POLISH MARITIME RESEARCH 1 (121) 2024 Vol. 31; pp. 94-101
10.2478/pomr-2024-0010

EFFECTS ON OF BLENDED BIODIESEL AND HEAVY OIL ON ENGINE COMBUSTION AND BLACK CARBON EMISSIONS OF A LOW-SPEED TWO-STROKE ENGINE

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ABSTRACT

The effects of heavy fuel oil and biodiesel blends on engine combustion and emissions were studied in a marine two-stroke diesel engine. The engine was operated under propeller conditions using five different fuels with biodiesel blends of 10% (B10), 30% (B30), 50% (B50), and sulphur contents of 0.467% low sulphur fuel oil (LSFO) and 2.9% high sulphur fuel oil (HSFO). Tests have shown that using a biodiesel blend increases the engine fuel consumption due to its lower calorific value. Heavy fuel oil has a high Polycyclic aromatic hydrocarbons (PAH) content, which leads to higher exhaust temperatures due to severe afterburning in the engine. A comparison of engine soot emissions under different fuel conditions was carried out, and it was found that the oxygen content in biodiesel promoted the oxidation of soot particles during the combustion process, which reduced the soot emissions of biodiesel. Compared to HSFO, B10, B30, B50 and LSFO, the soot emission concentrations were reduced by 50.2%, 56.4%, 61% and 37.4%, respectively. In our experiments, the soot particles in the engine exhaust were sampled with a thermal float probe. Using Raman spectroscopy analysis, it was found that as the biodiesel ratio increased, the degree of carbonisation of the soot particles in the exhaust became less than that in the oxygenation process, resulting in a decrease in the degree of graphitisation.

Keywords: Low-speed engine; biodiesel; black carbon; Raman spectroscopy; degree of graphitisation

INTRODUCTION

Global warming is causing continuous melting of the Arctic glaciers, and although the opening of new Arctic shipping routes offers great convenience to international shipping, it poses a great threat to the Arctic environment at the same time. Black carbon (BC) emissions from international shipping vessels are the main source of BC in the Arctic, and these emissions have greatly accelerated the melting rate of Arctic glaciers [1]. Maritime shipping is a key component of the global economy, representing 80–90% of international trade [2]. In view of the current impact of BC from international ship emissions on the deteriorating ecosystem of the Arctic, there is an urgent need for new alternative marine fuels to reduce BC emissions from ships. With its high oxygen content, biodiesel can reduce the emissions of BC in the exhaust gas during engine operation, and can reduce carbon emission over the whole life cycle; it has therefore attracted attention from researchers as an ideal alternative fuel in the field of shipping.

Teams from many countries have studied the effect of biodiesel on engine performance. Huang et al. [3] investigated the effects of intake pressure and EGR ratio on the performance and emission characteristics of a diesel engine running on biodiesel-diesel blends (B20, B30 and B40) and pure diesel (B0). Khanjani [4] et al. prepared different formulations of WFO biodiesel (made from waste fish oil) by ultrasound radiation, and used this WFO biodiesel to make emulsion fuel. Compared with the use of diesel, the engine torque decreased, the braking power decreased, and the brake fuel consumption increased. Nabi [5] et al. prepared three kinds of biodiesel mixtures and compared them with traditional diesel fuel; it was found that although the performance of the engine changed little, the combustion efficiency was improved. Zeńczak et al. [6] converted solid biomass into marine fuel by mechanical densification or pyrolysis, and described the results from the points of view of fire safety, environmental protection, rising liquid fuel prices and dwindling crude oil resources. The potential for fire hazards on board ships arising from the storage and transport of pellet fuels and the decomposition of pellet fuels due to high temperatures were also assessed. An et al. [7] carried out experiments on biodiesel with different blending ratios and ultra-low sulphur diesel under different loads, and found that biodiesel had a significant effect on the brake-specific fuel consumption and braking thermal efficiency of generators under partial load. Wang and Yao [8] and Changxiong et al. [9] investigated the effect of in-cylinder temperature and pressure of an engine at different mixing ratios for dimethyl ether (DME) and the oxygenated fuel polyoxymethylene dimethyl ether (PODE). Ghaemi et al. [10] presented a quick and relatively simple method of building a simulation model for a specific marine diesel engine based only on steady-state data, which are widely available in the publicly available data. These authors also described how to tune the model parameters for the simulation model and how to validate the results.

