressure of 100 MPa. High speed schlieren technique was used to record the highly transient spray penetration process, through which the spray macroscopic parameters such as spray tip penetration, spray cone angle, projected spray area and spray volume were deduced. In addition, droplet size, number density and its sauter mean values at specific location within the spray cone was analyzed, by using a particle/droplet image analyzing technique (PDIA). Results show that longer spray tip penetration and larger droplet diameters were observed for BD100, compared with BDB80, which was attributed to the lower viscosity and surface tension of BDB80. BDB80 has a spray volume less than BD100, the same trend is also observed in the spray tip penetration. BD100 presents bigger spray area than BDB80 under 1 MPa ambient pressure. This is mainly attributed to the bigger spray tip penetration of BD100. The results also show that droplets at the spray periphery have larger diameters than those in the center of the spray due to the effect of air entrainment at the spray periphery. The small particles of fuels are easily sucked into internal of spray. Furthermore, the droplets near the liquid core of spray have more small numbers, where the effect of viscosity is dominant.

**1. Introduction**

Fossil fuels such as natural gas, petroleum and coal have been meeting most industrial and commercial demands for relatively low cost, high energy density, transportable fuels for decades. However, being the main source of transportation fuels, petroleum is estimated to be running out within 50 years due to the limited storage under the stratum [1]. Because of the increasing fuel cost and stringent emissions, Biofuels, such as alcohols, DME, and biodiesel [2–6], have become an increasing attractive, efficient and less expensive fuels compared to gasoline. All these biofuels can be renewable resources instead of fossil feedstock.

As an alternative fuel, biodiesel has many similar or better properties than diesel fuel, such as cetane number, non-toxic, biodegradable and good inherent lubricity, which make it more suitable for diesel engines. Biodiesel fuels can be produced from various feedstocks. Some of them, especially soybean derived biodiesel fuels, have attracted attention due to its higher potential...
for a renewable source. Since soybean is more abundant in most of
developed countries and oil derivation can be up to 20% by weight,
its prices are generally more reasonable than the other feedstocks.
Thus, soybean oil has become the main favorable feedstock for bio-
diesel fuel production. Mohamed et al. [7] conducted an exper-
imental and theoretical study on a single cylinder, direct injection
diesel engine fueled with different blends of soybean methyl ester
(SME) and No. 2 diesel fuel. It was reported that the use of biodiesel
produced lower smoke with a 14.65% higher brake fuel specific
consumption (BSFC) compared to diesel fuel. The measured CO
emissions of B20% SME and B100% SME were found to be 11.36%
and 41.7% lower than that of diesel fuel respectively. All blends
of SME were found to emit significantly lower UHC concentration
compared to that of diesel over the entire load range. NOx emis-
sions were observed to be higher for all blends of SME. Özener
et al. [8] investigated the effect of soybean biodiesel addition on
the engine combustion, performance and emissions. The results
showed that when biodiesel was added, the brake torque was
reduced by 1–4% and BSFC increased by 2–9% with the increase of
the biodiesel blended ratio, when compared with diesel fuel.
Furthermore, CO and HC emissions were found to be 28% and
46% lower but it was observed that NOx and CO2 emissions
increased by 17.62% and 5.03%, respectively. Their combustion
analyses showed that the biodiesel addition to diesel resulted in
the decrease of the ignition delay and the peak pressure of the pre-
mixed combustion.

