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Experimental investigation on effect of ethanol and di-ethyl ether addition on the spray characteristics of diesel/biodiesel blends under high injection pressure

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A R T I C L E   I N F O

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STP
SMD

A B S T R A C T

In this work, a comprehensive experimental investigation on spray characteristics of four blended fuels, including diesel (D100), diesel-biodiesel (DB), diesel-biodiesel-ethanol (DBE), and diesel-biodiesel-diethyl ether (DBDE) has been conducted by using high pressure common rail injection system (up to 200 MPa). The transient spray behavior under various conditions was recorded by high speed photography with scattering light illumination. It is shown that higher injection pressure significantly accelerates the spray tip penetration (STP) evolution due to increased inertia of spray while increase in ambient pressure reduces the STP evolution due to higher gas resistance. With the addition of diethyl ether (DEE) into biodiesel, the STP of blended fuel tends to go down and corresponding projected area increases a lot when compared to DB. By means of particle droplet image analysis (PDA) optical diagnostic method, spray microscopic parameters such as Sauter Mean Diameter (SMD), droplet diameter distribution probability curve, cumulative volume curve and characteristic diameter have been investigated. Results show that both the injection pressure and ambient pressure have significant influence on the spray microscopic characteristics. In addition, for fixed injection pressure and ambient pressure, when DEE is added into DB blends, the number fraction of smaller droplets increases, though the statistic diameter with peak probability is fixed at a certain value. Furthermore, SMD of the four tested fuels decreases sequentially in the order of DB, D100, DBE, and DBDE, indicating that DEE addition favors the atomization process.

1. Introduction

Diesel engines can operate at a higher compression ratio than gasoline engines without causing the issue of knock or misfire. As a consequence, diesel engines typically obtain higher torque output and thermal efficiency, making it widely used in industrial fields such as on-road and marine transportation (especially for heavy-duty carriage), as well as power generation. But diesel engines are more likely to be used in commercial rather than passenger vehicles and they only account for 1% vehicle market share in China, while this value is 60% in Europe [1]. As it is known, diesel is refined from fossil fuel such as crude oil, which has limited reserves and it has been used as conventional fuel in diesel engines for over a century. In addition, the consumption of fossil fuel by diesel engines results in tremendous environmental impact through pollutant emissions, especially the particulate matter. Rogge and Hildeman [2] conducted an environmental investigation based on the emission of several types of vehicles in Los Angeles. Their results revealed that consumption of gasoline or diesel in internal combustion engine, contributes more than 21% of atmospheric particulate emissions. The fossil fuel depletion and public concerns on air pollution thus consequently drive the emerging needs for biofuels, which have been reported as being carbon neutral and potential for reducing fossil fuel consumption.

Hill et al. [3] pointed out that a viable biofuel should meet several criteria, including a net energy gain, environmental benefits, being economically competitive and producible in large scale without threatening food safety. However, the biofuel which perfectly satisfies above demands has not been found till now. Biodiesel [4] is typically produced from vegetable oils or animal fats through transesterification reaction process with alcohol. Because of its good solubility with diesel, biodiesel can be used as an additive into conventional diesel in any blending ratios. In addition, the presence of oxygen in biodiesel can significantly reduce soot emission [5]. Extensive engine tests on running biodiesel have been conducted and various kinds of biodiesel have been tested, including soybean oil, rapeseed oil and waste cooking oil based biodiesel. Specifically, Bakopulos et al. [6] evaluated the exhaust emission levels and engine performance of cottonseed biodiesel/diesel blends in a single-cylinder, four-stroke diesel engine. They found that...
when diesel is blended with biodiesel, higher thermal efficiency and higher brake mean effective pressure is achieved. In addition, their emission measurements showed that burning cottonseed biodiesel leads to reduced emission of unburned hydrocarbon, carbon monoxide and particle matter. Additionally, Lapuerta et al. [7] pointed out in their review that NOx emissions will be slightly increased when using biodiesel fuels, which can be effectively compensated by injection delay strategy. Zhang et al. [8] compared the combustion characteristics of biodiesel-diesel blends and pure diesel in a turbocharged diesel engine. The similarity of diffusion burning rate was found between blends and diesel, while blends experimented a shorter ignition delay time.

On the other hand, however, biodiesel is bound to several limitations. First of all, running pure biodiesel in engines is not cost-effective. The cost of biodiesel production is higher than that of diesel, and financial support from the local government is required to stimulate its emergence. In addition, considering the higher viscosity and surface tension of biodiesel, the spray and atomization process can’t match the same level of diesel under identical experimental conditions, which could result in bad performance of combustible mixture formation. Wang et al. [9] studied the spray characteristics of two kinds of biodiesels blended with basal diesel, and they found that, with the addition of biodiesel into basal fuel, longer spray tip penetration (STP), poorer ambient air entrainment and larger Sauter Mean Diameter (SMD) were found, which is expected to deteriorate the mixture formation process. It gets even worse in cold weather because of the poor cold flow behaviors of biodiesel [10,11], which definitely leads to deteriorated engine cold start performance. As a consequence, in previous engine studies [12,13], biodiesel has typically been blended into diesel with a same level of diesel under identical experimental conditions, which could result in bad performance of combustible mixture formation. Wang et al. [9] studied the spray characteristics of two kinds of biodiesels blended with basal diesel, and they found that, with the addition of biodiesel into basal fuel, longer spray tip penetration (STP), poorer ambient air entrainment and larger Sauter Mean Diameter (SMD) were found, which is expected to deteriorate the mixture formation process.

