SPRAY AND COMBUSTION VISUALIZATION OF BIODIESEL IN A DIRECT INJECTION DIESEL ENGINE

by

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By using the self-developed dynamic visualization photographic set-up, 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: *direct injection diesel engine, biodiesel, spray, combustion visualization*

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 and Lee [2] 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. Lee *et al*. [3] visualized the initial flame propagation in a 4-valve spark ignition (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

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flame development. Lachaux and Musculus [4] visualized in-cylinder unburned hydrocarbon during low-temperature compression-ignition engine combustion using formaldehyde planer laser induced fluorescence (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 unburned hydrocarbon (UHC) emissions. Fajardo and Sick [5] developed and applied a new, high-speed, UV PIV technique to a fired, spray-guided SI direct injection engine. An increase in the shear strain rate was observed in approximately 50% of the cycles. Wu *et al.* [6] 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 lager spray angle, and a shorter spray tip penetration than diesel fuel. Miles *et al.* [7] 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.

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.* [9] 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. Saravanan *et al.* [10] studied the performance, combustion and emission characteristics by injecting hydrogen in the intake port. It was observed that hydrogen with diesel resulted in increased brake thermal efficiency by 20% and NO_x showed an increase of 13% compared to diesel. Suh and Lee [11] 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. Chen *et al.* [12] studied combustion characteristics and particulate matter (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.

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.* [16] 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. Pogorevc *et al.* [17] 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. Kastengren *et al.* [18] 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 occured differently when different fuels are used. He *et al.* [19] 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. Kegl *et al.* [20] optimized fuel injection system for diesel and biodiesel usage. Rakopoulos *et al.* [21] revealed how the widely differing properties of these fuels against the normal diesel fuel affected the spray formation and combustion mechanism. Suh *et al.* [22] investigated the effect of biodiesel blend fuel on the spray, atomization characteristics, and emissions in a direct injection diesel engine. Ghorbani *et al.* [23] 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, SO_2, and CO_2 than diesel. 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*. [24], and Fang and Lee [25] 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. Mancaruso *et al.* [26] 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 exhaust gas recirculation (EGR), investigated the effect of fuels on the combustion process and pollutants formation. 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 set-up 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.

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 wavelength: 337 nm), 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/s). 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 tab. 1.

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 injec-

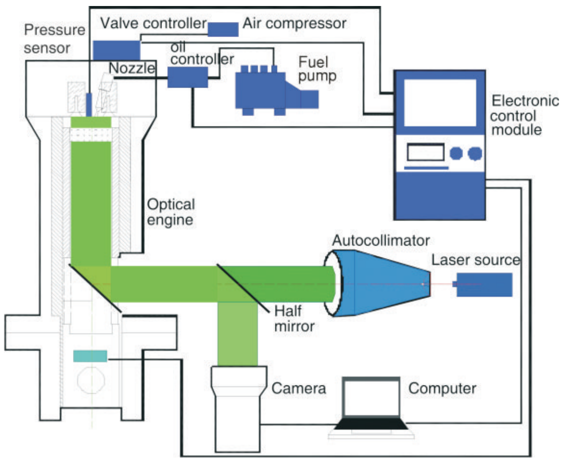

Figure 1. Schematic diagram of the experimental set-up

Table 1. Specifications of the tested engine

Engine	DLH1105
Type	2V, DI diesel
Bore	105 mm
Stroke	115 mm
Type of combustor	cylinder, ∅ = 62 mm
Displacement/cylinder	996 cm^{-3}
Compression ratio	16
Swirl ratio	2.2
Nozzle	4 × ∅ 0.32 mm

