Energy Conversion and Management 159 (2018) 244–253

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Effects of fatty acid methyl esters proportion on combustion and emission characteristics of a biodiesel fueled marine diesel engine

Zhiqing Zhang[a,b,c], Jiaqiang E[a,c,*], Yuanwang Deng[a,c,*], MinhHieu Pham[a,c], Wei Zuo[a,c], Qingguo Peng[a,c], Zibin Yin[d]

[a] State Key Laboratory of Advanced Design and Manufacturing for Vehicle Body, Hunan University, Changsha 410082, China
[b] Maritime College, Qinzhou University, Qinzhou 535000, China
[c] Institute of New Energy and Energy-saving & Emission-reduction Technology, Hunan University, Changsha 410082, China
[d] College of Marine Engineering, Jimei University, Xiamen 361021, China

ARTICLE INFO

Keywords:
Biodiesel
Marine diesel engine
Performance and emissions
Combustion

ABSTRACT

In this experimental investigation, four different types of biodiesel fuels were employed to investigate the effects of fatty acid methyl esters (FAMEs) proportion on emission and combustion characteristics of a marine diesel engine in terms of heat release rate, cylinder pressure, indicated power, brake specific fuel consumption (BSFC), CO emission, HC emission and NO_x emissions. In accordance with international IS08178 standards, the experiments were carried out on a four cylinders direct injection diesel engine fueled with four different types of biodiesel fuels and pure diesel at two test cycle modes of E3 and D2. The experimental results showed that the kinematic viscosity and ignition delay time (IDT) of biodiesel fuel in combustion process played very important roles. The chemical IDT can be shorten by the higher saturation level and the kinematic viscosity will be increased due to the higher saturation contents like C18:0 and C16:0 together with C18:1 which is a single double bond methyl ester. The increased kinematic viscosity can result in poor evaporation process and poor fuel–air mixing. Lower kinematic viscosity methyl esters like C18:3 and C18:2 are beneficial for better combustion and fuel–air mixing, but the higher nitrogen oxide emission is discovered. Thus, the relationship between emission and combustion characteristics and proportion of biodiesel is not straightforward and simple, the balance of five majority components of biodiesel fuel is very significant. Compared with pure diesel, the oxygen content of biodiesel fuel improves the in-cylinder combustion. It is beneficial to decreasing HC and CO emissions and increasing NO_x emissions. However, it is not obvious at low load.

1. Introduction

Fossil fuels are non-renewable energy sources [1,2]. In order to meet the needs of environment and resource issues, a lot of institutional and industrial scholars are looking for the clean and high efficiency energy sources such as solar, biomass and wind with the development of the economy [3–6]. It is a development trend to replace fossil fuels with biodiesel fuels in the field of energy industry. Firstly, the biodiesel fuel is a biodegradable energy from the transesterification of animal fat or vegetable oil [7,8]. Secondly, due to the characteristics of carbon neutral, degradation and non-toxic [9–11], the biodiesel fuel is defined as "environmentally friendly fuel" [12,13]. In addition, the experiment shows that it is only necessary to make a small modification to the engine diesel system such as the fuel supply system and the combustion system. Similarly, the biodiesel fuels can be directly burned in diesel engines [14,15]. More importantly, the physical and chemical characteristics of biodiesel fuel are similar to the traditional diesel, as well as the biodiesel fuels can be mixed with any proportion of diesel [16–18]. To improve biodiesel properties, lots of scholars have adopted various methods such as transesterification and heating the vegetable oils, emulsion with alcohol, and mixing with diesel fuel [17,19,20]. Compared with pure diesel, about 10% of oxygen content is the important property of biodiesel fuel. So the biodiesel fuel combustion in diesel engine can significantly reduce the HC emission, CO emission and PM emission. In summary, the biodiesel fuel is considered an ideal alternative to mineral diesel [15,21].

Many scholars have investigated the performance and emission characteristics of diesel engine fuelled with various biodiesel fuels [22–24]. The biodiesel fuels fuelled in the test were produced from various vegetable oils such as rubber seed oil, rapeseed oil, soybean oil, and sunflower oil. Compared with pure diesel fuel, the results obtained showed that the biodiesel fuel or biodiesel–diesel blend fuel combustion

* Corresponding authors at: State Key Laboratory of Advanced Design and Manufacturing for Vehicle Body, Hunan University, Changsha 410082, China.
E-mail addresses: ejiaqiang@hnu.edu.cn (J. E), dengyuanwang@hnu.edu.cn (Y. Deng).

https://doi.org/10.1016/j.enconman.2017.12.098
Received 12 November 2017; Received in revised form 25 December 2017; Accepted 30 December 2017
Available online 23 January 2018
0196-8904/

could decrease the HC, smoke, PM and CO emissions, but the NO_x emissions exhibited an increased trend [19,21,25]. Karabektas investigated the combustion characteristic of a turbo diesel engine using the rapeseed methyl ester (RME), which was tested at the speeds from 1200 to 2400 rpm (6 levels) under different conditions [26]. The results obtained showed that the biodiesel fuel could improve the performance characteristic of diesel engine, decrease the CO emission and increase the NOx emissions. Can had studied the combustion and emission characteristics of diesel engine fueled with the typical biodiesel fuels, which are produced from waste cooking oils and blended in 5% and 10% with diesel, respectively [27]. He had found the similar results. Rakopoulos have analyzed the effects of biodiesel-diesel blend fuels on the emission and combustion characteristics of a heavy-duty diesel engine under different conditions [28]. The biodiesels blended in the biodiesel-diesel blend fuel are cottonseed methyl ester (CSME) and sunflower methyl ester (SFME), respectively. Compared with pure diesel, the blend fuels have the low calorific value and high cetane number in general [29,30]. Due to the high cetane number, the IDT and peak cylinder pressure was reduced [31]. But the diesel engine has the high BSFC value due to the lower calorific value of biodiesel fuel [32]. Refs. [33–35] also showed that biodiesel fuels had the similar combustion and emission characteristics. Based on previous studies, the results obtained showed that the biodiesel fuel could decrease PM, CO, HC and NO_x emissions, on the other hand some experiments studied on biodiesel also showed that NO_x emission concentration increased [36–38].

Various investigations on physical and chemical properties of biodiesel fuel have suggested that a typical biodiesel fuel generally consists of five major long carbon chain FAMEs: methyl linolenate (C18:3, $C_{17}H_{32}O_2$), methyl linoleate (C18:2, $C_{19}H_{34}O_2$) and methyl oleate (C18:1, $C_{19}H_{36}O_2$) as unsaturated FAMEs, methyl stearate ($C_{19}H_{38}O_2$, C18:0) and methyl palmitate (C16:0, $C_{17}H_{34}O_2$) as saturated FAMEs [21,38,39]. Some researches have found a direct correlation between the emissions and chemical structure of FAME. They have reported that NOx emissions increase with the increase of the unsaturation degree and the reduction of the mean carbon chain length [40,41]. Refs. [42,43] have studies the FAMEs and found that the polyunsaturated fatty acids have the negative effect on the oxidation of biodiesel fuel. Refs. [21,44] have studied the effects of four different FAMEs proportion on combustion and emission characteristics. The results showed that the higher saturation contents like C18:0 and C16:0 together with C18:1 can shorten the chemical IDT and the lower kinematic viscosity methyl esters like C18:3 and C18:2 can improve the combustion and fuel–air mixing. Similarly, the researchers studied the influence of different unsaturated fatty acid and saturated fatty acid composition on emissions and combustion of diesel engine [45]. The result obtained showed that the higher cetane number could increase the IDT and NO_x emissions. But the esters which had more saturated fatty acid composition had the short IDT compared with other esters. Ref. [46] studied the free fatty acid crude soyabean oil and found that a significant reduction of HC, CO and smoke occurred as compared to pure diesel, but NOx and CO_2 emissions were slightly increased. Therefore, the effects of FAMEs proportion on combustion and emission characteristics can't be ignored.

As mentioned above, the studies were conducted on the effects of fatty acid methyl esters (FAMEs) proportion on emission and combustion characteristics of a biodiesel fueled marine diesel engine. The experiments were carried out on a marine diesel engine fueled with four different types of biodiesel fuels and pure diesel at two test cycle modes of E3 and D2. The combustion process of pure diesel and biodiesel fuels composed by different FAMEs proportion were compared and investigated.

Table 1
Performance index of fuel.

