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A study on emission performance of a diesel engine fueled with five typical methyl ester biodiesels

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ABSTRACT

As an alternative and renewable fuel, biodiesel can effectively reduce diesel engine emissions, especially particulate matter and dry soot. However, the biodiesel effects on emissions may vary as the source fuel changes. In this paper, the performance of five methyl esters with different sources was studied: cottonseed methyl ester (CME), soybean methyl ester (SME), rapeseed methyl ester (RME), palm oil methyl ester (PME) and waste cooking oil methyl ester (WME). Total particulate matter (PM), dry soot (DS), non-soot fraction (NSF), nitrogen oxide (NO_x), unburned hydrocarbon (HC), and carbon monoxide (CO) were investigated on a Cummins ISBe6 Euro III diesel engine and compared with a baseline diesel fuel. Results show that using different methyl esters results in large PM reductions ranging from 53% to 69%, which include the DS reduction ranging from 79% to 83%. Both oxygen content and viscosity could influence the DS emission. Higher oxygen content leads to less DS at high load while lower viscosity results in less DS at low load. NSF decreases consistently as cetane number increases except for PME. The cetane number could be responsible for the large NSF difference between different methyl esters.

1. Introduction

Diesel engines are efficient power machinery for automotive applications due to their better fuel economy compared to gasoline engines. However, stringent emission regulations and future depletion of petroleum reserves force us to explore new technologies to develop alternative fuel as well as reduce pollutant emissions. Biodiesel is an alternative, renewable, clean diesel fuel made by conversion of the triglyceride fats to esters via transesterification with methanol or ethanol. The triglyceride fats used for making biodiesel can be any kind of vegetable oil, animal fats or waste oil from cooking or industry (Graboski and McCormick, 1998; Babu and Devaradjane, 2003; U.S. EPA, 2002; Rakopoulos et al., 2006). Biodiesel could be used directly in any unmodified diesel engine in blends or in neat form (Babu and Devaradjane, 2003; Rakopoulos et al., 2006).

Many research projects have been conducted to examine emissions from biodiesels (Sharp et al., 2000; Tsolakis et al., 2007; Verhaeven et al., 2005; McCormick and Graboski, 2001; Chen et al., 2006; Cheng et al., 2003; Souligny et al., 2004). Most of these studies showed that biodiesel could effectively reduce particulate matter (PM), dry soot (DS), carbon monoxide (CO), unburned hydrocarbon (HC), but with a slight increase in nitrogen oxide (NO_x) relative to diesel fuel. Sharp et al. (2000) studied the effects of soybean methyl ester on FTP transient exhaust emissions from three modern engines. Compared with diesel fuels, PM was reduced by 28–50% for soybean methyl ester, which included a DS reduction of 61–71%. CO was reduced by 38–45% and NO_x was increased by 4–13%. Tsolakis et al. (2007) examined the effects of rapeseed methyl ester on emissions from a single-cylinder diesel engine. Using rapeseed methyl ester reduced smoke by 65–81%, CO by 34–50% and HC by 58%, while increasing NO_x by 47–70% relative to diesel fuel. Verhaeven et al. (2005) reported the results of emissions tests on two passenger cars and three trucks using waste methyl ester. Results showed that, compared with diesel fuel, the use of waste methyl ester reduced PM by 20%, which included a 32% reduction of NSF, HC by 40% and CO by 25%. It also increased NO_x emission by 24%.

Previous research on the application of biodiesel on diesel engines mainly focused on the comparison between biodiesel and diesel fuel. However, few literature studies were found to compare the emission differences of pure biodiesels from different sources on the same engine. However, the difference in source can influence their physicochemical properties, such as oxygen content, cetane number, viscosity, density, heat value, etc., and hence influence the emissions performance. Therefore, it becomes necessary to study the emission differences among biodiesels with different sources, and their relationship to the fuel properties.

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In this paper, the performance of five biodiesels with different sources was studied. Total PM, DS, NSF, NO_x, HC and CO were investigated in a Cummins ISBe6 Euro III diesel engine fueled with five biodiesels respectively and compared with diesel fuel. The relationship between emission test results and biodiesel properties was then discussed.