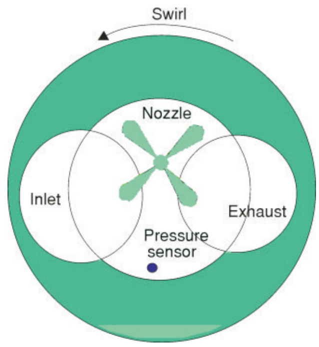

Figure 2. Schematic of the visible portion of the chamber

tion 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, take 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 80 mm 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 62 mm. 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. Blend fuel 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 2. Selected fuel properties

Properties	Biodiesel	Diesel oil
Density at 20 °C, [gcm^{-3}]	0.883	0.835
Flash point, [°C]	170	55
Calorific value, [MJL^{-1}]	33.650	35.000
Sulfur content, [wt.%]	0.0005	0.026
Oxygen content, [vol.%]	10	0
Cetane number	60.1	50.0
Solidifying point, [°C]	0	0
Condensation point [°C]	4	4
Viscosity at 20 °C, [mm^{2}s^{-1}]	8.06	3.39
Origin	Acidic oil from plant scrap	–
Saponification value	193.2	–
Iodine values	77	–
Bulk modulus [MPa]	1650	1490

The testing conditions (unless specially mentioned) are: Injection timing of 20° bTDC, needle opening pressure of 25 MPa, injection mass of 30 mg, engine speed of 800 rpm. Camera operated at a speed of 10.000 frames/s with a resolution of 128 × 128 pixel.

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.

Effect of fuel properties on spray and combustion

Figure 3 shows spray and combustion images with different types of fuel with respect to crank angle (CA). 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 indi-