Ethanol is a promising renewable fuel candidate for internal combustion engine. The viscosity and surface tension of ethanol is lower than that of diesel and biodiesel, which favors its spray and atomization behaviors. In addition, the high oxygen content in ethanol can significantly promote oxidation process of unburned hydrocarbon and PM [14]. Fernando et al. [15] evaluated the physical properties of diesel-biodiesel-ethanol (DBE) blended micro-emulsions. They found that the blends could be stable for a long time at a sub-zero temperature and have the similar energy density and better lubricity performance than diesel-biodiesel blends. Shi et al. [16] investigated the emission characteristics of DBE fuel in a four cylinder commercial diesel engine, and their results indicated that DBE shows an average 30% reduction in PM emissions, a general reduction of unburned hydrocarbon, and however, a 5.6–11.4% increase of NOx emissions at their test conditions.

Recently, diethyl ether (DDE) has been reported to be easily produced through industrial dehydrogenation technique by using acid clay catalyst with 90% conversion of hydrous ethanol. The physical properties of DDE, together with neat diesel, soybean biodiesel, ethanol, are presented in Table 1. Considering the high vapor pressure of DDE (approximately 110.2 kPa at 293 K), it is expected that DDE is more likely to result in even better atomization and mixture formation process. This behavior is beneficial for engine starting, especially at cold conditions [17]. In addition, the evaporation latent heat of DDE is higher than that of diesel and biodiesel. Thus blending DDE into either diesel or biodiesel will reduce the highest temperature in combustion process, which is expected to reduce the NOx emission. Bailey et al. [18] did a comprehensive literature review on DDE application in diesel engines. They claimed that the cost of fuel-grade DDE would be only slightly higher than that of anhydrous ethanol and the fuel property varies drastically. The cetane number of DDE is approximately twice that of diesel, and ten times that of ethanol. Presence of DDE in the blended fuels will significantly accelerate the auto-ignition process. What’s more, DDE’s Reid vapor pressure is much higher than that of ethanol, which implies that DDE possesses better volatility characteristics. The experimental results of Werberdemenezes et al. [19] shows that the mixtures with 5% DDE as additive possesses low fuel density, viscosity and surface tension at a low temperature compared to neat diesel. As to its combustion characteristics and engine performances, Rakopoulos et al. [20,21] evaluated the effect of DDE addition with different blending (8, 16, and 24% in volume) in a standard, single-cylinder, four-stroke diesel engine. They showed that with the increase of DDE blending ratio, the brake mean efficient pressure (BMEP) slightly goes down and brake specific fuel consumption (BSFC) shows a gradual rise due to the lower heating value of DDE. Additionally, Cinar et al. [22] investigated the effect of DDE addition on the regular emissions of a diesel engine fueled with diesel-biodiesel mixtures. When DDE is added into diesel and biodiesel mixture, a significant reduction in PM and CO was observed, with only slight increase in hydrocarbon and NOx emissions accompanied.

Regardless of these mentioned superiorities of DDE, both in engine performances and exhaust emissions, fundamental research work on the basic physical and chemical effects that induced by DDE addition is still quite inadequate. To understand the gas phase chemical oxidation process of DDE, Werler et al. [23] developed a DDE mechanism, which was validated against the measured ignition delay times data from 500 to 1300 K via a shock tube and a rapid compression machine. Considering the modern high-pressure common rail injection systems [24], the quality of mixture formation and injection system are becoming more and more important for a better engine performance and lower emission. We have recently investigated the effects of biofuel such as di-butyl ether, ethanol and bio-diesel blending on the spray characteristics of diesel [25,26], and results show that the spray characteristics such as the spray tip penetration evolution process, the spray cone angle, and

### Table 1

<table>
<thead>
<tr>
<th>Property</th>
<th>Diesel</th>
<th>Soybean Biodiesel</th>
<th>Ethanol</th>
<th>Diethyl ether</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/ml)</td>
<td>0.84</td>
<td>0.87</td>
<td>0.798</td>
<td>0.715</td>
</tr>
<tr>
<td>Reid vapor pressure (kPa) @ 25 °C</td>
<td>&lt; 0.2</td>
<td>–</td>
<td>15.8</td>
<td>110.2</td>
</tr>
<tr>
<td>Latent heat of evaporation (kJ/kg)</td>
<td>250</td>
<td>200</td>
<td>840</td>
<td>350</td>
</tr>
<tr>
<td>Lower calorific value (MJ/kg)</td>
<td>42.5</td>
<td>38.8</td>
<td>26.8</td>
<td>36.8</td>
</tr>
<tr>
<td>Octane number</td>
<td>40–55</td>
<td>&gt; 48</td>
<td>&lt; 8</td>
<td>&gt; 125</td>
</tr>
<tr>
<td>Boiling point (°C)</td>
<td>179–329</td>
<td>181–337</td>
<td>77</td>
<td>33</td>
</tr>
<tr>
<td>Viscosity (mPa.s) @ 25 °C</td>
<td>2.61</td>
<td>6.79</td>
<td>0.95</td>
<td>–</td>
</tr>
<tr>
<td>Oxygen content (wt%)</td>
<td>0</td>
<td>10</td>
<td>34.8</td>
<td>21.6</td>
</tr>
<tr>
<td>Carbon content (wt%)</td>
<td>87</td>
<td>78</td>
<td>52.2</td>
<td>64.9</td>
</tr>
<tr>
<td>Hydrogen content (wt%)</td>
<td>13</td>
<td>12</td>
<td>13</td>
<td>13.5</td>
</tr>
<tr>
<td>Molecular weight</td>
<td>170</td>
<td>296</td>
<td>46.1</td>
<td>74.1</td>
</tr>
</tbody>
</table>
SMD depends on the types of biofuel and their blending ratios. However, DEE blending on the spray and atomization characteristics of diesel, or diesel-biodiesel blends has been rarely conducted.

