2008-01-1812

Effects of Different Biodiesels and Their Blends With Oxygenated Additives on Emissions from a Diesel Engine

Fujia Wu, Jianxin Wang, Wenmiao Cheng, Shijin Shuai
State Key Laboratory of Automotive Safety and Energy, Tsinghua University, Beijing, China

ABSTRACT

Biodiesel is an alternative, renewable, clean fuel, which can effectively reduce emissions from diesel engines. However, the effects of biodiesel on engine emissions vary due to the difference in source. In this paper, performance of five different biodiesels was studied: CME, SME, RME, PME and WME. Engine power, fuel consumption, gaseous emissions and PM, DS and none soot fraction (NSF) were investigated in a Cummins ISBe6 Euro III diesel engine fueled with five biodiesels respectively and compared with the diesel fuel. Results revealed that using different biodiesels resulted in PM reductions ranging from 53% to 69%, which included DS reduction ranging from 79% to 83%. Observations showed that fuel oxygen content and viscosity had obvious effects on DS. Higher oxygen content biodiesels produced less DS at high load while lower viscosity biodiesels produced less DS at low load. Cetane number may be responsible to the NSF difference between biodiesels, for NSF decreased consistently with increasing cetane number exception for only one fuel.

Blended fuels with different physicochemical properties were obtained by blending biodiesels with certain proportions of ethanol, DMC and DMM and were tested on the same engine. The test results show that, as oxygen content increases, PM and DS emissions continue to decrease, but the decrease rate slows down. When oxygen content was up to 15% to 20%, nearly no DS was found. Biodiesel-Ethanol blends and Biodiesel-DMC blends are more effective in reducing PM and DS than Biodiesel-DMM blends. The NSF increase was observed with increasing oxygen content for all the three blended fuels. And increase of additives' cetane number from 8 to 36 did not show a reduction of NSF emission.

INTRODUCTION

Diesel engines are still fuel-efficient driving powerplants for automotive applications because of their superior fuel economy relative to spark ignition engines. However, stringent emission regulations and future depletion of petroleum reserves force us to explore new technologies to reduce fossil fuel consumption and reduce pollutants emission. 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 vegetable oil, animal fats or waste oil from cooking and industry [1-4]. Biodiesel can be used directly in any unmodified diesel engine in neat form or blended with diesel [2,4].

A number of studies have been conducted to examine emissions from biodiesels [5-8, 11, 13-14]. Most of these studies showed that biodiesel could effectively reduce particulate matter (PM), dry soot (DS), carbon monoxide (CO), unburned hydrocarbon (HC), while with a slightly increase of nitrogen oxide (NOx) relative to diesel fuel. Christopher A. Sharp et al. [5] 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% to 50% for soybean methyle ester, which included a DS reduction of 61% to 71%. CO was reduced by 38% to 45% and NOx was increased by 4% to 13%. A. Tsolakis et al. [6] examined the effects of rapeseed methyl ester on emissions from a single-cylinder diesel engine. Using of raperseed methyl ester reduced smoke by 65% to 81%, CO by 34% to 50% and HC by 58%, while increasing NOx by 47% to 70% relative to diesel fuel. Erik Verhaeven et al. [7] reported the results of emissions test 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 NSOF, HC by 40% and CO by 25%. It also increased NOx emission by 24%.

Previous researches on the application of biodiesel on diesel engines mainly focus on the comparison between biodiesels and conventional diesels. However, nearly no literature studies were found to compare the emission differences of pure biodiesels with different sources on the same engine. However, the difference in source can influence the physicochemical properties of biodiesels, such as oxygen content, cetane number, viscosity, density, heat value, etc., and hence influence emissions performance. Therefore, it becomes necessary to investigate the emission differences between biodiesels with different sources and their relationship to fuel properties. PM and NOx is the major issue of diesel engine emissions. Currently, there are mainly two strategies of emission control on Euro IV diesel engines: one is controlling PM formation in cylinder by high-pressure injection and reducing NOx by SCR aftertreatment; the other is controlling NOx formation in cylinder by EGR and reducing PM by DPF. Both strategies depend on aftertreatment devices, which are typically voluminous and costly. Since PM could be reduced in a large extent by using oxygenated fuels, the trade-off relationship between PM and NOx could be shifted by injection timing to reduce NOx while maintaining acceptable levels of PM. Therefore by using high oxygen content fuel, it is possible to meet Euro IV standard without aftertreatment. High oxygen content could be obtained by blending biodiesel with oxygenated additives.

In this paper, performance of five biodiesels with difference sources was studied. Engine power, brake specific fuel consumption (BSFC), gaseous emissions, total PM, DS and none soot fraction (NSF) were investigated in a Cummins ISBe6 Euro III diesel engine fueled with five biodiesels respectively and compared with the diesel fuel. To investigate the effects of higher oxygen content, three kinds of blended fuels with different oxygen content and physicochemical properties were obtained by blending biodiesels with certain proportions of ethanol, methyl carbonate (DMC) and dimethoxy methane (DMM). Emissions performance of these blended fuels was tested to explore the possibility of meeting Euro IV standard without aftertreatment.

EXPERIMENT SETUP

EXPERIMENTAL FACILITIES

The test engine is Cummins ISBe6 direct injection diesel engine, with a turborcharger and an intercooler, meeting Euro III standard. EGR is not used on this engine. The engine specification is shown in Table 1.

Table 1 Engine specifications

Engine Model	Cummins ISBe6
Type	4-stroke, in-line, turbo-charging, intercooling, direct injection
Cylinder number	6
Displacement (L)	5.9
Cylinder Bore (mm)	102
Bowl Geometry	ωcombustion chamber
Compress ratio	17.5
Rated power/speed	136 kW / 2500 $r \cdot min^{-1}$
Max toque/speed	670 N·m /1500 $r \cdot min^{-1}$
Fuel supply system	High pressure common rail

Figure 1 shows the schematic diagram of engine bench. Gaseous emissions, like NOx, HC, CO, and CO_2 are measured by AVL CEB-II exhaust gas analyzer. PM is sampled on filters (TX40HI20-WW of PALL Corporation) by AVL SPC-472 partial flow dilution smart sampler. The filters are weighed by an electronic balance with 10μg sensitivity before and after sampling and kept in a temperature controlled (22℃±3℃) room with relative humidity of 45%±8%. After total PM is weighted, the filters are extracted in dichloromethane (CH_2Cl_2) and de-ionized water, separating the PM into two parts: dry soot (DS) and none soot fraction (NSF).

