SPRAY AND COMBUSTION VISUALIZATION OF BIO-DIESEL IN A DIRECT INJECTION DIESEL ENGINE

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By using the self-developed dynamic visualization photographic setup, this article investigated some major factors affecting the spray and combustion process of diesel engine fueled by biodiesel. The experimental results show: With the increase of biodiesel percentage, fuel injection advances slightly, the ignition delay becomes shorter and the duration of combustion lengthens. Engine speed has little effect on the spray. However, the combustion rate is increased and the burning time becomes shorter with the increase of engine speed, although the duration of combustion in terms of crank angle increases. With the increase of needle opening pressure, both the spray cone angle and the spray penetration of biodiesel increases, the atomization of spray improves, the ignition delay and the duration of combustion becomes shorter, the peak pressure increases.

Key words: DI diesel engine, biodiesel, spray, combustion visualization

1. Introduction

Diesel engines are the axis of world industry[1]. With soaring oil prices and increased concern on greenhouse emissions, many are looking to biofuels as a renewable and cleaner source of energy. However, biofuels are different from fossil fuels in both chemical and thermophysical properties, and cannot be directly used in the engines without any other adjustment. It is well known that the performance and emissions of internal combustion engines are significantly affected by the combustion process, while fuel injection process has an important impact on the organization and effectiveness of the combustion process, so to improve the fuel efficiency and reduce emissions, it is essential to make a fundamental study on the spray and combustion process of diesel engine fueled by biodiesel or blend fuel.

Spray and combustion visualization is a powerful tool to study the working process of diesel engine. Lee et al. obtained the spray velocity through the particle image velocimetry (PIV) method and analyzed the spray characteristics under ambient pressure conditions and the injection timing in an optical engine. They found that the homogenous diffusion rate increased as the injection timing advanced [2]. Lee et al. visualized the initial flame propagation in a 4-valve SI engine by an ICCD camera, and investigated the effects of in-cylinder flow patterns on combustion. It was found that a correlation existent between the stronger tumble during induction and turbulence levels at the time of ignition results in a faster flame development[3]. Lachaux et al. visualized in-cylinder unburned hydrocarbon during low-temperature compression-ignition engine combustion using
formaldehyde PLIF. It was concluded that for long ID conditions, mixtures near the injector after the end of injection were too lean to achieve complete combustion, thus contributing to UHC emissions[4]. Fajardo et al. developed and applied a new, high-speed, UV PIV technique to a fired, spray-guided spark-ignition direct-injection engine. An increase in the shear strain rate was observed in approximately 50% of the cycles[5]. Wu et al. presented an experimental study on the spray structure of oxygenated fuel as well as diesel fuel by laser based visualization and PIV technique. They found that the spray of oxygenated fuel showed an umbrella-shape structure, a larger spray angle, and a shorter spray tip penetration than diesel fuel[6]. Miles et al. measured the vertical plane velocity with PIV in an operating direct-injection diesel engine. A stable toroidal vortex was formed above the piston top, which prevented fluid exiting the bowl and had potential to trap and inhibit further mixing of partially oxidized fuel and soot [7].

In recent years, to address people’s concern on greenhouse gas emission and global warming, many countries pay more attention to clean alternative fuel for power machine[8]. Alam et al. conducted in-cylinder visualization of spray and combustion with BP15 diesel fuel and three blends of diglyme with BP15. The highest premixed burn peak and the lowest premixed burn peak were observed with BP15 and O-95 fuels, respectively[9]. Saravanan et al. studied the performance, combustion and emission characteristics by injection hydrogen in the intake port. It was observed that hydrogen with diesel resulted in increased brake thermal efficiency by 20% and oxides of nitrogen (NOx) showed an increase of 13% compared to diesel [10]. Suh et al. investigated the effect of injection parameters on the characteristics of dimethyl ether (DME) in a diesel engine with experimental and analytical models based on empirical equations. The results indicated that DME showed better spray characteristics than conventional diesel fuel[11]. Chen et al. studied combustion characteristics and PM emission of diesel engines using ester-ethanol-diesel blended fuels. The results showed that with increasing ethanol in the blended fuel, both smoke and PM could be reduced[12].