Biodiesel has good effects in terms of reducing BC emissions from engines. Its use can significantly improve combustion efficiency, as it releases the oxygen atoms in its chemical structure to supplement oxygen in fuel-poor areas [11]. Abboud et al. [12] found that when using oxygenated fuel, the reduction of soot emission was closely related to the oxygen content, while soot formation was related to the ester function groups in the fuel. The alkyl chain length of the fuel was shown to affect the soot characteristics, where longer alkyl chains showed lower soot reactivity. Lemaire et al. [13] found that the soot volume fraction of rapeseed methyl ester (RME) in a turbulent flame was about 16% of that of pure diesel oil. Du et al. [14] studied the pore structure and oxidation activity of biodiesel soot; these authors reported that the carbon-oxygen ratio of biodiesel soot was lower than that of diesel soot, and the porosity of biodiesel soot was higher. Zandie et al. [15] developed a mechanism Compact combined diesel-biodiesel-gasline kinetic mechanism (CDBG) for diesel-biodiesel-gasoline mixtures, using a mixed Reynolds averaged navier strokes-Large eddy simulation (RANS-LES) model Detached eddy simulation (DES) model to simulate turbulence, in order to study the formation and emission of soot. The results showed that an increase in environmental oxygen concentration could improve the consumption of soot precursors and reduce both PAHs and soot formation. Sundararajan Rajkumar [16] proposed a multi-region phenomenological model to analyse the combustion and emission of biodiesel. The prediction results of the model were in good agreement with the measured data, and the maximum prediction error for soot emission was 18%.

Various methods are currently in use to analyse the composition of soot, such as Fourier transform infrared spectroscopy (FT-IR), transmission electron microscopy (TEM) and thermogravimetric analysis (TGA) [17]. Raman spectroscopy was first applied to the field of aerosol analysis by Raman in 1977, and was later widely used in the field of marine atmosphere analysis. Researchers used Raman techniques to study the morphology and size of soot from gas combustion in relation to fuel and added water [18]. The intensity of graphitisation of a material can be judged according to the height of the two characteristic peaks in the Raman spectrum, as there is a positive correlation between the degree of graphitisation and the microcrystal size of soot particles; that is, the higher the degree of graphitisation, the larger the microcrystal size [19].

Although scholars have extensively researched the combustion and BC emissions from biodiesel and heavy oil in an engine, few comparative studies have focused on combustion analysis of heavy oil and blended biodiesel in the same engine. There is also little research on the degree of graphitisation of BC produced from the combustion of different fuels in marine engines. In this study, the fuel consumption and exhaust temperature of a marine engine are monitored, and the effects of different fuels on the combustion performance of the engine are studied. The filter smoke count method (FSN) recommended by International maritime organization (IMO) is used to measure the BC emission concentration of different fuels, and the effects of different fuels on the BC concentration in engine exhaust are analysed. The degree of graphitisation of black carbon in exhaust gas is characterised by Raman spectroscopy, and the effects of different fuels on the formation of BC particles in marine engine are explained.

TEST CONDITIONS AND TEST METHODS

EXPERIMENTAL STEPS

Tests were carried out on a marine two-stroke low-speed engine, as this type of diesel engine has been widely used for international operation of ships, Therefore the conclusions of this test can be a good response to the results of biodiesel use in ships on international voyages. In this study, the engine was operated in a propeller characteristic mode which also means that the engine speed varies with the engine load. The engine parameters are shown in Table 1.

