Comparative Analysis of Combustion Behaviors and Emission Characteristics of Diesel Engines Fueled with Biodiesel or Biodiesel Blends

Junxing Hou,* Zhenghe Wang, Shuanghui Xi, Shuhao Li, and Xiaokui Xu

ABSTRACT: In this study, we carried out an experimental analysis of combustion behaviors and emission characteristics of pure biodiesel and biodiesel–dimethyl ether (DME) blends and determined the impacts of the biodiesel ratio and the nozzle parameter on the combustion pressure characteristics in the time domain/frequency domain and emission characteristics. The findings show that with a decrease in the biodiesel proportion in biodiesel–DME blends, the maximum combustion pressure and fuels in the premixed combustion stage decrease with a retarded maximum value phase, but the maximum heat release in diffusive combustion increases and the maximum amplitude of pressure rise acceleration decreases. All of the pressure level curves of BD100, BD80, and BD50 contain a rapid decrease stage 1, a slow decrease stage 2, and a fluctuating stage 3. With a decrease in the biodiesel proportion, the exhaust gas temperature, NO\textsubscript{x} emissions, and smoke emissions of BD100, BD80, and BD50 decrease gradually. Compared with a 5 × 0.43 mm nozzle, the maximum combustion pressure and maximum heat release rate of BD50 for a 4 × 0.35 mm nozzle were higher and the phase of the maximum value was advanced. Soot emissions for the 4 × 0.35 mm nozzle were lower, which is especially obvious under a high brake mean effective pressure (BMEP).

1. INTRODUCTION

Development of clean alternative fuels can reduce air pollution and alleviate energy problems. Therefore, it has become an important topic.\textsuperscript{1,2} Biodiesel is a kind of clean alternative fuel made from plant oil, fat, animal oil, waste oil, and so on. It has many advantages and has been widely used in diesel engines in recent years.\textsuperscript{3–8} First and foremost, it has a higher cetane number and contains about 12% oxygen, which is beneficial to combustion performance and reduces soot emissions. Moreover, it is a form of renewable energy and can be biodegraded. In addition, it has superior lubricity. A higher kinematic viscosity reduces wear and tear and prolongs the life of fuel injection pumps, engine cylinders, and connecting rods. Combustion behaviors of biodiesel have been investigated in many studies in the literature.\textsuperscript{9–12} However, biodiesel also has some disadvantages compared with petrodiesel, such as higher NO\textsubscript{x} emissions, poor atomization, and carbon deposition.\textsuperscript{13} Dimethyl ether (DME) has a higher cetane number and is also very suitable for diesel engines.\textsuperscript{14–16} It does not have a C–C bond in the molecule and contains about 34.8% oxygen, which inhibits soot formation and achieves nearly zero soot emissions. In addition, it has higher latent heat, thus reducing the in-cylinder temperature and NO\textsubscript{x} emissions. Last, but not the least, it has a lower boiling point and better atomization.

Both biodiesel and DME are clean alternative fuels for diesel engines, and their blends can make up for the disadvantages of biodiesel. The atomization research results indicate that there is high light intensity in the center regions of biodiesel spray and DME spray. The atomization performance of DME is better than that of biodiesel under the same conditions.\textsuperscript{17} Therefore, the atomization performance of biodiesel can be improved by blending DME into biodiesel because DME has a lower kinematic viscosity and surface tension than biodiesel and interacts with oxygen more actively.\textsuperscript{18} Biodiesel–DME blends improve the atomization and fluidity of biodiesel, help reduce NO\textsubscript{x} emissions, and make the engine work softly.

Hou et al. studied the injection rate and dynamic behavior of biodiesel–DME blends in a common rail injection system.\textsuperscript{19,20}

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The findings demonstrate that the injection timing of biodiesel–DME blends is similar to that of biodiesel. Their injection duration is prolonged significantly with a decrease in the biodiesel ratio, but the maximum injection rate does not vary much. The combustion behavior has also been explored.\textsuperscript{21} It can be seen that with an increase in the DME proportion in the blends, the peak combustion pressure, peak heat-release rate, and peak in-cylinder temperature decrease and their phases are retarded.

The combustion performance and emissions of DME–biodiesel blends, diesel–biodiesel blends, and pure diesel were investigated by Roh.\textsuperscript{22} Three fuels were used in the experiments, including 80% DME + 20% biodiesel blends, 80% biodiesel + 20% diesel blends, and 100% diesel. The findings reveal that the DME–biodiesel blend has a higher combustion pressure than the biodiesel–diesel blend and pure diesel, whereas it has a lower peak in the pilot injection.