The effects of biodiesel blends on the performance and emissions of diesel engines have been studied by quite a number of researchers, and almost all of them showed a significant potential to reduce emissions [8, 13-15]. For bio-diesel spray and combustion process, Delacourt et al. investigated the effect of needle opening pressure on the macroscopic spray characteristics via a constant volume chamber. The results obtained made it possible to extend the application fields of the temporal evolution law[16]. Pogorevc et al. did diesel and biodiesel fuel spray simulations, and found that biodiesel physical properties showed positive influence by distributing spray over a larger area of the piston chamber in the unmodified conventional injection M system. Nevertheless, there were some negative factors, such as bigger spray droplets and a slower evaporation process[17]. Kastengren et al. examined the structure of biodiesel-blend sprays from a common rail injector with X-ray radiography. The results suggested that gross spray structure of biodiesel-blend fuel is quite similar to the structure of Viscor. While the needle opening transient occurred differently when different fuels are used[18]. He et al. measured the spray characteristics of biodiesel, such as spray tip penetration and spray cone angle in a constant volume chamber. It was found that the final tip penetrations and cone angles of biodiesel were greater than that of diesel due to its higher viscosity, density and bulk modulus[19]. Kegl et al. optimized fuel injection system for diesel and biodiesel usage[20]. Rakopoulos et al. revealed how the widely differing properties of these fuels against the normal diesel fuel affected the spray formation and combustion mechanism[21]. Suh et al. investigated the effect of biodiesel blending fuel on the spray, atomization characteristics, and emissions in a direct injection diesel engine[22]. Ghorbani compared combustion of B5, B10, B20, B50, B80 and B100 with petroleum diesel over wide input air flows at two energy levels in an experimental boiler. The findings showed that at higher level energy diesel efficiency was a little higher than that of biodiesel, but at lower level energy biodiesel is more efficient than diesel. Except B10, Biodiesel and
other blends emitted less pollutants of CO, SO2 and CO2 than diesel[23]. However, the study on internal combustion engines fueled by biofuels or blend fuels is still at its early stage, only very limited works have been done to study the combustion process in an optical engine.

For the combustion process in an optical engine, Fang et al. investigated the influences of different injection strategies and biodiesel blends on the spray and combustion process, measured and analyzed the in-cylinder pressure, needle lift and net apparent heat release rate. Their research was based on common-rail injection system [24, 25]. Mancaruso applied optical diagnostic techniques in the cylinder of an optically accessible engine equipped with latest-generation EURO 5 diesel engine head and high percentage of EGR, investigated the effect of fuels on the combustion process and pollutants formation [26]. These studies focused on modern diesel engine with common-rail fuel supply system. Currently, there are still millions of diesel engines with normal injection system being used in developing countries such as China and India. Furthermore, the owners of these engines are more willing to use biodiesel or blend fuels. However, the study on it is still evidently premature, this is the reason behind the present study.

In this work, we developed a dynamic visualization photographic setup and investigated the effects of several important operating parameters on spray and combustion process in an optical engine with realistic piston geometry. It is expected that this work can help to better understand the major factors affecting the combustion process and the performance of biodiesel in an engine with low pressure fuel supply system.

2. Experimental Set-up and Method

The schematic of the experimental set-up is shown in Fig.1. It consists of an optical engine, a laser source (Model:5500ACM, the waveleng:337nm), an electronic control unit, a starter motor, an in-cylinder pressure measurement system, a needle lift measurement instrument (Model:WH-2) and a high-speed digital camera (Model:X4-Plus, maximum frame rates:200000 frames/sec). The optical engine was modified from a
single-cylinder engine via lengthening the cylinder and piston. The crown of the piston is made of quartz to provide optical access to the combustion chamber. Key specifications of the engine are summarized in Table 1.

