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A Study on the Impact of Biodiesel on the Combustion and Emissions of Common Rail Marine Engine

Emission Reduction Technologies - Engine Measures & Combustion Development

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ABSTRACT

Due to the significant compositional differences between biodiesel and traditional fossil fuels, an increase in the biodiesel blending ratio alters the properties of the blended fuel, thereby affecting the engine's combustion performance and emissions. This study conducted experiments based on a single-cylinder marine diesel engine with a 270 mm bore and a high-pressure common rail system. Biodiesel produced from waste cooking oil with a fatty acid methyl esterï¼ˆFAMEï¼‰ content of 99.5% and low-sulfur diesel were used to investigate the effects of different biodiesel volume ratios (0%, 10%, 20%, 50%, and 100%) on engine combustion and emission characteristics.

The experimental results indicate that after blending biodiesel, the ignition delay period shortens, the peak heat release rate increases, the combustion duration decreases, and the peak firing pressure (PFP) rises, with these trends being consistent across different load conditions. Among these, the ignition delay period, peak heat release rate, and peak combustion pressure are relatively insensitive to changes in the biodiesel blending ratio, while the combustion duration gradually shortens as the biodiesel blending ratio increases. As the biodiesel blending ratio increases, the break specific fuel consumption (BSFC) gradually rises, with the rate of increase becoming more pronounced at higher load levels. Additionally, with an increase in the biodiesel blending ratio, soot emissions show a decreasing trend, while NOx emissions exhibit an increasing trend. However, different blending ratios demonstrate varying patterns under low-load and high-load conditions. Biodiesel has a minimal impact on the exhaust temperature of the cylinder head and the temperature of the cylinder liner, indicating that it does not increase the engine's thermal load.

1 INTRODUCTION

The shipping industry accounts for over 80% of global trade volume and nearly 3% of global greenhouse gas emissions, with emissions having increased by 20% in just a decade [1]. The International Maritime Organization (IMO) and its technical committee, the Marine Environment Protection Committee (MEPC), as well as governments around the world, have placed great emphasis on the issue of greenhouse gas emissions from the shipping industry [2].

In 2023, member states of the IMO agreed to achieve net-zero emissions from international shipping by or around mid-century, with an interim target of reducing emissions by 70% to 80% by 2040 compared to 2008 levels [3]. The Chinese government has also set strategic goals to peak carbon emissions by 2030 and achieve carbon neutrality by 2060, promoting the development of China's shipping industry towards green fuels [4].

Therefore, fuels such as green ammonia, methanol, hydrogen, and biodiesel have been included in the discussion as alternatives to traditional fossil fuels. However, existing engines cannot directly operate using ammonia, methanol, or hydrogen as fuel, requiring extensive modifications or redesigns, and they also involve serious safety issues, making it impossible for them to be widely used in the market in the short term [5-7]. As a green fuel, biodiesel can be blended with diesel and does not require large-scale modifications to existing ship engines. This advantage allows for a more rapid implementation of carbon reduction in the shipping industry [8-9].

Affected by a variety of factors, including the limitations of feedstock availability, food crises, and government policies, the blending ratio of biodiesel is generally low, typically below 20% [10]. With the increasing stringency of carbon reduction policies and the development of related technologies such as the production of biodiesel from microbial oils [11], the possibility of biodiesel blending ratios reaching above 20%, up to 50%, or even 100% has significantly increased.

This paper, based on a single-cylinder marine high-pressure common rail diesel engine with a cylinder bore of 270 mm, carried out comparative experimental studies on the effects of different biodiesel blends on engine combustion, brake specific fuel consumption (BSFC), emissions, and thermal load. The experimental results indicate that, without any modifications, biodiesel can replace diesel to allow the engine to operate normally. As the proportion of biodiesel increases, the combustion speed increases, the fuel consumption rate rises, emissions exhibit different characteristics under various loads, and the thermal load remains within a controllable range**.**

2 RESEARCH OBJECT

This experiment was conducted using a single-cylinder marine high-pressure common rail diesel engine, with its main parameters as shown in Table 1. The intake pressure, exhaust back pressure, lubricating oil boundary, and cooling water boundary of the experimental platform can be customized as needed.

Figure 1. Biodiesel Used in the Experiment

Table 1. Main parameters of the single-cylinder engine

Parameter	Unit	Value
Fuel injection system	-	Common rail
Common rail pressure	MPa	160
Bore diameter	mm	270
Stroke	mm	320
Rated speed	r/min	1000
Rated power	kW	400

The biodiesel used in the experiment (Figure 1) was made from waste cooking oil, with the main component being fatty acid methyl ester (FAME, accounting for 99.5%). The diesel was ultra-low sulfur diesel. The main physicochemical properties of both are shown in Table 2.