Wu elucidated the oxidation mechanism of biodiesel–dimethyl ether and predicted the combustion characteristics by the skeletal mechanism.\textsuperscript{23} The results indicate that with an increase in the DME proportion, the ignition delay is extended and the peak combustion pressure increases, whereas NO\textsubscript{x} emissions and soot emissions decrease.

Nozzle opening pressure and injection timings also play a significant role in the biodiesel engine performance. Khayum studied the combined impact of the nozzle opening pressure and the injection timing on diesel engine fuels with exhausted tea and waste cooking oil.\textsuperscript{24} The findings display that a higher nozzle opening pressure can improve BTE significantly. The opening pressure is 240 bar, and the injection timing is 24.5 °CA BTDC. Mohan investigated the performance and emissions of a single-cylinder diesel engine with 225, 250, and 275 bar nozzle opening pressures and 19, 21, 23, 25, and 27° BTDC injection timings.\textsuperscript{25} The best injection pressure and injection timing were chosen, which are 275 bar and 21° BTDC, respectively.

It can be seen from the above that there are few studies on the characteristics of dimethyl ether–biodiesel blended fuels, and the relationships of the biodiesel ratio and the nozzle diameter with combustion behaviors and emissions have not been reported. To have a profound and comprehensive understanding of the combustion behaviors and emission characteristics of pure biodiesel and its blended fuels in diesel engines, in this study, we carried out experimental research on pure biodiesel BD100 and its blended fuels BD80 and BD50 on a naturally aspired engine. The combustion pressure-change behavior and emission characteristics were investigated. In addition, in recent years, research on alternative fuels for diesel engines at home and abroad mainly focus on emission characteristics, and there are few studies on combustion pressure acceleration and combustion pressure spectrum characteristics. In this study, fast Fourier transformation (FFT) was adopted to extract the time-domain and frequency-domain information of in-cylinder combustion pressure changes, determine the in-cylinder combustion pressure characteristics of each frequency band, and analyze the influence of nozzle parameters on the time-domain and frequency-domain characteristics of the in-cylinder combustion pressure, which can provide more abundant information for the study of in-cylinder combustion pressure characteristics.

2. EXPERIMENTAL APPARATUS AND TEST FUEL

Combustion experiments are carried out in a diesel engine, whose specifications are given in Table 1, and a schematic of the experimental apparatus is shown in Figure 1. A biodiesel–DME blended fuel system consists of a fuel tank, a filter, a low-pressure fuel system of biodiesel–DME blends, and pure diesel, whereas it has a lower peak in the pilot injection.

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| engine type | four-stroke CI engine |
|-------------|-----------------------|
| cylinder number | 2 |
| cooling system | water-cooled |
| bore × stroke (mm × mm) | 135 × 145 |
| compression ratio | 16.5 |
| maximum power (kW)/speed (rpm) | 29.4/1500 |
| nozzle orifice number × diameter (mm) | 4 × 0.35/5 × 0.43 |
| nozzle opening pressure (MPa) | 19/15 |

3. RESULTS AND DISCUSSION

3.1. Combustion Behaviors of Biodiesel and Biodiesel Blends. Figure 2 compares the characteristics of combustion pressure and heat-release rate of BD100, BD80 and BD50 at brake mean effective pressure (BMEP) values of 0.27 and 0.41 MPa. At 0.27 MPa BMEP, the maximum combustion pressures of BD100, BD80, and BD50 are 6.37 MPa at 3 °CA ATDC, 6.19 MPa at 0.5 °CA ATDC, and 5.72 MPa at 4.5 °CA ATDC, respectively. These values are 7.04 MPa at 4.5 °CA ATDC, 6.68 MPa at 4.5 °CA ATDC, and 6.23 MPa at 6.5 °CA ATDC at 0.41 MPa BMEP, respectively. With a decrease in the biodiesel proportion, the maximum combustion pressure decreases, with a retarded maximum combustion pressure phase. The cetane number of biodiesel is less than that of DME. As the biodiesel proportion decreases and the DME...
As the biodiesel proportion decreases and DME proportion increases, the change rate of fuel pressure in the pipe becomes slow. At the same fuel delivery advance angle, the fuel injection angle is retarded, and thus, the phase of maximum combustion pressure is delayed. The decreased maximum combustion pressure contributes to the reduction in the engine mechanical load and increases the thermal efficiency. As BMEP increases, the maximum combustion pressure increases with the retarded phase.

