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Oxygenated blend design and its effects on reducing diesel particulate emissions

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ABSTRACT

In order to meet Euro IV emission standards, diesel vehicles are compelled to install exhaust aftertreatment devices, which largely increases the overall cost. This paper explores the possibility to significantly reduce the particulate matter (PM) emissions by new fuel design. Several oxygenated blends were obtained by mixing the biodiesel, ethanol, dimethyl carbonate (DMC), and diesel fuels. The tests were conducted on two heavy-duty diesel engines, both with a high-pressure injection system and a turbocharger. The total PM and its dry soot (DS) and soluble organic fraction (SOF) constituents were analyzed corresponding to their specific fuel physiochemical properties. A blended fuel that contains biodiesel, DMC, and high cetane number diesel fuels was chosen eventually to enable the diesel engines to meet the Euro IV emission regulation. Based on the test results, the basic design principles were derived for the oxygenated blends that not only need the high oxygen content, but also the high cetane number and the low sulfur and low aromatic contents.

1. Introduction

Diesel engines though enjoying higher fuel economy than gasoline engines suffer from inherent higher PM and nitride oxide (NO_x) emissions. Currently there are many techniques that are capable of improving the combustion processes of diesel engines, such as the fuel injection retarding, exhaust gas recirculation (EGR), high-pressure injection, and air intake supercharging. However, due to the trade-off between the PM and NO_x emissions, it is very difficult to have simultaneous reductions of both. In order to meet Euro IV, or the Chinese 4th Stage Emission Standards, and the future regulations, diesel vehicles usually employ two types of technical strategies: (1) Reduce NO_x by EGR and PM by diesel particulate filter (DPF) and (2) Control PM by high-pressure injection and reduce NO_x by selective catalytic reduction (SCR). That is to say, the meeting of the 4th Stage or higher regulations requires exhaust aftertreatment devices to be installed. Because the cost of diesel aftertreatment devices are much higher than the three-way catalyst used on gasoline vehicles, the competitiveness and applicability of future diesel vehicles have been largely hindered.

The reduction of diesel engine emissions could be considered from three aspects: the combustion improvement technique, the exhaust aftertreatment technology, and the fuel melioration. However, the relevant research on fuels especially on liquid fuels was still less investigated until very recently. The research on dimethyl ether (DME) as an alternative fuel produced great enlightenment [1]. DME contains oxygen element and has no C–C bonds, which therefore helps to achieve smokeless combustion that is superior than with a diesel fuel even without high-pressure injection or turbocharger, however, the use of DME requires significant modifications on the fuel supply, delivery, and injection systems, which largely limits its application. The blending of oxygenates into a diesel fuel could effectively reduce the smoke emission from diesel engines, which has a strong synergy to the use of methanol, ethanol, or dimethyl carbonate (DMC). Nabi and Miyomoto et al. [2] had studied a set of oxygenated fuels, which include DMC, diethylene glycol dimethyl ether (DGM), and diethyl succinate (DES). The results indicated that the smoke emission decreased linearly as the oxygen content increased and notably near zero smoke emission was attained when the oxygen content was higher than 30%. The authors of this paper had utilized the highly soluble characteristics of biodiesel to blend a high proportion of ethanol with the diesel fuel, which produced a significant reduction in smoke emission. However, the PM was not found reducing by the same extent, because the worsened ignitability of ethanol had led to a large increase in the soluble organic fraction (SOF) of PM [3,4]. Biodiesel is also an oxygenated fuel and contains no aromatics. Many literatures reported that biodiesel could significantly reduce the smoke and PM emissions with slightly increase in NO_x [5–9]. From these studies, we considered it promising to significantly reduce the PM emission from diesel engines and thus to meet more stringent emission standards via fuel formulization design, at the current engine technology level and without using an exhaust aftertreatment device.

In order to explore the feasibility of drastically reducing the particulate matter (PM) via fuel re-formulization, this paper proposes the design principles for the oxygenated blends, i.e., the

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requirement for high oxygen content and high cetane number. Various oxygenated blends containing biodiesel, ethanol, DMC, and diesel fuel were tested for comparisons on the heavy-duty diesel engines with the high-pressure injection and turbo-charging technologies. The total PM and its dry soot (DS) and soluble organic fraction (SOF) fractions were analyzed accordingly. The fuel blend that contains biodiesel, DMC, and high cetane number diesel was chosen to pass the engine tests in European Steady Cycle (ESC), the European Transient Cycle (ETC), and the Chinese 4th Stage Regulations.

2. Design principles and plan

2.1. Basic ideas

PM is composed mainly of three components: DS, SOF, and sulfate [10]. Previous studies showed that $1 \sim 3\%$ of the fuel borne sulfur would be converted into the sulfate constituent of PM [11,12]. Thus, the sulfate emission should decrease correspondingly with the reduction in the fuel borne sulfur, which became a lesser concern as the progress proceeded towards low sulfur and zero sulfur fuels. Therefore, the DS and SOF constituents must be reduced substantially in order to reduce the total PM. However, the formation of DS and SOF has an inherent relationship with the fuel physiochemical properties including the auto-ignitability of the fuel.

