CIMAC CONGRESS 25
ZURICH, MAY 19 – 23, 2025

2025 | 489

Study on the performance and emission of biofuels for large marine low-speed engines

Fuels - Alternative & New Fuels

Hankun Liu, China Shipping Sinopec Suppliers Co.,LTD

Haikang Zhao, Shanghai Maritime University
Gang Wu, Shanghai Maritime University
Tie Li, Shanghai Jiaotong University
Xinyi Zhou, National University of Singapore

ABSTRACT

Abstract: An in-depth experimental study was conducted to investigate the practical application potential of biodiesel in large bore two-stroke marine diesel engines. The aim of this experiment was to evaluate the effects of biodiesel and conventional diesel fuel blends on the performance, emission and combustion characteristics of marine diesel engines and to provide a scientific basis for future fuel selection in the marine sector. The test results show that the effective thermal efficiency of the diesel engine is slightly reduced and the fuel consumption slightly increased due to the high viscosity and low calorific value. However, the high oxygen content of the biodiesel contributes to a more complete combustion of the fuel, which has a positive effect on emission reduction. The use of the B24 biodiesel blend reduces harmful emissions such as CO, NOx and soot compared to conventional diesel for ship operation. Overall, the results of the trials with biodiesel blends in marine diesel engines showed many advantages in terms of performance, emissions and combustion. This is an important support for the sustainable development of the marine sector in the future and an important reference for the application of biodiesel in other transportation sectors. With the increasing demand for renewable energy, biodiesel is expected to become one of the main alternatives for replacing conventional diesel in shipping, making a positive contribution to reducing greenhouse gas emissions, improving air quality and promoting sustainable economic development.

1 INTRODUCTION

Global warming is an urgent challenge for the world today. The Paris Agreement set the goal of mitigating climate change by limiting the increase in global average temperature to below 1.5°C[1]. The shipping sector is an important industry that supports global trade and transportation and accounts for 85% of global trade. However, as the global economy and population grow, the number and size of ships is increasing rapidly, leading to a rapid rise in shipping-related greenhouse gas emissions. The International Maritime Organization (IMO) has introduced a series of measures to reduce greenhouse gas emissions from ships, with the aim of achieving net zero emissions from shipping by 2050. In the meantime, other countries and alliances such as China and the European Union have set carbon peaks and carbon neutrality targets ("30-60") and introduced emission reduction legislation to prepare the shipping industry for more stringent international decarbonization challenges.

Common merchant vessels such as container ships, bulk carriers and tankers often use low-speed two-stroke diesel engines, which face problems such as nitrogen oxide (NOx) and sulfur oxide (SOx) emission limits. As the IMO’s 2030 emission reduction targets draw ever closer, existing solutions are still being re-searched, while new ships are gradually being converted to liquefied natural gas (LNG), ammonia and meth-anol. In the medium to long term, biofuels remain a promising carbon-neutral fuel derived from renewable resources that can quickly achieve the shipping industry's decarbonization targets without extensive changes to ships and engines.

In recent years, numerous studies have investigated the effects of biofuels on energy consumption and emissions reduction in small and medium-sized engines [2-3]. Overall, CO and HC emissions from biodiesel made from used cooking oil have decreased significantly, while NOx emissions have increased slightly [4]. However, there are no case studies on the use of biofuels in large ocean-going vessels, and important issues such as life-cycle carbon emission factors, especially ship carbon emissions and NOx emissions, remain un-known. To further clarify the data, the MAN 6S35ME-B9 low-speed two-stroke diesel engine was selected as the research subject for this experiment. This engine is an electronically controlled, low-speed, advanced two-stroke high-performance engine with automatic tuning operation.

This study compares 15% marine biofuel oil (B15 Marine), 24% marine biofuel oil (B24 Marine), 30% marine biofuel oil (B30 Marine), 50% marine biofuel oil (B50 Marine) and marine residual fuel oil (180 Marine HFO) in large-scale tests with low-speed marine engines. By testing the marine diesel engine at different loads, the study examines the characteristics of its gaseous pollutant emissions. At the same time, the physical and chemical properties of the mixed fuels and the changes in engine parameters are analyzed to investigate the emission characteristics of gaseous pollutants under different conditions. The aim of the study is to identify the influencing factors of each gaseous pollutant and provide a reference for the application of these mixed fuels on ships.

