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

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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

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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.

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