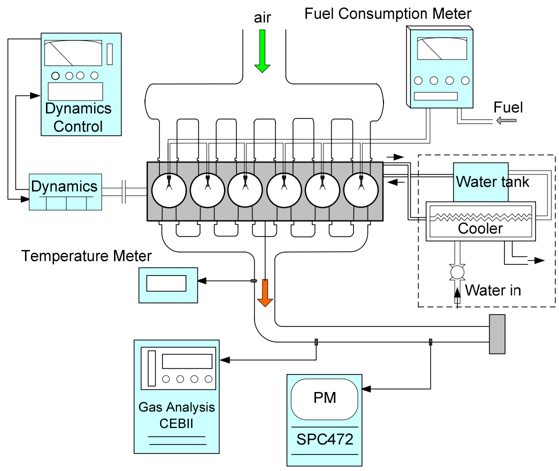

Figure 1 Schematic diagram of engine bench

TESTED FUELS

Diesel fuel was gained from local filling station and tested for reference. Its sulfur content is 160 ppm therefore are named D160. The five tested biodiesels are cottonseed methyl ester (CME), soybean methyl ester (SME), rapeseed methyl ester (RME), palm oil methyl ester (PME) and waster cooking oil methyl ester (WME). Physicochemical properties of tested diesel fuel and biodiesels are shown in Table 2. It can be seen that the main difference between biodiesels lies in cetane number, oxygen content and viscosity. Biodiesels show no or slight difference in their density, low heating value and T90 (<1%).

Three PME-Ethanol blended fuels were obtained by blending 10%, 20%, 30% ethanol (in volume) into PME and are denoted as PE10, PE20, PE30, respectively. Two WME-DMC blended fuels were obtained by blending 10%, 20% DMC (in volume) into WME and are denoted as WDMC10 and WDMC20, respectively. Another two WME-DMM blended fuels were obtained by blending 10%, 20% DMM (in volume) into WME and are denoted as WDMM10 and WDMM20, respectively. Physicochemical properties of ethanol, DMC, DMM, along with calculated properties of blended fuels are also shown in Table 2.

TESTED PROCEDURE

The test engine was not modified during all the tests. Engine power was examined under full load test. Fuel consumption, emissions performances were examined under 1500rpm part load test.

Table 2 Physicochemical properties of test fuels

	Cetane Number	Sulfur Content (ppm)	Density (kg/m^3)	T90 (^oC)	Boiling Point (^oC)	Low Heating Value (kJ/kg)	Viscosity (mm^2/s)	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
D160	55	160	830	318.5	341	43140	3.763	0.00	86.4	13.6
CME	54	5	880	343.0	--	39787	6.381	10.6	--	--
SME	51	1	873	343.5	--	39950	6.624	--	--	--
RME	53	6	873	341.5	--	39837	6.380	10.5	--	--
PME	64	1	878	334.9	--	40063	7.114	11.2	76.6	12.4
WME	56	7	870	342.5	--	40055	6.897	11.3	76.3	12.2
Ethanol	8	0	794	--	78	27000	1.060	34.8	52.2	13.0
DMC	36	0	1070	--	91	15780	0.630	53.3	40.0	6.7
DMM	30	0	860	--	43	22400	0.340	42.1	46.2	11.7
PE10	--	0 [a]	870 [a]	--	--	38870 [a]	--	13.3 [a]	74.3 [a]	12.4 [a]
PE20	--	0 [a]	861 [a]	--	--	37654 [a]	--	15.5 [a]	72.1 [a]	12.4 [a]
PE30	--	0 [a]	853 [a]	--	--	36414 [a]	--	17.7 [a]	69.8 [a]	12.5 [a]
WDMC10	--	6 [a]	890 [a]	--	--	37137 [a]	--	16.2 [a]	71.9 [a]	12.4 [a]
WDMC20	--	5 [a]	910 [a]	--	--	34346 [a]	--	21.1 [a]	67.8 [a]	11.7 [a]
WDMM10	--	6 [a]	869 [a]	--	--	38308 [a]	--	14.2 [a]	73.3 [a]	13.0 [a]
WDMM20	--	5 [a]	868 [a]	--	--	36557 [a]	--	17.3 [a]	70.3 [a]	12.9 [a]
a Calculated										

COMPARISON OF DIFFERENT BIODIESELS

ENGINE POWER

The full load torque of the engine using different biodiesels is shown in Figure 2. It can be seen that using all biodiesels resulted in a loss of power. Compared with D160, using biodiesels reduced engine power by 9% (CME) to 12% (WME). There are 3% difference between different biodiesels. Considering that the difference in low heating value of biodiesels is only within 1%, other properties may have non-negligible impacts on the spray and combustion, and hence the power output.

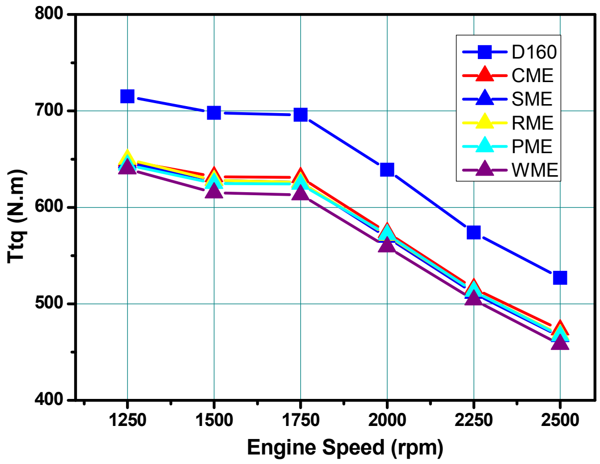

Figure 2 Full Load Torque with All Fuels

FUEL CONSUMPTION

The BSFC of the engine using different biodiesels is shown in Figure 3. It can be seen that using biodiesels resulted in an increase of BSFC. Compared with D160, using biodiesels increased BSFC by 13% (WME) to 15% (CME). There are a 2% difference of BSFC between different biodiesels.