2 EXPERIMENTAL EQUIPMENT AND METHODS

2.1 Low-speed engine for large ships

Here is an example of a subsection (second level heading). It uses the ‘Sub-heading 1.1’ heading style with the body in ‘standard’ or ‘paragraph’ style.

The low-speed engine is an electronically controlled diesel engine in which each cylinder is equipped with a piezoelectric pressure sensor to monitor the pressure changes in the cylinder. Table 1 summarizes the most important data of the diesel engine, which are crucial for the emissions and performance analysis. The test experiments are carried out in accordance with the following regulations: IMO NOx Technical Code (2008)[5].

Table 1. Performance Parameters of the Test Diesel Engine.

Name	Parameter
Type	Two-stroke
Number of cylinders	6
Structure	L-shaped
Bore	350mm
Stroke	1550mm
Rated speed	142r/min
Rated power	3570kW
Common power	3250KW
Compression ratio	17

2.2 Measurement Methods

This study follows the International Maritime Organization (IMO) Technical Code for Nitrogen Oxides (2008) and uses the operating load points specified by the E3 cycle for the engine tests. The engine is tested at four load points corresponding to 25%, 50%, 75% and 100% of rated power, with an additional test at a load point of 90. At each load point, the engine is kept in a stable operating condition for at least 120 minutes. Table 2 shows the parameters of the diesel engine defined for each operating condition.

Table 2. Five Test Load Points in E3 Test Mode

Operating Conditions	Load/ %	Power/KW	Engine Speed/(r/min)
1	25	900～925	89
2	50	1903～1928	113
3	75	2804～2822	129
4	90	3370～3391	138
5	100	3696～3713	142

2.3 Test Equipment

Engine power is measured with the NCK 2000 hydraulic dynamometer. Fuel consumption is measured with the RHE 08 mass flow meter. During the test, the engine parameters determined by the engine control unit are used, including power, peak combustion pressure and compression pressure. After stabilization at each operating condition, five measurements are taken to ensure the accuracy of the test. The cylinder pressure curve data is obtained from the engine's PMI system, with the pressure curves of all cylinders recorded simultaneously to avoid the influence of load fluctuations on the measurement process. The test facilities, equipment, measuring devices and instruments are all designed and equipped according to the standards of the 6S35ME-B9 test bench. The test facilities and equipment comply with the test requirements, and the measuring instruments and equipment are calibrated and within their valid certification period.

2.4 Engine Emission Measurements

An accredited exhaust gas analyzer for ships, AVL i60, is used to measure the exhaust gas composition. Before first use, the device is checked for leaks, zero calibration, full calibration and zero drift after measurement. During the measurement, the ambient conditions, including pressure, temperature, humidity and other factors specified by the International Maritime Organization, are recorded. Sampling points are selected on straight pipe sections with a distance of more than 1 meter from any bends and more than three times the pipe diameter to minimize the influence of turbulence. In all cases, measurements are taken after the main engine load has stabilized for approximately 15 minutes and data is recorded from all measurement devices within the same time period. To improve reliability, each load point is subjected to three 60-minute measurements, with the corresponding device data photographed for documentation, recorded in data logs and averaged for the final calculations. A schematic representation of the measurement setup is shown in Figure 1.

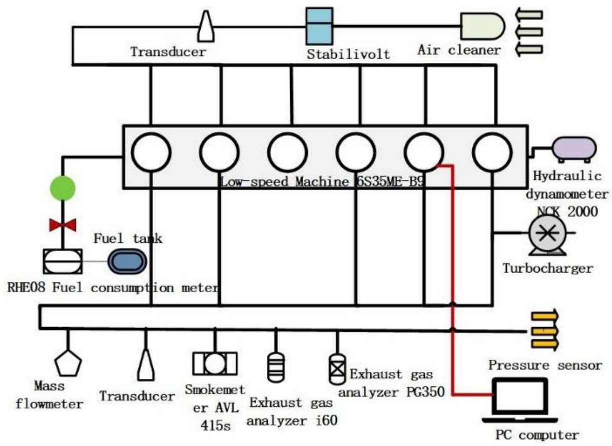


Figure 1. Test engine and device diagram

2.5 Fuel Characteristics

Five different biofuel oil blends were used in this experiment: B15, B24, B30, B50 and 180 heavy fuel oil (HFO). Before the test, each fuel was consumed to a low level using the daily fuel cabinet, and new fuel was topped up to a level of 0.5 meters before being consumed to the low level again. This process was repeated 2-3 times to ensure thorough cleaning before the start of the mobility test. In addition, before each emission test, it was ensured that the appliances had been running for at least 12 hours. Sufficient time was allowed for fuel changes and cleanliness of the entire fuel line. Table 3 shows the most important physical and chemical properties of the fuels.