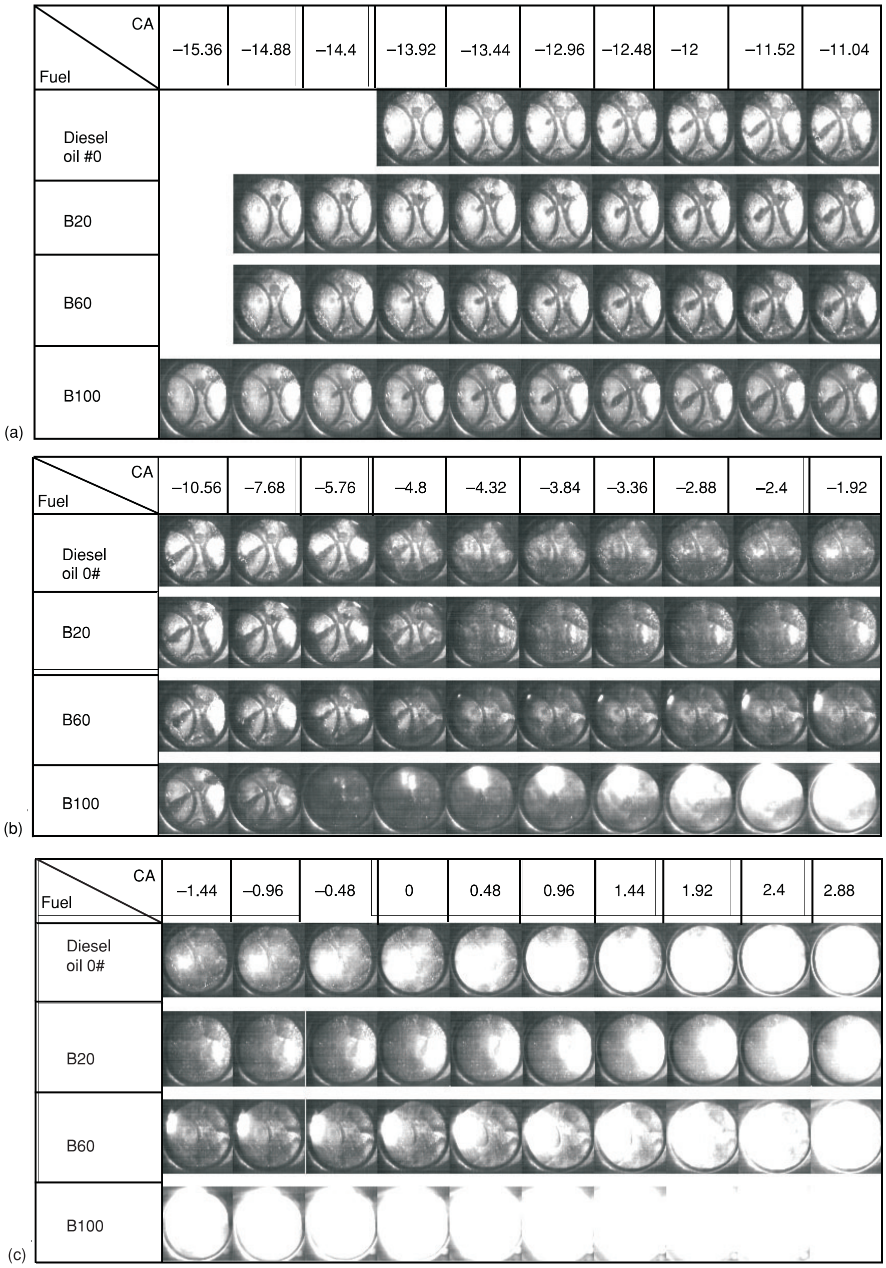

Figure 3. Spray and combustion images of different types of fuel *vs.* CA

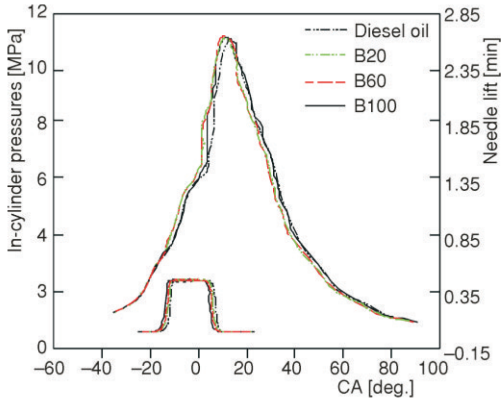

Figure 4. In-cylinder pressures and needle lift data

cate that the emergence time of the spray is 13.92° CA bTDC, 14.88° CA bTDC, 15.36° CA bTDC for 0# diesel oil, B20, B60, and B100, respectively.

Figure 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 bio-diesel percentage in the fuel.

Figure 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. The fuel ignition advances and the ignition delay reduces with the increase of biodiesel percentage. This can be explained by two reasons: biodiesel contains oxygen and is easier to reach ignition condition; The cetane number of biodiesel 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 CA. 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 11.154 MPa, 11.196 MPa, 11.207 MPa, and 11.249 Pa 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 biodiesel percentage.

Effect of engine speed on spray and combustion of biodiesel

Figure 5 shows the images of spray and combustion process for B100 at the rotating speed of 900 rpm and 1000 rpm, 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 900 rpm to 1000 rpm 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 1000 rpm respectively. It indicates biodiesel injection time in terms of CA retards as the engine speed increases.