Due to the larger surface tension and viscosity of biodiesel, the premixed charge formation of DB (diesel/biodiesel blends) spray is expected to be decelerated, indicating an enhanced soot formation mechanism due to increased locally rich mixture formation in combustion engine. Thus our objective is to add some less viscous liquids such as ethanol or DEE into DB to see if the spray characteristics can be similar to that of neat diesel. This can be achieved by comparing the spray characteristics of diesel, DB (diesel/biodiesel blends), DBE (DB/ethanol blends), and DBDE (DB/DEE blends). More specifically, the spray macroscopic characteristics of diesel, DB, DEE, and DBDE, such as spray tip penetration (STP), the spray cone angle (SCA) and the spray projected area will be obtained over a wide range of experimental conditions, and previous empirical models for these spray macroscopic parameters will be validated against our experimental measurements. In addition, the spray microscopic characteristics, such as SMD and other statistical characteristic droplet diameter, the droplet diameter distribution probability (PDF), and cumulative volume (CDF) of the four fuels will also be examined.

2. Experiment setup and procedures

2.1. Types of fuels

Four types of fuels were studied in this work. Commercial #0 diesel fuel was obtained in local gas station from SINOPEC. The soybean biodiesel used in this study was purchased from Xi’an Bluesky Biological Engineering Corporation. Anhydrous ethanol and diethyl ether, were purchased from Aladdin Bio-Chem Company, and its purity is of analytical grade (99.8 and 99%, respectively). Because ethanol is a promising alternative biofuel candidate which has already aroused much research interest, we also compared the effect of ethanol and DEE addition on diesel-biodiesel blends.

In this work, #0 diesel (D100) is used as the basal fuel and we firstly prepared a mixture (DB), which consists of 20% biodiesel and 80% diesel in volume. Another two mixtures were also prepared by blending DB with 20% ethanol or DEE, and were respectively designated as DBE and DBDE. The absolute volume fractions of each component for the four fuels studied in this work are shown in Table 2. Without water cooling system we initially found that temperature control because the boiling point of DEE is around 33 °C, as shown in Table 1. Without water cooling system we initially found that the experimental results for DBDE is of poor repeatability. This is because the fuel line pressure rise due to pump compression process leads to an increase in fuel line temperature and once the high temperature DBDE in the fuel line is injected out of nozzle exit, DEE component in DBDE may quickly become gas phase because of the so-called reduced pressure boiling. This phenomenon significantly influences the fuel atomization process and the measured droplet size distribution results. As such, we have then added water cooling system to the fuel supply line and the measured results are found to be very repeatable.

The constant volume vessel is made of stainless steel and could withstand a pressure of 10 MPa without leakage. The inner shape of the vessel is a cylinder with inner diameter 200 mm and length of 260 mm. Three quartz windows with diameter of 100 mm and thickness of 60 mm are installed to allow for optical access. The ambient pressure in the constant volume vessel is built up by high pressure nitrogen filling. In this work, two ambient pressures were tested (2 and 4 MPa). A thermocouple and a pressure gauge installed in chamber wall were used to monitor chamber inner environment.

The macroscopic transient spray evolution process was recorded by a high speed camera (Phantom V611) with a sampling rate of 20,000 fps. Scattering light from a Xeon lamp is used for illumination. The resolution was set as 352 pixel × 640 pixel, and it is approximately equivalent to an actual window size of 63 mm × 128 mm, which is large enough to cover the whole spray periphery. A series of images of the typical spray morphology development is presented in Fig. 2. These images were converted into the corresponding gray-scale ones for latter spray periphery extraction.

Fig. 3 shows the sketch of the particle droplet image analysis (PDIA) system for the local spray microscopic characteristics detection. A single pulsed Nd:YAG laser with the wavelength of 532 nm is used as the light source. A diffuser is attached to the laser for the homogeneous illumination. The diameter of the lens at the head of the diffuser is 120 mm, which is larger than the diameter of the chamber window, so that the whole spray flow field is illuminated. A CCD camera (ImagerProSX 5 M), attached with a long focus microscope (Queststar QM1) is used to capture the local droplet distribution in spray. The camera and the long focus microscope are mounted on an electric positioner MC600. The precise displacement control (1 μm) of the electric positioner ensures the accurate determination of the scanning target position.