As is shown in Figure 2b, a two-stage combustion is exhibited in the heat-release rate curves, including a premixed combustion stage and a diffusive combustion stage. At 0.27 MPa BMEP, the maximum heat release rates/phases of BD100, BD80, and BD50 are 281 (J/°CA)/3 °CA BTDC, 252 (J/°CA)/3 °CA BTDC, and 135 (J/°CA)/0.5 °CA BTDC, respectively. These values are 248 (J/°CA)/4 °CA BTDC, 255 (J/°CA)/3.5 °CA BTDC, and 129 (J/°CA)/3.5 °CA BTDC, respectively, at 0.41 MPa BMEP. At two different BMEPs, a decreased biodiesel proportion causes reduced premixed combustion, the maximum heat release rate, and a retarded phase, whereas with an increase in diffusive combustion, the maximum heat release in diffusive combustion increases. Because the cetane number of DME is higher than that of biodiesel, as the biodiesel proportion decreases and DME proportion increases, the ignition delay is shortened and the accumulated premixed fuels decrease. In addition, the starting of combustion is retarded.

Combustion acceleration is the fundamental factor that produces pressure oscillations, which is evaluated by the pressure rise acceleration in this study. As combustion gets into a rough phase, the peak pressure rise acceleration increases remarkably. The pressure rise accelerations of BD100, BD80, and BD50 are illustrated in Figure 3. There are two peaks of the maximum pressure rise acceleration for each of the three fuels, and the decreased biodiesel ratio results in the shift of two peaks. Compared with the first peak, the second peak for BD100 and BD80 is larger and that for BD50 is smaller. With a decrease in the biodiesel proportion, the maximum amplitude of pressure rise acceleration decreases. As DME has lower elasticity and larger compressibility, the fuel injection is retarded. As can be seen from Figure 3a, at 0.27 MPa BMEP, the maximum pressure rise accelerations/phases of BD100, BD80, and BD50 are 0.26 (MPa/°CA²)/3.5 °CA BTDC, 0.39 (MPa/°CA²)/4 °CA BTDC, and 0.21 (MPa/°CA²)/4 °CA BTDC, whereas the minimum pressure rise accelerations/phases are −0.63 (MPa/°CA²)/2.5 °CA BTDC, −0.63 (MPa/°CA²)/3 °CA BTDC, and −0.29 (MPa/°CA²)/1 °CA ATDC, respectively. Similar findings were obtained at
0.41 MPa BMEP. The maximum values/phases are 0.35 (MPa\(^{\circ}\text{CA}\))/5 \(\circ\text{CA BTDC}\), 0.44 (MPa\(^{\circ}\text{CA}\))/4 \(\circ\text{CA BTDC}\), and 0.24 (MPa\(^{\circ}\text{CA}\))/5.5 \(\circ\text{CA BTDC}\), whereas the minimum values/phases are \(-0.62\) (MPa\(^{\circ}\text{CA}\))/3.5 \(\circ\text{CA BTDC}\), \(-0.51\) (MPa\(^{\circ}\text{CA}\))/2.5 \(\circ\text{CA BTDC}\), and \(-0.28\) (MPa\(^{\circ}\text{CA}\))/2.5 \(\circ\text{CA BTDC}\), respectively.

Figure 4 compares the frequency characteristics of combustion pressures of BD100, BD80, and BD50. It can be seen from Figure 4 that according to the decreasing speed in the frequency domain, the cylinder pressure level curves of BD100, BD80, and BD50 can be divided into three stages: the rapid decrease stage 1, the slow decrease stage 2, and the fluctuating stage 3. At 0.27 MPa BMEP, the cylinder pressure level curves of BD100, BD80, and BD50 mostly overlap in the rapid decrease stage 1. In the slow decrease stage 2, the curves decrease and the differences among them increase gradually. In the fluctuating stage 3 (in the range of 2000–3000 Hz), the curves of BD100, BD80, and BD50 fluctuate sharply, and all of the curves of the three fuels decline gradually. The curves at 0.41 MPa BMEP are similar to those at 0.27 MPa BMEP, but the differences among the three fuels decrease.