<table>
<thead>
<tr>
<th>Table. 1 specifications of the tested engine</th>
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<tbody>
<tr>
<td>Engine</td>
</tr>
<tr>
<td>Type</td>
</tr>
<tr>
<td>Bore</td>
</tr>
<tr>
<td>Stroke</td>
</tr>
<tr>
<td>Type of combustor</td>
</tr>
<tr>
<td>Displacement/cylinder</td>
</tr>
<tr>
<td>Compression ratio</td>
</tr>
<tr>
<td>Swirl Ratio</td>
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<tr>
<td>Nozzel</td>
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</table>

The optical engine is driven by an external electric motor. When it reaches the specified speed, the electronic control system works and controls a series of events automatically, such as fuel injection and activating the camera. The basic measurement procedure is: switch on the laser light source; turn on the electrical motor and adjust the potentiometer so that the speed increases to the required value; Switch on the high speed camera and the control system; single injection in the next operating cycle, taking picture and test the in-cylinder pressure and the needle lift data.

The working principle of the photographic system is: The continuous laser light source is expanded to a parallel beam of 80mm in diameter by an autocollimator. After going through a half mirror, the light beam changes its direction by a reflector and goes through the quartz piston into the combustion chamber. The light beam with the information of spray and combustion is reflected by a metal coating painted on the cylinder head and return to the half mirror along the same route, and then enters the camera.

The visible portion of the chamber is shown in Fig. 2. The diameter of visual range reaches 62mm. The figure also shows the location of inlet valve, exhaust valve, nozzle (Multi-hole injector, Model: DLL154S432) and pressure sensor (Model: 6052B). The offset of the combustion chamber and nozzle is 5 mm, and the nozzle installation angle is 25°.
Two types of base fuels and two blended fuels were experimented with. Table 2 shows some properties of the two base fuels. Blended fuels is defined according to the ratio of the biodiesel, such as B20 is 80% volume diesel oil along with 20% volume biodiesel, B100 is pure biodiesel.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Biodiesel</th>
<th>Diesel oil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density @ 20°C, g/cm³</td>
<td>0.883</td>
<td>0.835</td>
</tr>
<tr>
<td>Flash Point,°</td>
<td>170</td>
<td>55</td>
</tr>
<tr>
<td>Calorific Value, MJ/L</td>
<td>33.650</td>
<td>35.000</td>
</tr>
<tr>
<td>Sulfur Content, wt%</td>
<td>0.0005</td>
<td>0.026</td>
</tr>
<tr>
<td>Oxygen Content, Vol.%</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>Cetane Number</td>
<td>60.1</td>
<td>50.0</td>
</tr>
<tr>
<td>Solidifying Point,°</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Condensation Point,°</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Viscosity @ 20°C, mm²/s</td>
<td>8.06</td>
<td>3.39</td>
</tr>
<tr>
<td>Origin</td>
<td>Acidic oil from Plant scrap</td>
<td></td>
</tr>
<tr>
<td>Saponification value</td>
<td>193.2</td>
<td>-</td>
</tr>
<tr>
<td>Iodine values</td>
<td>77</td>
<td>-</td>
</tr>
<tr>
<td>Bulk modulus [MPa]</td>
<td>1650</td>
<td>1490</td>
</tr>
</tbody>
</table>

The testing conditions (unless specially mentioned) are: Injection timing of 20°BTDC, needle opening pressure of 25 MPa, injection mass of 30mg, engine speed of 800 r/min. Camera operated at a speed of 10,000 frames/sec with a resolution of 128 × 128 pixel.

3. Results and discussion

The impact of various operating parameters on the spray, combustion process and performance of the diesel engine are investigated. Below is a detailed description and discussion.