Tab. 1. Engine parameters

Engine type	MAN 6S35MEB
Engine stroke	2 stroke
Engine speed	142 rpm
Cylinder bore	350 mm
Stroke	1500 mm
Torque	240 kN
Engine power	3570 kW
Charge type	Exhaust gas turbine charge

Blended heavy fuel oil with a high sulphur content has been the main fuel for international ships for a long time, as fuel oil makes up a large proportion of the operating costs. Hence, in order to better study the effects of biodiesel blending on engine performance and BC emission compared with heavy fuel oil, the fuels used in this experiment were marine heavy fuel oil with 2.9% high sulphur content fuel oil (HSFO), marine heavy fuel oil with 0.467% low sulphur content fuel oil (LSFO), and diesel oil blended with 10%, 30%, and 50% biodiesel by volume, denoted as B10, B30, and B50, respectively. The biodiesel used in this trial was refined from waste grease from the restaurant industry. Due to the high viscosity of heavy fuel oil at room temperature, it must be heated to 80°C in the fuel cabinet before use, and the heater in the line must be switched on to ensure good fuel flow. The physicochemical properties of the five fuels used in the test are shown in Table 2.

In this test, a Kistler cylinder pressure sensor (6613C) mounted on the engine cylinder head was employed to measure the cylinder pressure, and a thermocouple temperature sensor installed in the engine exhaust pipe was used to measure the engine exhaust temperature. Fuel consumption was calculated using an inlet and return oil mass flow meter, which was installed in the engine oil supply unit. Of the current BC testing techniques, the Filtered Smoke Number (FSN) method is the one considered more applicable to marine engine testing. The BC concentration of the engine at 25%, 50%, 75%, and 100% loads with different fuels was measured using AVL415 in these tests. A copper tube and a vacuum pump were used to sample the BC particles in the engine exhaust during the test. According to EPA regulations, the sampling temperature needs to be maintained at 55±3°C to avoid particulate loss due to coalescence of BC particles and cold-wall adherence during the sampling process. A 47 mm quartz fibre optic filter (filtration accuracy 0.3 μm) was used for a sampling time of 60 min at a flow rate of about 90 l/min. To prevent the influence of moisture in the air on

Tab. 2. Fuel composition analysis

Fuel type	LSFO	HSFO	B10	B30	B50
Density (20°C) kg/m^3	950.2	974.1	842.8	845.0	849.9
Viscosity (40°C) mm^2/s	122.3	331.2	3.267	3.283	3.437
Flash point °C	73.0	85.0	77.0	79.0	82.0°C
cetane index	/	/	53.0	53.2	53.5
Polycyclic aromatic hydrocarbon (PAH) % (m/m)	11.2	11.9%	1.0%	0.9%	0.7%
Fatty acid methyl ester content % (m/m)	/	/	15.3	29.5	45.3
Net calorific value MJ/kg	41.080	40.068	41.697	41.037	40.236
Sulphur content % (m/m)	0.467	2.91	/	/	/