As a biomass-based renewable fuel, n-butanol has many advan-
tageous properties, such as better miscibility in diesel, higher energy
content and higher cetane number. These properties, make
butanol an attractive alternative fuel or blending component to
diesel fuel compared with other alcohols, such as methanol and
ethanol. Recently, some investigations have been carried out on
the combustion and emission characteristics about n-butanol/
biodiesel blends. Specifically Tüccar et al. [9] studied the engine
performance and exhaust emissions of diesel–microalgae biodie-
sel(MB)–n-butanol blends on a four-cylinder diesel engine. Their
results showed that the power and torque output of engine
reduced slightly when butanol was added to the diesel–MB blends.
CO and NOx emission and smoke opacity values decreased with the
addition of butanol. Rakopoulos [10] studied the combustion and
emissions of cottonseed oil and its biodiesel in blends with n-
butanol or diethyl ether in high-speed direct injection (HSDI) die-
sel engine. Their results showed that the tested blended fuels pro-
duced lower smoke, NOx, and CO emission but higher HC emission
than neat biodiesel. The BSFC decreases with the usage of these
fuel blends, compared with the neat biodiesel, and the correspond-
ing brake thermal efficiencies increase. Yilmaz et al. [11] studied
the effect of butanol–biodiesel blends on the emissions and perfor-
mance characteristics using an indirect-injection diesel engine.
Their results showed that butanol blended fuels produced lower
NOx emissions and higher CO and HC emissions than neat biodie-
sel. Furthermore, butanol blended fuels produced lower CO and
higher NOx emissions than diesel fuel for low concentrations of
butanol (5% and 10%), but there was no significant change in terms
of HC emissions. The biodiesel blend with the highest concentra-
tion of butanol (20%) produced higher CO and HC emissions but
lower NOx emission than diesel.

It is well known that fuel spray characteristics and atomization
have an important effect on combustion process and final engine
performance and emission. In some studies, the experimental
and numerical investigation on spray atomization characteristics
of biodiesel fuel have been conducted [12–20]. Park et al. [14]
investigated the spray atomization characteristics of soybean oil
methyl ester (SME) compared with that of diesel fuel in a diesel
engine. Their results showed that the spray tip penetration of bio-
diesel fuel had almost similar behavior pattern compared with that
of diesel fuel at various experimental conditions. The spray area of
biodiesel fuel decreases when the ambient pressure increases. Fur-
thermore, the Sauter Mean Diameter (SMD) of biodiesel fuel
decreases along the spray axis, and biodiesel fuel had a slightly lar-
gro droplets size than diesel fuel. Deshmukh et al. [17] studied
the high pressure spray characterization of Straight Vegetable Oils (Jat-
ropa and Pongamia). Their results showed that Pongamia fuel
had higher injection delays at low injection pressures and this is
attributed to its higher viscosity. The spray tip penetration for Pon-
gamia and Jatropha is less than that of diesel. Deshmukh and
Ravikrishna [20] studied the high pressure spray characterization
of Pongamia oil and its blends with diesel under various ambient
pressures. Their results showed that the spray cone angle for bio-
fuels was lower than that of diesel. The Pongamia had 200% higher
SMD than that of diesel. The spray atomization performance was
typically characterized by the droplet size. Because there were
large number of droplets within the spray, there have been several
methods to characterize the average droplet size. Among these de-
finitions, SMD is the most commonly used. However, studies on the
spray atomization characteristics of n-butanol blending with diesel
and biodiesel are not sufficient so far. Liu et al. [21,22] studied the
effects of volatility on butanol–biodiesel–diesel spray characteris-
tics. The results indicated that for the non-combusting case, the
tip of the spray jet erupted into a plume sometime after injection
for the butanol–biodiesel–diesel blend at an ambient temperature
of 1100 K. Such phenomenon was not seen with the biodiesel–die-
sel blend, neither with the same fuel but at a lower ambient tem-
perature of 900 K. It is concluded that micro-explosion could occur
under particular conditions for the butanol–biodiesel–diesel blend.
Wu et al. [23] conducted an experimental study of spray character-
istics of different fuel mixtures and analyzed the influence of dif-
ferent proportions of acid oil biodiesel and n-butanol on the
macroscopic parameters of spray. The results show that after add-
ing n-butanol in acidic oil biodiesel and diesel mixture fuel, the
surrounding air entrainment is enhanced, and spray front end
widen. With the increasing of mixing ratio, spray penetration
increasing first, then decreases. The spray cone angle increases
after adding n-butanol, and decreases with the increase of mixing
ratio. The results show that adding n-butanol can be used as one of
the methods to improve biodiesel spray characteristics. In the
research of Liu et al. [24], the spray, flame natural luminosity and
soot quantitative measurement by fueling n-butanol and soybean
biodiesel on a constant volume chamber were investigated. Results
demonstrate that the transient liquid penetration length of n-
butanol is less affected by the downstream flame and is shorter
than that of biodiesel under similar conditions. Compared to bio-
diesel, the flame luminosity of n-butanol is lower and its propaga-
tion and distribution is less sensitive to ambient temperatures.
Ambient temperature is confirmed as the dominant impact on the
soot emissions as the net soot increases for both tested fuels
with elevated ambient temperature. No soot emission is detected
for either n-butanol or biodiesel at low ambient temperature of
700 K. The soot starts to appear at both downstream of the jet
and near wall regions from 800 K for biodiesel whereas the soot
do not emerge until 900 K for n-butanol. The higher soot formation