The calibration was carried out via a scaling plate with an accuracy of 25 μm. After calibration, the field of view was 1.7 mm × 1.3 mm. The commercial software DaVis 8.0.0 from LaVision is used to process the captured images, through which size of each droplet and its location coordinate are obtained. The position for the spray microscopic characteristic measurements is presented in Fig. 4. It is 50 mm down the center of injection nozzle exit, and 6 mm off the spray injection center.

<table>
<thead>
<tr>
<th>Fuels</th>
<th>Vol.% Properties of fuels</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>D100</td>
</tr>
<tr>
<td>Diesel</td>
<td>100%</td>
</tr>
<tr>
<td>biodiesel</td>
<td>0</td>
</tr>
<tr>
<td>ethanol</td>
<td>0</td>
</tr>
<tr>
<td>di-ether ether</td>
<td>0</td>
</tr>
<tr>
<td>Density (g/ml)</td>
<td>0.82</td>
</tr>
<tr>
<td>Viscosity (mPa.s)</td>
<td>2.96</td>
</tr>
<tr>
<td>Surface tension (mN/m)</td>
<td>25.9</td>
</tr>
</tbody>
</table>

Fig. 1 shows the sketch of the test rig. It includes primarily the high pressure fuel supply assembly, synchronization circuit, constant volume chamber and macroscopic optical path. A commercial high pressure common rail system, including the high pressure pipeline, high pressure pump, fuel filter, common rail and injector was purchased from Wuxi Fuel Injection Equipment Research Institute (FAW), China, and the whole fuel line can withstand a pressure as high as 220 MPa. The nozzle exit diameter is 0.2 mm, and the length to diameter ratio (L/D) of injector is 5.

In this study, four injection pressures (P_{ino}) were investigated (50, 100, 150 and 200 MPa). The fuel tank and fuel line temperature is kept at 25 °C by water cooling system. Special attention is needed for this temperature control because the boiling point of DEE is around 33 °C, as shown in Table 1. Without water cooling system we initially found that the experimental results for DBDE is of poor repeatability. This is because the fuel line pressure rise due to pump compression process leads to an increase in fuel line temperature and once the high temperature DBDE in the fuel line is injected out of nozzle exit, DEE component in DBDE may quickly become gas phase because of the so-called reduced pressure boiling. This phenomenon significantly influences the fuel atomization process and the measured droplet size distribution results. As such, we have then added water cooling system to the fuel supply line and the measured results are found to be very repeatable.

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axial. Vague droplets that are not on the focal plane will not be selected for statistics by setting gray intensity threshold value. Our previous studies [25,26] have shown that PDA measurements were consistent with that of Phase Doppler Anemometry (PDA) results [27] under identical conditions (< 5% deviation).

The common rail pressure is monitored by a remote electronic controller OD2301 from Beijing PowerMac Corporation with a closed-loop control. A pressure sensor installed on common rail can detect transient rail pressure, so that OD2301 controller can subsequently adjust the workload of high pressure pump to meet the designed rail pressure. Besides the rail pressure, the injection width, the camera trigger delay and laser trigger delay are also synchronized by OD2301. Because atomization is a highly transient process, it is necessary to investigate the time resolved spray characteristics. Since the NG:YAG laser pulse width is 4 ns, which is much shorter than the duration of the injection and the spray evolution as well as the CCD camera exposure time, transient spray at a specific time instant can be frozen by setting the laser trigger delay after the trigger signal of injection. The injection pulse width is set as 1.5 ms in this study.

Fig. 1. Schematic diagram of fuel supply system and macroscopic optical path.

Fig. 2. Typical raw images of the spray evolution process; diesel, $P_{ inj} = 60$ MPa, $P_{amb} = 2$ MPa.

Fig. 3. Schematic diagram of spray microscopic characteristic measurement system.

Fig. 4. Measurement position and typical image of microscopic characteristics.
or all other experimental conditions studied in this work, we ∼− ρ and the PP ρ, S C. Zhan et al. between the injection and the ambient gas pressure. When diameter of the nozzle, and t with t < break, the spray resides in the primary breakup region and STP grows linearly that the STP evolution process is divided into two stages, separated by a time after spray tip exits from the nozzle. Hiroyasu et al. [31] shows characterized the STP evolution behavior as a function of t that the density (ρi) difference among four fuel blends is negligibly small as shown in Table 2 (D100 ∼ DB, DBE ∼ DBDE), Eq. (1) then indicates that tbreak for different fuels are similar, which is evidenced by our experimental measurements as shown in Fig. 7(d).

\[ t_{\text{break}} = 0.39 \left( \frac{2 \Delta P}{\rho_i} \right)^{0.5} \cdot t \quad t > t_{\text{break}} \]

\[ STP = 2.95 \left( \frac{\Delta P}{\rho_i} \right)^{0.25} \cdot (D-T)^{0.5} \quad \text{tbreak} = 28.65 \cdot \rho_i \cdot D \left( \rho_i \Delta P \right)^{0.5} \]

In addition, with the increase of ΔP = P_{inj} − P_{amb} = P_{inj}, the Eq. (1) also shows a strong decrease of tbreak. This is also observed by the experimental observations. Mechanistically, we note that with the increase of P_{inj}, t0 is increased because t0 ∼ \sqrt{2(P_{inj}−P_{amb})/\rho_i}, and the increased t0 favors the breakup process and the tbreak time is then decreased with the increase of P_{inj}. This phenomenon about tbreak is coincident with spray evolution empirical model of Hiroyasu. The difference between experimental results and empirical model may be attributed to the injector structure, fuel supply system, and optical path setup, etc.