Table 3. Main physical and chemical properties of fuel

Name	B15	B24	B30	B50	HFO
Density20℃kg /m^3	944.8	936.2	931.0	911.2	958.0
viscosity50℃ cSt	60.12	47.40	26.48	13.51	168.6
Sulfur content %	0.404	0.383	0.332	0.253	0.470
Oxygen %	3.0	3.3	3.8	10.7	0.8
Carbon %	84.9	84.6	83.8	82.0	86.5
Hydrogen %	10.9	11.0	11.4	11.2	11.1

2.6 Exhaust Gas Mass Flow Calculation Method

After reviewing and analyzing the measured and estimated data, the exhaust gas mass flow of the marine engine was calculated using the carbon balance method in accordance with the requirements of the official guidelines of the International Maritime Organization (IMO) Nitrogen Oxide Technical Code (2008) for marine engines [6].

$$q_{mew} = q_{mf} \cdot \left(\left(\frac{\dfrac{W_{BET} \cdot W_{BET} \cdot 1.4}{\left(\dfrac{1.4 \cdot W_{BET}}{f_c} + W_{ALF} \cdot 0.08936 - 1 \right) \dfrac{1}{1.293} + f_{fd}}}{f_c \cdot f_c} + W_{ALF} \cdot 0.08936 - 1 \right) \cdot \left(1 + \frac{H_a}{1000}\right) + 1 \right) \quad (1)$$

In the formula: q_{mf} is the fuel mass flow rate, $H_a$is the absolute humidity at the compressor inlet, W_{ALF} and W_{BET} are the mass percentages of hydrogen (H) and carbon (C) in the fuel,f_{fd} is the fuel-specific constant, f_c is the fuel carbon coefficient.

The carbon coefficient f_c is obtained from Equation (2):

$$f_c = \left(c_{CO_2 d} - c_{CO_2 ad} \right) \cdot 0.5441 + \frac{c_{COd}}{18522} + \frac{c_{HCw}}{17355}$$
(2)

Where C_{CO2d} is the dry CO_2 concentration in the exhaust gas,in %.C_{CO2ad} is the dry CO_2 concentration in the ambient air,in %.C_{COd} is the dry CO concentration in the exhaust gas;C_{HCw} is the wet HC concentration in the exhaust gas, in ppm.

2.7 Emission Factor Calculation

The mass flow rate of each component's emissions in the raw exhaust gas at each operating condition should be calculated according to the following equation, $q_{mgas} = u_{gas} \times c_{gas} \times q_{mew} \times k_{hd}$ (For NO_X) (3)

$q_{mgas} = u_{gas} \times c_{gas} \times q_{mew}$ (For other gases) (4)

In the equation, q_{mgas} represents the mass flow rate of each gas emission, in g/h. u_{gas} is the wet basis factor. c_{gas} is the volume concentration of each exhaust component, in ppm (wet basis), where 1.0% = 10,000 ppm. q_{mew} is the exhaust mass flow rate, in kg/h (wet basis). k_{hd} is the temperature and humidity correction factor, as shown in Table 4.

Table 4. Wet base coefficient

Gas	u	c
NO_X	0.001 587	ppm
CO	0.000 966	ppm
HC	0.000 479 0.000 516*	ppm
CO_2	15.19	%

Note*: Applicable to NG fuel.

The calculation formula for the mass flow rate of each gas_x component in the exhaust per unit of brake power is as follows:

$$gas_x = \frac{\sum_{i=1}^{i=n} q_{mgas,i}}{\sum_{i=1}^{i=n} P_i} \quad (5)$$

In the equation, gas_x is the emission factor, in g/kWh. P_i is the brake power at the ii-th operating condition, in kW.