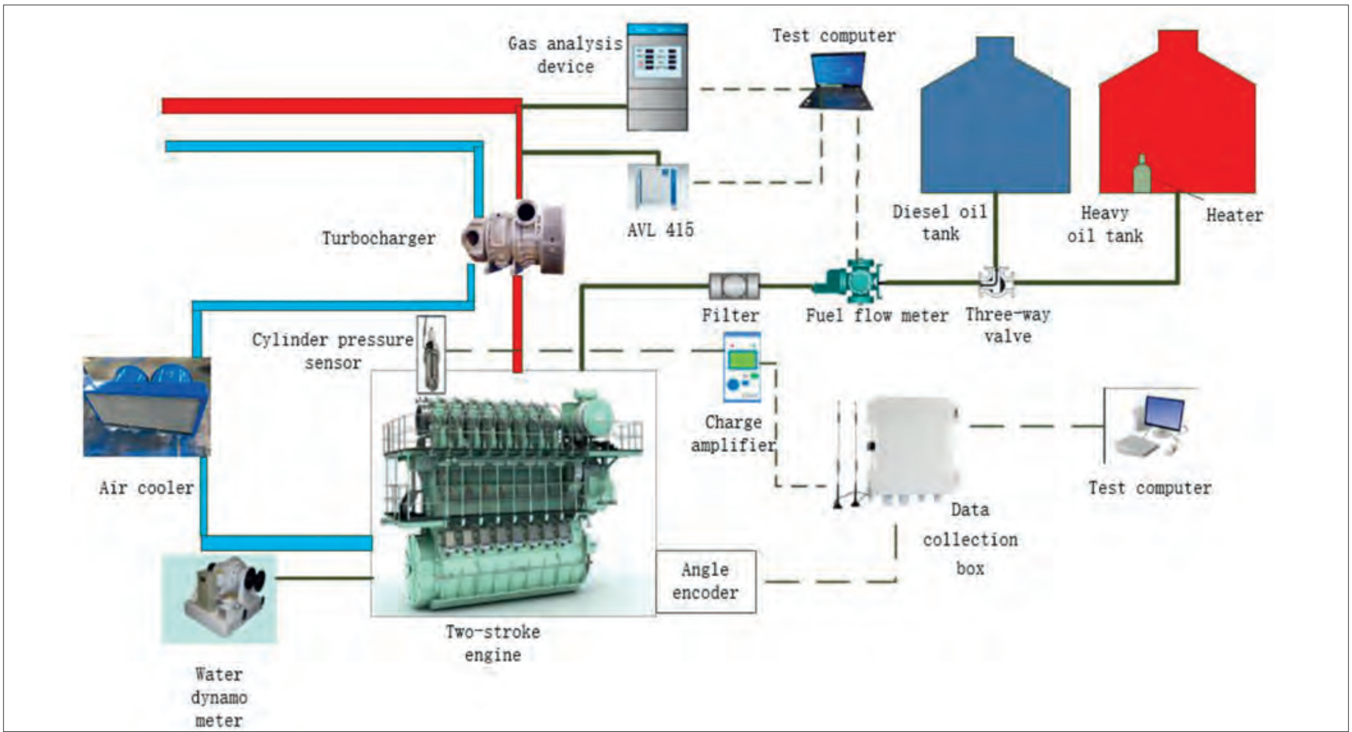

Fig. 1. Layout of the test equipment

the samples, the samples were stored in a desiccator after sampling. The BC particles produced by the combustion of different fuels were monitored using a Raman spectrometer. The experimental setup is illustrated in Fig. 1.

UNCERTAINTY ANALYSIS

Uncertainty affects the reliability and confidence of the test results. The uncertainty of the measurements made by the equipment used in the test is shown in Table 3.

Tab. 3. Uncertainty in measurement equipment

Parameter	Range	Uncertainty(%)
Speed (r/min)	0–150	±1
Flow rate of fuel (kg/h)	0–1800	±0.1
Exhaust temperature (°C)	0–500	±0.5
Black carbon (FSN)	0–10	±2
Cylinder pressure (bar)	0–250	±0.2

CALCULATION OF BC AND ENVIRENTAL CONDITIONS

The formula used to calculate the BC concentration was [20]:

$$\rho = \frac{1}{0.405} * 5.95 * FSN * e^{0.38FSN} \tag{1}$$

where ρ is the concentration of BC (mg/m^3) and FSN is the smoke value.

When conducting marine engine bench tests, the laboratory environment needs to be judged by the parameter f_a.The equation used to calculate the laboratory environment was [21]:

$$f_a = \left(\frac{99}{P_s}\right)^{0.7} * \left(\frac{T_a}{298}\right)^{1.5} \tag{2}$$

where T_a (°C) is the absolute temperature of the intake air and P_a (kPa) is the dry air pressure.

The marine engine exhaust emission limits and measurement methods specify that the calculated value of f_a for the laboratory environment should be between 0.93 and 1.07 in order to be considered as meeting the requirements of the marine engine test [21].

RESULTS AND DISCUSSION

EFFECTS OF BIODIESEL ON ENGINE PERFORMANCE

Biodiesel is an alternative fuel that is typically converted from vegetable oils or animal fats. It has different physicochemical properties from traditional petroleum diesel, and therefore has an impact on engine performance and in-cylinder combustion when burned in the same engine. This section analyses the effects of five different fuels on engine performance and in-cylinder combustion during the combustion process in the engine.