The brake thermal efficiency (BTE) of the engine using different biodiesels is shown in Figure 4. BTE was calculated according to the following equation:

$$BTE = \frac{3.6 \times 10^6}{BSFC \times H_u} \qquad (1)$$

Where, *BTE* is brake thermal efficiency, *BSFC* is brake specific fuel consumption and its unit is g/kW.h, H_u is the low heating value and its unit is kJ/kg. The number 3.6×10^6 is the result of unit conversion.

It can be observed from Figure 4 that the engine BTE using biodiesels is lower than that using diesel fuel at all load. The average BTE with biodiesels is 1.6% (WME) to 2.0% (CME) lower than that with D160. The cause of the lower BTE with biodiesels may be the change of combustion phasing. Some studies [1,6,8-10] indicated that biodiesel can shorten the ignition delay and the combustion duration. Change of combustion phasing may reduce the constant volume ratio (CVR), especially considering that this engine was unmodified during all the tests.

By comparison between BTE of different biodiesels, oxygen content showed a slight improvement to BTE. WME has the highest oxygen content and its thermal efficiency is also the highest in all biodiesels. Higher oxygen content in fuel could improve the combustion efficiency in local rich regions.

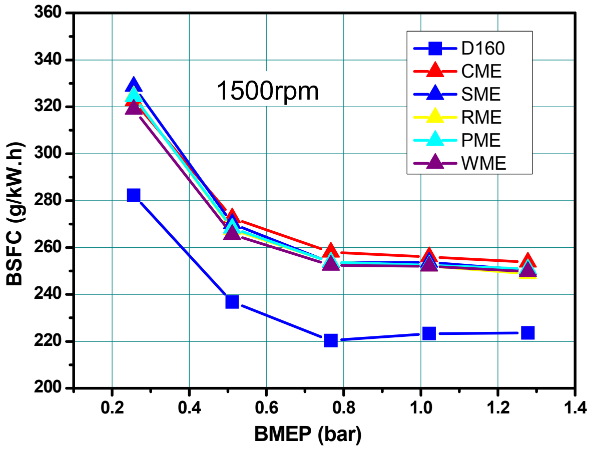

Figure 3 Fuel Consumption with All Fuels (n=1500rpm)

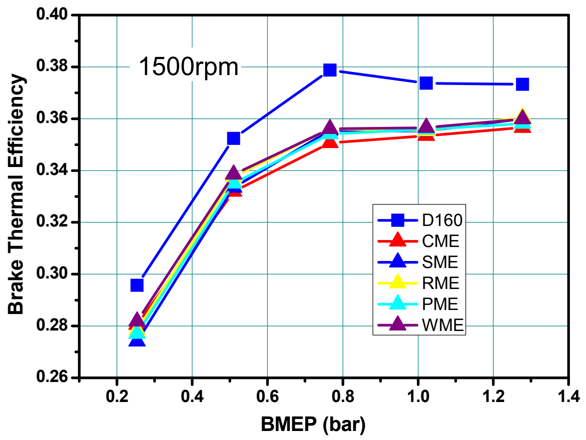

Figure 4 BTE with All Fuels (n=1500rpm)

PM EMISSION

The PM, DS and NSF emission of the engine using different biodiesels is shown in Figure 5. It should be stated that from Figure 4 to Figure 8 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. It can be seen that using biodiesels can significantly reduce total PM emission and the extent of PM reduction increases with the loads. In addition, there are obvious difference in PM emission between different biodiesels. Compared with D160, different biodiesels reduce average PM emission by 53% to 69%. The biodiesels that reduced the most PM in descending order are: WME, PME, CME, RME, SME. Reason for the difference of PM emission between different biodiesels will be discussed later.

The emissions of DS and NSF in PM are also shown in Figure 5. Using biodiesels largely reduce DS emission at all load, and the reduction extent is greater than that of PM. Compared with D160, different biodiesels reduce average DS emission by 80% to 82%. The biodiesels that reduced the most DS in descending order are: PME, WME, CME, RME, SME. Although average DS emissions with different biodiesels are close, there are considerable difference at different loads. Higher oxygen content could enhance the oxidation of soot in local rich regions and therefore reduce DS emission[1,6]; while higher viscosity could worsen spray and atomization and therefore could increase DS emission [1,2,12]. Figure 5 shows that at high load, PME and WME, which have higher oxygen content and high viscosity, produce less DS; at median load, DS emission are close for all biodiesels; at low load, CME and RME, which have lower oxygen content and low viscosity produce less DS. This indicates that at high load the effect of oxygen content is likely to be greater than viscosity; while at low load the effect of viscosity becomes more obvious. This phenomenon can also be easily explained by mixture formation: at high load there are more local rich regions, therefore higher oxygen content is more effective in reducing DS; at low load oxgen conent becomes less effective due the the lean mixture. At the same time, temperature inside the cylinder are relatively low at low load, the vaporization and atomization rate is slower. Therefore, viscosity effect on spray becomes more important.

For diesel fuel, NSF includes soluable organic fraction (SOF) and sulfate. Since biodiesel contain nearly zero sulfur, SOF should be the main component of NSF from biodiesel. Many studies reported that biodiesel resulted in higher NSF emission [5,7,13-15], but the reason is unknown. It can be observed from Figure 5 that NSF emissions largely depends on fuels. SME and RME resulted in an increase of NSF by 11% and 45% relative to D160; NSF of PME was close to D160; CME and WME resulted in an decease of NSF by 8% and 21% relative to D160. Except for PME, NSF emissions with biodiesels decrease consistently with the increase of cetane number. Therefore cetane number is, to a large extent, responsible to the NSF emissions with biodiesels. However, further research is needed to clear other possbile factors.