Item	Diesel	RME	SFME	SME	CSME
Cetane number (−)	50	53.88	53.01	53.65	52
Lower calorific value (MJ/kg)	42.7	39.53	39.73	39.72	39.68
Density at 15 °C (kg/m^3)	837	882	885	886	864
Oxygen content (%m/m)	0.3	10.7	~10.5	~10.5	~10.5
Viscosity (cPs/40 °C)	2.75	4.556	4.224	4.31	4.24
Saturation (%)	–	4.45	9.54	15.20	29.70

2. Materials and methods

2.1. Properties of test fuel

In the study, four different types of vegetable biodiesel fuels and pure commercial 0# diesel are used in the experiment. The performance indexes of individual fuel are shown in Table 1 and the properties of test fuels are shown in Table 2. In Table 2, Cm:n is the shorthand of FAME, n is the number of double bond, m is the number of carbon atoms. More detailed properties of biodiesel fuels can be obtained from Refs. [21,44,47]. As shown in Tables 1 and 2, the SFME contains the most C18:2, RME contains the most C18:1, soybean methyl ester (SME) and CSME have similar content of C18:2, but different in other compositions. Among four different types of biodiesel fuels, the differences of input energy is very tiny, thus the difference could be ignored in this experiment.

2.2. Engine test bed

The main specifications of marine diesel engine are listed in Table 3 and the schematic of the experimental system is shown in Fig. 1. A four-cylinders marine engine was used to study the effects of fatty acid methyl esters proportion on engine emission and combustion in this research. The loads were controlled by a Xiangyi FC2010 eddy current dynamometer. A emission analyser exhaust gases (Horiba MEXA-1600D/DEGR NO_x sampling type meter) was used to measure the NO_x, CO, CO_2 and HC of exhaust gases. The measurement range and accuracy are shown in Table 4. A FCMM-2 fuel combustion measurement meter was employed to measure the BSFC.

2.3. Experimental procedures

Experiments have been carried out on a four cylinders marine engine whose cylinder geometry is identical to the L4 engine. The test engine is a marine auxiliary diesel engine or a main engine of the small-scale inland river ship. In accordance with international IS08178 standards, the marine diesel engine was performed at two test cycle modes of E3 and D2. The speed and load of each test point of the marine diesel engine are shown in Table 5. Due to the experiments in a temperature-controlled laboratory, the influence of environment on the marine diesel engine could be ignored. The intake pressure was controlled by an electronic pressure, which offered precise control (accuracy: ± 100 Pa). Fig. 2 shows the experimental procedure of the study. The emission and combustion were measured at two test cycle modes of E3 and D2. The corresponding experimental steps are as follows:

Step 1. The preparations for the start of diesel engine.

(1) According to the international identification marks, four different types of vegetable biodiesel fuels and pure commercial diesel fuel were prepared and characterized to identify their chemical and physical properties.
(2) Check the diesel engine systems, such as the lubrication oil system, the cooling water system, and emission monitoring system.

Step 2. Engine testing.

Table 2
Properties of biodiesels and O_2 mass required for 1 g biodiesel completed combustion.

Biodiesel fuels	Cm:n, fatty acid composition, % by volume					C:O	H:O	O_2 mass (g)
	C18: 3	C18: 2	C18: 1	C18: 0	C16: 0			
RME	8.11	22.27	65.18	0.87	3.57	9.46	17.6	2.91
SFME	–	73.38	17.08	3.33	6.21	9.43	17.2	2.89
SME	6.19	55.19	23.43	3.22	11.98	9.37	17.2	2.89
CSME	–	56.98	13.33	0.91	28.79	9.20	17.1	2.90

Table 3
Engine specifications.

Type	Value
Bore × stroke (mm)	190 × 210
Number of cylinder	4
Connecting rod (mm)	410
Nozzle radius (mm)	0.26
Fuel injection holes	8
Mean effective pressure (MPa)	1.109
Compression ratio	14

(1) Start the diesel engine and the control equipments, such as the Horiba emission analyzer, and the FCMM-2 fuel mass flow meter.
(2) Adjustment of the operating point of diesel engine. The marine diesel engine was tested at two test cycle modes of E3 and D2. The speed and load of each test point of the marine diesel engine are shown in Table 5. In order to ensure steady state measurement, the results were recorded at each operating condition after running for 25 min. The experiments were carried out three times and the results were recorded and averaged then.

Step 3. Results analysis.

Table 4
List of measurements, the measuring rang and accuracy.

Measurements	Measuring rang	Accuracy
Engine speed	1–2000 rpm	± 0.2%
Exhaust gas temperature	0–1000 °C	± 1 °C
Torque	0–5000 N·m	± 0.2%FS
NO_x emissions	0–5000 ppm	Below1.0%FS
CO_2 emission	0–16%vol	Below ± 1.0%FS
HC emission	0–20,000 ppm	Below ± 1.0%FS
CO emission	0–3000 ppm	Below ± 1.0%FS
Air flow mass	0–33.3 kg/min	± 1%
Fuel consumption	1000 g	± 0.2%
Crank angle encoder	0–720 °CA	± 0.2 °CA

Table 5
Test cycle for D2 and E3 application.

Type	Item	Valve				
D2	Engine speed (rpm)	1000				
	Load	100%	75%	50%	25%	10%
E3	Engine speed (rpm)	1000	909	799	628	
	Power	100%	75%	50%	25%	
	Weighting coefficient	0.2	0.5	0.15	0.15	

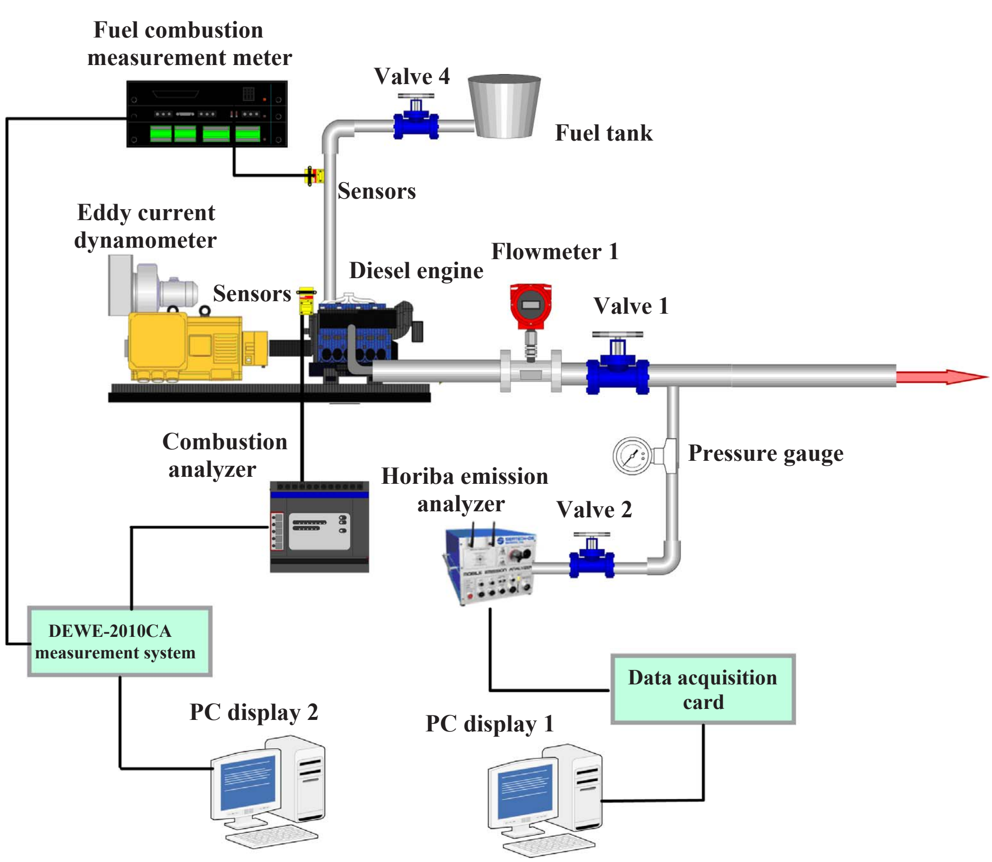


Fig. 1. Schematics of experimental device.