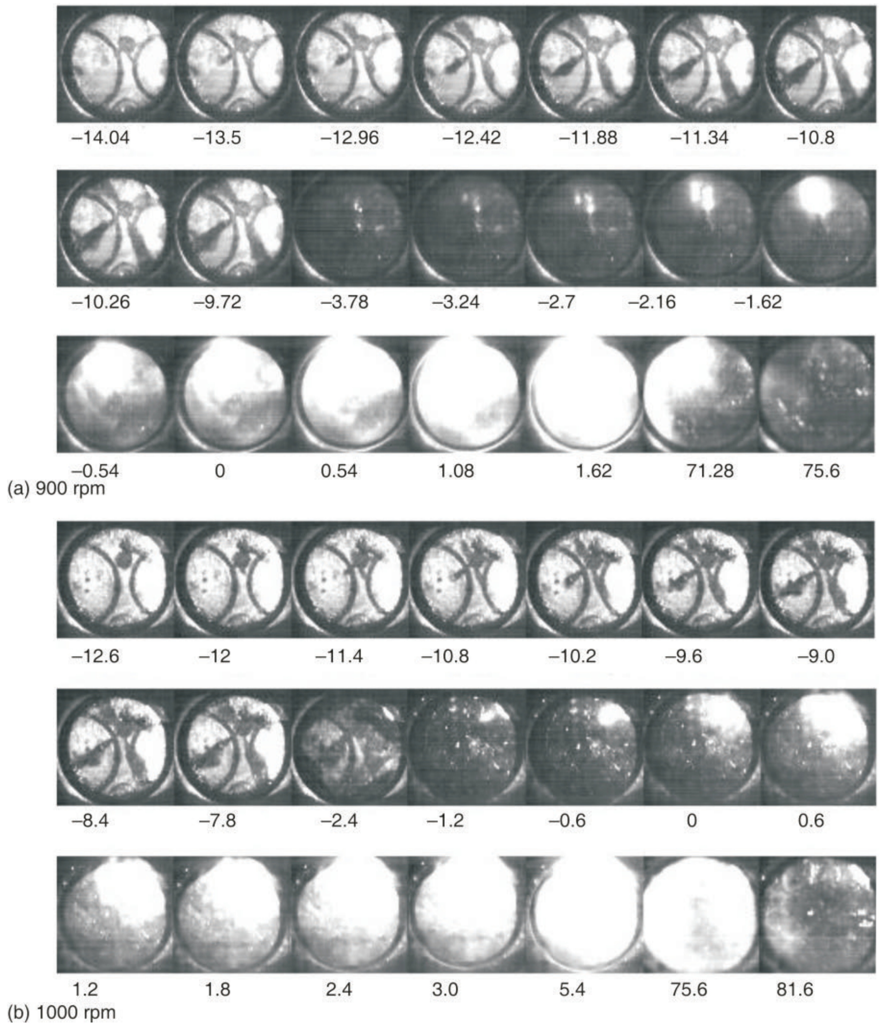

Figure 5. Spray and combustion images of different rotate speed at different CA

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 rpm, respectively. Figure 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.

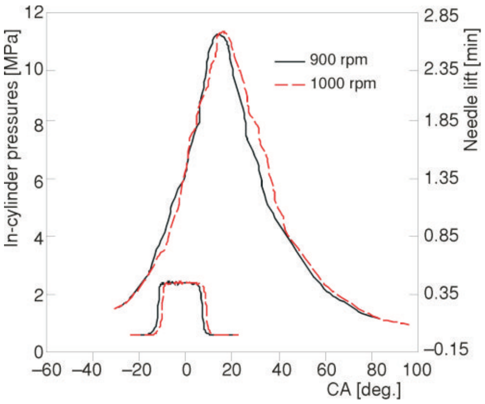

Figure 6. In-cylinder pressures and needle lift data

By comparing the combustion process of biodiesel under different engine speed (the end point of combustion is 70.08° CA aTDC at 800 rpm, 75.6° CA aTDC at 900 rpm, and 81.6° CA aTDC at 1000 rpm, respectively), it is found that the combustion duration in terms of CA increases with the increase of engine speed, but the burning time slightly shortens (14.6 ms for 800 rpm, 14 ms for 900 rpm, 13.6 ms for1000 rpm).

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 rpm are shown in fig. 7. Figure 8 shows the in-cylinder pressure and needle lift data. From figs. 3, 7, and 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 32 MPa. 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 32 MPa. However, It is only 19° at 12° CA bTDC for the needle opening pressure of 18 MPa.

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.

