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EXPERIMENTAL STUDY OF FUEL COMBUSTION AND EMISSION CHARACTERISTICS OF MARINE DIESEL ENGINES USING ADVANCED FUELS

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ABSTRACT

In order to explore the potential application of oxygenated fuels, polyoxymethylene dimethyl ethers (PODE), as an alternative fuel for marine diesel engines, the fuel combustion performance and gas emission characteristics of pure diesel oil, diesel-blended PODE, and pure PODE were tested on a marine diesel engine under different running conditions. The experimental results indicate that oxygen consumption can be reduced by diesel-blended PODE and pure PODE. The in-cylinder pressure and exothermic curve were consistent with the trend of diesel oil. Also, the ignition delay of diesel-blended PODE and pure PODE decreased, and the diffusion rate was accelerated, which helped to improve the combustion performance of diesel engines. Diesel blended PODE and pure PODE reduced the particulate matter (PM) emissions by up to 56.9% and 86.8%, respectively, and CO emissions by up to 51.1% and 56.3%, respectively. NOx emissions were gradually decreased with engine load. CO2 emissions were slightly increased, and the effective fuel consumption was increased up to 48% and 132%, respectively. It was shown that PODE could provide comparable power in a marine diesel engine and improve the fuel combustion and gas emission of the engine as a clean alternative fuel for marine diesel engines.

Keywords: Marine diesel engine; PODE; Combustion characteristics; Emission performance

INTRODUCTION

Diesel engines are widely used in ships due to their high thermal efficiency, power, and reliability, but one of the main technical challenges is the increase in environmental hazards from the generated exhaust emissions. To address this, the International Maritime Organization has issued a series of strict emission regulations to limit harmful emissions from ships [1-2]. The existing in-engine treatment and outside-engine pre-treatment technologies for diesel engines are unable to meet the Tier III emission standards, while clean alternative fuel-efficient combustion technologies and exhaust after-treatment have become the main technological ways to reduce harmful emissions from marine engines. Although the exhaust after-treatment can meet the requirements of Tier III emission regulations, it will also increase engine operation costs. Cleaner alternative fuels can reduce harmful gas emissions and effectively cope with the fossil energy crisis. This has become one of the hot research topics in the field of energy conservation and emission reduction for ships.

Oxygenated fuels are effective in reducing carbon soot emissions from engines [3-4]. This is due to their high cetane number, which not only enhances compression ignition performance but also reduces the emission of soluble organic compounds in the particulate matter [5-7]. Lipids, alcohols, and other fuels can be used as alternative fuels in internal combustion engines. Biodiesel, as a lipid fuel with a high cetane number, is suitable for compression ignition engines. So it can help improve combustion performance and reduce harmful emissions while blending with Ultra Low Sulphur Diesel-Fuel for marine ancillary diesel engines [8]. However, the oxygen content of biodiesel is only about 20%. This helps to reduce particulate matter but not in-cylinder combustion very significantly [9]. Alcohol fuels with a low cetane number, mostly below 20, are commonly used in spark plug ignition engines [10]. Michal Puškár et al. [11] conducted experimental research using ethanol and gasoline fuel mixtures in the intake pipe of a 4-cylinder turbocharged direct injection engine. This showed that nitrogen oxide, carbon monoxide, and unburned hydrocarbon emissions were all reduced. Ether fuels with both a high cetane number and a high oxygen content are suitable for compression ignition diesel engines and have good particulate reduction performance. Ether fuels have potential as an alternative fuel for marine diesel engines [12-13].

Polymethoxydimethyl ether ($CH_3O(CH_2O)_nCH_3$, PODE) is a new type of coal-based ether-oxygenated fuel. It is produced by the polymerisation of methanol in formaldehyde solution. PODE production will be low cost due to China's "rich coal, lack of oil, less gas" energy structure. So, PODE is beneficial for optimising the energy structure as an alternative fuel for marine diesel engines in China. With strong solubility, high oxygen content, high cetane number, and no carbon-carbon bonds, PODE has properties close to that of diesel fuel and shows excellent combustion and emission characteristics in diesel engine applications [14-16]. PODE has gradually received attention from the clean fuel industry.