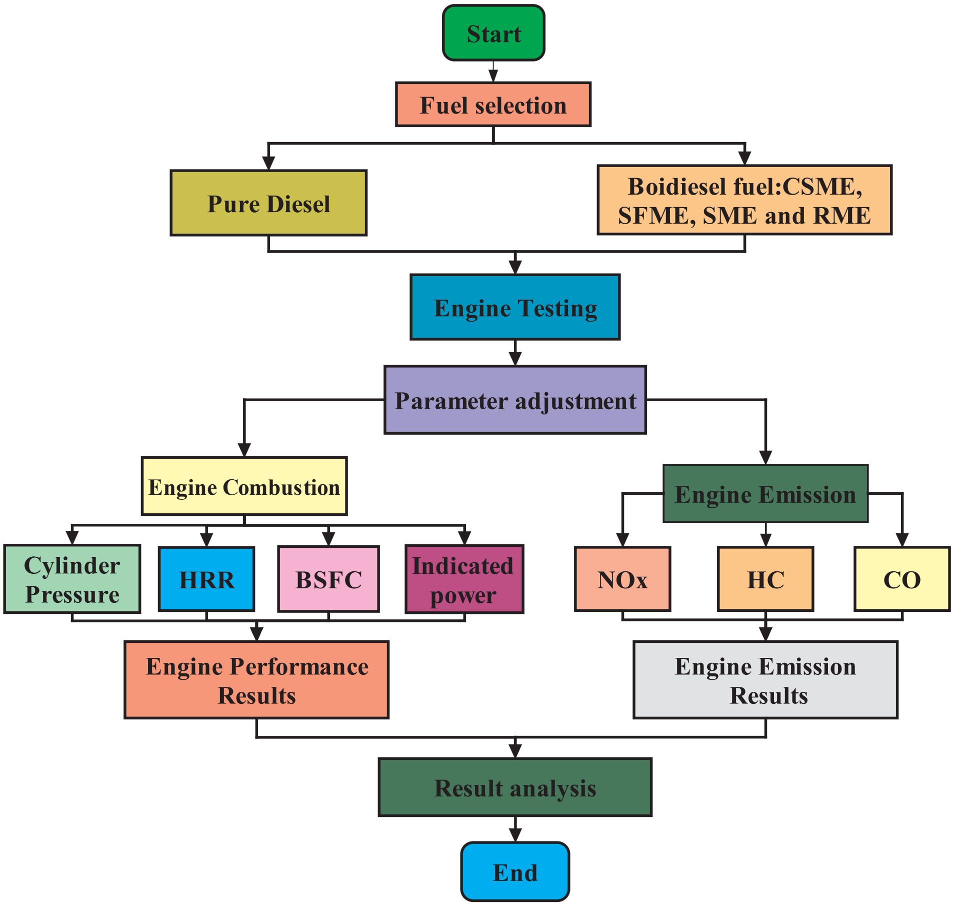


Fig. 2. Experimental procedure of the study.

The experimental data were dealt and these were compared with each other.

2.4. Uncertainty analysis

The uncertainty analysis for parameters of the marine diesel engine performance is calculated on the basis of 200 cycles. It can be calculated the measurement error of indicated power which consists of the error of measurement of the instantaneous displacement and the error of in-cylinder pressure measurement. The error of the amplifier is 2.0% and the error of piezoelectric pressure transducer is 0.5%. Thus, the measurement error of indicated power is 2.2% and expressed by the error bar in the graphs. The measurement error of BSFC consists of the measurement error of power and the measurement error of fuel consumption. The measurement error of fuel consumption consists of the error of instantaneous time measurement, leakage error and systematic error. Similarly, the uncertainty errors presented in emissions were calculated on the basis of analyzers data presented in Table 4. The errors are all expressed by the error bar in the corresponding graphs.

3. Results and discussion

The experimental results of five fuels, including pure diesel, CSME, SME, SFME and RME were reported and discussed in this section.

3.1. Combustion

3.1.1. Heat release rate

The heat release rates with respect to crank angle for pure diesel and four different types of biodiesel fuels are shown in Fig. 3. It can be seen that the HRRs are different at 1000 rpm under different load conditions, even though the calorific values and injection mass are almost equal except pure diesel. In the five major components, the kinematic viscosity of C18:1 is ranked second, and the RME contains the mostly C18:1 leading to the highest kinematic viscosity. On the other hand, the SFME contains the mostly C18:2, which leads to the lowest kinematic viscosity. Furthermore, because the CSME contains less C18:1 and C18:0, the CSME has a lower kinematic viscosity than SME. From RME to SME, CSME and SFME, the completeness of combustion is increasing between four different types of biodiesel fuels. It is due to the fact that the lower kinematic viscosity of SFME is beneficial to improving fuel spray, fuel/air mixing and fuel evaporation. The kinematic viscosity of SFME is the lowest, followed by CSME, SME and RME.

Actually, as you can see in Fig. 3, the kinematic viscosity plays a very important role in fuel spray and combustion process. Due to the lowest kinematic viscosity, the pure diesel shows the earliest engine ignition in all cases, followed by CSME, SFME, SME and RME. As well as the balance of five majority components of biodiesel fuel is very important to ignition delay time (IDT). In a finding, Westbrook et al. found that the five major components had similar chemical IDTs at temperature above 900 K [48]. While the temperature is below 900 K, the C18:0 and C16:0 have the shorter IDTs than C18:1, C18:2 and C18:3, but C18:3 have the longest IDT. Thus, if only chemical delay is considered, the CSME ignites slightly earlier than others because of the advantage of saturation level. On the contrary, the SFME ignites slightly later than others because of lots of C18:2. Actually, the physical ignition delay also plays an important role in contributing to engine ignition delay. As mentioned earlier, the lower kinematic viscosity is beneficial to improving the fuel spray, fuel-air mixing and evaporation process, thereby resulting in shorter ignition delay and complete combustion. Thus, the kinematic viscosity is a key factor. The ignition delay of SFME is shorter than RME and SME. In addition, if the kinematic

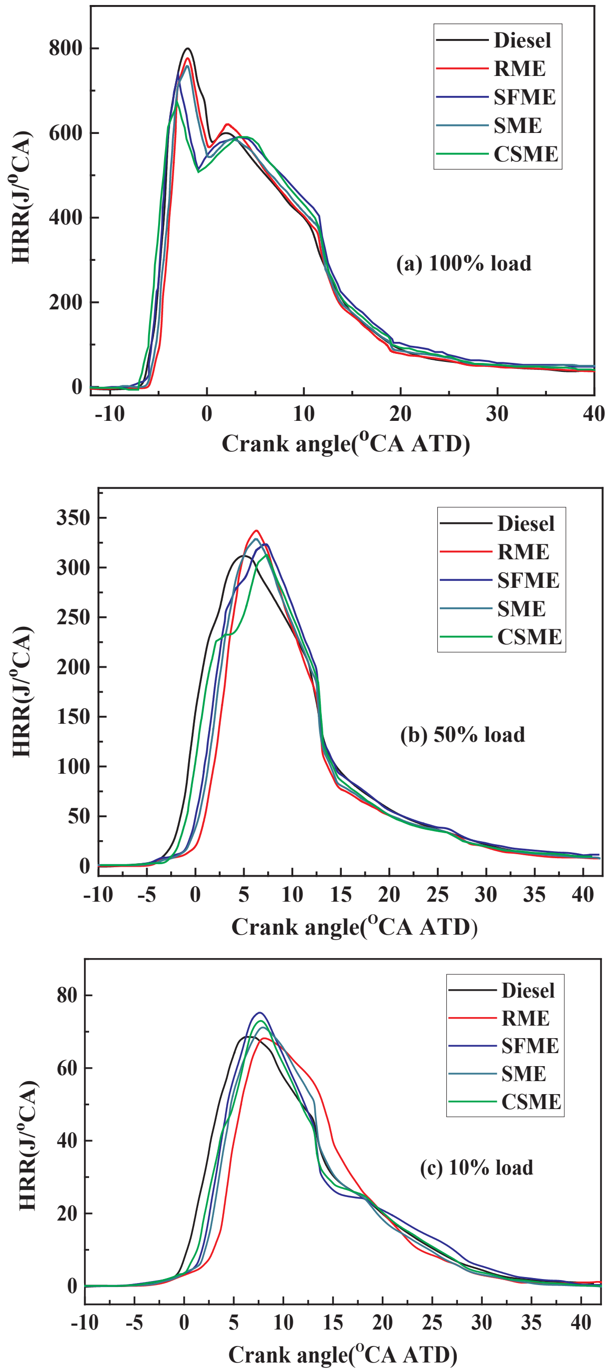


Fig. 3. Heat release rate at 1000 rpm under different load conditions.

viscosity is similar, the chemical ignition delay is very important. The ignition delay of SFME is longer than CSME because of the longer chemical ignition delay of the SFME. Similarly, the RME shows the longest ignition delay because of its poor fuel spray and fuel-air mixing. So the ignition delay is affected by the physical ignition delay and the chemical ignition delay, and the former is more important [49–51].