NOx EMISSION

NOx emission of the engine using different biodiesels is shown in Figure 6. All biodiesels resulted in higher emission of NOx, but the extent of increase varies, ranging from 10% to 23% relative to D160. The biodiesels that resulted in the least NOx in descending order are: CME, PME, SME, WME, RME. Many studies reported that biodiesel can result in higher NOx, but the reason is unknown. Fuel oxygen content is believed to be the main reason, because PM and soot was effective

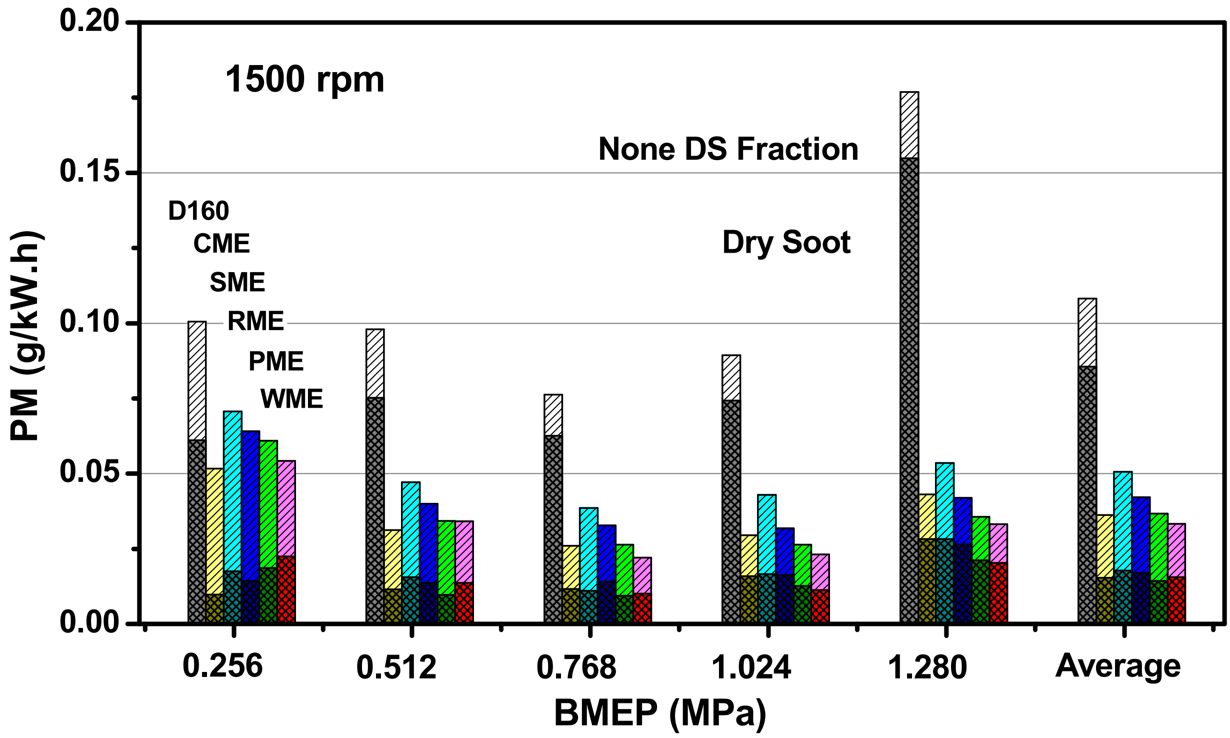

Figure 5 PM, DS and NSF Emission with Different Fuels (n=1500rpm)