<table>
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<th>Table 1: Physical properties of test fuels.</th>
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<td>Fuel</td>
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<td>Biodiesel</td>
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<td>20% n-Butanol of biodiesel blend</td>
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for biodiesel is explained by the fact that fuel-bound oxygen is less
effective in reducing soot production and that higher viscosity and
boiling point results in more local high equivalence-ratio region in
mixing process. In this regard, \( n \)-butanol is more effective in sup-
pressing the soot formation and shows stronger soot reduction
capability than that of biodiesel.

In this study, \( n \)-butanol will be used as an additive into soybean
biodiesel and the spray characteristics of biodiesel/\( n \)-butanol

Fig. 1. Experimental setup for macro-spray measurements.

Fig. 2. Comparison of spray development images with time after injection trigger (0.7 ms, 1.0 ms, and 1.5 ms) at 60 MPa injection pressure and different \( P_{amb} \) (1, 2 MPa).

BD100  BDB80  BD100  BDB80  BD100  BDB80

(a) \( P_{amb}=1 \) MPa

BD100  BDB80  BD100  BDB80

(b) \( P_{amb}=2 \) MPa
blends will be investigated. Table 1 lists the physical properties of test fuels. In the following, the experimental system will be specified in detail. The macroscopic spray characteristics of biodiesel/n-butanol blends at different injection pressures and ambient pressures in terms of the spray tip penetration (STP), spray angle, spray volume and projected area will be examined from the spray images captured through high speed schlieren photography. Additionally, microscopic and statistical spray characteristic parameters such as the droplets size/number distribution will be compared.

2. Experimental methods

In the present study, biodiesel/n-butanol sprays were generated inside the high pressure constant volume chamber. The spray characteristics play a critical role in the engine performance and understanding the spray of alternative fuels for diesel is important in applying these fuels in practical combustion engine. Studies of the fuel spray behavior can be classified into two categories: the macroscopic and microscopic characteristics. Macroscopic parameters such as the spray tip penetration and cone angle can be measured by direct visualization methods such as the high speed schlieren photography techniques. Microscopic parameters such as the droplet velocity, droplet size and number density distribution can be measured through particle image velocimetry (PIV), phase Doppler particle analyzer (PDPA) or laser diffraction particle analyzer (LDPA) systems. These microscopic and macroscopic spray parameters quantify the atomization quality of a certain fuel and essentially influence the mixture formation process and eventually the combustion and emission performance of the engine.