As seen in Fig. 3, the peak HRRs are different under different load conditions due to the effect of difference ignition delay. The low fuel-air ratio, low pressure and low temperature will result in deteriorating the combustion process especially for the biodiesel fuel with high kinematic viscosity like RME. As a result, the peak HRR value is lower and the ignition delay is longer [52]. When the engine load increases, the increased fuel-air ratio, pressure and in-cylinder temperature are beneficial to fuel evaporation and combustion [37]. The biodiesel fuel with higher kinematic viscosity has the longer ignition delay, but its peak HRR is higher because of more fuel-air mixture prepared during ignition time.

Actually, with the increase of load, the difference of ignition delay is reduced. More specifically, due to the lower kinematic viscosity, the ignition delay of pure diesel is shortened about 2 °CA at low load. But the difference of ignition delay is not obvious at high load. It is due to the fact that the increasing in-cylinder temperature improves the fuel evaporation and combustion. The peak HRR is different between all loads because of the effect of difference ignition delay. Due to the higher calorific value of pure diesel, the HRR is the first to reach the peak.

3.1.2. Cylinder pressure

The cylinder pressure with respect to crank angle for pure diesel and four different types of biodiesel fuels is shown in Fig. 4. It is shown that the ignition delay and the cylinder pressure curves are in the similar sequence. The CSME ignites slightly earlier than the other biodiesels, so more fuel is burnt, leading to relatively higher peak pressure and earlier pressure rise at the earlier stage, followed by SFME, SME and RME. Compared with biodiesel fuels, the pure diesel has the low kinematic viscosity and high calorific value. So the ignition delay is shorter than that of biodiesel fuels at low load. It also results in the earlier combustion pressure rise and higher pressure. The maximum phase is about 2 °CA. But with the increase of load, the difference is reduced and not obvious due to the improved evaporation and combustion.

3.1.3. Brake specific fuel consumption

The fuel consumption is an important parameter to evaluate the performance characteristic of diesel engine fueled with various fuels. In this paper, the BSFC is used as a conventional evaluation parameter. While the density and calorific value of fuels vary considerably and measurement errors occur, the BSFC value is not reliable. In the case, the variations of density and calorific value are below 2.5% and the measurement error is less than 1%. So the BSFC value is considered a more reliable assessment. Fig. 5 shows the BSFC values of the marine diesel engine fueled with various fuels under the working condition of D2 and E3. The results obtained show that the BSFC values of biodiesel fuels also increases by about 10%. It is due to the lower calorific value and higher density. As shown in Table 1, the lower calorific value of biodiesel fuel is lower about 9% than that of pure diesel and the density of biodiesel fuel is higher about 5% than that of pure diesel. Therefore the two factors result in the increase of BSFC.

Fig. 5 shows that the BSFC value is the lowest at 75% load or 909 rpm for all analyzed fuels. On the contrary, the BSFC value is the highest at low load or low speed. Compared with pure diesel, the BSFC values of biodiesel fuels will increase by about 10%. More specifically, for instance, when the marine diesel operated at full load of E3 condition, the BSFC values for RME, SME, SFME and CSME were 240.733 g/(kW·h), 235.677 g/(kW·h), 234.202 g/(kW·h) and 237.702 g/(kW·h) respectively as compared with 216.814 g/(kW·h) in case of baseline data of pure diesel. Fig. 5(b) shows that the BFSC firstly decreases and then increases. Between 799r/min and 910r/min, the BFSC is less than the other operating points, because the operating points are the common operating points of design. Not surprisingly, SFME contains the largest C18:2 with a lower kinematic viscosity. Thus, the SFME fuel has a better performance than other biodiesels in all cases, followed by CSME, SME and RME. It could be due to the improved the combustion efficiency. The fine fuel spray and good fuel-air mixing are caused by the lower kinematic viscosity. As the engine load increase, the effect of kinematic viscosity on BFSC could be gradually decreased due to the increased in-cylinder temperature. The oxygen content of biodiesel is about 10%. It is beneficial to the improvement of the in-cylinder combustion, especially in the cases of high load or high speed conditions. Thus, in the cases of high load or high speed, the difference of BSFC between diesel and biodiesel is further reduced.

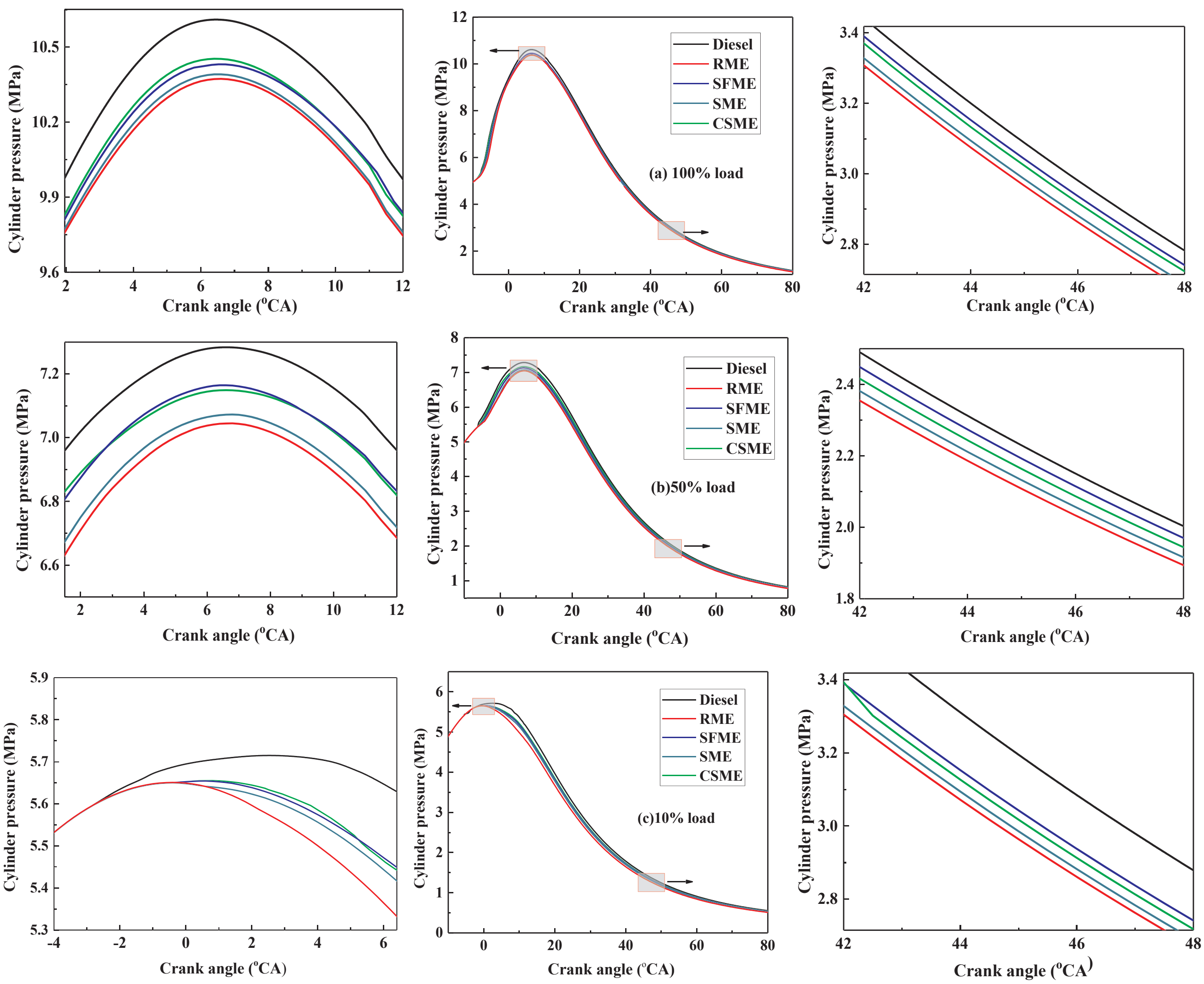


Fig. 4. Cylinder pressure at 1000 rpm under different load conditions.