In recent years, much research has been carried out domestically and internationally on the properties, preparation, emission characteristics, and compatibility of PODE with diesel fuel [17-21], especially on diesel engines with blended PODE [22-24]. Wang et al. [25] conducted experimental studies on diesel blended with different ratios of PODE. It was found that soot, HC and CO emissions decreased with the increase of blended PODE ratio, and the effective thermal efficiency increased at low and medium engine load conditions, while the effective thermal efficiency changed less at high load conditions. The results on the combustion and emission characteristics of PODE/diesel blended fuels from Liu H et al. [26] showed that diesel blended PODE can significantly reduce HC, CO, and carbon soot emissions, and the thermal efficiency of blended fuel combustion is higher than that of pure diesel at low and medium loads. Liu et al. [27] tested the combustion characteristics of diesel blended with PODE in a diesel engine. The results showed that HC, CO, and carbon soot emissions were significantly reduced, and NOx emissions were slightly increased after using diesel blended with PODE. Wang H.F et al. [28] tested the emission characteristics of diesel blended PODE in an electronically controlled high-pressure common rail diesel engine under low load conditions. It was confirmed that the effective thermal efficiency of diesel-blended PODE increased, HC and CO emissions decreased, soot decreased significantly, and NOx emissions increased. Wang Z et al. [29] verified that diesel blended PODE could significantly reduce HC, CO and carbon soot emissions, and the thermal efficiency of the blended fuel combustion was higher than that of pure diesel. Feng et al. [30] studied the effect of PODE-diesel fuel blends on diesel combustion and emissions. The tests showed that when diesel engines were blended with PODE, the ignition delay period was shortened, and the maximum in-cylinder pressure increased. The specific fuel consumption increased slightly, and the effective thermal efficiency increased. CO, HC, and exhaust smoke were significantly reduced. NOx emissions were nearly unchanged. Zhu et al. [31] evaluated the effect of blending PODE on the combustion and emission performance of inter-cooled supercharged diesel engines, and the results proved that the combustion duration was shortened, and the maximum in-cylinder combustion temperature was increased when PODE was blended in diesel oil. With the increase of the blended PODE ratio, the peak pressure and pressure rise rate in the cylinder increased, the combustion duration was shorter, and the combustion temperature was higher. The NOx emission of diesel engines increased, and HC emission decreased with PODE blends, but the effect on CO emission was not significant. In addition, PODE blends reduced the equivalent fuel consumption rate of the engine and improved its economy.

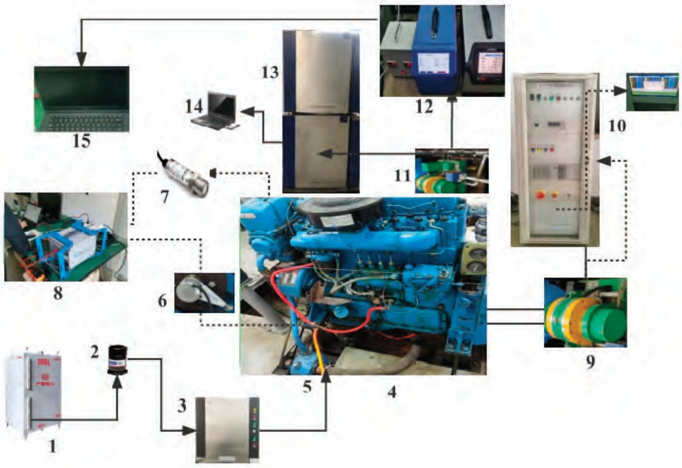
As mentioned above, many researchers have carried out the application of PODE in automotive diesel engines, but there are few research papers about marine diesel engines using PODE. Since marine diesel engines are different from automotive diesel engines in their operating environment, thermal system, power requirements, and working characteristics, it is necessary to analyse and study the combustion performance and emission characteristics of marine diesel engines with PODE. In this paper, pure PODE, PODE/diesel blends, and diesel oil were tested on a marine diesel engine to compare and analyse their effects on the combustion performance and emission characteristics of diesel engines and to provide evidence for PODE as a clean alternative fuel in marine diesel engines.

EXPERIMENTAL SETUP

The marine diesel engine of the experimental setup is a Dongfeng 4135ACa, an inline 4-cylinder, naturally aspirated, water-cooled, four-stroke marine diesel engine. For the injection system, the tested fuel was pressurised by an injection pump and supplied to the injectors of each cylinder for injection into cylinders. There were 4 holes 0.37mm in diameter in each injector. The fuel was injected at 22-24°CA before TDC with 24 MPa injection pressure and 15°CA injection duration. The main structure and technical parameters are listed in Table 1. The engine was coupled with a hydraulic dynamometer and a control system that could adjust the torque and speed of the diesel engine, and a constant speed and constant torque mode was used to obtain the test conditions.

Table 1. Structure and technical parameters of the 4135ACa marine diesel engine

Description	Parameter
Compression ratio	17:1
Bore/Stroke (mm/mm)	135/150
Displacement (L)	8.6
Rated power/kW	66.2
Rated speed/($r\cdot min^{-1}$)	1500
Intake valve closing timing /°CA	48 after BDC
Exhaust valve opening timing /°CA	48 before BDC
Maximum valve lift /mm	16
Fuel advance injection angle /°CA	22~24 before TDC
Fuel injection quantity /(mm 3 /CY)	130
Combustion chamber shape	ω



1-Diesel fuel tank, 2-Fuel filter, 3-Fuel consumption monitor, 4-Marine diesel engine, 5-Oil pipe, 6-Crank angle sensor, 7-Pressure sensor, 8-Data acquisition 9-Hydraulic dynamometer, 10-Dynamometer controller, 11-Exhaust pipe, 12-Gas analyser, 13-Particulate analyser, 14- Control Computer, 15- Monitoring Computer

Fig. 1. Schematic diagram of the experimental system.