Fig. 1 shows the spray test rig used in this study. The whole test rig is composed of the fuel injection system, the constant volume chamber and the imaging system. A common rail fuel injection system (BOSCH CP1H3) was used for generating the high pressure fuel jet. A single hole injector nozzle with a diameter of 250 \( \mu \text{m} \) was used in this work. In this study, three injection pressures were tested: 60, 80, and 100 MPa. The cylindrical constant volume chamber with optical windows was used to provide ambient pressures by filling the compressed nitrogen. Two ambient pressures were tested (1 and 2 MPa) at room temperature. Two sides of the
chamber were installed with quartz windows (100 mm in diameter × 80 mm in thickness) so as to provide optical access for visualization. The schlieren method is employed for the spray macroscopic characteristic investigation. A high-speed digital video camera (Phantom V611) was used to capture the images of the fuel spray. The sampling rate was set at 10,000 frames per second with a resolution of 608 × 800 pixels. An 850 W light source was used as the light source for the high speed camera. Typical high speed camera recorded instant spray images were shown in Fig. 2, from which the spray tip penetration and spray cone angle data were measured as a function of time after injection.

For the microscopic characteristic investigation, the photographic and illumination system for the spray tip penetration and spray cone angle measurements shown in Fig. 1 was replaced by the particle/droplet image analysis (PDIA) system, the detailed information of the PDIA system has been introduced previously [25]. Briefly, An Nd:YAG laser (532 nm) was attached by a LaVision Diffuser (1108420) to provide homogeneous illumination for the test region. A long focus microscope (Queststar QM1) and a CCD camera (ImageProSX 5M) was used for capturing the image of the target window within the spray. The spray injection, the laser pulse and the camera was synchronized so as to make sure the image captured can reflect meaningful information of droplets within the target window. The target window was a rectangular with a dimension of 3286 l × 2753 l. Several target windows were tested for scanning the droplet information within the spray and these target windows were located at different distance down the nozzle tip (axis direction \( L = 6 \) cm) and from the spray nozzle center line (radial direction \( R = 0.6, 0.8, \) and \( 1.0 \) cm), as shown in Fig. 3. The electronic positioner (MC600) was used to move the long focus microscope and the camera with an accuracy of 1 \( \mu \)m. Table 2 lists the main parameters for the PDIA system measurement.
3. Experimental results and discussion

In this section, the macroscopic spray characteristics will be investigated, including the spray tip penetration (STP), the spray cone angle and the spray area for BD100 and BDB80. In addition, the microscopic characteristics including droplets number and size distribution will be analyzed at injection pressure of 60 MPa and ambient pressure of 1 MPa for BD100 and BDB80. The experiment was repeated three times under each condition to ensure the reliability of the results. The injection duration is 1.5 ms under all conditions. Fig. 4 shows the definition of spray parameters used in this study [26]. The spray tip penetration is defined as the distance between the injector exit and the spray tip (S in the Figure). The spray cone angle is defined as the angle between two lines connecting the nozzle tip and two half penetration points on the spray boundary. The spray area correspond the shadow area in the graph.
3.1. Spray tip penetration

Fig. 5 illustrates the comparison of the spray tip penetration between BD100 and BDB80. Hiroyasu and Arai [27] studied that spray evolution is divided into two stages, a critical time ($t_{\text{break}}$) is defined as the cut-off point of two stages. When $t < t_{\text{break}}$, STP has a linear relationship with time. As shown in Fig. 5a, under the ambient pressure of 1 MPa, BD100 gives obviously longer spray tip penetration than BDB80 at a specific time ($t_{\text{break}}$) after about 0.9 ms, while BD100 and BDB80 give similar values of spray tip penetration before about 0.9 ms. This is because for $t < t_{\text{break}}$, the STP is mainly affected by the fuel density and all test fuels show the similar density, leading to the STP evolution insensitive to the $n$-butanol addition. However, for $t > t_{\text{break}}$, $n$-butanol addition tends to decelerate the spray tip penetration. This is because blended fuels have lower viscosity and smaller surface tension and their droplets are easier to deform and breakup, resulting in a decrease of spray droplet size and loss in spray momentum which eventually slows down the penetration [27,28]. Furthermore, as the injection pressure increases, $t_{\text{break}}$ decreases: 0.8 and 0.7 ms at 80 and 100 MPa, respectively. This is because the high injection pressure promotes the breakup of the primary spray due to the increased hydrodynamic instability. This is consistent with the study of Hiroyasu and Arai [27] and they proposed the empirical equation of $t_{\text{break}}$ that is inversely proportional to the difference between the injection and ambient pressure. The difference of STP between two fuels is small under high ambient pressure (2 MPa). Under the ambient pressure of 1 MPa, spray tip penetration difference between BD100 and BDB80 is decreased with increasing injection pressure. We note that every test condition was repeated five times. The STP and the spray cone angle in the following were presented with averaged values and standard deviation.