Although lots of researchers have investigated the possibility of using biodiesel fuel as diesel substitute, the economic conditions have not inhibited development. Some researchers found that the costs of vegetable biodiesel fuel mainly included the following six parts: annual cost of a unit area for cultivation, local cost of refining per liter and mineral oil, labor cost for the cultivation, fuel cost for cultivating and harvesting, fertilizer cost of the land and fuel taxation [36]. For the aforementioned reasons, the biodiesel fuel is not economical. The reasons have also affected its widespread use. Xing et al. found that the production cost excluding feedstock and the purchase cost reached about 76–82% and 14–21% of the total cost, respectively [53]. For example, now in China the rapeseed oil is about ¥RMB 10,000 per ton. But the diesel is about ¥RMB 8500 per ton. Compared with pure diesel, the biodiesel fuel cost is more than 35%. The biodiesel fuel not only can reduce about 40% of emission than pure diesel, but also works more efficiently as a carbon sink [14]. It is more beneficial to human health and the environment. As well as it can reduce a large amount of air pollution control cost.

3.1.4. Indicated power

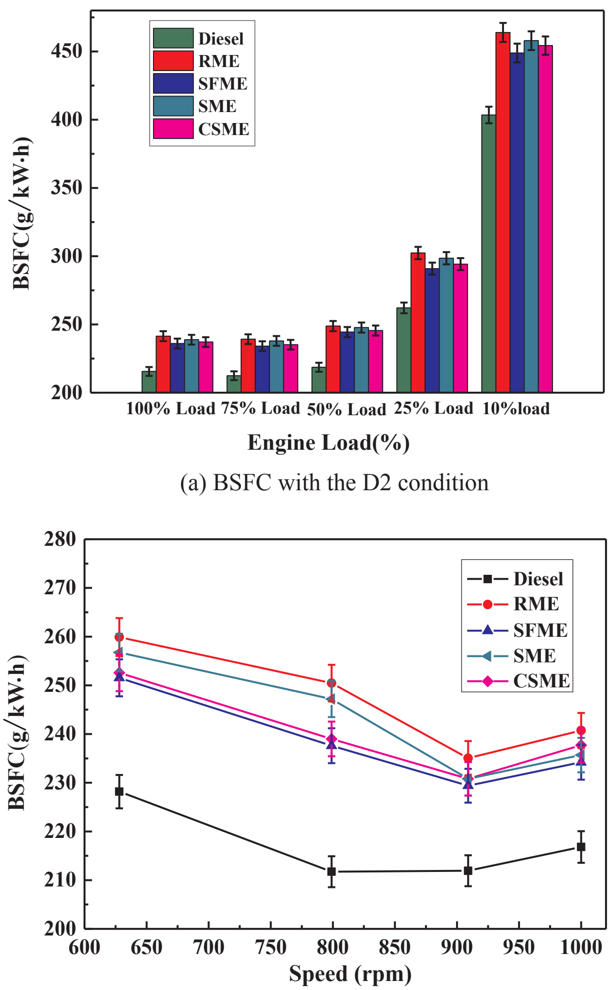
Fig. 6 shows that the indicated powers are compared with each other under the D2 and E3 conditions. Not surprisingly, the pure diesel has a better performance than biodiesels in all cases due to the fact that pure diesel contains the highest calorific value and the lowest kinematic viscosity [48,49]. The indicated power of pure diesel is more than 9%. As mentioned above, the SFME has a better performance characteristic than other biodiesel fuels in all cases. It might be due to the fact that the SFME contains the more C18:2 with a lower viscosity, which results in a better combustion and evaporation. With the increase of C18:1 and C18:0, as well as C16:0, the physical ignition would be delayed [37]. So the RME produced the highest BFSC and the lowest indicated power.

3.2. Engine emissions

Figs. 7–13 show the emission characteristics of pure diesel and four different types of biodiesels under the D2 and E3 conditions.

3.2.1. HC emission

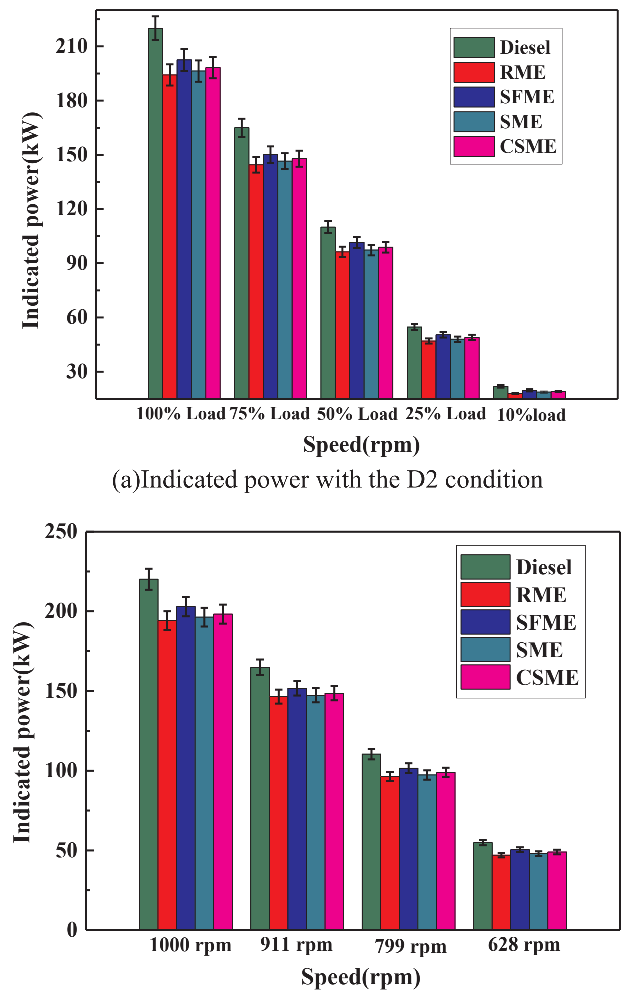
Figs. 7 and 8 show the variations of HC emission for pure diesel and four different types of biodiesel fuels. The results obtained show that the HC emission is reduced with the increasing of the engine load for all analyzed fuels. HC emission of pure diesel is less than that of biodiesel fuel at low load. On the contrary, HC emission of pure diesel is more than that of biodiesel fuel at the medium and high load. The main influencing factors include atomization, fuel-air mixture and proper ignition. At low load, the combustion process is deteriorated due to the low fuel injection pressure and temperature. It results in increasing lots of incomplete oxidation products especially for the higher kinematic viscosity of biodiesel fuel. As a result, the biodiesel fuel will generate more HC emission than pure diesel. Moreover, the lower combustion



(a) BSFC with the D2 condition

(b) BSFC at 100% load of E3 condition

Fig. 5. Variation of BSFC with the working condition.



(a)Indicated power with the D2 condition

(b) Indicated power at 100% load of E3 condition

Fig. 6. Indicated power with the working condition of IS08178 standards.

temperature of diesel engine is not beneficial to oxidizing the incomplete oxidation products. When the engine load increases, the increased fuel-air ratio, pressure and in-cylinder temperature are beneficial to fuel evaporation and combustion. In addition, among four different types of biodiesel fuels, it can be clearly found that the lowest HC emission is SFME, followed by CSME, SME and RME. This might be due to the fine fuel spray and good combustion efficiency caused by the lower kinematic viscosity. Thus, the SFME fuel has the lowest HC concentration than other biodiesels in all cases. Compared with pure diesel, the oxygen content of biodiesel fuel plays an important role and it is beneficial to improving the combustion process at the medium and high load. Therefore, the decreased trend of HC emission for biodiesel fuels might be due to the presence of oxygen molecules in the biodiesel fuels. The oxygen molecules in the biodiesel are beneficial to completing combustion. Similarly, lots of scholars have studied it and found the similar results [54].

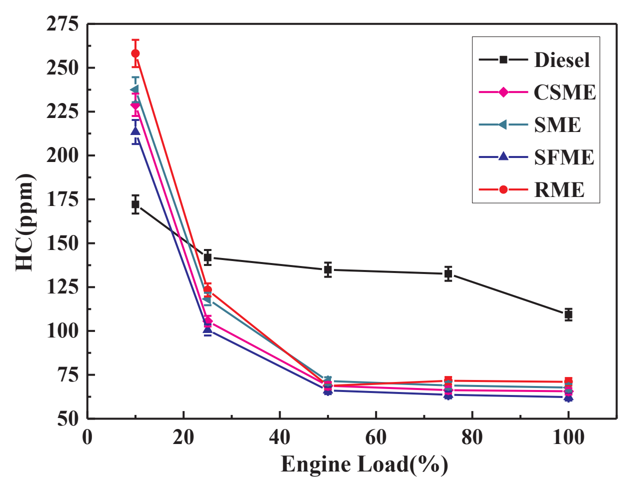


Fig. 7. Variation of HC with the D2 condition.