Fig. 8(a) shows the influence of the injection pressure on the STP evolution for DBDE. The ambient pressure was set as 4 MPa. It can be seen that as the injection pressure rises, the STP evolution is significantly accelerated. This is because higher injection pressure results

3. Results and discussion

3.1. Spray macroscopic characteristics

The spray tip penetration (STP) and spray cone angle (SCA) are two important parameters for fuel spray macroscopic behavior characterization [28]. As shown in Fig. 6, STP is defined as the axial distance from the center of the injection nozzle exit to the tip of spray cone. Because the periphery of spray is not perfectly cone shaped, it is difficult to directly measure its cone angle. The SCA is then defined as the angle covered by the two tangent lines, which connects the nozzle tip and the periphery points at the position of STP/2. Spray projected area is calculated through two steps. Firstly, calibration by correlating the actual spray area with captured image pixel is conducted. Secondly, the pixels within spray contour are counted through a Matlab program and the total projected spray area is calculated. The validity of our experiment apparatus has been demonstrated previously [25,26]. For each condition, we conduct three repeated experiments in order to gain the average macroscopic parameters.

3.1.1. Spray tip penetration and break-up regime

Fig. 7(a) shows measured STP and tbreak time for four blended fuels (D100, DB, DBE, and DBDE) under the P_{inj} of 50 MPa. The ambient pressure was 2 MPa. Previously, several studies [28–30] have characterized the STP evolution behavior as a function of t, which is the time after spray tip exits from the nozzle. Hiroyasu et al. [31] shows that the STP evolution process is divided into two stages, separated by a characteristic time tbreak, as referred by Eq. (1), in which \rho_i and \rho_g are the density of injected fuel and ambient gas respectively. D is the exit diameter of the nozzle, and \Delta P represents the pressure difference between the injection and the ambient gas pressure. When t < t_{break}, the spray resides in the primary breakup region and STP grows linearly with t. During this stage the emerging liquid jet from the nozzle hole exit immediately breaks up into large ligaments or droplets due to turbulence or cavitation that are generated inside the nozzle. These ligaments and droplets form the dense spray region near the nozzle. After t > t_{break}, subsequent breakup of the large sized liquid bulk in the dense spray region then further disintegrates into smaller droplets due to aerodynamic forces and the spray resides in the so-called second breakup region. The STP evolution in the second breakup stage is slower compared to that in the primary breakup stage. This is because the spray tip in this stage primarily consists of the droplets, and their velocity is gradually decreased because the momentum is transferred to the entrained gas. The STP shows a square root dependence on t, i.e., STP ∼ \sqrt{t} or all other experimental conditions studied in this work, we observed this consistent two stage STP evolution behavior, as shown in Fig. 7(b) and (c).

In addition, Fig. 7(a) also shows the effect of fuel type on STP evolution. Specifically, The STP evolution for different fuels remain almost the same in the primary breakup stage (t < t_{break}). While in the second breakup stage (t > t_{break}), slight difference among different fuels can be observed. The STP curve of DB is always higher than other three curves, while the STP curve of D100, DBE and DBDE almost overlap. This STP evolution behavior on the fuel type is more prominent at higher injection pressures, as shown in Fig. 7(b) and (c). The reason for this STP dependence on the fuel type should be attributed to physical property of four blended fuels listed in Table 2. Due to the addition of biodiesel, the surface tension and viscosity of DB is the highest among four blended fuels. Higher viscosity and surface tension makes DB harder to break up into small droplets when compared to other blended fuels. It is noted that though the viscosity and surface tension of DBE is slightly smaller than that of DB, however its final stage STP is larger than DBE, as shown by the data in the square in Fig. 7(c). This is because, DEE is more easily vaporized, compared to ethanol and the STP evolution of DBDE resembles DB more than DBE.

Furthermore, since t_{break} is a characteristic time that separates the primary break-up and secondary break-up stage. We have experimentally determined t_{break} for all test conditions, as shown in Fig. 7(d). The empirical equation (Eq. (1)) for t_{break} by Hiroyasu et al. [31] is also presented. Because the density (\rho_i) difference among four fuel blends is negligibly small as shown in Table 2 (D100 ∼ DB, DBE ∼ DBDE), Eq. (1) then indicates that t_{break} for different fuels are similar, which is evidenced by our experimental measurements as shown in Fig. 7(d).

Fig. 6. Definition of STP and spray cone angle.
in higher initial jet velocity $u_0$, which is equal to the slope of STP $\sim t$ line before $t_{\text{break}}$. The measured $u_0$ and $\sqrt{2(P_{\text{inj}}-P_{\text{amb}})/\rho_i}$ is compared in the inset figure and both of them show significant increase with the injection pressure. In addition, the measured $u_0$ is systematically smaller than $\sqrt{2(P_{\text{inj}}-P_{\text{amb}})/\rho_i}$. The spray tip will then gain more initial momentum and faster evolution at higher injection pressure. We have also included the empirical equation of Hiroyasu et al. (secondary break-up regime) on STP evolution in Fig. 8, and STP both shows a similar dependence on $t$.