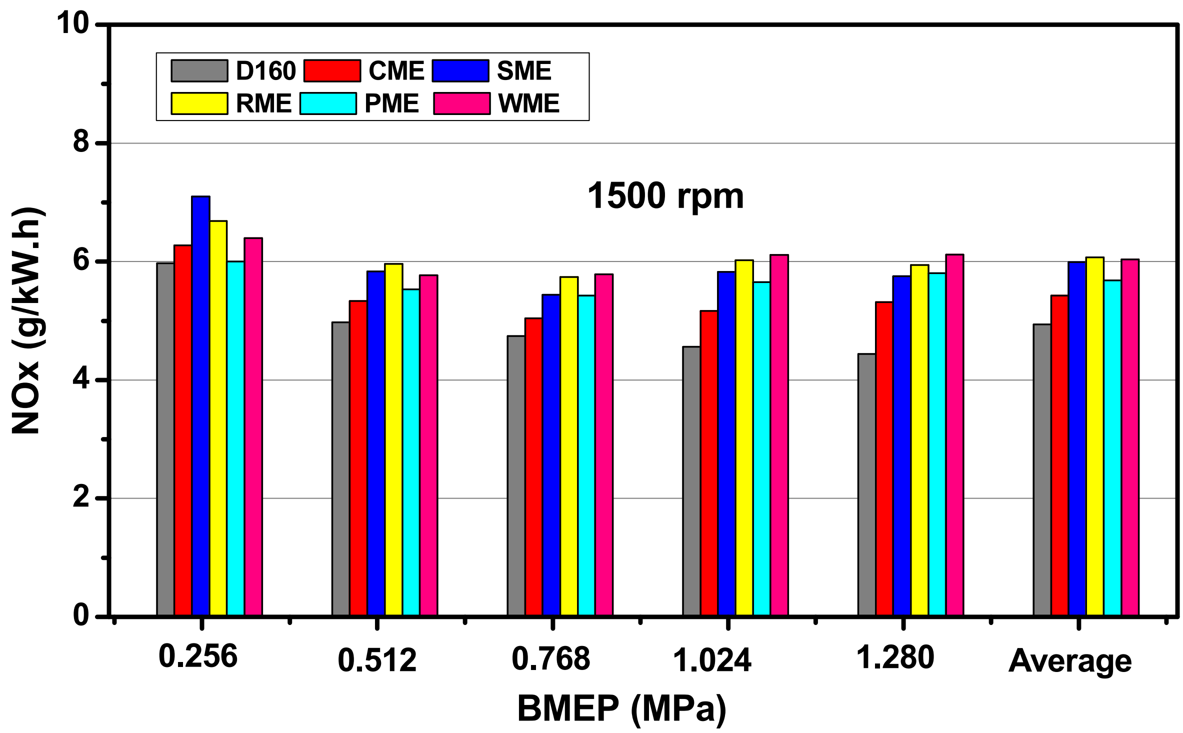

Figure 6 NOx Emission with Different Fuels (n=1500rpm)

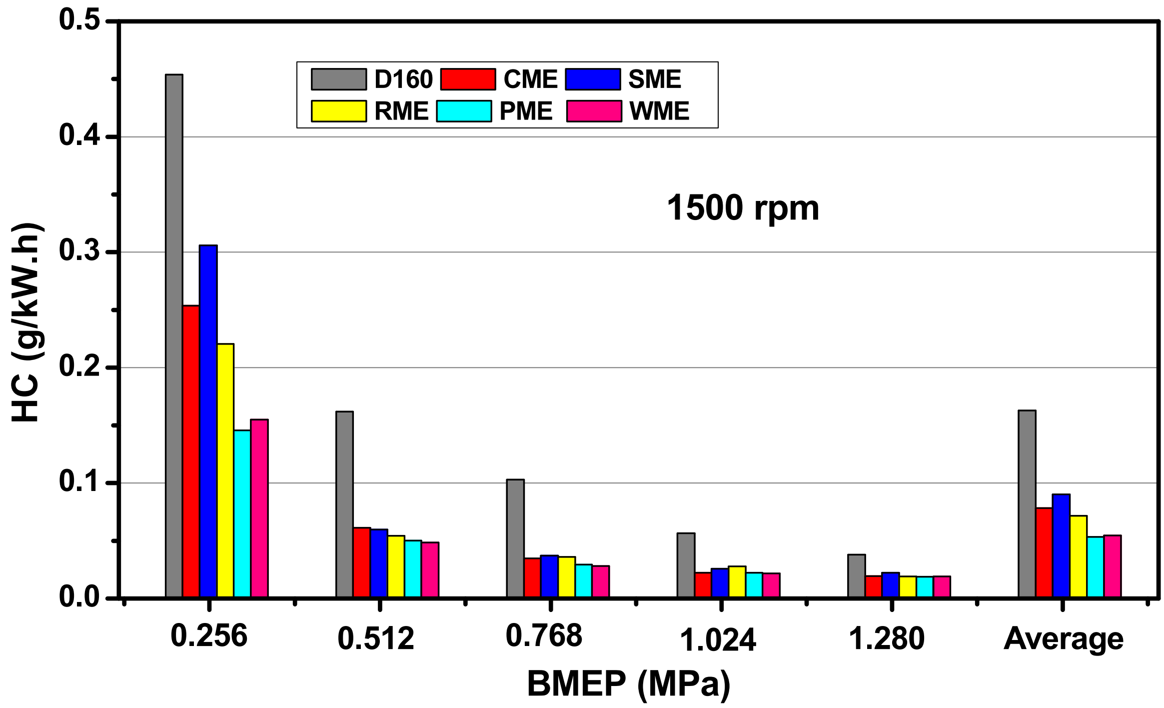

Figure 7 HC Emission with Different Fuels (n=1500rpm)

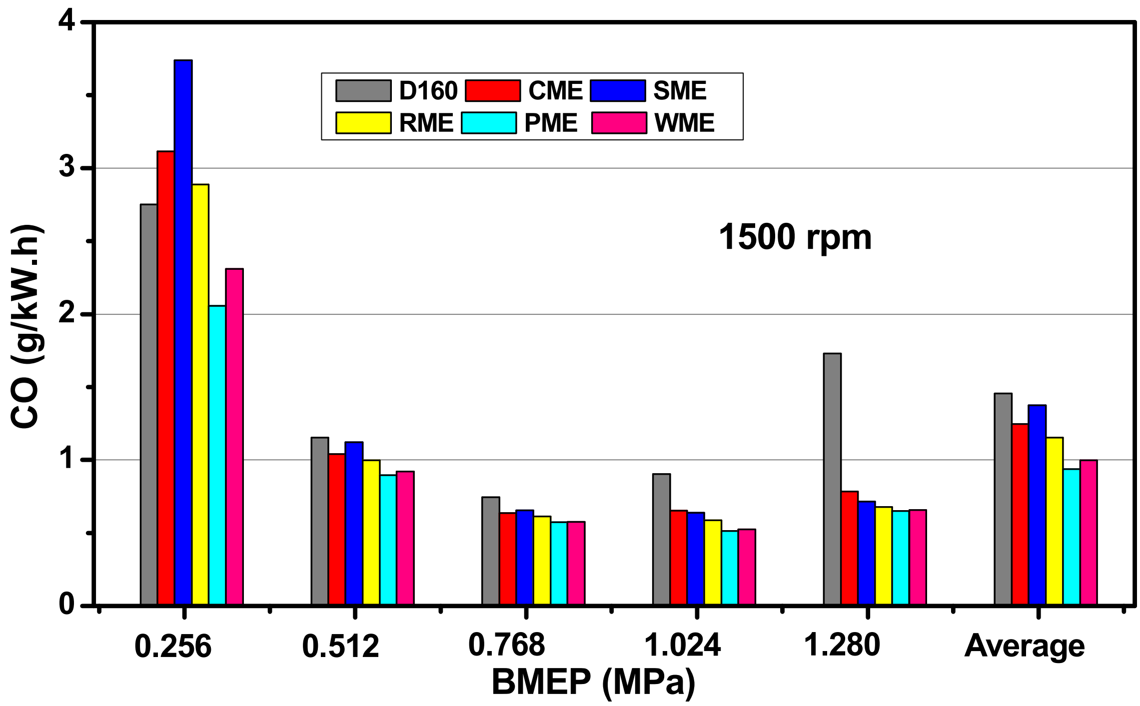

Figure 8 CO Emission with Different Fuels (n=1500rpm)