3.1 Effect of Fuel Properties on Spray and Combustion
Fig. 3 Spray and combustion images of different types of fuel vs crank angle

Fig. 3 shows spray and combustion images with different types of fuel with respect to crank angle. The detected intensity of image changes with the transparency of the combustion chamber and the luminous intensity from combustion reaction. For example, the image changes to dusk during fuel atomization and turn to bright when burning starts. The images indicate that the emergence time of the spray is 13.92 ° CA BTDC, 14.88 ° CA BTDC, 14.88 ° CA BTDC, 15.36 ° CA BTDC for 0# Diesel oil, B20, B60, B100, respectively.
Fig. 4 shows in-cylinder pressures and needle lift data under the same engine speed. It can be seen from these figures that the fuel injection start point advances slightly with the increase of biodiesel percentage. This is because the volume modulus of the biodiesel is larger than 0 # diesel oil, and its compressibility is lower than the 0 # diesel oil. So pressure wave spreads faster, the time of fuel moving from oil supply valve to the nozzle becomes shorter with the increase of biodiesel percentage in the fuel.

Fig. 3 shows that the spray impinges the inner wall of the combustion chamber, then most of the spray spreads toward the direction of swirl, and only a small amount of oil spreads reversely along the wall. It can be seen from the figure, at the point of about 4 ° CA BTDC, the combustion chamber is dimmer for B60 than for B20, which indicates that more droplets is rebounded for B60. This trend is more evident for B100. This is because the viscosity of fuel increases with the increase of biodiesel percentage, resulting in a greater penetration.

From Fig. 3, we can see that the ignition locations and ignition timing are varied for different fuels. The ignition location is close to the center of the combustion chamber for 0 # diesel and B20, while it appears near the combustion chamber wall for B60 and B100. This is because B60 and B100 have a greater viscosity, its spray penetration increases and the spot to reach ignition conditions appears at a relatively remote place. Visible flame appeared at 2.88 °, 3.84 °, 4.32 ° and 5.76 ° CA BTDC for the four kinds of fuels, and the ignition delay periods are 11.04 °, 11.04 °, 10.56 ° and 9.63 ° CA, respectively. In another word, the fuel ignition advances and the ignition delay reduces with the increase of biodiesel percentage. This can be explained by two reasons: bio-diesel contains oxygen and is easier to reach ignition condition; The cetane number of bio-diesel is higher than that of 0 # diesel oil and can meet the requirements of working conditions faster.

For different fuel, combustion duration is different in terms of crank angle. For example, it is 57.74 °, 62.46 °, 63.36 ° and 70.08 ° CA ATDC for diesel, B20, B60 and B100, respectively. The results indicate that the combustion duration is lengthened with the increase of biodiesel content in the case of the same fuel supply advance angle. This is due to the fact that biodiesel has a higher viscosity, resulting in a poor atomization and evaporation.

It can be seen from Fig. 4 that the peak pressure are 11.154MPa, 11.196MPa, 11.207MPa, 11.249Pa for 0
# diesel, B20, B60 and B100 respectively, there is a slight increase in the peak pressure. Furthermore, the peak pressure of B20, B60 and B100 comes earlier than 0 # diesel oil. This can also be explained by the fact that the ignition timing advances with the increase of bio-diesel percentage.

### 3.2 Effect of engine speed on spray and combustion of biodiesel

![Spray and combustion images](image)

(a) 900 rpm

(b) 1000 rpm

**Fig. 5** Spray and combustion images of different rotate speed at different crank angles

Fig. 5 shows the images of spray and combustion process for B100 at the rotating speed of 900 r/min and 1000 r/min, respectively. From Fig.3 and Fig.5, it can be seen that spray cone angle and spray penetration are almost unchanged with the increase of engine speed, it indicates changing engine speed from 900r/m to 1000 r/min has little effect on Spray Characteristics of Biodiesel. However, the injection time is different at different engine speed. For example, it is 15.36 °, 14.04 ° and 12.6 ° CA BTDC for the engine speed of 800, 900 and 1000r/min respectively. It indicates biodiesel injection time in terms of crank angle retards as the engine speed increases.
Visible flame appeared in the combustion chamber at 5.76 °, 3.78 ° and 2.4 ° CA BTDC for the engine speed of 800, 900 and 1000 r/min respectively. Fig.6 shows in-cylinder pressure curve. The peak pressure has the highest value for the engine speed of 1000 r/min. This is due to a couple of reasons: First, the swirl intensity in the combustion chamber increases with the increase of engine speed; second, the leakage of gas and heat loss reduces, resulting in a higher compression pressure and temperature, subsequently improving the atomization and evaporation of fuel.