Effects of biodiesel on engine cylinder pressure

Fig. 2 shows the cylinder pressure at engine runing in 75% rated engine load. It can be seen that an increase in the biodiesel blending ratio causes the pressure in the engine cylinder to increase, and that the pressure of blended biodiesel is higher than that of heavy oil. Specifically, the maximum pressure in the engine cylinder is 1.2% higher when running on B50 compared to B10. The main reason for this is the increase in the oxygen atom content of the fuel as the biodiesel blend ratio increases, which accelerates the combustion rate in the cylinder. The piston moves up to the top stop and then starts to move down, and the faster combustion rate also leads to a higher pressure in the cylinder. Due to the high viscosity of heavy oil, poor atomisation leads to relatively slow combustion, which causes the rate of increase in the in-cylinder pressure to decrease, as can be seen from Fig. 3. In addition, this causes the pressure in the cylinder to decrease.

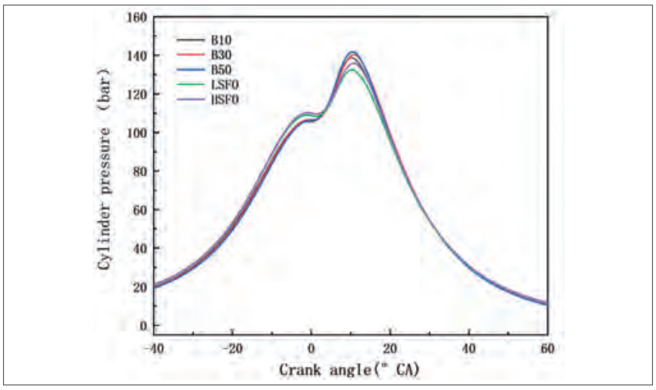

Fig. 2. Cylinder pressure at 75% engine load

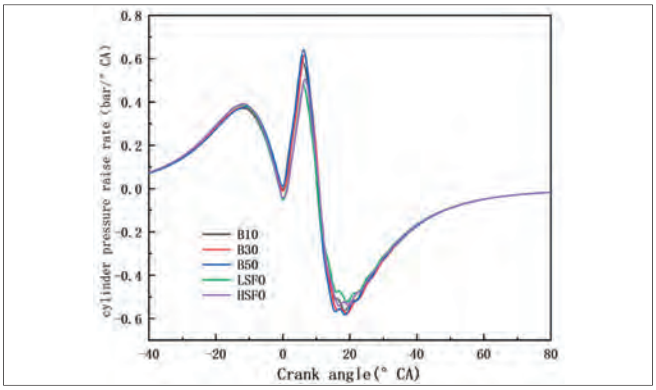

Fig. 3. Rate of rise in cylinder pressure at 75% engine load

Effects of biodiesel on engine thermal efficiency

Thermal efficiency is a metric of the efficiency of the engine in terms of converting the chemical energy of the fuel into useful work. The energy loss during engine operation not only depends on the engine speed but also varies with the combustion characteristics of the fuel. From the variation in thermal efficiency with load for three different biodiesel blends in Fig. 4, it can be seen that increasing the biodiesel content reduces the calorific value of the blended fuel, and more fuel must be injected to meet the set load of the engine under the same engine operating conditions. Under the same injector conditions, an increase in the amount of injected fuel can lead to problems such as poor atomisation, which reduces the thermal efficiency of the engine. Although HSFO and LSFO have higher viscosities than biodiesel and are heated during use, their higher PAH content results in more incomplete combustion and therefore lower thermal efficiencies.