3 TEST RESULTS AND ANALYSIS

3.1 Fuel Consumption

Figure 2 shows the results of the specific fuel oil consumption (SFOC) of the five fuels.

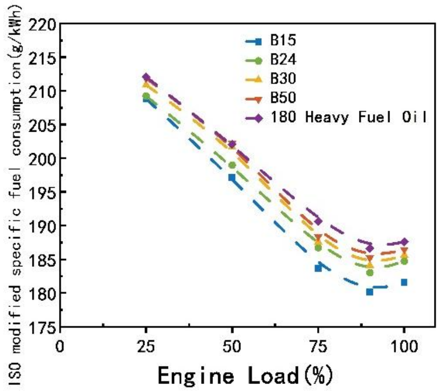
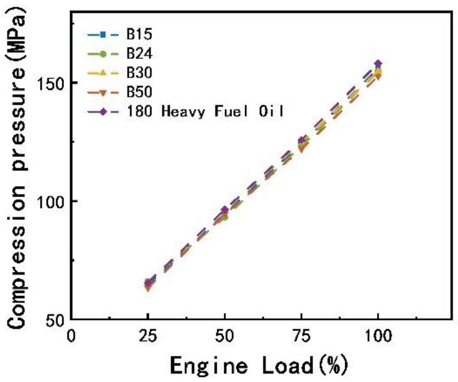


Figure 2. ISO correction ratio of fuel consumption

It can be observed that the SFOC gradually decreases with increasing load and reaches the lowest value at the point of optimum efficiency. Overall, the SFOC of biofuels is slightly higher than that of 180 heavy fuel oil. In addition, the SFOC value increases slightly with increasing blend ratio. According to the test results on physical and chemical properties, 180 heavy fuel oil has a higher carbon-to-hydrogen ratio, i.e. it contains more energy per unit mass of fuel. There-fore, less fuel is needed for the same power. Considering the operating conditions of the vessel (e.g. cruise), it is important to take into account the potential increase in fuel consumption, which may require an appropriate increase in the storage capacity of the oil tank[7].

3.2 Spacing and Indenting:

Engine performance and emissions are mainly influenced by several important operating parameters, including ignition advance angle, cylinder pressure, compression pressure, peak combustion pressure and cylinder exhaust temperature[8].



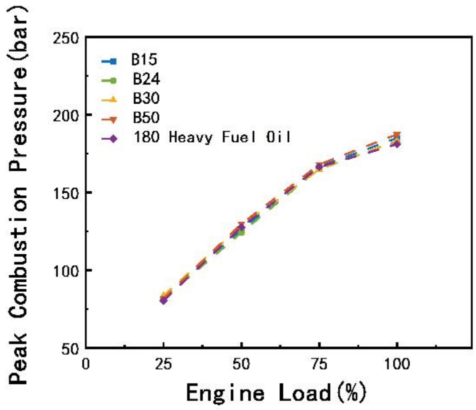
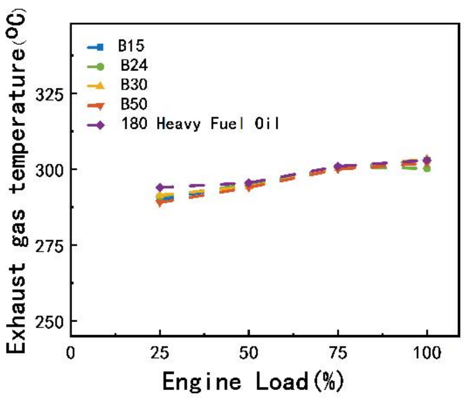


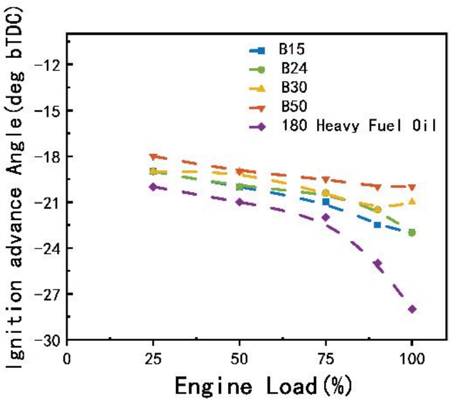
Figure 3. compression pressure and peak combustion pressure

Figure 3 shows the compression pressure and peak combustion pressure of cylinder no. 4. It can be observed that the compression pressure values for biofuels are similar to those of 180 heavy fuel oil, which is due to the combustion mechanism and the fuel itself. Figure 4 shows the peak combustion pressure for cylinder No. 4 [9]. It can be seen that the peak combustion pressure of biofuels is almost the same as that of heavy fuel oil, which indicates that biofuels have little effect on engine performance. However, the differences between the different engine types and operating conditions still need to be monitored and verified in marine applications.