2. Experimental set-up

2.1. Experimental facilities

The test engine is a Cummins ISBe6 direct injection engine, with turbocharger and intercooler, meeting the Euro III standard. This engine is widely used in China. The engine specifications are shown in Table 1.

Fig. 1 shows the schematic diagram of the test bench. NO_x, HC and CO are measured by an AVL CEB-II exhaust gas analyser. PM is sampled on filters (TX40HI20-WW of PALL Corporation) by an AVL SPC-472 partial flow dilution smart sampler. The filters are weighed by an electronic balance with 10 μg sensitivity before and after sampling, and kept in a temperature-controlled (22 °C ± 3 °C) room with relative humidity of 45% ± 8%. After total PM is weighed, filters are extracted in dichloromethane (CH_2Cl_2) and then in de-ionized water, separating the PM into two parts: dry soot (DS) and non-soot fraction (NSF).

2.2. Tested fuels

The baseline diesel fuel was obtained from a Beijing local filling station and was tested for reference. The five tested biodiesels were made and provided by Chinese local bioengineering companies, and included cottonseed methyl ester (CME), soybean methyl ester (SME), rapeseed methyl ester (RME), palm oil methyl ester (PME) and waste cooking oil methyl ester (WME). Physicochemical properties of the tested diesel fuel and biodiesels are shown in Table 2. It can be seen that differences between the biodiesels mainly lies in three of the properties: cetane number, oxygen content and viscosity. These biodiesels show either no differences or only slight differences in density, low heating value and T90 (less than 1%).

2.3. Testing procedure

The test engine was unchanged during all the tests. All the emissions were tested at 1500 min^{-1} with a part load test. Five test points with the same speed and different brake mean effective pressure (BMEP) were selected. The BMEP chosen are 0.256 MPa, 0.512 MPa, 0.768 MPa, 1.024 MPa, 1.280 MPa, and correspond roughly to 120 N m, 240 N m, 360 N m, 480 N m, 600 N m on this engine.

Table 1
Engine specifications.

Engine model	Cummins ISBe6
Type	4-stroke, direct injection, turbo-charging, intercooling
Cylinder number	6
Displacement (*L*)	5.9
Cylinder bore (mm)	102
Bowl geometry	Omega combustion chamber
Compress ratio	17.5
Rated power/speed	136 kW/2500 min^{-1}
Max toque/speed	670 N m/1500 min^{-1}
Fuel supply system	High pressure common rail

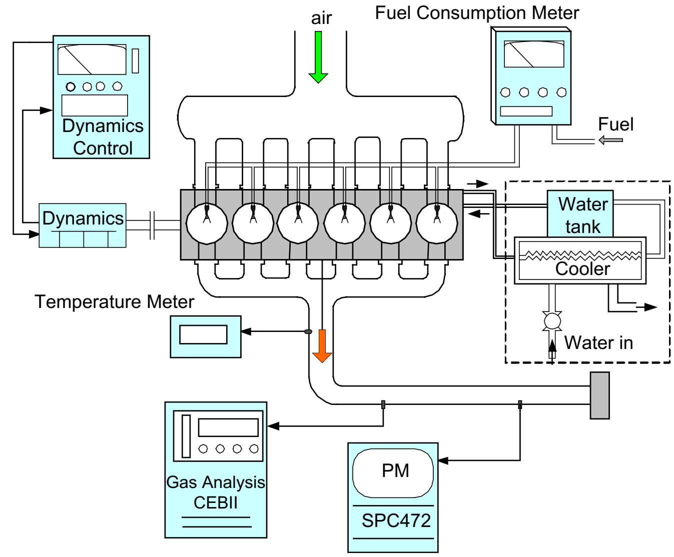

Fig. 1. Schematic diagram of the engine bench.