3.2.2. CO emission

The carbon monoxide (CO), which is an intermediate product in the combustion process, is mainly affected by the composition of mixed gases and temperature. As is shown in Fig. 9, The CO emission is rising with the increase of marine diesel engine speed. This might be due to the improved fuel evaporation and combustion caused by the higher fuel injection pressure and higher gas temperature of in-cylinder, consequently more CO is oxidized to CO_2. However, with the increase of speed, CO emission will increase due to the decreased excess air coefficient. Fig. 10 shows the variations of CO emission for pure diesel and four different types of biodiesel fuels under the E3 condition. The results obtained indicate that the CO emission decreases by increasing engine load and reaches a minimum, but increases again by further amplifying the engine load. As mentioned above, this might be due to the lower in-cylinder temperature. Consequently, the low in-

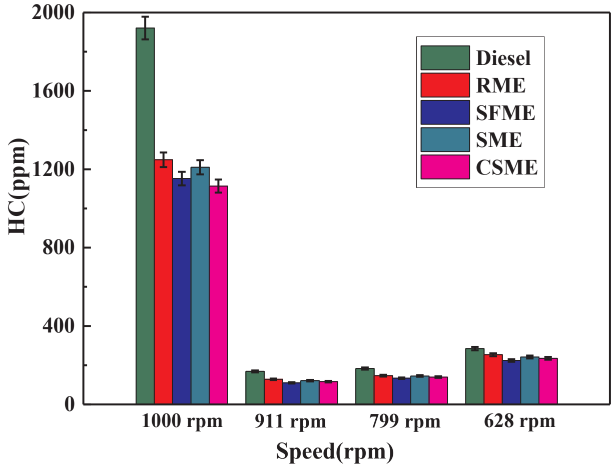


Fig. 8. Variation of HC with the E3 condition.

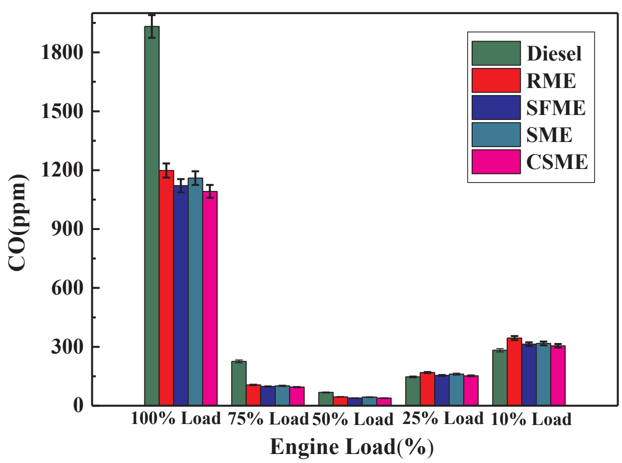


Fig. 9. Variation of CO with the D2 condition.

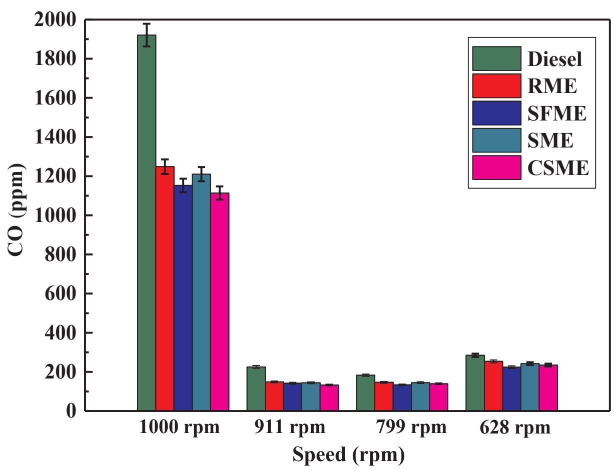


Fig. 10. Variation of CO with the E3 condition.

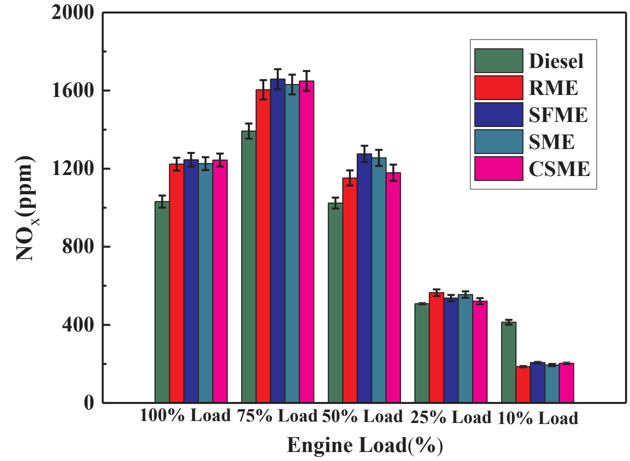


Fig. 11. Variation of NO_x with the D2 condition.

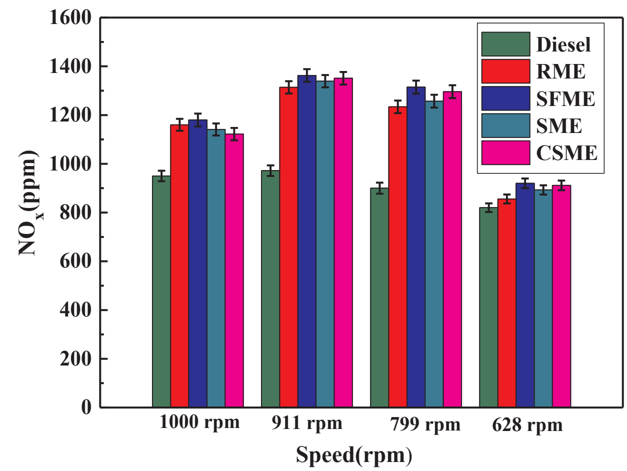


Fig. 12. Variation of NO_x with the E3 condition.

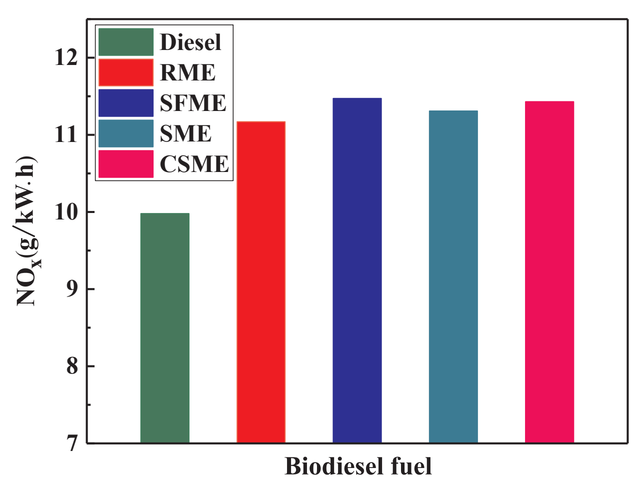


Fig. 13. Brake specific NO_x emission with the E3 condition.

cylinder temperature reduces the oxidation of CO. By further increasing the engine load, the increased in-cylinder temperature is beneficial to the oxidation of carbon monoxide. At medium and high load, due to low air-fuel ratio, the oxygen in the cylinder is relative insufficient, and the influence of the high oxygen content of biodiesel on CO emission is very obvious. Thus the CO emission decreases significantly. In addition, among four different types of biodiesel fuels, it can be clearly found that the lowest CO concentration is SFME, followed by CSME, SME and RME. This might be due to the fine fuel spray and good combustion efficiency caused by the lower kinematic viscosity. Thus, the SFME fuel has the lowest CO concentration than other biodiesels in all cases, followed by CSME, SME and RME. Compared with pure diesel, the high viscosity and poor atomization of biodiesel fuel result in the increase of the CO emission at low load. But the CO emission is reduced compared with pure diesel at high load or high speed. It might be due to the fact that the oxygen content of biodiesel fuel is beneficial to improving combustion, resulting in decreasing CO emission [55].