3.2. Emissions Characteristics of Biodiesel and Biodiesel Blends. Exhaust gas temperature and emissions of BD100, BD80, and BD50 at 1500 rpm are shown in Figure 5. Figure 5a displays the exhaust gas temperature of the three fuels. It can be seen that the exhaust temperatures of BD100, BD80, and BD50 decrease gradually at the same engine load. The characteristics are similar among the four various engine loads. With a decrease in the biodiesel ratio, combustion is delayed. Figure 5b,c shows NO\(_x\) emissions and smoke emissions of BD100, BD80, and BD50. As displayed in Figure 5b, NO\(_x\) emissions increase with an increase in BMEP, and at the same BMEP, NO\(_x\) emissions of BD100, BD80, and BD50 decrease gradually. The key factors influencing thermal NO\(_x\) formation are a high combustion temperature, high oxygen concentration, and the residence time in the high-temperature environment. Therefore, increased BMEP increases the temperature in the cylinder and causes higher NO\(_x\) emissions. With a decrease in the biodiesel ratio, premixed combustion reduces and the higher latent vaporization heat of DME lowers the maximum temperature in the cylinder. Besides, the addition of DME retards the injection and combustion and restricts NO\(_x\) formation. As can be seen from Figure 5c, as BMEP increases, smoke emissions increase, especially for BD100 and BD80, but smoke emissions change little for the blended fuel BD50. At the same BMEP, the increased DME proportion reduces smoke emissions, especially at high BMEP. With an increase in BMEP, the excessive air coefficient
decreases and combustion is deteriorated, which leads to increased smoke emissions. However, the blended fuel BD50 has a higher oxygen content and better atomization performance, and so BD50 shows lower smoke emissions compared with BD100 and BD80, especially under high BMEP.

Exhaust gas temperature and emissions of BD100 and BD50 at 1000 rpm are shown in Figure 6. With an increase in BMEP, there is no significant change in soot emissions of BD50, but

Figure 5. Exhaust gas temperatures and emissions of BD100, BD80, and BD50 at 1500 rpm.

Figure 6. Exhaust gas temperature and emissions of BD100 and BD50 at 1000 rpm.
exhaust temperature and NO\textsubscript{x} emissions of both BD50 and BD100 increase. It can be seen from Figure 6a that when BMEP increases from 0.05 to 0.14 MPa, the exhaust temperature of BD100 is slightly higher than that of BD50. With an increase in BMEP from 0.27 to 0.41 MPa, the exhaust temperature of BD100 is remarkably higher than that of BD50. In Figure 6b and c, it can be seen that NO\textsubscript{x} emissions and soot emissions of BD100 are significantly higher than those of BD50.

3.3. Effects of Nozzle Parameters on Combustion Behaviors of BD50. Nozzle parameters are of vital importance to the engine injection system and have considerable influence on the injection rate, spray quality, fuel/air mixing state, combustion behaviors, and emissions. The nozzle parameters include the nozzle number and nozzle diameter. In this study, the impacts of nozzle parameters on combustion behaviors and emissions are investigated for the fuel BD50. The combustion pressure and heat release rate with two types of nozzles are compared in Figure 7. It can be seen from Figure 7 that the maximum combustion pressure and maximum heat release rate of BD50 for the 4 × 0.35 mm nozzle are higher than those for the 5 × 0.43 mm nozzle at 0.27 and 0.35 MPa BMEP, and the phase of the maximum value is advanced. At 0.27 MPa BMEP, the maximum combustion pressures with 4 × 0.35 and 5 × 0.43 mm nozzles are 5.71 and 5.18 MPa. The maximum heat release rates are 134.77 and 116.71 J/°CA, and their phases are 0.5 °CA BTDC and 1.5 °CA ATDC, respectively. At 0.35 MPa BMEP, the maximum combustion pressures with the two types of nozzles are 5.75 and 5.48 MPa. The maximum heat release rates are 132.92 and 129.14 J/°CA, and their phases are 1.5 and 2 °CA ATDC, respectively. A nozzle with a small diameter improves atomization and forms a better fuel/air mixture, and so combustion is more complete and has a higher maximum cylinder pressure and maximum heat release rate. As BMEP is increased from 0.27 to 0.35 MPa, there are no significant differences between these two types of nozzles.

Figure 9 compares the frequency characteristics of the combustion pressure of BD50 with the two types of nozzles. It can be seen clearly in Figure 9 that the cylinder pressure level be seen that the amplitude of pressure rise acceleration with the 4 × 0.35 mm nozzle is higher than that with the 5 × 0.43 mm nozzle at 0.27 and 0.35 MPa BMEP. At 0.27 MPa BMEP, the amplitudes of pressure rise acceleration with the two types of nozzles are 0.497 and 0.299 MPa/°CA\textsuperscript{2}. When BMEP increases to 0.35 MPa, the amplitudes of pressure rise acceleration with the two types of nozzles are 0.51 and 0.369 MPa/°CA\textsuperscript{2} respectively.
curves with the two types of nozzles almost overlap in the rapid decrease stage 1. In the slow decrease stage 2, the cylinder pressure level curve with the $4 \times 0.35$ mm nozzle is higher than that with the $5 \times 0.43$ mm nozzle, and the differences between the curves with the two types of nozzles gradually become significant. In the fluctuating stage 3, the cylinder pressure level curves with the two types of nozzles fluctuate violently in the range of 2000–3000 Hz. Signal characteristics of the combustion pressure in the frequency domains can be extracted by a spectral analysis, which can provide more abundant information for the study of the impacts of the biodiesel ratio and nozzle parameters on the time- and frequency-domain characteristics of combustion pressure.