The experimental setup schematic is shown in Fig 1. The combustion condition in the cylinder was monitored by a 6613CG1 pressure sensor, Kistler 2614CK1 angular scaler and Kistler KiBox 2893BK8 combustion analyser. The fuel consumption rate was measured with a ToCeil-CMFD015 dynamical fuel consumption meter with 0.12% accuracy. A Hariba PG-350 analyser was used to measure carbon monoxide, carbon dioxide, and nitrogen oxide emissions. An AVL SPC478 particulate sampling system was used to collect particulate emissions under steady-state and transient engine conditions to determine whether the diesel engine met the relevant marine pollutant emission measurement regulations under a constant temperature and humidity environment. The PM was sampled on filter paper and weighed with a Sartorius MSA2.7S-0CE-DF super microgram balance with a 0-2.1 mg range and 0.01μg resolution in an RXCH500-II environmental weighing chamber. The main technical parameters of the data acquisition and analysis instruments are listed in Table 2.

Table 2. Technical parameters of data acquisition and analysis instruments

Instrument	Type	Parameter	Range	Resolution/ Uncertainty
Cylinder pressure sensor	6613CG1	Cylinder pressure	0-250 bar	0.05 mA/ bar
Crank angle detector	Kistler 2614CK1	Crank angle	0-1200 r/min	0.1 °CA
Combustion Analyzer	KiBox 2893Bk8	--	--	--
Hydraulic Dynamometer Changtong		Speed Torque	0-5000 rpm 0-1200 Nm	1 rpm 0.4%
Fuel consumption meter	ToCeil-CMFD015	Fuel consumption	0-400 g/ kWh	0.12%
Particulate collector	AVL SPC478	PM	--	--
Weighing chamber	RXCH500-II	PM	--	--
Ultramicrogram balance	MSA2.7S-0CEDF	PM	0-2.1 mg	0.01μg
NOx Analyzer	Hariba PG-350	NOx	0-2500 ppm	0.2%
CO Analyzer	Hariba PG-350	CO	0-5000 ppm	0.2%
CO_2 Analyzer	Hariba PG-350	CO_2	0-30 vol%	0.2%
O_2 Analyzer	Hariba PG-350	O_2	0-25 vol%	0.2%

For new types of marine fuels, it is valuable to conduct engine tests in laboratory conditions to comprehensively assess their suitability [32]. To verify the effect of the blended PODE fuel on the performance of marine diesel engines, three fuels, including pure diesel, diesel blended PODE and pure PODE, were used. D100 was 100% diesel, D/P50 was a diesel/PODE blend with a 1:1 mass ratio, and P100 was 100% PODE. The main physicochemical parameters are listed in Table 3.

Table 3. Physicochemical properties of tested fuels

Fuels	D100	D/P50	P100
Oxygen content/%	0	28.72	47.85
Cetane number	50	69	85
Density (20°C/g·cm^{-3})	0.83	0.97	1.06
Viscosity(20 °C (mm^{2}·s^{-1})	4.74	3.76	1.05
Flash point/°C	69	65	63
Low calorific value /(MJ·kg^{-1})	42.8	30.9	18.3
Latent heat of vaporization /(kJ·kg^{-1})	260	320	393
Boiling point /°C	200	191.23	161.3

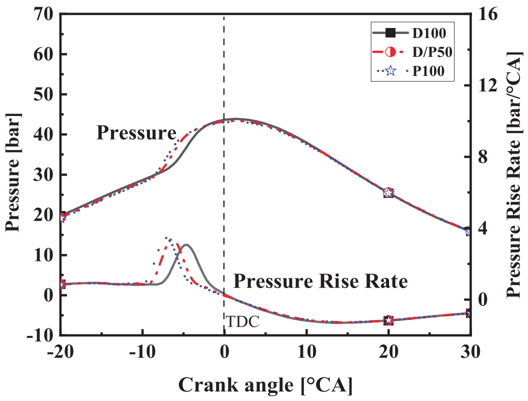
The experimental procedure was arranged based on the "Emission Limits and Measurement Methods for Marine Engine Exhaust Pollutants (China Stage I and II)" (GB15097-2016) to set the working conditions as listed in Table 4.

Table 4. Working condition of the tests

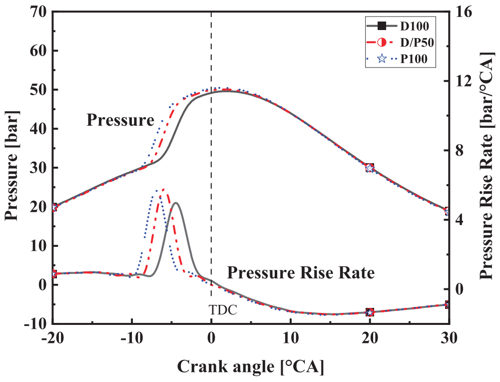
Working condition NO.	1#	2#	3#	4#
Speed n (r/min)	525	705	945	1200
Power Pe (kW)	1.9	6.6	16.6	33.1