3.2.3. NO_X emissions

As is shown in Fig. 11, the results obtained indicate that the NO_x emissions increase by increasing engine load and reach a maximum, but decrease again by further amplifying the engine load. The three factors of the NO_x formation are temperature, oxygen concentration and reaction time. Any one factor changed which will affect the NO_x emissions. At low load, the formation of NO_x is mostly dependent on the localized high temperature zones but not the oxygen content of biodiesel due to the sufficient oxygen in the cylinder. At the same time the reaction time is reduced by the lower in-cylinder temperature and the shorter combustion duration. With the increase of the engine load, the in-cylinder temperature and the combustion duration also increase gradually. Thus, the NO_x emissions increase. As the load reaches 75%, the NO_x emissions reach a maximum and decease again by further amplifying the engine load. It is suggested that the high fuel/air ratio and poor oxygen are not favorable for increasing NO_x emissions. Compared with pure diesel, the oxygen content of biodiesel fuel is beneficial to enhancing combustion, resulting in increasing the in-cylinder temperature and NO_x emissions. It is suggested that the oxygen content of biodiesel fuel is the main reason for increased NO_x emissions [56].

As is shown in Fig. 12, the results obtained indicate that the NO_x emissions increase by increasing engine speed and reach a maximum but decrease again by further amplifying the engine speed. As mentioned above, with the increase of the speed, the engine load increases gradually. The increased in-cylinder temperature and the combustion duration are beneficial to the production of NO_x. When the speed gets to 909 rpm, NO_x emissions will reach a maximum. NO_x emissions will decease again by further amplifying the engine speed due to the high fuel/air ratio and poor oxygen.

To further study the effects of proportion on engine working process, the NO_x emissions for four different types of biodiesel fuels are compared with each other. It can be clearly found that the highest NO_x concentration is SFME, followed by CSME, SME and RME. This might be due to the fact that the lower viscosity enhancing the fuel evaporation process and combustion process, consequently increasing the in-cylinder temperature of localized zones. In addition, the oxygen levels required for complete combustion and C/H/O ratio are shown in Table 2. It is very close between the four different types of biodiesel fuels. Thus it might be due to the in-cylinder high temperature of localized zones caused by improved combustion.

3.2.4. Weighted algorithm for NO_X emissions

The brake specific NO_x emission is an important parameter for the environmental friendliness of diesel engine. To further study the NO_x emissions control from marine diesel engines, the brake specific NOx emissions for E3 test cycle model are investigated based on experimental results according to the Annex VI of MARPOL 73/78. The Weighting coefficient of E3 test cycle model is shown in Table 5. The brake specific NO_x emissions (in g/(kW·h) can be calculated by Eq. (1).

The brake specific emission values GAS_x (in g/kWh) can be expressed as:

$$GAS_x = \frac{\sum_{i=1}^{i=n} M_{GAS_x} \cdot W_{Fi}}{\sum_{i=1}^{i=n} P_i \cdot W_{Fi}} \tag{1}$$

where GAS_x is the brake specific emission values, the W_{Fi} is the Weighting coefficient, P_i is the brake power, M_{GAS_x} is the mass flow of exhaust gas.

According to the Annex VI of MARPOL 73/78, the standards of Tier I, Tier II and Tier III are 11.3 g/(kW·h), 8.98 g/(kW·h) and 2.26 g/(kW·h), respectively. The brake specific NO_x emissions are shown in Fig. 13. It can be clearly found that the highest brake specific NO_x emissions are SFME, followed by CSME, SME, RME and diesel. Compared with pure diesel, the brake specific NO_x emissions of biodiesel fuel are more than 14%. The brake specific NO_x emissions of diesel and REM are only satisfied with the requirement of Tier I. Therefore, as the emission legislation is becoming stricter and stricter, the combination between internal purification technology and exhaust gas treatment can reduce both of NO_x and PM emissions and meet the requirements in the future work.

4. Conclusions

In the work, the marine diesel engine operation trials were carried out to investigate the emission and combustion characteristics of four types of biodiesel fuels with different FAMEs proportion and pure diesel at two test cycle modes of E3 and D2. The results obtained showed that the kinematic viscosity was an important factor, and the relationship between FMAEs proportion and emission, combustion characteristics was not straightforward and simple.

The physical and chemical ignition delay of compositions can collectively affect the global ignition time. The physical ignition could be delayed with the increase of C18:1 and C18:0, as well as C16:0. It is due to the fact that the higher kinematic viscosity is not favorable for improving the fuel-air mixing, fuel evaporation and combustion efficiency. Moreover, the higher saturation would shorten the chemical ignition delay time. So the RME produced the least NO_x emissions and the lowest indicated power, while it produced the highest HC and CO emissions. On the contrary, the SFME showed the best performance and emission characteristics except NOx emissions.

Compared with pure diesel, biodiesel fuel showed the slightly poorer performance characteristic. It is due to the relatively lower calorific value and higher kinematic viscosity. Compared with pure diesel, the CO and HC emissions are increased by about 10% at low load, but are reduced by about 40% at medium and high load. In addition, the NOx emissions are increased by about 10% at low load, but are reduced by about 40% at medium and high load. The oxygen content of biodiesel fuel is beneficial to improving the in-cylinder combustion, especially at high load.

Acknowledgements

This work is supported by the National Natural Science Foundation of China under the research grant of 51676066.

Conflict of interest

The authors declare that they have no conflict of interests regarding the publication of this paper.

References

[1] Dincer I, Rosen MA. Thermodynamic aspects of renewables and sustainable development. Renew Sustain Energy Rev 2005;9(2):169–89.
[2] Ahmadi P, Dincer I, Rosen MA. Development and assessment of an integrated biomass-based multi-generation energy system. Energy 2013;56:155–66.
[3] Al-Nimr MA, Kiwan SM, Talafha S. Hybrid solar-wind water distillation system. Desalination 2016;395:33–40.
[4] Al-Nimr MA, Tashtoush BM, Jaradat AA. Modeling and simulation of thermoelectric device working as a heat pump and an electric generator under Mediterranean climate. Energy 2015;90:1239–50.
[5] Saleh A, Qudeiri JA, Al-Nimr MA. Performance investigation of a salt gradient solar pond coupled with desalination facility near the Dead Sea. Energy 2011;36(2):922–31.
[6] Lubis LI, Kanoglu M, Dincer I, Rosen MA. Thermodynamic analysis of a hybrid geothermal heat pump system. Geothermics 2011;40(3):233–8.
[7] Cynthia OB, Lee KT, Lim JK. Comparative exergy analyses of Jatropha curcas oil extraction methods: Solvent and mechanical extraction processes. Energy Convers Manage 2012;55:164–71.
[8] Zhao H, Li G, Zhao D, Zhang ZG, Sun DK, Yang WM, et al. Experimental study of equivalence ratio and fuel flow rate effects on nonlinear thermoacoustic instability