Table 2. Main parameters of the biodiesel and diesel

Parameter	Unit	Biodiesel	Diesel
Cetane number	-	60	50.2
Flash point	℃	172	61
Kinematic viscosity @20℃	mm^2/s	4.3	3.7
Net calorific value	MJ/kg	40	43
Sulfur content	ppm	9	3.74

Density@20℃	kg/m³	877	825.4

Before the experiment, biodiesel was blended with diesel at volume ratios of 10%, 20%, and 50%, respectively, and stored in fuel tanks. The blended fuels were named B10, B20, and B50 accordingly. Pure diesel was designated as B0, and pure biodiesel as B100. When conducting experiments with different fuels, the engine operating conditions, intake pressure, exhaust back pressure, lubricating oil, cooling water, injection pressure, and injection timing were kept essentially consistent.

The main test parameters of the engine include fuel consumption rate, cylinder head exhaust temperature, cylinder liner temperature, and emissions, among others. The soot emissions were measured using the AVL415S Smokemeter device, while NOx and hydrocarbon emissions were tested using the HORIBA MEXA-1600DSEGR motor exhaust gas analyzer. Cylinder liner temperature and exhaust temperature at cylinder head were monitored by thermocouples.

3 EXPERIMENTAL STUDY

3.1 Influence of biodiesel proportion on engine combustion characteristics

Figures 2 to 5 show the changes in cylinder pressure and heat release rate of different blends of biodiesel under various loads. It can be observed that, under the same rail pressure and injection timing, the peak firing pressure（PFP） slightly increases by about 0.1 to 0.2 MPa after blending with biodiesel, and overall, the cylinder pressure changes are not significant across different loads.

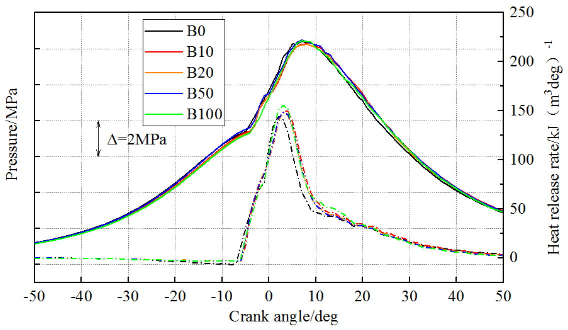

Figure 2. Comparison of cylinder pressure and heat release rate at 25% load under different biodiesel proportions

The ignition delay is postponed by 1deg crank angle (CA) after blending with biodiesel, and the peak heat release rate increases by 7.6% to 10.7%, with no significant differences in peak heat release rates among different blends. The main reason is that the main component of biodiesel is fatty acid methyl ester. According to the basic physicochemical properties in Table 1, although the heating value of biodiesel is slightly lower, its density is higher, resulting in its unit volume energy (volume*density*heating value) being essentially consistent with that of diesel. However, biodiesel contains oxygen, which allows it to start burning more quickly during the diffusion combustion phase, whereas diesel needs to be broken up and evaporated to form a combustible mixture before it can start burning. Therefore, more fuel is burned in a unit of time with biodiesel compared to diesel, leading to a significant increase in peak heat release rate.

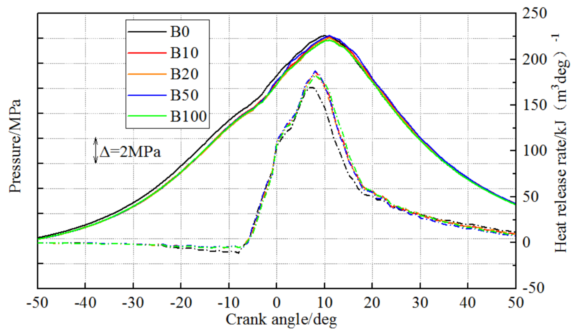

Figure 3. Comparison of cylinder pressure and heat release rate at 50% load under different biodiesel proportions

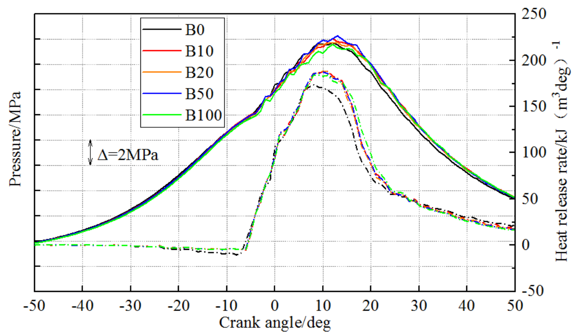

Figure 4. Comparison of cylinder pressure and heat release rate at 75% load under different biodiesel proportions