EXPERIMENTAL SETUP RESULTS AND COMBUSTION CHARACTERISTICS ANALYSIS

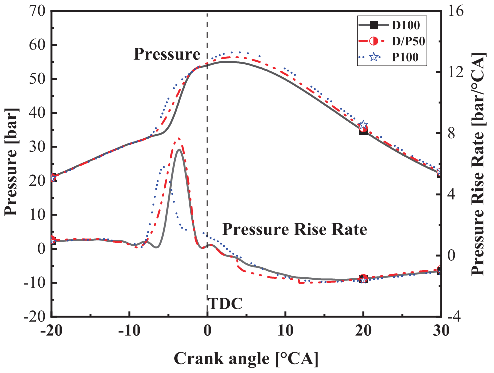
COMBUSTION CHARACTERISTICS



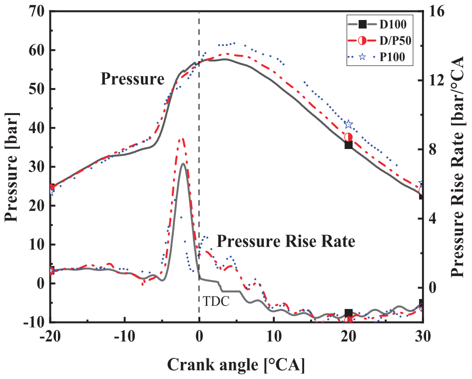
(a) n = 525 r/min, Pe = 1.9kW



(b) n = 705 r/min, Pe = 6.6kW



(c) n = 945 r/min, Pe = 16.6kW



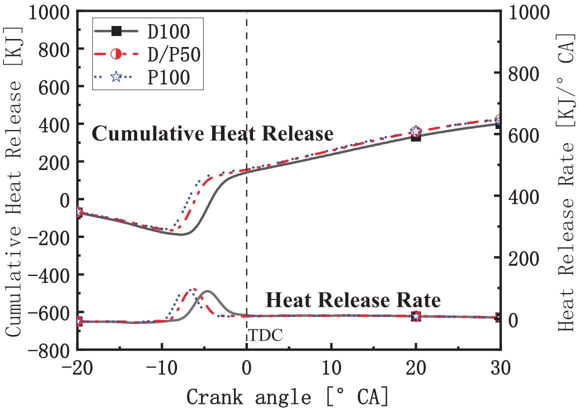
(d) n = 1200 r/min, Pe = 33.1kW

Figure 2. Cylinder pressure and pressure rise rate.

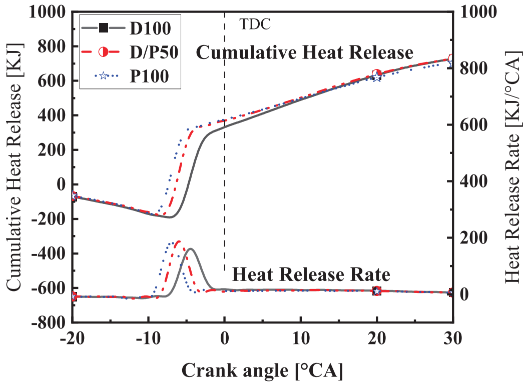
The curves of the engine in-cylinder pressure, p, and its rise rate, dp/dϕ, with crankshaft angle are shown in Fig. 2 with D100, D/P50, and P100 fuels under marine diesel engine propulsion characteristics. It can be seen that the in-cylinder maximum pressure, P_{MAX}, increases with all three fuels when the load increases. There is little difference between the peak pressures under the 1# condition and the 2# condition. There is a significant difference between the 3# condition and the 4# condition. Comparatively, the peak pressure increase of D/P50 is the highest, reaching 14.6 bar, with an increase of 49.8%, followed by P100 at 12 bar, with an increase of

39.2%, and D100 at 10.1 bar, with an increase of 31.2%. This is because PODE contains oxygen and has better combustion performance in low and medium load conditions compared to diesel oil, so its peak pressure increases more than diesel oil. Since the test diesel engine is designed for burning diesel oil, P100 cannot fully show its own advantages. Blended fuel can provide good combustion performance in the diesel engine, as the addition of PODE further improved the performance of blended fuel, and its pressure peak increased the most among the three fuels. It can be seen that PODE can effectively improve the combustion performance of the diesel engine under low load conditions.

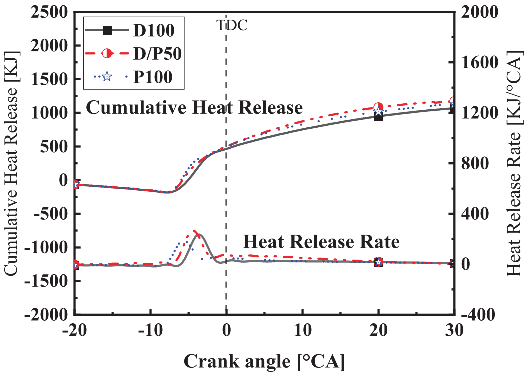
Overall, due to the characteristics of the engine itself, the ignition time of the three fuels showed a pattern of firstly advancing and then delaying with the increase of speed and load. However, the variation of the ignition delay period of the three fuels was different. Under 1# and 2# operating conditions, the ignition point of D/P50 was earlier, and the ignition delay period was shorter than that of D100. P100 had a shorter ignition delay period than that of D/P50, which is due to the lower cetane number and high oxygen content of PODE. The earlier combustion starting point and longer time resulted in a more uniform mixture at low load and low speed. Under the 3# working condition, due to the increase in speed, the combustion start point of the three fuels was delayed, but D/P50 was delayed the most, very close to the TDC, while pure diesel changed the least. Under the 4# working condition, the P100 combustion start point was delayed the most, followed by D100 and D/P50 (the smallest). The main reason for this change is that PODE helped improve the performance of diesel, and a second reason is that the increase in engine load improves the combustion performance. PODE provided a good advantage in the low load but showed little advantage in the combustion performance with the speed and load increase.