in a swirl combustor. Appl Energy 2017;208:123–31.
[9] Rahnama P, Paykani A, Reitz RD. A numerical study of the effects of using hydrogen, reformer gas and nitrogen on combustion, emissions and load limits of a heavy duty natural gas/diesel RCCI engine. Appl Energy 2017;193:182–98.
[10] Liu T, E J, Yang W, Hui A, Cai H. Development of a skeletal mechanism for biodiesel blend surrogates with varying fatty acid methyl esters proportion. Appl Energy 2016;162:278–88.
[11] Lam MK, Lee KT. Potential of using organic fertilizer to cultivate Chlorella vulgaris for biodiesel production. Appl Energy 2012;94:303–8.
[12] Zhao D, Li L. Effect of choked outlet on transient energy growth analysis of a thermoacoustic system. Appl Energy 2015;160:503–10.
[13] Öztürk E. Performance, emissions, combustion and injection characteristics of a diesel engine fuelled with canola oil–hazelnut soapstock biodiesel mixture. Fuel Process Technol 2015;129(9):183–91.
[14] Pali HS, Kumar N, Alhassan Y. Performance and emission characteristics of an agricultural diesel engine fueled with blends of Sal methyl esters and diesel. Energy Convers Manage 2015;90:146–53.
[15] Kumar BR, Saravanan S, Rana D, Nagendran A. Combined effect of injection timing and exhaust gas recirculation (EGR) on performance and emissions of a DI diesel engine fuelled with next-generation advanced biofuel–diesel blends using response surface methodology. Energy Convers Manage 2016;123:470–86.
[16] He BQ. Advances in emission characteristics of diesel engines using different biodiesel fuels. Renew Sustain Energy Rev 2016;60:570–86.
[17] Ali OM. Analysis of blended fuel properties and engine performance with palm biodiesel-diesel blended fuel. Renewable Energy 2016;86:59–67.
[18] Işık MZ, Aydın H. Analysis of ethanol RCCI application with safflower biodiesel blends in a high load diesel power generator. Fuel 2016;184:248–60.
[19] Li J, Yang W, Zhou D. Modeling study on the effect of piston bowl geometries in a gasoline/biodiesel fueled RCCI engine at high speed. Energy Convers Manage 2016;112:359–68.
[20] Zhao D, Ji C, Li X, Li S. Mitigation of premixed flame-sustained thermoacoustic oscillations using an electrical heater. Int J Heat Mass Transf 2015;86:309–18.
[21] E J, Liu T, Yang W, Deng Y, Gong J. A skeletal mechanism modeling on soot emission characteristics for biodiesel blend surrogates with varying fatty acid methyl esters proportion. Appl Energy 2016;181:322–31.
[22] Yadav AK, Khan ME, Dubey AM, Pal A. Performance and emission characteristics of a transportation diesel engine operated with non-edible vegetable oils biodiesel. Case Stud Therm Eng 2016;8:236–44.
[23] Lei T, Wang Z, Xia C, Lu L, Yan X, Sun Y, et al. Performance and emission characteristics of a diesel engine running on optimized ethyl levulinate–biodiesel–diesel blends. Energy 2016;95:29–40.
[24] Rashed MM, Kalam MA, Masjuki HH, Mofijur M, Rasul MG, Zulkifli NWM. Performance and emission characteristics of a diesel engine fueled with palm, jatropha, and moringa oil methyl ester. Ind Crops Prod 2016;79(11):70–6.
[25] Karabektas M. The effects of turbocharger on the performance and exhaust emissions of a diesel engine fuelled with biodiesel. Renewable Energy 2009;34(4):989–93.
[26] Kyunghyun R. Effects of pilot injection pressure on the combustion and emissions characteristics in a diesel engine using biodiesel-CNG dual fuel. Appl Energy 2013;76(12):506–16.
[27] Can Ö. Combustion characteristics, performance and exhaust emissions of a diesel engine fueled with a waste cooking oil biodiesel mixture. Energy Convers Manage 2014;87:676–86.
[28] Rakopoulos DC. Heat release analysis of combustion in heavy-duty turbocharged diesel engine operating on blends of diesel fuel with cottonseed or sunflower oils and their bio-diesel. Fuel 2012;96(1):524–34.
[29] Ibrahim A. Performance and combustion characteristics of a diesel engine fuelled by butanol–biodiesel–diesel blends. Appl Therm Eng 2016;103:651–9.
[30] Chiatti G, Chiavola O, Fulvio Palmieri. Vibration and acoustic characteristics of a city-car engine fueled with biodiesel blends. Appl Energy 2017;185:664–70.
[31] Roy MM, Calder J, Wang W, Mangad A, Diniz FCM. Cold start idle emissions from a modern Tier-4 turbo-charged diesel engine fueled with diesel-biodiesel, diesel-biodiesel-ethanol, and diesel-biodiesel-diethyl ether blends. Appl Energy 2016;180:52–65.
[32] Can Ö, Öztürk E, Solmaz H, Aksoy F, Çinar C, Yücesu HS. Combined effects of soybean biodiesel fuel addition and EGR application on the combustion and exhaust emissions in a diesel engine. Appl Therm Eng 2016;95:115–24.
[33] Tutak W, Jamrozik A, Pyrc M, Sobiepański M. A comparative study of co-combustion process of diesel-ethanol and biodiesel-ethanol blends in the direct injection diesel engine. Appl Therm Eng 2017;117:155–63.
[34] Patel PD, Lakdawala A, Chourasia S, Patel RN. Biofuels for compression ignition engine: A review on engine performance, emission and life cycle analysis. Renew Sustain Energy Rev 2016;65:24–43.
[35] Han D, Li K, Duan Y, Lin H, Huang Z. Numerical study on fuel physical effects on the split injection processes on a common rail injection system. Energy Convers Manage 2017;134:47–58.
[36] Çelik M. Combustion, performance and exhaust emission characteristics of organic based manganese addition to cotton methyl ester. Appl Therm Eng 2016;108:1178–89.
[37] Tosun E, Aydin K, Bilgili M. Comparison of linear regression and artificial neural network model of a diesel engine fueled with biodiesel-alcohol mixtures. Alexandria Eng J 2016;55(4):3081–9.
[38] Channapattana SV, Pawar AA, Kamble PG. Effect of injection pressure on the performance and emission characteristics of VCR engine using Honne biodiesel as a fuel. Mater Today: Proc 2015;2(4–5):1316–25.
[39] Nalgundwar A, Paul B, Sharma SK. Comparison of performance and emissions characteristics of DI CI engine fueled with dual biodiesel blends of palm and jatropha. Fuel 2016;173:172–9.
[40] Schönborn A, Ladommatos N, Williams J, Allan R, Rogerson J. The influence of molecular structure of fatty acid monoalkyl esters on diesel combustion. Combust Flame 2009;156:1396–412.
[41] Graboski MS, McCormick RL, Alleman TL, Herring AM. The effect of biodiesel composition on engine emissions from a DDC Series60 diesel engine. In: National renewable energy laboratory, Golden, Colorado; 2003.
[42] Puhan S, Gopinath A, Nagarajan G. Combustion, performance and emission characteristics of a DI CI engine using biodiesel with varied fatty acid composition. Int J Renewable Energy Technol 2009;1(1).
[43] Altaie MAH, Janius RB, Rashid U, Rashid U, Yun TY, Yunus R, et al. Performance and exhaust emission characteristics of direct-injection diesel engine fueled with enriched biodiesel. Energy Convers Manage 2015;106(11):365–72.
[44] E J, Liu T, Yang W, Li J, Gong J, Deng Y. Effects of fatty acid methyl esters proportion on combustion and emission characteristics of a biodiesel fueled diesel engine. Energy Convers Manage 2016;117:410–9.
[45] Selvan T, Nagarajan G. Combustion and emission characteristics of a diesel engine fuelled with biodiesel having varying saturated fatty acid composition. Int J Green Energy 2013;10(9):952–65.
[46] Hira A, Das D. Performance and emission evaluation of diesel engine fuelled with biodiesel produced from high free fatty acid crude soyabean oil. Biofuels 2016;7(4):413–21.
[47] Mohamed IH, Ng HK, Gan S, Lucchini T, Onorati A. Development of a reduced biodiesel combustion kinetics mechanism for CFD modelling of a light-duty diesel engine. Fuel 2013;106:388–400.
[48] Westbrook CK, Nailk CV, Herbinet O, Pitz WJ, Mehl M, Sarathy SM, et al. Detailed chemical kinetic reaction mechanisms for soy and rapeseed biodiesel fuels. Combust Flame 2011;158(4):742–55.
[49] Chen S, Zhao D, Li HKH, Ng TY, Jin Y. Numerical study of dynamic response of a jet diffusion flame to standing waves in a longitudinal tube. Appl Therm Eng 2017;112:1070–82.
[50] Peng Q, E J, Chen J, Zuo W, Zhao X, Zhang Z. Investigations on effects of wall thickness and porous media on the thermal performance of a non-premixed hydrogen fueled cylindrical micro combustor. Energy Convers Manage 2018;155:276–86.
[51] Peng Q, E J, Zhang Z, Hu W, Zhao X. Investigation on the effects of front-cavity on flame location and thermal performance of a cylindrical micro combustor. Appl Therm Eng 2018;130:541–51.
[52] Zhao D, Li S, Zhao H. Entropy-involved energy measure study of intrinsic thermoacoustic oscillations. Appl Energy 2016;177:570–8.
[53] Xing AH, Ma J, Zhang YH, Wang Y, Yong Jin. Life cycle assessment of economy for biodiesel. J Tsinghua Univ 2010;50:923–7.
[54] Shehata MS, Attia AMA, Razek SMA. Corn and soybean biodiesel blends as alternative fuels for diesel engine at different injection pressures. Fuel 2015;161:49–58.
[55] Tsukatani H, Tobiishi K. Development of a skeletal multi-component fuel reaction mechanism based on decoupling methodology. Energy Convers Manage 2015;105(6):1223–38.
[56] E J, Pham M, Zhao D, Deng Y, Le D, Zuo W, et al. Effect of different technologies on combustion and emissions of the diesel engine fueled with biodiesel: A review. Renew Sustain Energy Rev 2017;80:620–47.