heat radiators, and when they are mostly oxidized by oxygen, temperature inside the cylinder may increase and resuilt in higher NOx [1]. However, comparison between PME and WME revealed that, although they have almost same oxygen content, the former produced less NOx than the latter. The most likely reason is the high cetane number of PME (64). Higher cetane number could reduce ignition delay and fuel consumed in the premixed phase, and therefore reduce temperature inside the cylinder.

HC EMISSION

HC emission of the engine using different biodiesels is shown in Figure 7. It can be seen that using biodiesels reduced considerable HC emissions, especially at high load. Compared with D160, different biodiesels reduce average HC emission by 45% to 67%. The biodiesels that reduced the most PM in descending order are: PME, WME, RME, CME, SME. Considering that HC is mainly caused by misfire in local rich region or local lean region, the difference in HC emission with different biodiesels is likely to be a combined effect of oxygen content and cetane number. It can be seen from Figure 7 that as cetane number increases, HC emissions decrease consistently for biodiesels, but because of oxygen content they are still lower than that with D160.

CO EMISSION

CO emission of the engine using different biodiesels is shown in Figure 8. Compared with D160, biodiesels reduce average CO emission by 4% to 16%. Fuel effects on CO emission is very similar to that on HC. A obvious effect of cetane number and oxygen content could observed. At high load, oxygen content may be helpful in reducing CO. But at low load effect of oxygen content becomes weak and cetane number is likely to be the only factor for CO emissions: as cetane number increase, CO decrease consistently for both biodiesels and diesel fuel.

EFFECTS OF OXYGENATED BLENDED FUELS

To further investigate the effect of high oxygen content, PME and WME were selected as base biodiesels and blended with three oxygenated additives: ethanol, DMC, and DMM. Fuel consumption, emission were tested at a high load condition: n=1500rpm, BMEP=1.28MPa.

FUEL CONSUMPTION

Figure 9 presents the engine BSFC fueled with different blended fuels as a function of oxygen content. It can be seen that BSFC generally increases as more additives are blended. This is because the lower heat value of oxygen additives.

Figure 10 presents the engine BTE as a function of fuel oxygen content. BTE was calculated according to the equation (1). It can be seen that, although the BTE with biodiesels are lower than with diesel to a certain extent, blending oxygenated additives into biodiesels seems to increase BTE and draw it back to the level of diesel. For PME-Ethanol blended fuel, BTE increases consistently as more ethanol is blended. For WME-DMC blended fuels, BTE did not increase for 10% blend, however, for WDMC20 the BTE increased greatly. For WME-DMM blended fuel, blending DMM showed a consistently but slightly improvement to BTE. Oxygenated additives' improvement to BTE may be attributed to two reasons First, adding oxygenated additives in biodiesels may change combustion phase towards improving the CVR. Second, all the three additives have low viscosity. When they are blended into biodiesel, the viscosity of blended fuels are lowered, and the effect of fuel spray may be improved.

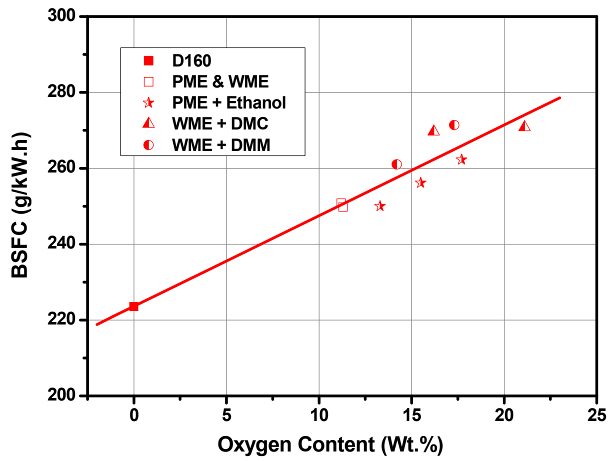

Figure 9 BSFC as A Function of Oxygen Content (n=1500rpm, BMEP=1.28MPa)

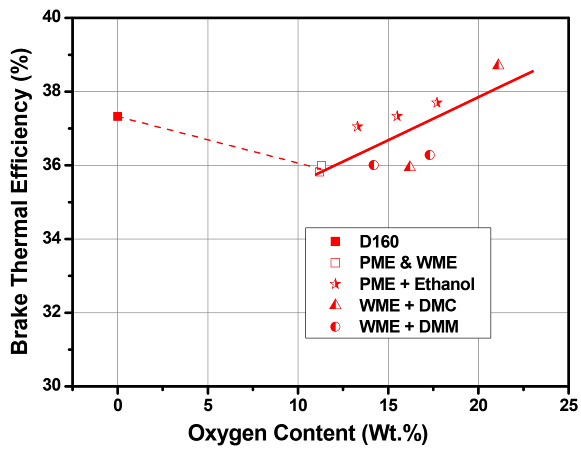

Figure10 BTE as A Function of Oxygen Content (n=1500rpm, BMEP=1.28MPa)

PM EMISSION

Figure 11 presents the PM, DS and NSF emission with all blended fuels and Figure 12 shows the percent value of PM and DS compared with D160 as a function of oxygen content. PM dereases as more oxygen is added for all blended fuels but WDMM10. For the PME-Ethanol blends, from PE10 to PE30, the PM reduction compared with D160 increases from 80% to 90%; for the WME-DMC blends, from WDMC10 to WDMC20, PM reduction compared with D160 increases from 81% to 88%; for the WME-DMM blends, the effect is mixed. The WDMM10 showed surprisingly increase in PM compared with WME. But blending 20% DMM increase PM reduction from 81% to 87%. It can be seen that biodiesel-ethanol blends and biodiesel-DMC blends showed better effect in reducing PM than biodiesel-DMM blends.