3. Results and discussion

3.1. Total PM emission

In Figs. 2–6 the emission results for various biodiesels and diesel fuel are compared at the same power output and thus the same BMEP value. This indicates that the fuel supply for biodiesels is higher than diesel due to the lower heat content of the biodiesels. The total PM, DS and NSF emissions of the engine using different biodiesels are shown in Fig. 2. It can be seen that using biodiesels can significantly reduce total PM emission and the extent of PM reduction increases with load. In addition, there are significant differences in total PM emission between different biodiesels. Compared with the diesel fuel, different biodiesels reduce PM emission by 53–69% on average. The biodiesels that reduced PM the most, in descending order, are: WME, PME, CME, RME, and SME. The reasons for the difference of PM emission between different biodiesels will be discussed later.

3.2. DS emission

The emissions of DS and NSF in PM are also shown in Fig. 2. Using biodiesels largely reduces DS emission at all loads, and the extent of the reduction is greater than that of PM. Compared with diesel fuel, different biodiesels reduce DS emission by 80–82% on average. The biodiesels that reduced DS the most, in descending order, are: PME, WME, CME, RME, and SME. Although average DS reductions with different biodiesels are close in value, DS emissions are considerably different at different loads. Higher oxygen content could enhance the oxidation of soot in locally rich regions and therefore reduce DS emission (Graboski and McCormick, 1998; Tsolakis et al., 2007). Higher viscosity could worsen spray and atomization, and therefore increase DS emission (Graboski and McCormick, 1998; Babu and Devaradjane, 2003; Ahmed et al., 2006). The effect of oxygen content and viscosity on DS emissions at high load and low load are shown in Fig. 3. We found that, at high load, oxygen content has a larger effect on DS than does viscosity. DS emissions decrease as oxygen content increases, as shown in Fig. 3(a). However, at low load, the effects of the difference in viscosity become more dominant. DS emissions show an increasing trend as viscosity increases, as shown in Fig. 3(b). This phenomenon

Table 2
Physicochemical properties of test fuels.

	Cetane number	Sulfur content (ppm)	Density (kg m^{-3})	T90 (°C)	Boiling point (°C)	Low heating value (kJ kg^{-1})	Viscosity (mm^2 s^{-1}) (at 20 °C)	Oxygen content (wt.%)	Carbon content (wt.%)	Hydrogen content (vol%)
Test method	GB/T 386	SH/T 0253	GB/T 2540	GB/T 6536	GB/T 6536	GB/T 384	GB/T 265	Element analyser	SH/T 0656	SH/T 0656
Diesel	55	160	830	318.5	341	43,140	3.763	0.00	86.4	13.6
CME	54	5	880	343.0	–	39,787	6.381	10.6	–	–
SME	51	1	873	343.5	–	39,950	6.624	–	–	–
RME	53	6	873	341.5	–	39,837	6.380	10.5	–	–
PME	64	1	878	334.9	–	40,063	7.114	11.2	76.6	12.4
WME	56	7	870	342.5	–	40,055	6.897	11.3	76.3	12.2