By comparing the combustion process of biodiesel under different engine speed (the end point of combustion is 70.08 ° CA ATDC at 800 r/min, 75.6 ° CA ATDC at 900 r/min and 81.6 ° CA ATDC at 1000 r/min respectively), it is found that the combustion duration in terms of crank angle increases with the increase of engine speed, but the burning time slightly shortens (14.6ms for 800 r/min, 14ms for 900 r/min, 13.6 ms for 1000 r/min).

### 3.3 Effect of needle opening pressure on spray and combustion process of biodiesel

The spray and combustion images of biodiesel under different needle opening pressure at the speed of 800 r/min are shown in Fig.7. Fig.8 shows the in-cylinder pressure and needle lift data. From Fig.3, Fig.7 and Fig.8, it can be seen that fuel appeared in the combustor at about 15 ° CA BTDC, and the spray cone angle and the spray penetration are slightly larger at the needle opening pressure of 32MPa. For example, the spray cone angle (only liquid phase was considered, The actual spray angle including vapor phase should be much larger) is 21° at 12.96 ° CA BTDC for the needle opening pressure of 32Mpa. However, It is only 19° at 12 ° CA BTDC for the needle opening pressure of 18Mpa.
This is because the flow velocity of fuel increases with the increase of the needle opening pressure, so the Reynolds number increases, resulting in a bigger spray cone angle.

Fig. 7 shows that the rebounding of spray occurs at about 8° CA before burning. With the increase of the needle opening pressure, the amount of fuel accumulated near the wall reduces slightly. This is because more air is entrained into the spray with the increase of the needle opening pressure, meanwhile, due to the higher speed of spray, the impact force increases, resulting in a stronger rebounding.

The ignition delay is different under different needle opening pressure. It becomes shorter with the
increase of the needle opening pressure. From the Fig. 3 and Fig. 7, it can be observed that the ignition delay were 9.6 ° CA, 9.76 ° CA and 10.56 ° CA when the needle opening pressure were 32MPa, 25MPa and 18MPa respectively. The reason is that the fuel atomization is improved with the increase of needle opening pressure, and the mixing of fuel and air is enhanced, so the ignition delay reduces.

The duration of combustion is also different under different needle opening pressure. Biodiesel began to burn at the crank angle of about 5.76 ° CA BTDC when the needle opening pressure is 32MPa, and the combustion ends at about 65.28 ° CA ATDC. As the needle opening pressure is 18MPa, biodiesel began to burn at 4.8 ° CA BTDC, and the combustion ends at about 73.92 °CA ATDC, the duration of combustion is 7.68 °CA longer. In another word, the duration of combustion decreases with the increase of the needle opening pressure.

Fig.8 shows the in-cylinder pressure curve at different needle opening pressure. The maximum needle lift increases with the increase of the needle opening pressure. The peak pressure has the highest value for case with needle opening pressure of 32 MPa, and it is 0.625MPa higher than the 25MPa case and 0.951MPa higher than the 18MPa case. Furthermore, it comes earlier than the other two cases. This phenomenon further prove that the fuel atomization and combustion process is improved with increase of the needle opening pressure.

4. Conclusions

This work has been dedicated to investigating the effects of bio-diesel on the combustion process in an optical diesel engine. The findings are summarized as follows:

(1) With the increase of biodiesel percentage, fuel injection advances slightly, the ignition delay is shorter and the duration of combustion becomes longer.

(2) Changing engine speed from 800r/p to 1000 r/m has little effect on spray characteristics of biodiesel.

(3) Within the test range, the higher the engine speed, the faster the bio-diesel’s burning rate, and the bigger the peak pressure. However, the duration of combustion in terms of crank angle increases.

(4) The needle opening pressure has a significant impact on the bio-diesel spray characteristics. With the increase of the needle opening pressure, the spray cone angle and penetration increase, the ignition delay and the combustion duration shortens, and the peak pressure increases.

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