Figure 4(a) shows the results of the exhaust gas temperature test for cylinder No. 4. It can be seen that biofuels do not cause a significant increase in exhaust gas temperature at low load. Due to the oxygen content in biofuels, water vapor and carbon dioxide are produced during combustion, which expand at low engine load and dissipate some of the heat, causing the temperature in the combustion zone to drop. However, due to factors such as fuel combustion efficiency, combustion conditions and engine management strategies, the exhaust gas temperature of biofuels increases slightly at high loads. Nevertheless, it can be concluded that the use of biofuels from B15 to B24 and even up to B30 or B50 can fully achieve the performance of 180 heavy fuel oil, and no ab-normal combustion problems have been observed in ship management[10].



(a)



(b)

Figure 4. exhaust gas temperature and fuel ignition advance Angle.

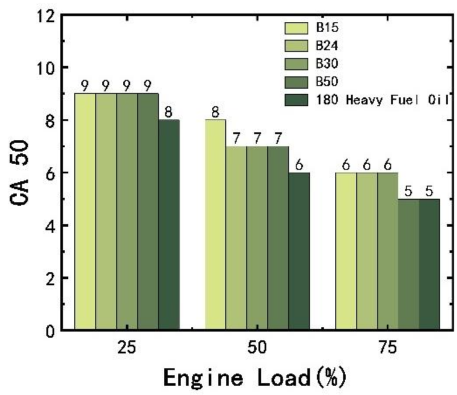
Figure 4(b) shows the influence of the fuel on the ignition timing angle. It shows that the ignition timing at low load is slightly earlier with heavy fuel oil 180. Due to its high viscosity and high carbon-hydrogen ratio, a correspondingly early ignition angle can form a sufficient gas mixture during combustion[11]. An ignition timing that is too late can lead to incomplete combustion and thus to exhaust gas pollution and energy loss. It shows that the ignition angle of biodiesel compared to 180 heavy fuel oil is higher at high loads than at low loads. This means that biodiesel can ignite earlier at higher load and ambient temperatures, allowing a relatively lower injection advance, which is consistent with the results in reference [12].

3.3 In-cylinder pressure and heat Release Rate

Based on the engine's PMI system, the pressure curve for cylinder No. 4 was plotted and the cylinder pressures at 25%, 50%, 75% and 100% load were compared[13]. It can be seen that the differences between these pressures at different mixture ratios are very small, indicating that the engine's performance can be fully achieved. The differences are mainly due to the changes in scavenging pressure and combustion heat release. Since the cylinder pressures remain largely unchanged when using biofuels, it is not necessary to adjust the injection timing [14].

Due to the significantly higher viscosity of Marine 180 heavy fuel oil compared to biofuels, there is a higher probability of poorer atomization quality when the fuel enters the injector [15].At the same time, the high oxygen content in biofuels improves the quality of the air-fuel mixture and thus compensates for the slight decrease in calorific value[16].It should be noted that the difference in heat release rate between B24 and 180 heavy fuel oil is not significant despite the calorific value of biofuels and high fuel consumption of low-speed marine engines.

Figure 5 shows the calculated results of combustion duration [17]using the cumulative heat release at 50% and 95% of total combustion. It can be observed that the combustion duration at CA50 decreases with increasing engine load. The differences between the biofuels at different blend ratios are small at each operating condition. At CA95, the combustion duration for 180 heavy fuel oil remains relatively stable. The fastest combustion rate is observed for B24, which is related to the fuel density and viscosity. According to IMO regulations, a ship refueling marine biofuels with a blend ratio of 25 or less (by volume) must meet the re-quirements of MARPOL Annex I for general tankers. It can therefore be assumed that the fuel will have a faster combustion rate if the focus of future large-scale use of biofuels for shipping is on B24 [18].