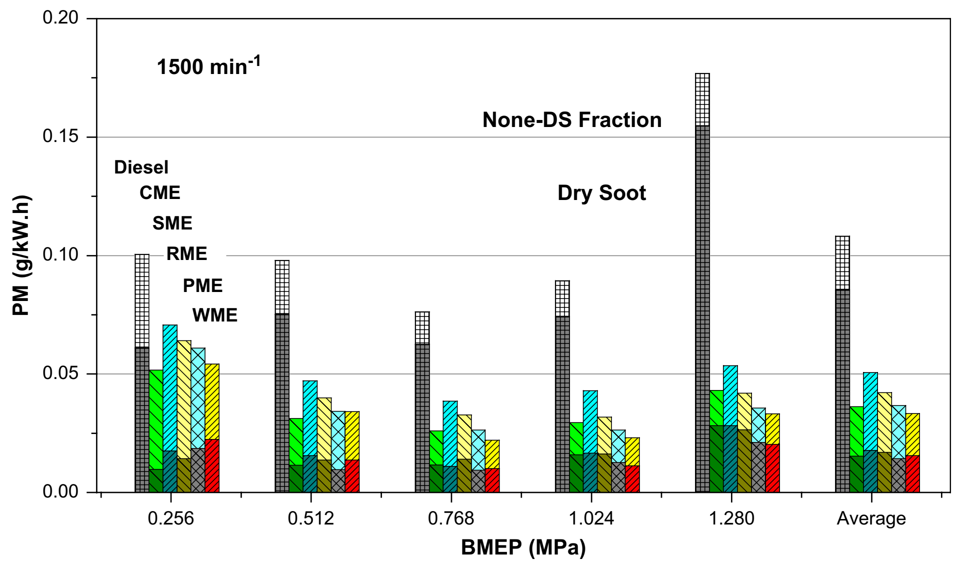

Fig. 2. PM, DS and NSF emission with different fuels ($n = 1500$ min^{-1}).

can be physically explained as follows: at high load there are more locally rich regions, and therefore more oxygen in fuel molecules is more effective in reducing DS; whereas at low load, oxygen in fuel become less useful due to the lean mixture, and low cylinder temperature will cause worse vaporization and atomization, which causes soot formation to be more sensitive to viscosity.

3.3. NSF emission

For diesel fuel, NSF includes the soluble organic fraction (SOF) and sulfate. Since biodiesel contains nearly no sulfur, SOF would be the main component of NSF emitted from biodiesel. Many studies reported that biodiesel resulted in higher NSF emission (Sharp et al., 2000; Verhaeven et al., 2005; Cheng et al., 2003; Chang, 1998), but the reason is still unclear. It can be observed from Fig. 2 that NSF emissions largely depend on fuels. SME and RME result in an increase in NSF of 45% and 11% relative to diesel fuel; NSF of PME is close to the diesel fuel; CME and WME resulted in an NSF decrease of 8% and 21% relative to diesel fuel. Except for the fuel PME, NSF of other biodiesels decreases consistently as cetane number increases. Therefore cetane number might be, to a large extent, responsible for the NSF emissions of biodiesels. However, further research is needed to look for other possible factors.

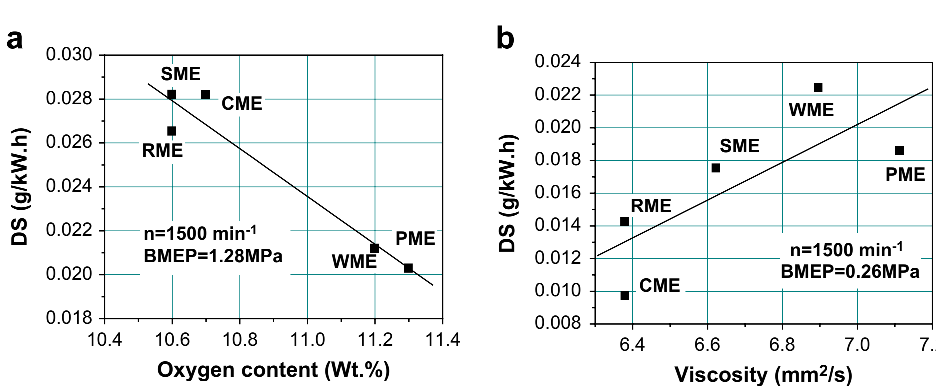

Fig. 3. Effect of oxygen content and viscosity on DS emissions. (a) Oxygen effect at high load; (b) viscosity effect at low load.