Fig. 6 presents the effect of injection pressure on spray tip penetration. Spray tip penetration increases with increasing the fuel injection pressure due to higher initial momentum of the jet. This is consistent with the study of Park and Lee [29]. As shown in Fig. 6a, BD100 has smaller STP difference between 100 and 80 MPa than that between 80 and 60 MPa, which is more obviously of BDB80. In addition, for higher injection pressure, the STP increase due to increased injection pressure is less significant, as can be seen in Fig. 6b.

3.2. Spray cone angle

The spray cone angle is an important characteristic parameter of a full-cone spray that has been investigated by Hiroyasu and Arai [27]. During the first stage of the spray penetration, the needle opens and the evolution is transient. The low axial injection velocity and the strong radial velocity fluctuations leads to large spray cone angle near the nozzle. In a later stage, when the needle is fully opened, the injection is stable and the spray cone angle reaches a nearly constant value. However, ambient
pressure has an obvious influence on the spray cone angle, and high ambient pressure supply strengthened the resistance to fuel spray and inhibits spray axial development, which results in a larger spray cone angle [31]. Furthermore, the spray cone angle of the test fuels converge to a constant value at around 0.9 ms after start of injection at 60 MPa injection pressure, and steady state is achieved earlier after injection as the injection pressure increases, i.e., 0.8 and 0.7 ms for 80 and 100 MPa, respectively. This is because higher injection pressure leads to smaller $t_{\text{break}}$, as reported by Guan et al. [25].

### 3.3. Spray area and volume

The projected spray area can be employed to represent the quality of fuel air mixing [26]. Fig. 8 presents spray area versus injection time for all conditions. The results show that BD100 presents larger spray area than BDB80 under 1 MPa ambient pressure. This is mainly attributed to the longer spray tip penetration of BD100, as shown in Fig. 2. The difference of spray area among two fuels is quite small under high ambient pressure (2 MPa).

To further understand the fuel–air mixing, the spray volume is estimated. Fuel spray is assumed to consist of a cone and half a sphere, thus the spray volume is then described by the following correlation [26],

$$V = \frac{(\pi/3)S^2[\tan^2(\theta/2)]}{\left(1 + \tan(\theta/2)\right)^3}$$

where $S$ is the spray tip penetration and $\theta$ is the spray cone angle. Fig. 9 shows the calculated spray volumes of different fuels used in this study with time after the start of injection. The spray volumes develop as exponential curves under low injection pressure (60 MPa) and become proportional when increasing the pressure. This is considered as the effect of higher injection pressure delivering the fuel faster than low pressure and causing the sprays to reach steady state earlier. The spray volume gives the similar results with
those of spray area. Moreover, the distribution in spray volume for the test fuels follows the same trend as spray tip penetration. It is seen that spray volume is mainly determined by the spray tip penetration, since the variation of spray cone angles among different fuels is not significant. Our results show that BDB80 has a spray volume less than BD100, the same trend is also observed in the spray tip penetration.

3.4. Droplets size/number distribution

The droplets size and number distribution characteristics represent the quality of spray and atomization and it affects the subsequent combustion and emissions in engines. The spray is broken into spray particles or droplets of various sizes with the atomization process. Managing the size of spray droplets is critical in managing spray drift. When the size of spray droplets is reduced, the potential for drift increases. Due to the high droplets density at the central of the spray that attenuate the background illumination light [25], the droplets size/number distribution of BD100 and BDB80 were measured at 6 cm below the nozzle tip and 0.6, 0.8, 1.0 cm from the spray axis at injection pressure of 60 MPa and ambient pressure of 1 MPa. The recorded images were processed by the software Davis 8.0.0 of LaVision. Fig. 10 shows the typical shadow images of droplets at three observation windows. It is seen that the number of droplets was reduced along the radial direction from the spray center line. It is more difficult to process the image which got closer to the spray center because the droplets are too dense. Furthermore, BDB80 has more droplets than BD100 at all detector windows.