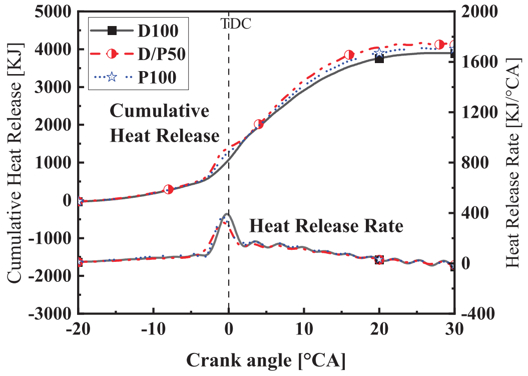
（a）n = 525 r/min, Pe = 1.9kW



（b）n = 705 r/min, Pe = 6.6kW



（c）n = 945 r/min Pe = 16.6kW



（d）n = 1200 r/min, Pe = 33.1kW

Fig. 3. Cumulative heat release and heat release rate with different fuels.

The cumulative heat release (CHR) and heat release rate curves with crankshaft angle are shown in Fig. 3 with P100, D100, and D/P50 blended fuels under marine diesel engine propulsion characteristics. The CHR shows that the change of ignition timing and delay period of the three fuels is consistent with the above. The CHR of P100 and D/P50 under the 1# working condition is larger than that of D100, which indicates that P100 and D/P50 burn more fully than D100, which is also an advantage of highly oxygenated fuel. Although the latent heat of vaporisation of PODE is greater, the CHR curves of P100 and D/P50 presented higher values than D100 because the fuel injection was less, and the combustion heat release was greater than the heat absorbed by fuel vaporisation. At low load, the increase of D100 CHR was greater than P100 and D/P50, which indicates that the effect of vaporisation heat absorption increased when the load and the fuel injection increased. Due to the lower latent heat of vaporisation of diesel fuel, the CHR curves of the three fuels are not much different under the 2# working conditions. The CHR of the single fuels under the 3# and 4# working conditions is not as good as that of blended fuel. Although the low calorific value of PODE is only half that of diesel, the density of PODE is greater, resulting in a larger mass of fuel injected into the cylinder. In summary, PODE can meet the power requirements under diesel engine low load conditions, and in-cylinder combustion was more efficient due to the high oxygen content. PODE makes the blended fuel provide the combined advantages of diesel oil and high oxygen fuel, having more outstanding performance.

EFFECTIVE FUEL CONSUMPTION RATE

Fig.4 shows the effective fuel consumption (EFC) rates of the three fuels under different operating conditions. Under the same engine conditions, D100 has the lowest EFC rate, followed by D/P50, and P100 was the highest as the load increased. The EFC rate of all three fuels decreased to different extents. Compared with D100, the EFC rates of D/P50 and P100 increased by 33% and 80% under the 2# working load, respectively. Under the 3# working condition, the EFC rates of D/P50 and P100 increased by 36% and 110%, respectively. Under 4#, the EFC rates of D/P50 and P100 increased by 48% and 132%, respectively.

The EFC rate is influenced by the fuel calorific value and effective combustion. A higher fuel calorific value and better combustion will result in a lower EFC rate. The calorific value of D/P50 is 30.9 MJ·kg^{-1} and P100 is 18.3 MJ·kg^{-1}, which are 27.8% and 57.2% lower than that of D100 (42.8 MJ·kg^{-1}). Therefore, under the same load condition, the effective fuel consumption rate of D100 is the lowest, and the effective fuel consumption rate of P100 is the highest. As the load increases, the EFC rates of all three fuels decrease. This is because when the load increases, the temperature and pressure inside the cylinder increases, and the combustion quality improves. Since PODE has a higher cetane number than diesel, it can take advantage of highly oxygenated fuel under low engine load.