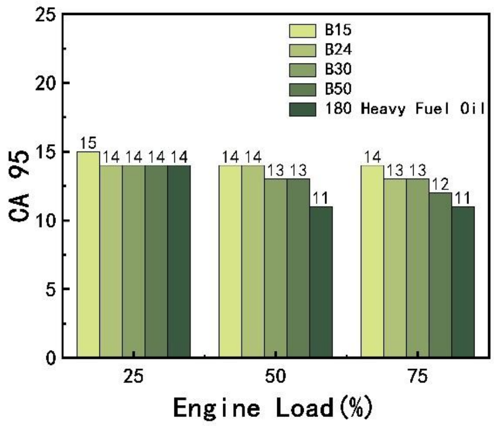


Figure 5 .CA50 and CA95

3.4 Emissions

3.4.1 Carbon Dioxide Emissions

Engine emissions are an important factor influencing fuel usage and are also a key issue regulated by laws and regulations [19].

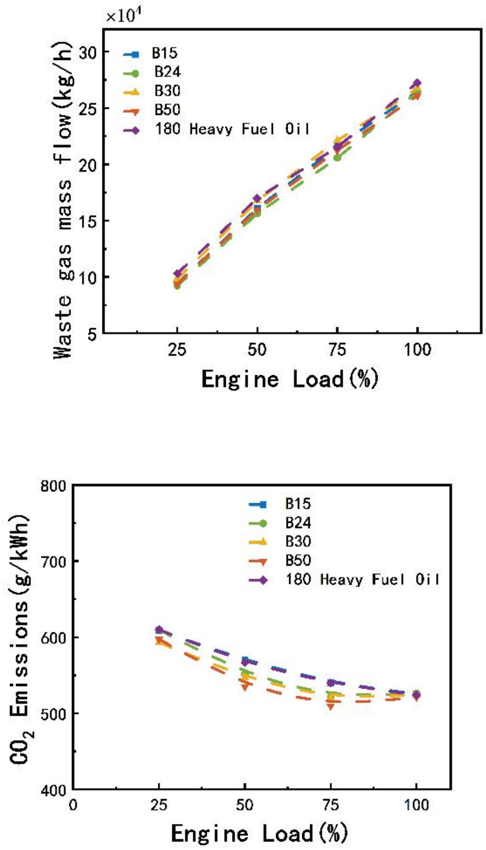


Figure 6. Waste gas mass flow and Carbon dioxide emissions

As shown in Figure 6, the estimated values of the exhaust gas mass flow are calculated. It can be observed that the exhaust gas mass flows are approximately the same, with 180 heavy fuel oil being slightly higher than biofuels. Biofuels have relatively lower flash points and auto-ignition points, burn faster and release more energy during combustion, which helps to improve cylinder efficiency and slightly reduces the exhaust gas mass flow [20].

CO_2 emissions depend on the carbon content in the fuel and the completeness of combustion [21-23]. As shown in Figure 11, the results for the CO_2 emission factor are presented. It can be observed that emissions decrease to varying degrees with increasing pollution. It is noteworthy that biofuels tend to reduce CO_2 emis-sions as the blending ratio increases. More complete combustion and higher oxygen content allows oxygen to participate more in the reaction during combustion, which contributes to better combustion efficiency and a reduction in unburned hydrocarbons. As the load increases, the engine's fuel supply increases accordingly, but the more complete combustion allows the low-speed engine to maintain lower CO2 emissions even under the increased load. Overall, the CO2 emission factor for biofuels and marine fuels is in the range of 500-600 g/kWh.

3.4.2 Nitrogen Oxide Emissions

According to the IMO, when using marine biofuels with a blend ratio of B30 or higher, the fuel must meet the requirements of MARPOL Annex VI and the Technical Code for Oxides of Nitrogen MEPC.177(58), sec-tion 6.3, using a simplified on-board measurement method or testing by direct measurement and monitoring methods. As can be seen in Figure 7, after applying the weighted values required by the International Maritime Organization (IMO) Technical Code for Nitrogen Oxides, the specific NOx emission factors are calculated to verify that they meet the official total weighted emission limit. It can be seen that compared to 180 heavy fuel oil, the largest difference is at B30, which increases by approximately 5.72%, while the smallest difference is at B50, which increases by approximately 1.40%. It can be seen that the total weighted NOx emissions for all fuels meet the IMO requirements [24].