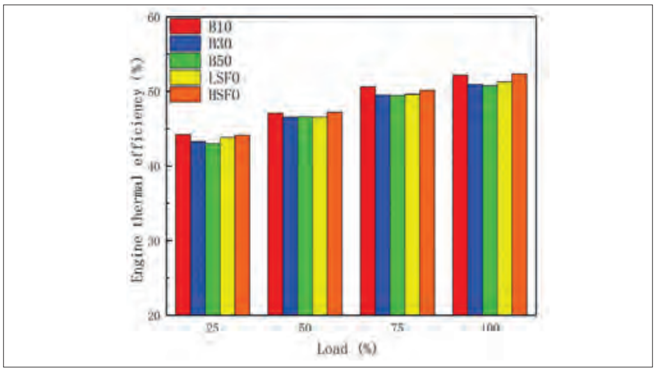

Fig. 4. Engine thermal efficiency of different fuels under different loads

Effects of biodiesel on fuel consumption

The fuel consumption rate is an important indicator of fuel economy. Fig. 5 shows the fuel consumption rate of the engine using B10, B30, B50, LSFO and HSFO, for varying loads. It can be seen that the fuel consumption rate increases with the percentage of biodiesel blend. From a comparison of the average fuel consumption of the engine for each fuel at the four loads, it can be found that the fuel consumption rates for B10, B30 and LSFO compared to HSFO decrease compared to HSFO by 0.6%, 0.4% and 1.2%, respectively, and the fuel consumption rate of B50 increases by 1.7%. This is mainly the result of one increase the other decreases between the calorific value of the fuel and the injection and combustion of the fuel in the cylinder. The calorific value of the fuel is an important factor affecting the fuel consumption of the engine, and under normal circumstances, higher calorific values tend to be associated with lower fuel consumption rates. The atomisation and combustion of the fuel in the engine cylinder are also important factors affecting the fuel consumption, as a good combustion process will also reduce the engine fuel consumption. Of the fuels considered here, B10 has the highest calorific value, and although B50 has more oxygen atoms to promote combustion, the calorific value of the fuel dominates. Compared to HSFO and LSFO, B10 has a lower content of polymer PAHs, which ultimately results in a lower fuel consumption.

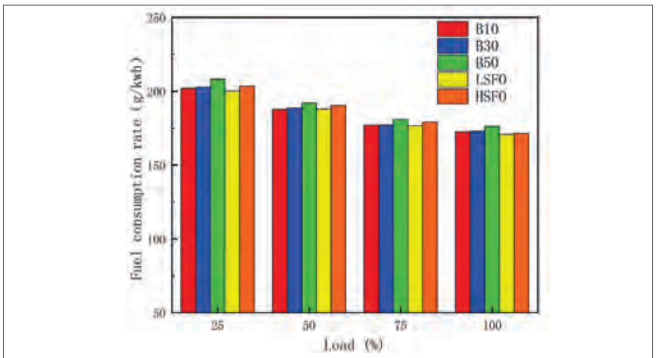

Fig. 5. Engine fuel consumption rates for different fuels at different loads

Effects of biodiesel on engine exhaust temperature

The engine exhaust temperature is a further important indicator of the combustion process in the engine cylinder. Some researchers have suggested that biodiesel gives a better combustion process in the engine due to its higher oxygen content, which leads to higher exhaust gas temperatures; however, the opposite conclusion was reached in this study. From a comparison of the engine exhaust temperatures at different biodiesel blends in Fig. 6, it can be seen that the engine exhaust temperature slightly decreases with an increase in the biodiesel blend. This may be due to the lower calorific value of biodiesel, which gives it a lower temperature for the combustion process in the cylinder, resulting in a lower engine exhaust temperature. A comparison of the engine exhaust temperatures of heavy fuel oil and biodiesel in this experiment shows that the engine exhaust temperature is slightly higher than that of biodiesel blended with heavy fuel oil. This may be due to the fact that heavy oil contains more polymeric PAHs, which are difficult to burn, meaning that the combustion time of heavy oil is longer than that of biodiesel blend, resulting in higher engine exhaust temperatures. In this test, due to the high viscosity of the heavy oil at room temperature, the temperature was heated up to about 92°C during injection, whereas the blended biodiesel was not heated up, which may also have contributed to the relatively high exhaust temperature of the heavy oil.

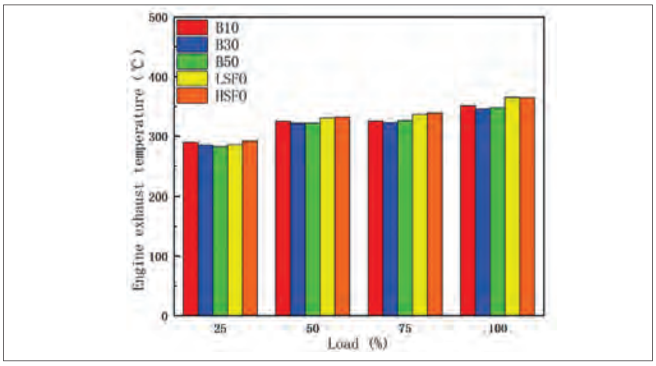

Fig. 6. Engine emission temperatures of different fuels under different loads

IMPACT OF BIODIESEL ON BC EMISSIONS

The quality and composition of the fuel directly affect the degree of completeness of the combustion process. Low-quality or contaminated fuels may contain impurities or incomplete combustion products, which can increase the production of BC. To enable a better assessment of the BC emissions from blended biodiesel and heavy fuel oil, this section presents a comparative analysis of BC emissions and degree of graphitisation for different fuels.