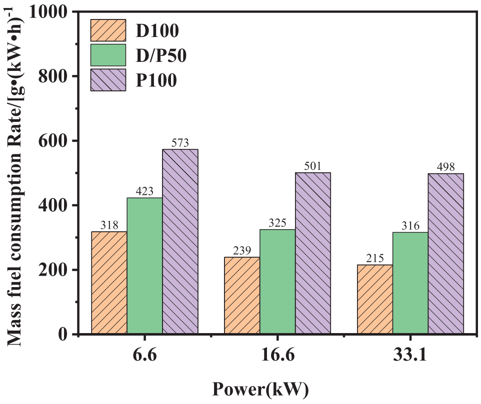


Fig. 4. Effective specific fuel consumption

EXPERIMENTAL SETUP RESULTS AND EMISSION CHARACTERISTICS ANALYSIS

ANALYSIS OF PARTICULATE MATTER EMISSIONS

Fig. 5 shows the engine particulate matter (PM) emissions with the three fuels under different working conditions. It can be seen that the PM emissions of the three fuels firstly decreased significantly, then decreased slowly, and finally increased slightly with the increase of load. The PM emissions of the three fuels decreased significantly from the 1# to the 2# working conditions. D100 dropped the most at 85.7%, D /P50 dropped the least at 73.8%, and P100 dropped between the two at 80.5%. From 2# to 3#, the PM emissions decreased slightly for the other two fuels except P100. The reduction rates of D100, D/P50, and P100 were 8%, 1.8%, and 55.4%, respectively. From 3# to 4#, the PM emissions increased slightly for the other two fuels except P100. D100, D/P50, and P100 increased by 17.1%, 0.7%, and 256.1%, respectively. Overall, the change in PM emissions for the three fuels was small at low and medium engine loads. In terms of magnitude, D100 and D /P50 did not fluctuate much, while P100 fluctuated more, mainly because PODE, as an oxygenated fuel, had sufficient burnout and almost no PM emissions under the 3# condition. With the increase in engine load and speed, the fuel injected into the cylinder increased, and the in-cylinder combustion time shortened, so the particulate ratio emissions increased slightly.

Under the same engine working conditions, D100 had the highest PM emissions, followed by D/P50 and P100, the lowest. Compared with D100, the PM emissions of D /P50 and P100 were reduced by 56.9% and 80.1% under the 1# working conditions, respectively. Under 2#, the PM emissions of D/P50 and P100 were reduced by 20.8% and 72.7%, respectively. Under 3#, the PM emissions of D/P50 and P100 were reduced by 15.5% and 86.8%, respectively. Under 4#, the PM emissions of D/P50 and P100 were reduced by 25.3% and 59.8%, respectively.

Compared with diesel fuel, the PM emissions of both blended PODE and pure PODE were significantly reduced after in-cylinder combustion mainly because of the following: (1) PODE is a chain of C-O bonded highly oxygenated fuel with nearly 50% oxygen content, and the oxygen in the fuel aids the combustion, especially in the high fuel concentration region, such as the spray core, and significantly reduces the incomplete combustion in this region [31, 33]. (2) PODE has no C-C bond, does not contain aromatic hydrocarbons, and has few C_2H_2 and C_2H_4 fragments in the combustion products, which reduces the formation of the carbon soot precursor PAH. The -OH group generated during combustion has a strong oxidising effect [33], which not only inhibits the formation of carbon soot but also adsorbs the SOF on carbon soot. (3) The low viscosity of PODE facilitates good atomisation, and both high oxygen content and high cetane number make the combustion faster and more complete with higher combustion temperature and accelerate the oxidation of PM. (4) The lowest PM emission was under the 3# working condition, mainly because carbon soot was mainly generated in the diffusion combustion process. Under 3#, the ignition delay period of the three fuels was extended, and the diffusion combustion was shortened, which significantly reduced the generation of carbon soot [33].

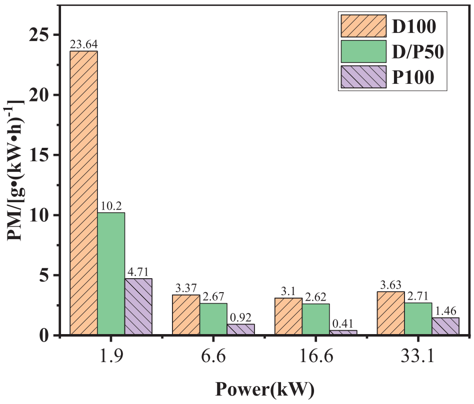


Fig. 5. Specific particulate matter emissions

ANALYSIS OF CO EMISSIONS

Fig. 6 shows the CO emissions of the three fuels under different working conditions. With the increase in engine load, the CO emissions of the three fuels showed a decreasing trend, and the decreasing range of CO emissions from the 1# to 4# working conditions showed an increasing and then a gradually decreasing trend. From the 1# to 2# working conditions, the CO emissions of all three fuels decreased significantly. The largest decrease was 44.2% for D100, while the smallest was 20.2% for D/P50, and it was 27.7% for P100. From 2# to 3# working conditions, the CO emission rate of all three fuels decreased more substantially. D100, D/P50, and P100 decreased by 49.4%, 48.5%, and 52.8%, respectively. From 3# to 4# working conditions, the CO emission rate of all three fuels decreased slightly. D100, D/P50, and P100 were 26.8%, 35.3%, and 33.8%, respectively. Overall, the CO emissions of the three fuels showed a decreasing trend with an increase in engine load. The main reason is that as the load increases, the in-cylinder pressure and temperature increase, the chemical reaction becomes more and more complete, and more CO is oxidised to CO_2. The decreasing range of CO emissions of the three fuels firstly increased and then decreased with the increase of load, mainly because the pressure and temperature of fuel combustion in the cylinder increased from 2# to 3# working conditions, while the engine speed was low, the combustion lasted longer, so there was sufficient time for chemical reaction, resulting in better combustion in the cylinder. The test engine is a naturally aspirated engine, so the air drawn in at low load conditions can provide sufficient oxygen for fuel combustion. However, as the engine load increased from 3# to 4# conditions, more fuel was injected into the cylinder. Meanwhile, more fresh air was needed accordingly, but not enough fresh air was actually sucked in. Furthermore, the engine speed increased, and the chemical reaction time of in-cylinder combustion decreased, so the CO emission decreased extent reduced.