Fig. 8(b) demonstrates the influence of the ambient pressure on STP evolution for DBDE. The $P_{\text{inj}}$ is 200 MPa. It is seen that in the primary break-up region, the STP of two curves nearly overlap with each other. This is because in the primary break-up regime, the break-up of the jet at the immediate nozzle down-stream only forms large ligaments or droplets and the STP of primary break-up regime then primarily depends on the initial jet velocity $u_0$ and 2 MPa increase in ambient pressure yields a negligible decrease in $\Delta P$, thus the decrease in $u_0$ due to ambient pressure increase is weak. However, as in the secondary break-up stage, as the spray tip penetrates, higher ambient pressure tends to slow down the spray tip penetration. This is because when $t > t_{\text{break}}$, the spray tip velocity is no longer the initial jet velocity $u_0$ because of significant formation of much smaller droplets in the secondary break-up stage. In addition, the increased density of ambient gas increases the shear stress on the spray cone periphery and the resistance force at the spray tip. Consequently the spray evolution is decelerated. In addition, the ambient pressure effect on the spray tip penetration is more obvious at later stage of spray evolution because more droplets are formed at spray periphery.
the steady injection process is then defined, as suggested by previous work \cite{25,26}.

Fig. 10 shows the mean SCA of DBDE under different $P_{\text{inj}}$ and $P_{\text{amb}}$. The mean SCA increases as the ambient pressure rises. This is because in the secondary break-up region, the increased ambient pressure increases the aerodynamic shear stress and favors the break-up of spray cone. In addition, the momentum of the droplets at the tip is converted to the radial direction due to the aerodynamic resistance force at the spray tip, and increased ambient pressure makes this resistance force effect more prominent. In addition, the mean SCA shows very weak dependence with the injection pressure because injection pressure increases the momentum flux and thus the STP and the injection pressure does not necessarily affect the SCA evolution. Fig. 11 shows the mean SCA of the four fuels, it is seem that the mean SCA of the DB and D100 are very similar, the mean SCA of DBE is higher. This is because the density of DB and D100 are slightly higher than that of DBE and DBDE. For liquids with smaller density of DB and D100 are slightly higher than that of DBE and DBDE. We also note that the mean SCA for DBDE is less than DBE this is because the high volatility of DEE in DBDE favors the vaporization of droplets in DBDE spray cone periphery and it results in a reduced mean SCA of DBDE than DBE. If we do not consider the case for DBDE, which will be influenced by DEE vaporization, our experimental observation on the dependence of mean SCA on the ambient pressure, injection pressure and liquid density is qualitatively consistent with the empirical correlation of Hiroyasu and Arai \cite{31}.

3.1.3. Spray projected area

Fig. 12 respectively shows the measured spray projected area of the four blended fuels as a function of time. The $P_{\text{inj}}$ is set as 50 MPa and $P_{\text{amb}}$ is set as 4 MPa. Spray projected area represents the mixing extent of fuel mass with ambient gas, and larger spray area is expected to result in a better mixture formation.

The spray area curve of DBE which owns the largest mean SCA is at the top of three other blended fuels. However, the difference between four curves is not significant because the weak dependence of the SCA on the fuel type, as presented in Fig. 11. In order to evaluate the spray projected area, the cross section of the spray is assumed as a combination of an isosceles triangle and a semi-circle, such that the spray projected area $A$ can be roughly estimated by Eq. (2).

$$
A = \frac{STP^{2}\tan\left(\frac{\phi}{2}\right)}{1 + \tan\left(\frac{\phi}{2}\right)} + \frac{\pi STP^{2}\tan\left(\frac{\phi}{2}\right)^{3}}{2\left[1 + \tan\left(\frac{\phi}{2}\right)^{2}\right]^{3}}
$$

(2)

In Eq. (2), when the SCA ($\phi$) is kept constant, the spray area $A$ is proportional to $STP^{2}$. So the evolution of spray area is also divided into two stages, similarly as STP evolution. In the primary break-up regime, we can gain a linear relation between spray area and $t$ at logarithmic coordinate system in Fig. 12. When it comes into secondary break-up regime, the slope of line is smaller than that of primary break-up regime.

Fig. 13(a) and (b) respectively demonstrates the effect of injection pressure and ambient pressure on DBDE spray projected area. In Fig. 13(a), the spray area is mainly affected by STP because SCA is insensitive to variation of $P_{\text{inj}}$ (see Fig. 10), while STP significantly increases with $P_{\text{inj}}$. In addition, Fig. 13(b) shows that for a fixed injection pressure, higher ambient pressure increases the SCA before $t_{\text{break}}$. While it reduces the spray projected area in secondary break-up regime. This is because in the primary breakup stage, the STP is not affected by ambient pressure, but higher ambient pressure increases the mean SCA as shown by Fig. 10. In the secondary break-up stage, the STP is significantly reduced by increasing ambient pressure (see Fig. 5b), and its effect is more prominent that the increased SCA on the projected area, resulting in a reduced spray projected area after $t_{\text{break}}$. 