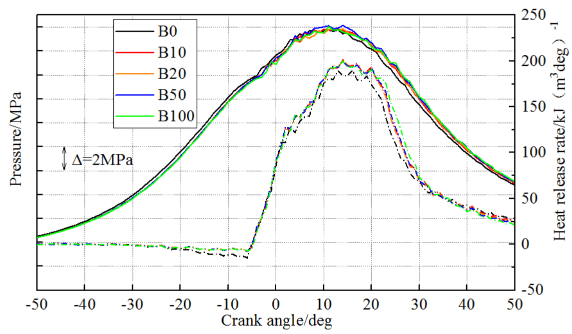

Figure 5. Comparison of cylinder pressure and heat release rate at 100% load under different biodiesel proportions

Figure 6 shows the effect of different biodiesel blending ratios on the combustion duration under various loads. It can be observed that biodiesel can significantly reduce the combustion duration, and the duration shortens as the blending ratio increases. As mentioned above, the blending ratio of biodiesel has little effect on the peak heat release rate, but mainly affects the combustion speed in the later stage. The higher the blending ratio, the greater the oxygen content in the fuel, which is more conducive to the combustion of the mixture in the later stage.

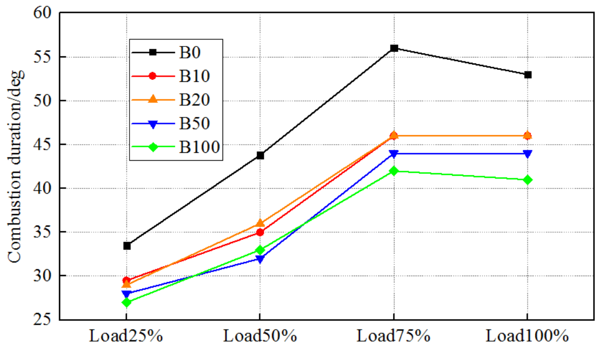

Figure 6. Comparison of combustion duration at various loads under different biodiesel proportions

3.2 Influence of biodiesel proportion on BSFC

Figure 7 shows the influence of different biodiesel blending ratios on fuel consumption rate under various loads. It can be observed that as the blending ratio of biodiesel increases, the fuel consumption rate gradually rises. This is because the heating value of biodiesel is lower, requiring more fuel to produce the same power output. However, under 25% load, the difference in BSFC within the blending ratio range of 10% to 50% is relatively small, indicating that blending with biodiesel to some extent promotes combustion at low loads and improves combustion efficiency.

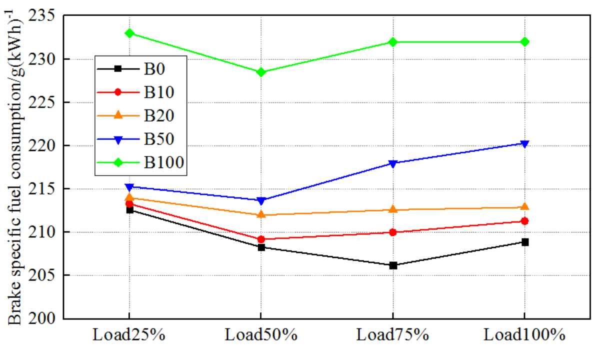

Figure 7. Comparison of BSFC at various loads under different biodiesel proportions

3.3 Influence of biodiesel proportion on emissions

Figure 8 illustrates the impact of different biodiesel blending ratios on soot emissions under various loads. It can be observed that the influence of biodiesel proportion on soot emissions exhibits different patterns at low and high loads: at 75% and 100% loads, soot emissions gradually decrease with increasing biodiesel proportion, and the difference is relatively significant; at 50% load, soot emissions also decrease with increasing biodiesel proportion, but the emissions of B10 and B20 are the same, as are those of B50 and B100; at 25% load, the impact of different biodiesel proportions on soot emissions is relatively small. Overall, soot emissions tend to decrease with increasing biodiesel proportion.

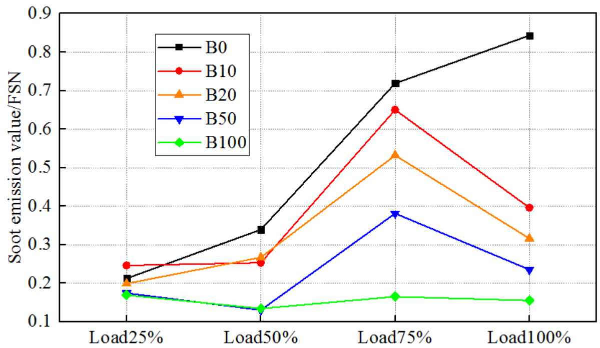

Figure 8. Comparison of soot emission at various loads under different biodiesel proportions