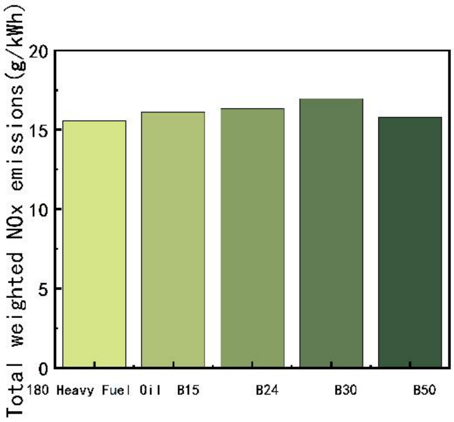


Figure 7. Total weighted NOx emissions

3.5 Numerical simulation

This section follows the three-dimensional geometric parameters of the original low-speed engine with a cylinder diameter of 350 mm, including the cylinder diameter, stroke, compression ratio, and combustion chamber shape, and establishes a three-dimensional simulation model based on CONVERGE, covering pro-cesses such as compression, fuel injection, gas-oil mixing, combustion, expansion, in-cylinder heat transfer, and emission generation. The turbulent flow process is modeled with the RANS model [25]. The heat transfer at the inner wall of the cylinder is modeled with the Amsdenmodel [26]. The spray fragmentation process is modeled with the KH-RT model [27]. The droplet collision process is modeled with the NTC model [28]. The chemical reaction kinetics mechanism used in this simulation study is from the College of Wisconsin [29]On this basis, MD represents the saturated components in biodiesel, MD9D represents the unsaturated components in biodiesel, and the NO generation reaction (N+OH=NO+H process) is optimized to obtain the chemical re-action kinetics mechanism, which contains 4 elements, 70 substances and 192 reactions.

In this section, the prediction accuracy of the simulation is checked using experimental data at different mixing ratios. Figure 8 shows the comparison of the cylinder pressure curve of a 350cc low-speed engine under different mixture ratios for simulation and experiment. The engine load here is 100%, the speed is 142 rpm and the fuels are B24, B30 and B50. It can be seen that the cylinder pressure development of the simulation and the experiment overlap well, which indicates the predictive accuracy of the simulation model.

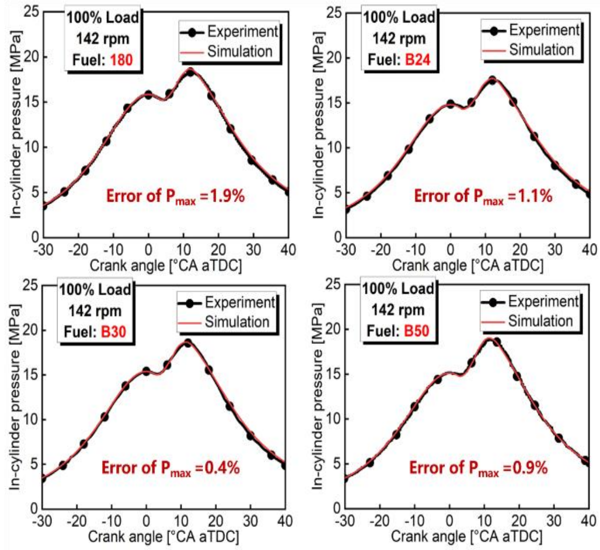
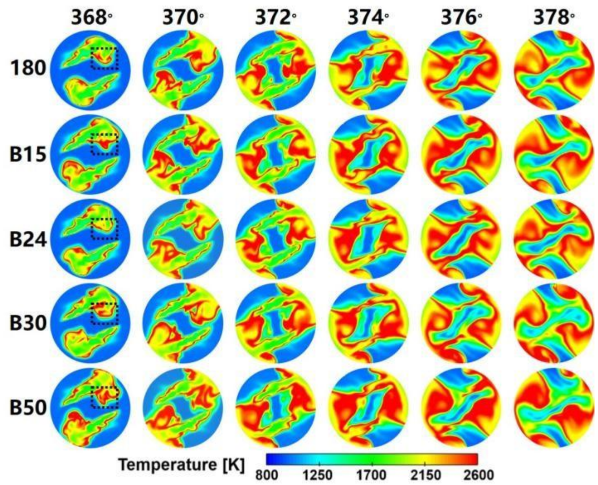
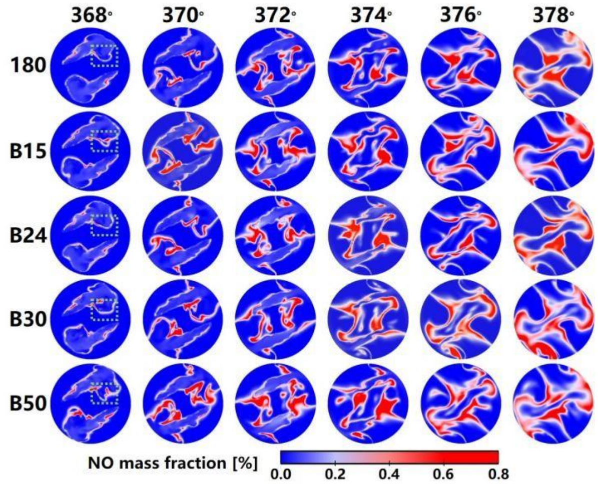