Fig. 11 shows the summation of the detected droplets of BD100 and BDB80 in the whole observation region. The black spots were employed to represent the droplets. As shown in Fig. 12, droplets tend to aggregate on the left half of the focal plane (close to the liquid core [17]) for all fuels studied here. It is seen that there were a larger number of droplets close to the central of the spray than at the periphery of it. In addition, for BD100, the droplet number seems to have a larger gradient along the radial direction, compared to BDB80. This might be attributed to its higher viscosity and larger surface tension, which inhibit the droplets diffusion.

Fig. 12a–d shows the droplets number fraction of BD100 and BDB80 at three detecting positions and whole part, respectively. As shown in Fig. 12a, BDB80 has a larger number of small droplets close to the central of the spray. This is because BDB80 has the lower viscosity and smaller surface tension, which favors the droplet breakup process near the spray core region. As the test region is shifted to slightly far away from the spray center line, as shown in Fig. 12b, BDB80 has very similar droplet number fraction to that of BD100. Fig. 12c illustrates the similar trend like Fig. 12b, it is due to the fast pressure drop far away from the liquid core. The effect of pressure drop is larger than that of viscosity difference at the spray periphery. Fig. 12d illustrates that BDB80 has more small droplets than BD100 overall. Fig. 13 shows droplets number distribution of
BD100 and BD880 along the radial direction. The droplets number of BD100 decreases more obviously along the radial distance, compared to BD880. This is because BD100 has higher viscosity and surface tension and the primary breakup of the spray is relatively inhibited, compared to BD880. The higher number density gradient of BD100 was also shown in Fig. 11.

Fig. 14 shows droplets size distribution of BD100 and BD880 along the radial positions in the whole test region. The SMD difference among the fuels is mainly due to the differences in their viscosity and surface tension. A higher viscosity leads to a lower fuel jet velocity, leading to larger droplet size. A lower surface tension makes the spray easier to break up into small droplets. As shown in Fig. 14, the droplets size increases along with the radial distance. It is due to the combined impact of the fuel viscosity and the air entrainment. The small particles of the test fuels are easily sucked into internal of spray. Furthermore, the droplets near the liquid core of spray have more small numbers, where the effect of viscosity is dominantly.

4. Conclusions

In this work, the spray and atomization characteristics were investigated for neat soybean biodiesel and 20% n-butanol biodiesel blend. The schlieren method was employed to measure macro spray characteristic and the PDIA technique was used to measure droplets size distribution and characteristic diameters. Results from the measurement of spray tip penetration show a combined effect of density and viscosity. BD100 has the longest penetration of the fuels investigated. Longer penetration of fuel spray is observed under higher injection pressure and lower ambient pressure. For example, the spray penetrations at 100 MPa injection pressure are about 10% longer than those at 60 MPa. Effect of injection pressure on spray cone angle is not evident compared with that on droplet size and spray tip penetration. Spray cone angle converges to its steady state very rapidly with increasing injection pressure. At 1 MPa ambient pressure, the spray area of BD100 is higher as compared to BD880 because of relatively lower density and viscosity of BD880. And at 2 MPa ambient pressure, the test fuels have similar spray area. Spray volume is mainly determined by the spray penetration length, since the variation of spray cone angles among different fuels is not significant. The results show that droplets at the spray periphery have larger diameters than those in the center of the spray due to the effect of air entrainment at the spray periphery. The small particles of fuels are easily sucked into internal of spray. Furthermore, the droplets near the liquid core of spray have more small numbers, where the effect of viscosity is dominantly.

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