Under the same engine operating conditions, D100 had the highest CO emissions, followed by D/P50, and P100 was the lowest. Compared with D100, the CO emissions of D/ P50 and P100 were reduced by 51.1% and 56.3%, respectively, under 1# working conditions. Under 2# working conditions, the CO emissions of D/P50 and P100 were reduced by 30.1% and 43.3%, respectively. Under 3# working conditions, the CO emissions of D/P50 and P100 were reduced by 28.9% and 47.1%, respectively. The CO emissions of D/P50 and P100 were reduced by 37.1% and 52.1% under 4# working conditions, respectively.

Under the same engine running conditions, both blended PODE and pure PODE resulted in significantly lower CO emissions from in-cylinder combustion. The main reason is that the high oxygen content of PODE is equivalent to increasing the air-fuel ratio and strengthening the intensity of CO conversion to CO_2, especially in the high-fuel concentration area. PODE can significantly improve the incomplete combustion in this area due to its own oxygen content. In addition, the high temperature in the cylinder and high cetane number also promote the oxidation of CO, and the lower viscosity of PODE makes it easier to form a homogeneous mixture, which is conducive to full combustion, thus significantly reducing CO emissions.

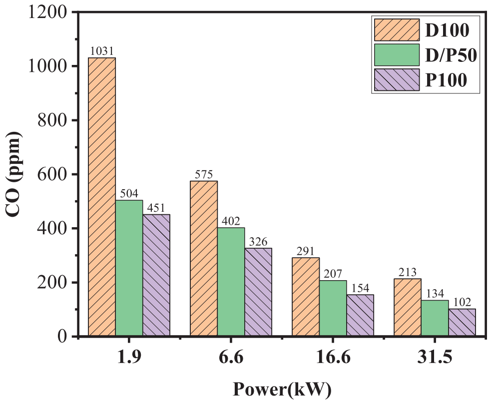


Fig.6. CO emissions under different running conditions

ANALYSIS OF CO_2 EMISSIONS

Fig. 7 shows the CO_2 emissions of the three fuels under different running conditions. With the increase in load, the CO_2 emissions of the three fuels showed an increasing trend. From 1# to 2# operating conditions, the CO_2 emissions of all three fuels increased. D100, D/P50, and P100 increased by 0.77%, 0.84%, and 0.87%, respectively. From 2# to 3#, the CO_2 emissions of D100, D/P50 and P100 increased by 1.13%, 1.19%, and 1.36%, respectively. The increase of CO_2 emissions of all three fuels decreased slightly from #3 to #4 operating conditions. D100, D/P50, and P100 increased by 0.82%, 0.89%, and 1.06%, respectively. Overall, the CO_2 emissions of the three fuels showed an increasing trend with the increase of engine load, mainly because the fuel injected into the cylinder for combustion increases with the increase of engine load, and the corresponding CO_2 emissions increased.

Under the same operating conditions, D100 had the lowest CO_2 emission, followed by D/P50, and P100 was the highest. Compared with D100, the CO_2 emissions of D/P50 and P100 increased by 0.02% and 0.07% under 1# working conditions, respectively. Under 2# working conditions, the CO_2 emissions of D/P50 and P100 increased by 0.09% and 0.17%, respectively. Under 3# working conditions, CO_2 emissions increased by 0.15% and 0.4% for D/P50 and P100, respectively. Under 4# working conditions, CO_2 emissions increased by 0.22% and 0.64% for D/P50 and P100, respectively.

Under the same engine running conditions, CO_2 emissions of D/P50 and P100 presented an increasing trend compared to D100, and the magnitude of the increase increased as the engine load increased. Although the carbon content of PODE is lower compared to diesel, theoretically, the CO_2 emission is lower with complete combustion of PODE. However, because of the low viscosity of PODE, the in-cylinder injection fuel atomisation quality is higher, which helped the formation of a homogeneous mixture. Also, the high oxygen content and high cetane number of PODE are more conducive to complete combustion at low and medium loads, especially in the high fuel concentration area in the cylinder. The fuel's own oxygen content helped convert CO into CO_2, resulting in more CO_2 emissions.