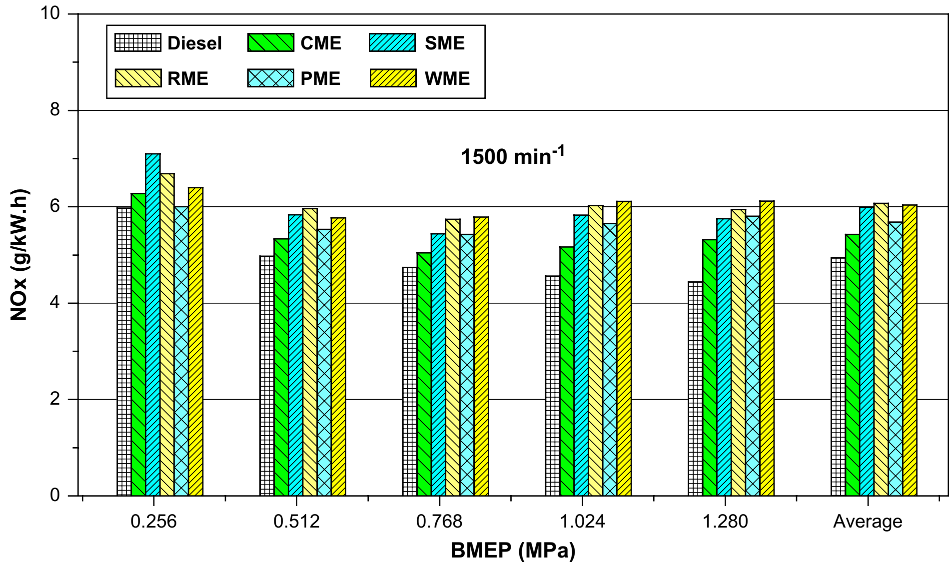

Fig. 4. NO_x emission with different fuels ($n = 1500\ min^{-1}$).

3.4. NO_x emission

NO_x emissions of different biodiesels are shown in Fig. 4. All five biodiesels result in higher NO_x emissions than diesel fuel, but the extent of the increase varies, ranging from 10% to 23% relative to diesel fuel. The biodiesels that result in the least NO_x, in descending order, are: CME, PME, SME, WME, and RME. Many studies have reported that biodiesel can result in higher NO_x, but the reason is unknown. Fuel oxygen content is believed to be the main reason, because PM and soot are effective heat radiators, and when they are mostly oxidized by oxygen, temperature inside the cylinder may increase and result in higher NO_x (Graboski and McCormick, 1998). However, comparison between PME and WME reveal that, although they have almost the same oxygen content, PME produces less NO_x than WME. The most likely reason is the high cetane number of PME, which is 64. Higher cetane number could reduce ignition delay and fuel consumed in the premixed phase, and therefore reduce in-cylinder temperature.

3.5. HC emission

HC emissions of the engine using different biodiesels are shown in Fig. 5. Compared with diesel fuel, different biodiesels reduce HC emission by 45–67% on average. The biodiesels that reduce HC the most, in descending order, are: PME, WME, RME, CME, and SME. Theoretically HC is mainly caused by misfire in a locally rich region or locally lean region. The difference in HC emission with different biodiesels is likely to be a combined effect of oxygen content and cetane number. From Fig. 5, as cetane number increases, HC emissions decrease consistently for biodiesels, but the HC is still lower than for diesel fuel due to the existence of oxygen in fuel molecules.

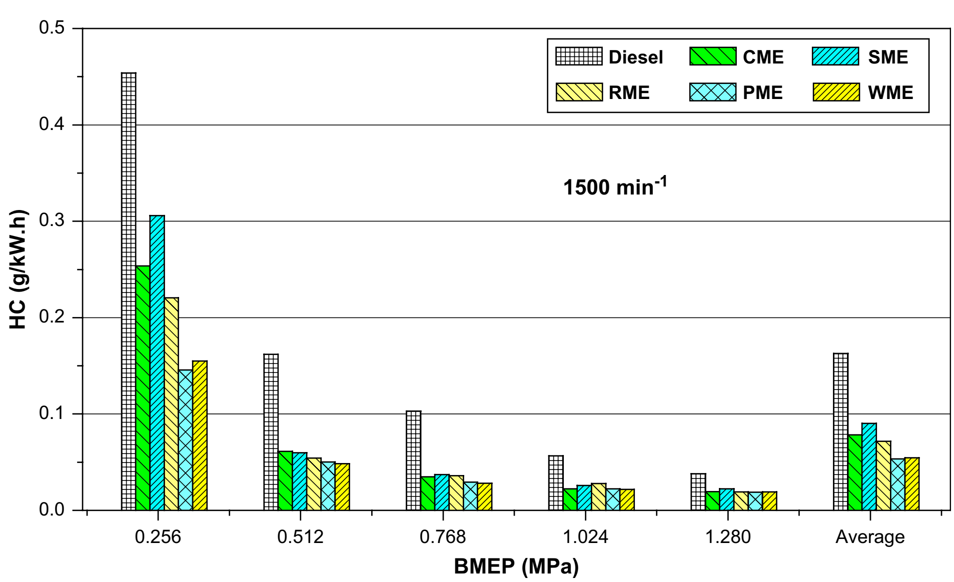

Fig. 5. HC emission with different fuels ($n = 1500\ min^{-1}$).