From Figure 11 and 12, it can be seen that as the oxygen content increases, DS emission with blended fuels drops greatly on the basis of neat biodiesel and presents a higher reduction rate than the total PM. When the oxygen content in fuel was up to 15% to 20%, nearly no DS was found.

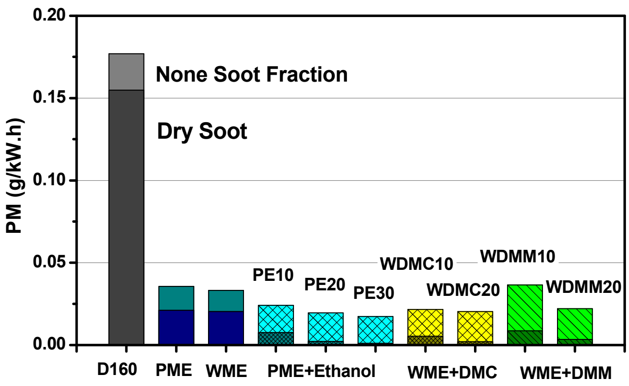

Figure 11 PM, DS and NSF Emission with Blended Fuels (n=1500rpm, BMEP=1.28MPa)

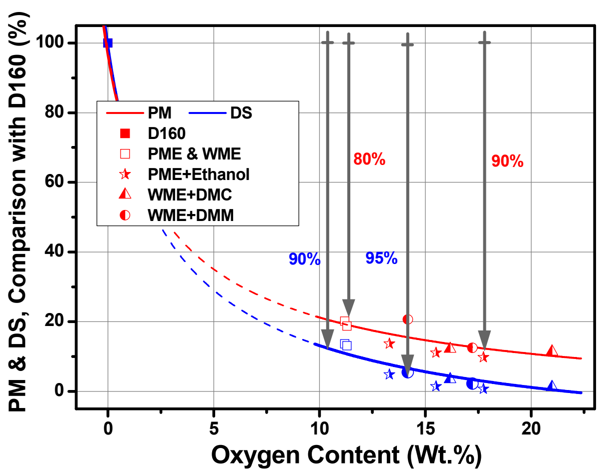

Figure 12 PM, DS Compared with D160 as A Function of Oxygen Content(n=1500rpm, BMEP=1.28MPa)

Figure 11 also represents the NSF emission with all blended fuels. It can be seen that blending three kinds of oxygenated additives in biodiesel all produce higher NSF emissions compared with neat biodiesel. While DS can be reduced largely, high oxygen content can not reduce NSF emissions. PME-Ethanol blends increase NSF by 20% to 28% relative to neat PME. The lower cetane number (6) of ethanol may be the cause for the increase in NSF with PME-ethanol blends. Considering that DMC and DMM have relatively higher cetane number (30 and 36) than ethanol, their blends with biodiesel are expected to prevent the increase in NSF or reduce NSF. But unfortunately test results are opposite: WME-DMC and WME-DMM blends both produced higher NSF and even higher than PME-ethanol blend. The increase in NSF for WME-DMC are 20% to 35% and the increase in NSF for WME-DMM are 38% to 106%. The cause of this phenomenon is unknown. However, there were studies [15] reported that some unburned HC have high volatility and are easily been absorbed by filters and form organic fraction in PM. Therefore component analysis of NSF is necessary.

<u>NOx EMISSION</u>

NOx emission with all blended fuels are shown in Figure 13 as a function of oxygen content. It can be seen that NOx generally increases as the more oxygen content is in the fuel, but the increase rate depends on fuels. For WME-DMC and WME-DMM blends, NOx emission increases quickly as more additives are blended; however, for PME-ethanol blends the NOx increases slightly and for PE10 NOx are even lower than PME. The cause for low NOx emission with biodiesel-ethanol may be attributed to the relatively higher latent heat of vaporization of ethanol. Since the ethanol absorbs more heat, the temperature inside cylinder drops down.

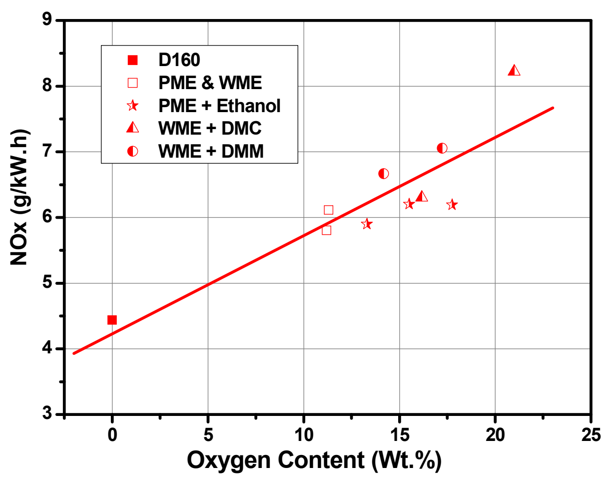

Figure 13 NOx Emission as A Function of Oxygen Content (n=1500rpm, BMEP=1.28MPa)

CONCLUSIONS

The effects of five biodiesels with different sources on emissions from a diesel engine were investigated. And the effect of biodiesel blending with three oxygenated additives on emissions were also investigated. The following conclusions can be drawn:

(1) Using biodiesels reduced engine power by 9% to 12% and increased BSFC by 13% to 15% relative to diesel fuel. The average BTE also droped about 2% for biodiesels without any modifications on engines.