Impact of biodiesel on the concentration of BC in engine exhaust

From Fig. 7, it can be seen that the concentration of BC in the engine exhaust decreases as the engine load increases, and reaches a minimum at 100% load; this is mainly due to the fact that with an increase in the engine load, the increase in the engine exhaust temperature promotes the oxidisation process of BC particles, which reduces the concentration of BC in the engine exhaust. An analysis of the BC emissions of the engine when burning different fuels showed that the emission concentration was reduced by 50.2%, 56.4%, 61% and 37.4% compared to HSFO for B10, B30, B50 and LSFO, respectively. The BC concentration in the engine exhaust decreased as the biodiesel blending ratio increased. This was mainly because the oxygen content in the fuel increased with the biodiesel blending ratio, thus promoting the oxidation of BC during the combustion process and reducing the BC concentration in the exhaust emission. The main reason for the lower BC concentration in LSFO compared to HSFO may be that the heavy oil used in this test was a blend of residual oil and marine diesel fuel, and the HSFO had a higher residual oil content, which was more likely to lead to incomplete combustion and the formation of more BC particles during operation of the engine.

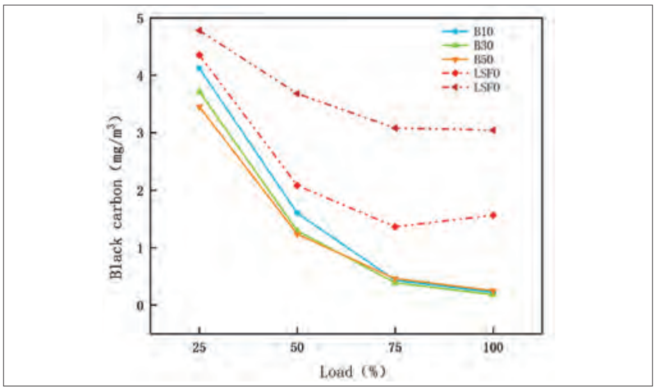

Fig. 7. Black carbon concentrations for different fuels under varying loads

Impact of biodiesel on the graphitisation of black carbon

Fig. 8 shows the Raman spectra for the BC particulate matter produced by engine combustion. The characteristics of the samples at wavelengths of 500–4500 cm^{-1} were scanned in the experiment. Two characteristic peaks near 1345 cm^{-1} and 1594 cm^{-1} can be clearly seen from the Raman spectra of the particles. The peak at 1345 cm^{-1} is generally considered to be generated by the transformation of the local structural hexagonal symmetry of the crystals to a lower symmetry or to a loss of symmetry, and is known as the disordered peak or D-peak. The one located near 1595 cm^{-1} is known as the G-peak, and is generated by the phonon vibrational mode (the in-plane telescopic vibration of the sp^2 hybridisation of carbon atoms). It can be used to characterise the structure of the ordered carbon layers in the particles.

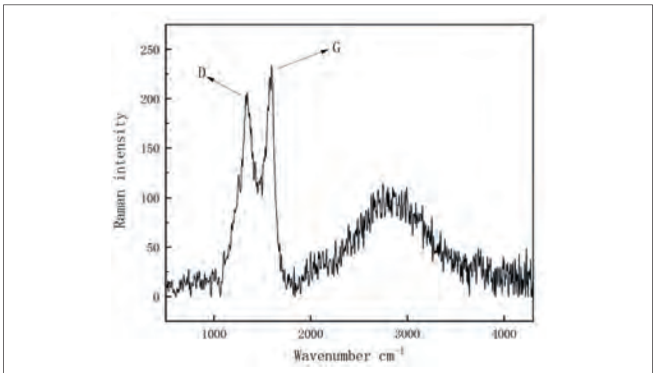

Fig. 8. Raman spectrum for black carbon

In order to enable an analysis of the effects of different fuels on the degree of graphitisation of BC particles in the engine, The collected BC generated from different fuels were subjected to Raman detection, and the Raman spectrograms were smoothed for ease of analysis.., and all the spectral lines were normalised with reference to their respective G-peak peaks as a standard. The degree of graphitisation of the particles was characterised by the value of the G peak value divided by the value of the D peak IG/ID , with larger values indicating a lower and smaller ratios a higher degree of graphitisation.