3.1.2. Average spray cone angle

Fig. 9 shows spray cone angle (SCA) evolution of DBDE at $P_{\text{inj}}$ 200 MPa, $P_{\text{amb}}$, 4 MPa. At initial stage of the injection process, SCA varies a lot because the overall morphology of spray cone has not come into a steady state due to the transient nature of initial needle valve opening, inner nozzle flow and low pressure fuel deposit of the last injection. When needle valve is completely opened, the SCA is almost constant before the needle valve closes, and a mean value of SCA during
4. Spray microscopic characteristics

In this section, we will discuss the spray microscopic characteristics for the four blended fuels studied in this work. There are several statistical parameters which are frequently used to represent spray microscopic characteristics. These parameters include the droplet diameter distribution probability, the cumulative volume fraction and the characteristic diameter listed in Table 3. The probability of droplet diameter, or the so called probability density function (PDF) is the number of droplets with a particular diameter divided by the total number of droplets [25,26,32,33]. The cumulative volume fraction (CDF) is defined as the volume of the droplets whose diameter is lower than a particular value, divided by the total volume of all droplets. The increase of cumulative volume fraction for a particular diameter indicates that more droplets with diameters is smaller than this particular diameter. Sauter mean diameter (SMD) is equal to the value of the sum of all droplets surface area divided by the sum of all droplets volume, as in Eq. (3).

\[
SMD = \frac{\sum_{i=1}^{n} d_i^3}{\sum_{i=1}^{n} d_i^2}
\]  

Fig. 14 shows the SMD as a function of the number of droplets. It is seen that, when the droplet number is smaller than 4000, the SMD of the droplets shows a random dependence on the total number of droplets. When the droplet number is large enough (> 4000), the statistical SMD is a constant, indicating that a physically meaningful statistical SMD can only be achieved with enough droplet samples. For each blended fuel, more than 4000 number of droplets are sampled for statistics under identical condition to ensure the reliability of experiment results. Other frequently used characteristic diameters such as Dv10, Dv50 Dv90 are also listed. Dv10 (50, and 90) respectively means that the sum of the volume of droplets whose diameter is smaller than Dv10 (50, 90) accounts for 10 (50, and 90) percentage of the summation of the volume of all the droplets. Relative diameter range (Δs) represents the inhomogeneity of total droplets diameter distribution and is defined in Eq. (4). Small Δs means there is a higher level of homogeneity of the droplet sizes.

\[
\Delta s = \frac{Dv_{90} - Dv_{10}}{Dv_{50}}
\]  

4.1. Droplet diameter distribution probability

Fig. 15 shows the droplet diameter distribution probability curves for (a) four blended fuels different fuels, (b) different injection pressures and (c) different ambient pressures. For given injection and ambient pressure (Fig. 15(a)), the number fraction of larger droplets decreases sequentially in the order of DB, D100, DBE, and DBDE, while the number fraction of smaller droplets increases in the same order. In addition, though the peak number fraction droplet diameter for different fuels are similar (15 μm), the peak value increases sequentially in the order of DB, D100, DBE, and DBDE. This implies that in engines, the addition of biodiesel will decelerate the droplet evaporation and mixture formation process of diesel spray, and further addition of ethanol or DEE will compensate this decreased mixture formation process.

With the increase of injection pressure (Fig. 15(b)), the curve is gradually shifted to the smaller droplet side. In addition, the peak value of the number fraction increases. With the increase of ambient pressure (Fig. 15(c)), the number fraction of larger droplet increases while the number fraction of smaller droplet decreases. In addition, the peak value of the number fraction decreases with the increase of the ambient pressure.

4.2. Droplet cumulative volume distribution fraction

Fig. 16 shows the effect of (a) fuel type, (b) injection pressures and (c) ambient pressures on the cumulative volume curves as a function of droplet diameter. For given injection and ambient pressure (Fig. 16(a)), the cumulative volume curve of DBDE is higher than the other three blended fuel curves. What’s more, for fixed cumulative volume, take 50% as an example, Dv50 for DBDE is the smallest (23 μm), followed by D100, DBE and finally DB. The decreased characteristic diameter in the order of DB, D100, DBE, and DBDE is consistent with the observation in Fig. 15(a). With the increase of the injection pressure in Fig. 16(b), the characteristic droplet diameter tends to decrease. Specifically, Dv50 decreases from 30 to 20 μm when P inj increases from 50 to 200 MPa. With the increase of the ambient pressure in Fig. 16(c), the characteristic droplet diameter tends to mount up, however this increase seems to be weakened at higher ambient pressure.
4.3. Characteristic droplet diameter

The effect of fuel type, injection pressure and ambient pressure on the PDF in Section 3.2.1 and CDF in 3.2.2 all indicate that the formation of smaller droplet will be favored by the higher injection pressure, and the lower ambient pressure. In addition, fuel type also shows a noticeable influence on the formation of smaller droplet. These results can be further demonstrated by the characteristic droplet diameter ($D_{v10}$, $D_{v50}$, and $D_{v90}$) dependence on the fuel type as in Table 2 and the SMD dependence on the fuel type, injection pressure and ambient pressure as in Fig. 17.

It can be seen from Table 3 that, average droplet diameter of DBDE that can be characterized either by $D_{v10}$, $D_{v50}$ or $D_{v90}$ and these characteristic diameters for DBDE are the smallest, and even smaller than that of diesel, while the characteristic diameters of DB are the largest. It is then suggested that blending 20% biodiesel into diesel (DB) will lead to a larger average droplet diameter, which will potentially slow down the fuel evaporation and mixture formation process. Addition of 20% ethanol into DB decreases the average droplet diameter to a similar value of $D_{100}$. Blending 20% DEE into DB will be potentially capable for improving the mixture formation process because the average diameter is even smaller than $D_{100}$.