(2) Biodiesels do reduce PM emissions, but the reduction extent depends on fuels. Different biodiesels reduce average PM emission by 53% to 69% relative to diesel fuel. The biodiesels that reduced the most PM in descending order are: WME, PME, CME, RME, SME. Using biodiesels also largely reduce DS emission and the reduction extent is greater than that of PM. Higher viscosity may resuilt in more DS emissions. Results showed that at high load the effect of oxygen content is likely to be greater than viscosity; while at low load the effect of viscosity becomes more obvious. NSF in PM emissions also vary between different biodiesels. NSF decreases consistently with the increase of cetane number, with only one exception which is PME.

(3) Blending biodiesels with oxygenated additives, PM and DS continue to decrease. The reduction rate in DS is greater than that in PM. When the oxygen content in fuel went up to 15% to 20%, nearly no DS was found. NSF increases as more additives are blended for all the three kinds of blends. Higher cetane number of additives did not show effect in preventing NSF increase.

(4) Different biodiesels increase average NOx emission by 10% to 23%. The biodiesels that resulted in the least NOx in descending order are: CME, PME, SME, WME, RME. Results showed that for biodiesels that have same oxygen content, higher cetane number may result in lower NOx. For blended fuels, NOx generally increases as more oxygen is in the fuel. However, biodiesel-ethanol blends showed lower NOx than the other two blends.

(5) All biodiesels produce less HC and CO than diesel fuel. The difference in HC and CO is likely to be the combined effect of oxygen content and cetane number. Fuel effects on CO emission is very similar to that on HC.

ACKNOWLEDGEMENTS

This research is part of Tsinghua-Cummins Cooperation Project. The authors would like to thank Cummins Company for its technical support and great contribution to the program.

REFERENCES

[1] MS.Graboski, RL. McCormick. “Combustion of fat and vegetable oil derived fuels in diesel engines[J].” Progress in Energy and Combustion Science, 1998, 24(2):125-164.

[2] AK. Babu, G. Devaradjane. “Vegetable Oils And Their Derivatives As Fuels For CI Engines: An Overview.” SAE 2003-01-0767.

[3] U.S. EPA. “A Comprehensive Analysis of Biodiesel Impacts on Exhaust Emissions.” EPA-Draft Technical Report, EPA420-P-02-001, October 2002.

[4] CD Rakopoulos, KA Antonopoulos, DC Rakopoulos, etc. ”Comparative performance and emissions study of a direct injection Diesel engine using blends of Diesel fuel with vegetable oils or bio-diesels of various origins.” Energy Convers Manage, Vol. 47, pp. 3272-3287, 2006.

[5] Christopher A. Sharp, Steve A. Howell, Joe Jobe. “The Effect of Biodiesel Fuels on Transient Emissions from Modern Diesel Engines, Part I Regulated Emissions and Performance.” SAE 2000-01-1967.

[6] A. Tsolakis, A. Megaritis, ML. Wyszynski, K. Theinnoi. “Engine performance and emissions of a diesel engine operating on diesel-RME (rapeseed methyl ester) blends with EGR (exhaust gas recirculation).” Energy 32 (2007) 2072-2080.

[7] Erik Verhaeven, Luc Pelkmans, Leen Govaerts, Rudolf Lamers, Frans Theunissen. “Results of demonstration and evaluation projects of biodiesel from rapeseed and used frying oil on light and heavy duty vehicles.” SAE 2005-01-2201.

[8] Robert L. McCormick, Michaes S.Graboski. “Impact of Biodiesel Source Material and Chemical Structure on Emission of Criteria Pollutants from a Heavy-Duty Engine.” Environmental Science and Technology 2001,35:1472-7.

[9] Andre L. Boehman, David Morris, James Szybist. “The Impact of the Bulk Modulus of Diesel Fuels on Fuel Injection Timing.” Energy & Fuels 2004, 18, 1877-1882.

[10] James P. Szybist, Andre L. Boehman. “Behavior of a Diesel Injection System with Biodiesel Fuel.” SAE 2003-01-1039.

[11] Chen Hu, Wang Jian-Xin, Shuai Shi-Jin, An Xin-Liang, Chen Wen-Miao. “Effects of Ethanol in Ester-Ethanol-Diesel Blended Fuels on Spray Behavior and PM Emission.” SAE 2006-01-0236.

[12] M. A. Ahmed, C. E. Ejim, B. A. Fleck, A. Amirfazli. “Effect of Biodiesel Fuel Properties and Its Blends on Atomization.” SAE 2006-01-0893.

[13] A. S. Cheng, Bruce A. Buchholz, Robert W. Dibble. “Isotopic Tracing of Fuel Carbon in the Emissions of a Compression-Ignition Engine Fueled with Biodiesel Blends.” SAE 2003-01-2282.

[14] Michel Souligny, Lisa Graham, Greg Rideout, Pierre Hosatte. “Heavy-Duty Diesel Engine Performance and Comparative Emission Measurements for Different Biodiesel Blends Used in the Montreal Biobus Project.” SAE 2004-01-1861.

[15] David Y. Chang. “Determination of Particulate and Unburned Hydrocarbon Emissions from Diesel Engines Fueled with Biodiesel.” SAE 982527.

[16] Szybist JP, Kirby SR, Boehman AL. ”NOx emissions of alternative diesel fuels: a comparative analysis of biodiesel and FT diesel.” Energy Fuels 2005,19:1484–92.

DEFINITIONS, ACRONYMS, ABBREVIATIONS

CME: Cottonseed Methyl Ester

SME: Soybean Methyl Ester

RME: Rapeseed Methyl Ester

PME: Palm Oil Methyl Ester

WME: Waster Cooking Oil Methyl Ester

DMC: Methyl Carbonate

DMM: Dimethoxy Methane

PM: Particulate matter

DS: Dry soot

NSF: None Soot Fraction

SOF: Soluble organic fraction

HC: Hydrocarbons

NOx: Nitrogen oxides

BSFC: Brake specific fuel consumption

BTE: Brake Thermal Efficiency

CVR: Constant Volume Ratio

BMEP: Brake mean effective pressure

CONTACT

For further information regarding this paper please contact: wufj02@mails.thu.edu.cn