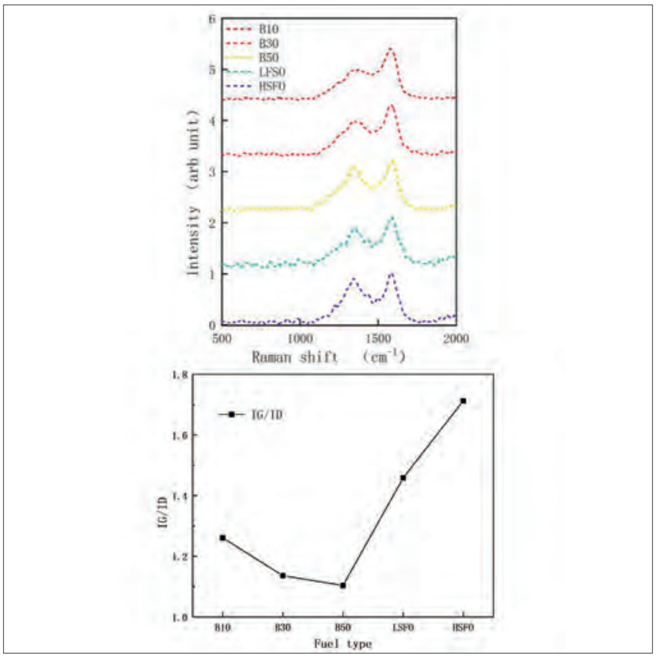

Fig. 9. Degree of graphitisation of black carbon (IG/ID)

From Fig. 9, it can be observed that the degree of graphitisation of BC particles in the engine exhaust decreases as the biodiesel blending ratio increases, and the degree of graphitisation of the BC particles produced by the engine during the combustion of heavy oil is greater than for blended biodiesel. An increase in the biodiesel blending ratio decreases the IG/ID ratio, which is mainly due to the higher oxygen content of biodiesel promoting the oxidation of BC particles in the combustion process. The greater the number of oxygen atoms in biodiesel participating in the combustion, the more obvious the oxidation process compared to the carbonisation process of the fuel, and the lower the degree of graphitisation of the resulting particles. An increase in the maximum flame temperature also leads to an increase in the degree of graphitisation, which is positively correlated with the trend in the engine discharge temperature when burning different fuels, as shown in Fig. 6.

CONCLUSIONS

In terms of engine performance, an increase in the oxygen atom content of the biodiesel blends leads to faster in-cylinder combustion, resulting in a 1.2% increase in maximum in-cylinder pressure with B50 compared to B10. The thermal efficiency of the fuel and the fuel consumption of the engine are determined by both the calorific value and the combustion characteristics of the fuel. Of the fuels used in this study, B10 has the highest calorific value and combustion characteristics, and hence the highest thermal efficiency and lowest fuel consumption.

Incomplete combustion of heavy fuel oil due to the presence of polymeric compounds such as PAHs and the higher fuel inlet temperatures leads to an increase in exhaust temperature. Marine heavy oils usually have more asphaltenes and lower levels of combustible aromatic and naphthenic hydrocarbons, meaning that the engine has a higher concentration of BC emissions when burning heavy oils compared to blended biodiesel. The higher oxygen content of biodiesel causes the BC concentration in the engine exhaust to decrease with an increase in the biodiesel blending ratio.

The degree of graphitisation of BC also differs slightly when the engine burns different fuels. An increase in the biodiesel blending ratio promotes the oxidation process of BC particles and reduces the degree of graphitisation of BC particles. The higher content of polymeric cycloalkanes and aromatic hydrocarbons and the higher discharge temperature during combustion of heavy fuel oil results in higher BC graphitisation during combustion.

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