Figure 8. Comparison of the development process of cylinder pressure in simulation and experiment under different mixing ratios (Engine load 100%, speed 142rpm)

Numerical simulations can predict experimental conditions that were not performed and also explain observed experimental phenomena. To interpret the variation patterns of NOx under different mixing ratios in experiments, Figure 9(a) shows the temperature field distribution inside the cylinder for different mixing ratios. As can be seen in Figure 9(a), the black dashed line on the left shows that at a crankshaft angle of 368, the local combustion temperatures of B15 and B30 are higher, which is consistent with the higher NOx emissions ob-served in Figure 9(b). Since the control system was not changed during the experiment, parameters such as in-jection timing and injection duration were not consistently controlled across different mixture ratios. Therefore, in addition to differences in fuel composition, variations in injection parameters are also important factors influencing NOx emission differences at different blend ratios. According to the results of the simulation study on the use of biofuel oil with different cylinder diameter for low-speed engines in this section, parameters such as injection timing, injection pressure and fuel supply can be strictly controlled to ensure that the fuel mixture ratio is a single variable, and the impact on engine performance and emissions can be optimized.



(a) Temperature field distribution in the cylinder



(b) NO distribution in the cylinder

Figure 9. Distribution of temperature field and NO distribution in the cylinder under different mixing ratios

(Engine load 100%, speed 142rpm)

Figure 10. shows the indicative thermal efficiency (ITE) curves for a low-speed engine with 350 mm cyl-inder diameter using different blending ratios of biodiesel fuels (180, B24, B50, B100). The thermal efficiency data in Figure 6 shows that the thermal efficiency of the engine decreases slightly as the biodiesel blend ratio increases. This is mainly due to the lower heat of the biofuel, which requires a larger fuel mass and a longer injection time to achieve the same energy input at the same injection pressure. As a result, the impact of the spray flame on the wall and the resulting rapid heat transfer increase, leading to a slight decrease in the thermal efficiency of the engines.

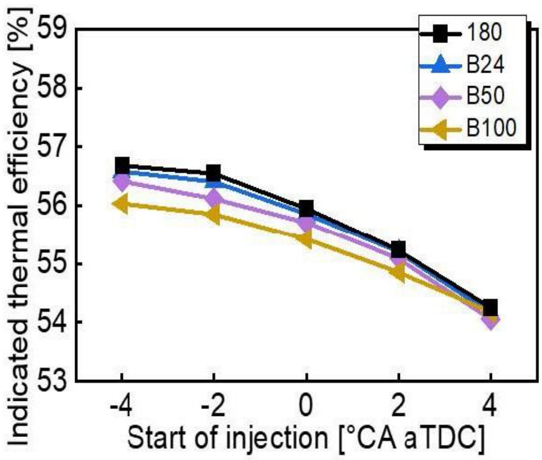


Figure 10. Indicated thermal efficiency of 350mm bore low-speed engine with different blending ratios of biofuel

4 CONCLUSIONS

In this study, the effects of different biofuel blends on engine performance, combustion efficiency and emission values were investigated using test bench tests at low engine speeds. The results of the study are as follows.

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