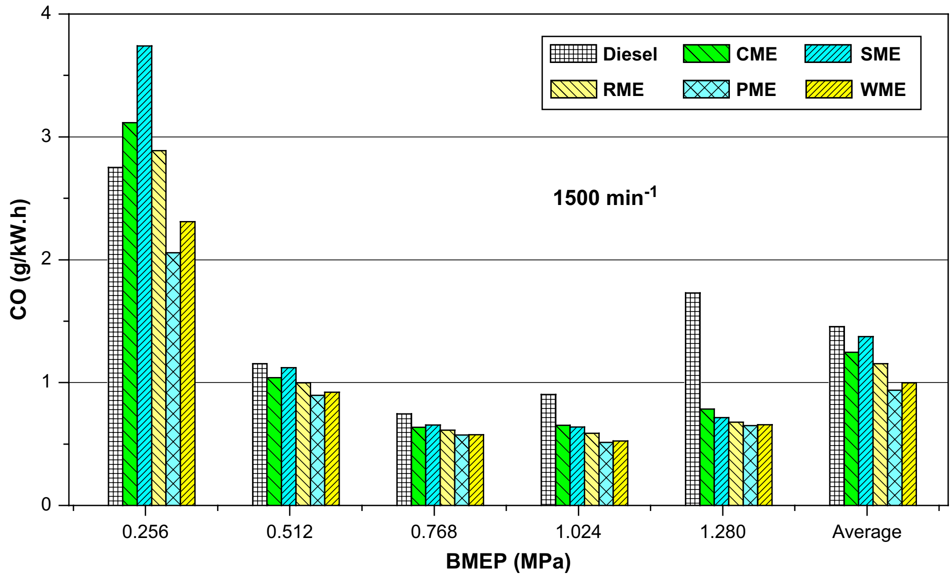

Fig. 6. CO emission with different fuels ($n = 1500\ \text{min}^{-1}$).

3.6. CO emission

Fig. 6 shows the CO emissions using different biodiesels. Compared with diesel fuel, biodiesels reduce CO emission by 4–16% on average. Effects of different fuels on CO emission are similar to that of HC. Large effects of cetane number and oxygen content can be observed. At high load, oxygen content may be helpful in reducing CO, while at low load effects of oxygen content become weak and cetane number is likely to be the only factor for CO: as cetane number increases, CO decreases consistently for both biodiesels and diesel fuel.

4. Conclusions

The effects of five biodiesels with different sources on emissions from a diesel engine were investigated. Based on the test results, the following conclusions can be drawn:

(1) Biodiesels do reduce PM emissions, but the extent of reduction varies from 53% to 69% and largely depends on the fuel. The biodiesels that reduce PM the most, in descending order, are: WME, PME, CME, RME, and SME.
(2) Using biodiesels also largely reduces DS emission, and the extent of reduction is greater than that of PM. Higher viscosity may result in more DS emissions. Results show that at high load the effect of oxygen content is greater than that of viscosity, while at low load the viscosity effects becomes more dominant.
(3) NSF emissions also vary with different biodiesels. NSF decreases consistently with the increase in cetane number for all fuels except PME.
(4) Different biodiesels increase NO_x emission by 10–23% on average. The biodiesels that result in the least NO_x, in descending order, are: CME, PME, SME, WME, and RME. Results show that for biodiesels with the same oxygen content, higher cetane number could result in lower NO_x.
(5) All biodiesels produce less HC and CO than diesel fuel. The results show the combining effects of oxygen content and cetane number on HC and CO emissions.

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