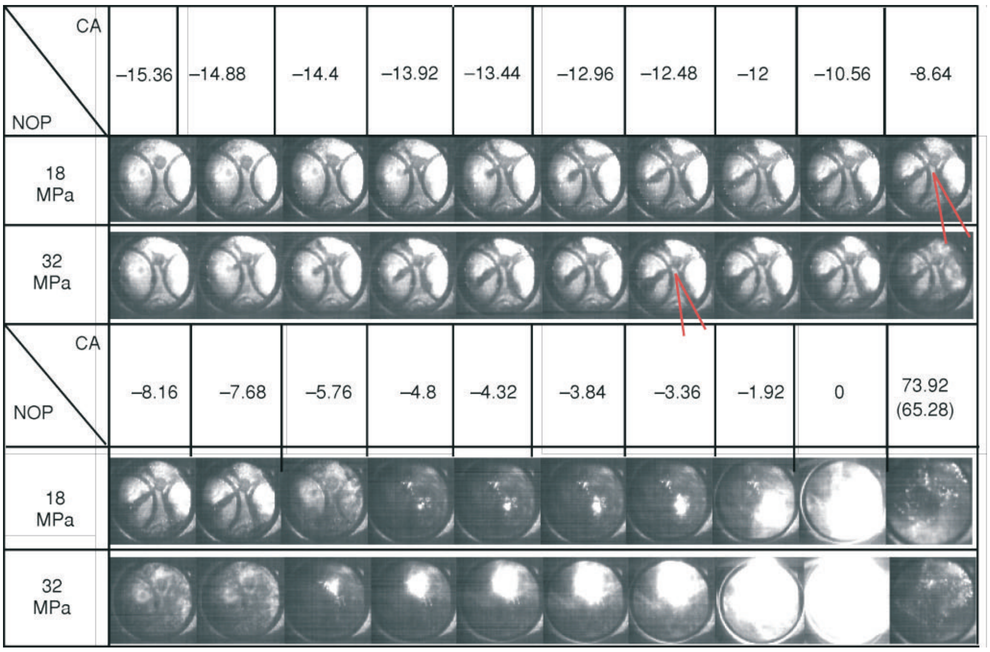

Figure 7. Spray and combustion images of different nozzle opening pressure at different CA

Figure 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 figs. 3 and 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 32 MPa, 25 MPa, and 18 MPa, 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.

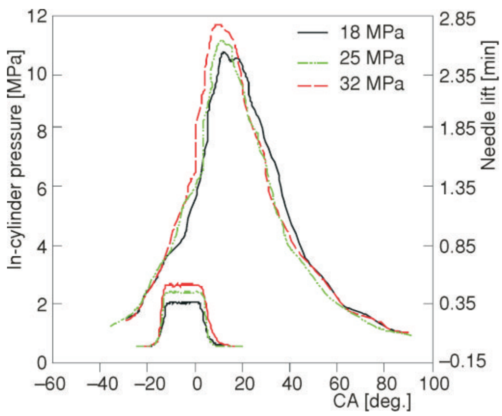

Figure 8. In-cylinder pressures and needle lift data

The duration of combustion is also different under different needle opening pressure. Biodiesel begins to burn at the crank angle of about 5.76° CA bTDC when the needle opening pressure is 32 MPa, and the combustion ends at about 65.28 ° CA aTDC. As the needle opening pressure is 18 MPa, biodiesel begins 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.

Figure 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 0.625 MPa higher than the 25 MPa case and 0.951 MPa higher than the 18 MPa case. Furthermore, it comes earlier than the other two cases. This phenomenon further proves that the fuel atomization and combustion process is improved with increase of the needle opening pressure.

Conclusions

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

- With the increase of biodiesel percentage, fuel injection advances slightly, the ignition delay is shorter and the duration of combustion becomes longer.
- Changing engine speed from 800 rpm to 1000 rpm has little effect on spray characteristics of biodiesel.
- Within the test range, the higher the engine speed, the faster the biodiesel's burning rate, and the bigger the peak pressure. However, the duration of combustion in terms of CA increases.
- The needle opening pressure has a significant impact on the biodiesel 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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