Fig. 17 shows SMD curves of four blended fuels as a function of (a) injection pressure and (b) ambient pressure. As shown in Fig. 17(a), for $P_{inj}$ is set as 50 MPa, the Sauter mean diameter of DBDE is the smallest one among four blends, and similar dependence of the characteristic diameter on the fuel type is observed at other injection pressure conditions. For given fuel, the SMD is significantly reduced with the increase of the $P_{inj}$ in Fig. 17(a) and slightly decreased with the increase of the $P_{amb}$ in Fig. 17(b). What’s more, the SMD curve of DBDE is always

### Table 3

Spray characteristic diameters of four blended fuels under 200 MPa injection pressure.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>D100</th>
<th>DB</th>
<th>DBE</th>
<th>DBDE</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_{v10}/\mu m$</td>
<td>15.42</td>
<td>16.23</td>
<td>15.80</td>
<td>14.53</td>
</tr>
<tr>
<td>$D_{v50}/\mu m$</td>
<td>24.34</td>
<td>25.77</td>
<td>24.41</td>
<td>22.58</td>
</tr>
<tr>
<td>$D_{v90}/\mu m$</td>
<td>34.44</td>
<td>37.17</td>
<td>35.64</td>
<td>31.81</td>
</tr>
<tr>
<td>Δs</td>
<td>0.78</td>
<td>0.81</td>
<td>0.81</td>
<td>0.77</td>
</tr>
<tr>
<td>Number</td>
<td>4487</td>
<td>4900</td>
<td>4772</td>
<td>4108</td>
</tr>
</tbody>
</table>

Fig. 14. Variation of SMD with the total number of sampling droplets for statistics.

Fig. 15. Probability curves of DBDE under different experimental conditions.
at the bottom of D100 curve in Fig. 17 (b), which means that the addition of DEE will facilitate the droplets break up process in tested $P_{\text{amb}}$ compared to D100.

In fact, SMD, droplet diameter distribution probability (PDF), cumulative volume (CDF) and SMD are the different data processing approaches in statistics based on the same original droplets diameter. Our experiment result (Figs. 15–17) both shows that the addition of DEE, high $P_{\text{inj}}$ and low $P_{\text{amb}}$ will accelerate the little droplets formation process in secondary break-up regime. Because the surface tension and dynamic viscosity of DEE is much lower than that of diesel and biodiesel (shown in Table 2), the fuel ligaments and large droplets are more easily to break up into smaller droplets and hence more small droplets will be produced with the addition of DEE. Similarly, by comparing the volume curves in Fig. 16(b), we can conclude that, the increase of injection pressure will intensify air-fuel entrainment process. And this is because that the initial momentum will get immense increase in high $P_{\text{inj}}$, thus induce more instability factors and adequate energy for break-up process. In addition, as shown in Fig. 17(b), dense ambient gas can enhance the ambient gas resistance and reduce the large droplet velocity, which is not benefit to the formation of tiny droplets.

5. Conclusion

In this work, we have investigated the spray macroscopic as well as microscopic characteristics for four blended fuels, D100, DB, DBE, and
DBDE, at injection pressure as high as 200 MPa.

For macroscopic characteristics, the spray tip penetration exhibits a two stage behavior separated by a critical time $\Delta t_{break}$, i.e., in the primary break-up stage, the STP shows no dependence on the fuel type, while in the secondary break-up stage the STP decreases sequentially in the order DB, DBE, D100 and DBDE. The measured critical time for primary to secondary break up transition ($\Delta t_{break}$) shows very weak dependence on the fuel type, but it greatly decreases with the increase of the injection pressure, which qualitatively agrees with previous empirical equations. The mean SCA is the most sensitive to the increase of the ambient gas density because it increases aerodynamic resistance which tends to push the droplets aside to spray periphery. The fuel type shows weak influence on the spray cone angle, though the SCA of the DBE is the largest among the four fuels. The spray projected area can be estimated by STP and mean SCA.

For microscopic characteristics, results show that for given fuel, the characteristic droplet size is significantly decreased with the increase of the injection pressure and is moderately decreased at lower ambient pressure. Adding 20% biodiesel into diesel increases the characteristic droplet size. Further adding 20% ethanol into DB decreases the characteristic droplet size to the value that is comparable to neat diesel, while adding 20% DEE into DB leads to a characteristic droplet size even smaller than that of neat diesel, indicating that the presence of ethanol or DEE will be potentially favoring the atomization process of DB.

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[15] E. Zhan et al. the secondary break-up stage the STP decreases sequentially in the order DB, DBE, D100 and DBDE. The measured critical time for primary to secondary break up transition ($\Delta t_{break}$) shows very weak dependence on the fuel type, but it greatly decreases with the increase of the injection pressure, which qualitatively agrees with previous empirical equations. The mean SCA is the most sensitive to the increase of the ambient gas density because it increases aerodynamic resistance which tends to push the droplets aside to spray periphery. The fuel type shows weak influence on the spray cone angle, though the SCA of the DBE is the largest among the four fuels. The spray projected area can be estimated by STP and mean SCA.

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