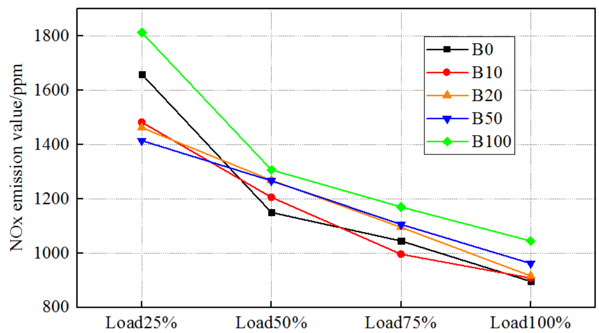

Figure 9. Comparison of NOx emission at various loads under different biodiesel proportions

Figure 9 shows the effect of different biodiesel blending ratios on NOx emissions. Generally, NOx emissions increase with increasing biodiesel proportion. It should be particularly noted that the NOx emissions of B10 are lower than those of B0 at both 25% and 75% loads, while at 100% load, the NOx emissions of B10 and B0 are comparable, with only B10 having higher NOx emissions at 50% load. According to the weighted algorithm for NOx emissions from marine propulsion engines (with a weight coefficient of 0.2 for 100% load, 0.5 for 75% load, and 0.15 for both 25% and 50% loads), the weighted NOx emissions of B10 are 1083 ppm, lower than the 1123 ppm of B0. This indicates that B10 not only reduces CO2 emissions but also reduces NOx emissions to a certain extent.

3.4 Influence of biodiesel proportion on thermal load

During the experimental process, cylinder head exhaust temperature and cylinder liner temperature were used as parameters to characterize the thermal load of the engine and were continuously monitored.

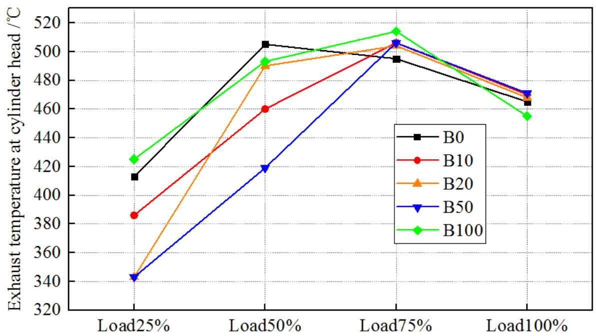

Figure 10. Comparison of exhaust temperature at cylinder head at various loads under different biodiesel proportions

Figure 11 shows the effect of biodiesel blending ratio on cylinder liner temperature at 100% load. It can be observed that the cylinder liner temperature does not change significantly with the variation of blending ratio, and there is still a considerable margin from the limit value of 200°C.

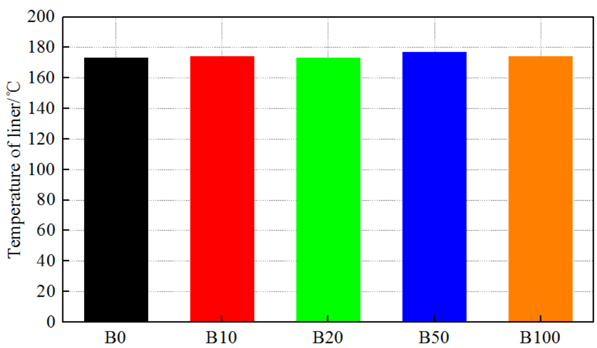

Figure 11. Comparison of liner temperature at 100% load under different biodiesel proportions

In conclusion, the impact of biodiesel on engine thermal load is limited and does not cause negative effects on its long-term stability.

4 CONCLUSIONS

(1) Blending different proportions of biodiesel into diesel has little effect on the PFP, extends the ignition delay by 1°CA, and increases the peak heat release rate by 7.6% to 10.7%, with minimal influence from the blending ratio. However, the combustion duration gradually shortens as the blending ratio increases.

(2) Due to the lower heating value of biodiesel compared to diesel, the fuel consumption rate gradually increases with the increase in blending ratio.

(3) Because biodiesel contains oxygen, the overall soot emissions decrease and NOx emissions increase as the blending ratio increases. However, for B10, its weighted NOx emissions are actually lower than those of pure diesel.

(4) The addition of biodiesel to diesel fuel has a minimal impact on the engine's thermal and mechanical loads. From the perspective of ensuring long-term stable operation of the engine, further increasing the blending ratio of biodiesel is generally feasible. However, emissions need to be optimized through the re-matching of aftertreatment systems to meet regulatory requirements.

5 DEFINITIONS, ACRONYMS, ABBREVIATIONS

FAME: Fatty Acid Methyl Ester

PFP: Peak Firing Pressure

BSFC: Brake Specific Fuel Consumption

IMO: International Maritime Organization

MEPC: Marine Environment Protection Committee

CA: Crank Angle

FSN: Filter Smoke Number

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