3.4. Effects of Nozzle Parameters on Emission Characteristics of BD50. The exhaust gas temperature and emissions of BD50 for the two types of nozzles at 1500 rpm are illustrated in Figure 10. From the exhaust gas temperature diagrams in Figure 10a, it can be seen that with an increase in BMEP, the exhaust gas temperature increases for the two types of nozzles. Under the same BMEP, the exhaust gas temperature is similar for the two types of nozzles, and there is no significant difference. It can be seen from Figure 10b that NO$_x$ emissions for the two types of nozzles increase with an increase in BMEP. Compared with the $5 \times 0.43$ mm nozzle, NO$_x$ emissions for the $4 \times 0.35$ mm nozzle are lower under the same BMEP. It can be seen from Figure 10c that soot emissions for the $5 \times 0.43$ mm nozzle increase with an increase in BMEP, and there is no significant increase for the $4 \times 0.35$
mm nozzle. Under the same BMEP, soot emissions for the 4 × 0.35 mm nozzle are lower than those for nozzle the 5 × 0.43 mm nozzle, which is especially obvious under high BMEP.

The exhaust gas temperatures and emissions of BD50 for the two types of nozzles at 1000 rpm are compared in Figure 11. As can be seen from Figure 11, both the exhaust temperature and NO\textsubscript{x} emissions increase with an increase in BMEP for the two types of nozzles, but there is no remarkable change in soot emissions. NO\textsubscript{x} emissions for the 5 × 0.43 mm nozzle are higher at low BMEP, and those for the 4 × 0.35 mm nozzle are higher at medium and high BMEPs, which is because the fuel supply pressure is low at 1000 rpm and the fuel atomization is poor. At medium and high BMEPs, the fuels in the cylinder are not uniformly mixed, and so NO\textsubscript{x} emissions for the 4 × 0.35 mm nozzle are higher. There are no distinct differences in the exhaust gas temperature and soot emissions between the two types of nozzles.

4. CONCLUSIONS

This study investigates the combustion behaviors and emission characteristics of BD100, BD80, and BD50 and determines the relationships of the biodiesel ratio and the nozzle diameter with the combustion behaviors and emission characteristics. The conclusions are as follows:

(1) With a decrease in the biodiesel proportion, the maximum combustion pressure and premixed combustion decline with the retarded maximum value phase, but the maximum heat release in the diffusive combustion phase increases and the maximum amplitude of pressure rise acceleration decreases.

(2) All of the combustion pressure curves of BD100, BD80, and BD50 contain a rapid decrease stage 1, a slow decrease stage 2, and a fluctuating stage 3. The curves of BD100, BD80, and BD50 mostly overlap in stage 1. The curves fall and the differences among them increase gradually in the slow decrease stage 2. The curves of BD100, BD80, and BD50 fluctuate sharply, and all of the curves of the three fuels drop gradually in the fluctuating stage 3 (in the range of 2000–3000 Hz).

(3) With a decrease in the biodiesel proportion, the exhaust gas temperature, NO\textsubscript{x} emissions, and smoke emissions of BD100, BD80, and BD50 decline gradually.

(4) Compared with the 5 × 0.43 mm nozzle, the maximum combustion pressure and maximum heat release rate of BD50 with the 4 × 0.35 mm nozzle are higher at 0.27 and 0.35 MPa BMEP, and the phase of the maximum value is advanced. The amplitude of pressure rise acceleration with the 4 × 0.35 mm nozzle is higher. In the rapid decrease stage 1, the cylinder pressure level curves with the two types of nozzles almost coincide. In the slow decrease stage 2, the curve of the 4 × 0.35 mm nozzle is higher than that of the 5 × 0.43 mm nozzle, and the difference between the curves with the two types of nozzles gradually becomes significant. In the fluctuating stage 3, the cylinder pressure level curves with the two types of nozzles fluctuate violently in the range of 2000–3000 Hz.

(5) Compared with the 5 × 0.43 mm nozzle, soot emissions for the 4 × 0.35 mm nozzle are lower, which is especially obvious under high BMEP. NO\textsubscript{x} emissions for the 4 × 0.35 mm nozzle are also lower at 1500 rpm. At 1000 rpm, NO\textsubscript{x} emissions for the 5 × 0.43 mm nozzle are

higher at low BMEP and those for the 4 × 0.35 mm nozzle are higher at medium and high BMEPs.
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Notes
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