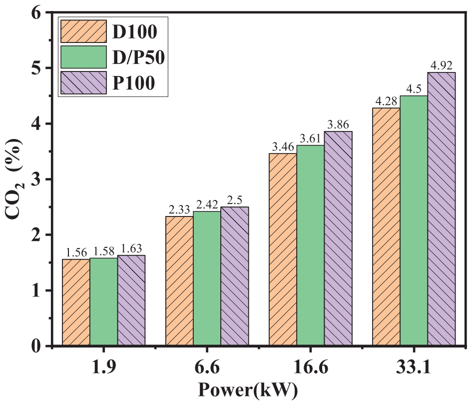


Fig. 7. CO_2 emissions under different running conditions

ANALYSIS OF NOX EMISSIONS

Fig. 8 shows the NOx emissions of the three fuels under different working conditions. With the increase in load, the NOx emissions of the three fuels showed an increasing trend. The NOx emissions of D100 were the lowest and P100 the highest under 1# working conditions. Under 2# working conditions, D100 was the lowest, and D/P50 was the highest. Under 2# working conditions, the NOx emissions of D100 and D/P50 were comparable and both higher than P100 under 3# working conditions. D100 emissions were the highest, and P100 emissions were the lowest under 4# working conditions. From 1# to 2#, NOx emissions of all three fuels increased, with the largest increase of 147.5% for D100, the smallest increase of 70.1% for P100, and an increase of 91.8% for D/P50 between the two. The NOx emissions of D100, D/P50, and P100 increased by 59.4%, 40.7%, and 29% from 2# to 3#, respectively. From 3# to 4# working conditions, the increases in NOx emissions of D100, D/P50, and P100 were 23.8%, 6.36%, and 5.8%, respectively. Overall, the NOx emissions of the three fuels steadily increased at low and medium engine loads. In terms of magnitude, the increase gradually decreased with increasing load. Among these, D100 increased the most, while P100 increased the least.

Although the latent heat of vaporisation of PODE is larger than that of diesel, the effect of latent heat of vaporisation is not obvious because the fuel consumption is smaller at low engine load. Due to the lower calorific value, more fuel must be injected to meet the load requirements when the load increases. Meanwhile, PODE vaporisation latent heat increased, resulting in lowering the temperature in the cylinder. Therefore, the NOx emissions increase was consequently lower than diesel.

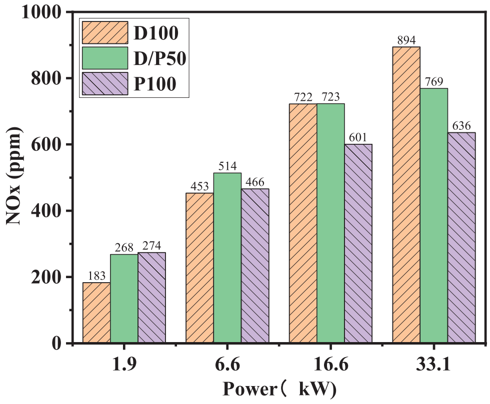


Fig. 8. NOx emissions under different running conditions

ANALYSIS OF O_2 EMISSIONS

Fig. 9 shows the O_2 emissions of the three fuels under different working conditions. With the increase in engine load, the O_2 emissions of the three fuels show a decreasing trend. The O_2 emissions of the three fuels showed slight differences under the 1# and 2# operating conditions, and the differences in the O_2 emissions of the three fuels widened under the 3# and 4# operating conditions. The main reason is that the test engine is a naturally aspirated engine, which requires less fuel and low oxygen consumption at low load, but as the load increases, the fuel required increases, and the corresponding oxygen consumption increases.

Under the same engine operating conditions, the D100 had the lowest O_2 emissions, followed by the D/P50 and the P100 the highest. Compared with D100, the O_2 emissions of D/P50 and P100 increased by 0.19% and 0.23% under 1# working conditions, respectively. Under the 2# working conditions, the O_2 emissions of D/P50 and P100 increased by 0.05% and 0.12%, respectively. Under 3# working conditions, the O_2 emissions of D/P50 and P100 increased by 0.71% and 0.91%, respectively. Under 4# working conditions, the O_2 emissions of D/P50 and P100 increased by 0.46% and 1.38%, respectively. Obviously, blended PODE and pure PODE had higher O_2 emissions than diesel, mainly because PODE contains oxygen, which can replace part of the oxygen consumption of air in-cylinder combustion.

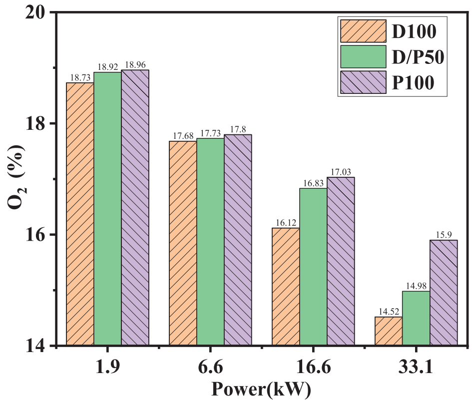


Fig.9. O_2 emissions under different running conditions

CONCLUSIONS

This paper studied the improvement of combustion performance of a diesel engine with blended PODE and pure PODE under low and medium engine load conditions. It was shown that with the increase in engine load, the effective fuel consumption rate of all three fuels was reduced to a different extent. Under low and medium engine load conditions, both blended PODE and pure PODE can provide power comparable to diesel oil, but the effective fuel consumption rate of PODE-blend and pure PODE increased. Furthermore, the NOx emission of the three fuels tends to increase with increasing engine load, and the NOx emission of D/P50 and P100 is higher than that of D100 under 1# and 2#working conditions, while the NOx emission of D100 is higher than that of D/P50 and P100 under medium engine load conditions. The blended PODE and pure PODE can significantly reduce the particulate matter and CO emissions, but the CO_2 emissions increase. The O_2 emissions of the three fuels showed a decreasing trend with increasing load, as the addition of oxygenated fuels helped to reduce the in-cylinder O_2 consumption. In general, PODE can improve the combustion performance of marine diesel engines and can obtain power comparable to diesel oil; besides, the emissions can be reduced significantly. PODE will be an ideal alternative clean fuel oil for marine diesel engines in the future.

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DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could influence the work reported in this paper.

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