The local oxygen deficiency caused by diffusion combustion attributes to the formation of DS or soot in a diesel engine, which could be effectively alleviated by the fuel borne oxygen [5,13]. However, excessive oxygen content would decrease the fuel energy density. Additionally, the soot formation theory suggests that the aromatics especially the polycyclic aromatic content of the fuel is a precursor of soot formation [14,15]. Therefore, reduction in the aromatic content will produce lower DS emissions.

The SOF mainly comes from the unburned heavy hydrocarbon (HC) species absorbed on the DS [3,10]. The excessive rich or lean mixtures caused by the non homogeneity of mixing, in addition to the low combustion temperature adjacent to the cylinder wall at low loads, are the main causes of unburned HC. Thus, fuel auto-ignitability and flammability improvements will reduce HC emissions. Unfortunately most fuel oxygenates, excluding biodiesel, have a low cetane number and hence emit higher SOF. Therefore, it should be noted that the auto-ignition ability, i.e. the cetane number, of the oxygenated fuels must be retained.

The viscosity and surface tension of the fuel will affect the fuel spray characteristics [5,16] and thus affect the soot, NO_x, HC, and carbon monoxide (CO) emission characteristics. Therefore, the atomization and evaporation characteristics of the fuel should be kept equal to or higher than a conventional diesel fuel. Additionally, attention should also be made to the fuel applicability that includes the fuel solubility, boiling range, and causticity.

In summary, in order to reduce the PM emissions, the intended fuel should have a high oxygen content, high cetane number, low sulfur content, and low aromatic content. Additionally, appropriate levels of viscosity and surface tension are also necessary.

2.2. Components of the blended fuel

When designing the oxygenated blends, in addition to the above basic principles the availability of the energy resources should also be considered. Biodiesel as a promising energy source has been currently applied in many countries worldwide. Biodiesel should be considered because it contains about 10% of oxygen and holds a cetane number slightly higher than a conventional diesel does. However, biodiesel viscosity is higher than the convention of a diesel fuel, which will deteriorate the spray characteristics.

Among alcohol fuels, ethanol has good solubility, biodegradability, causticity and emissions performance [17], and is therefore more appropriate than methanol for a diesel engine. A merit of ethanol is that the oxygen content is as high as 34.8%, but its disadvantageous cetane number is as low as merely eight and its viscosity as low as less than 1/3 of a diesel fuel. Additionally, the boiling point of ethanol is relatively low, and therefore its transportation and storage safety control should be treated the same as gasoline.

Dimethyl carbonate (DMC) and dimethoxy methane (DMM) also have high oxygen content and have been considered as diesel fuels [18–20]. DMC and DMM contain 53.3% and 42.1% of oxygen by mass respectively; and both of which are higher than the ethanol oxygen content. Their cetane numbers are 36 and 30, respectively, higher than ethanol's cetane number too. Therefore, according to the above basic principles – a high oxygen content and a high cetane number – these two oxygenates are both better than ethanol especially ideal for DMC. The boiling point of DMC is 91 °C which is higher than ethanol's 78 °C and DMM's 43 °C. The viscosity values of DMC, DMM, and ethanol are all very low, which could be used to offset the high viscosity of the biodiesel constituent in the blended fuel.

According to the supply availability, diesel fuel should still be the main constituent. Nevertheless, according to the design requirements the fuel blend should have a high cetane number, low sulfur content, and low aromatic content.

In summary, the ideal combination is "diesel + biodiesel + DMC". However, when considering the resource availability issue, the "diesel + biodiesel + ethanol" combination could also be considered.

3. Test fuel and test method

3.1. Test fuel

The fuels used in this study include a baseline diesel fuel, three types of biodiesels, and their blends with ethanol, DMC, DMM, and straight-run (or directly distilled) diesel fuel, whose main physiochemical properties are shown in Table 1. Ethanol, DMC, and DMM are used as oxygenates to raise the oxygen content, while the straight-run diesel fuel is used to improve the auto-ignition capability of the blended fuel. In this paper, the baseline diesel fuel is denoted as D. The straight-run diesel fuel is denoted as SD. The three biodiesels derived from palm oil, waste cooking oil, and acidified oil, are denoted as PB, WB, and AB, respectively. Ethanol, DMC, and DMM are denoted as E, C, and M, respectively.

A variety of oxygenated blends were formulated, as shown in Table 2, based on the primary fuels listed in Table 1. The blended fuels are such denoted that the notation symbol of each constituent followed by the enumeration of the volumetric percentage of each constituent; and consecutively denoted for all the constituents. For example, D90PB10 represents that the fuel blend comes from 90% baseline diesel fuel and 10% palm oil biodiesel, on volumetric basis. The properties of the blended fuels could be estimated with the following formulas according to the volumetric concentration of each constituent:

(1) Cetane number

$$CN_{\mathrm{H}} = \sum_i CN_{\mathrm{i}} * x_{\mathrm{i}} \quad (1)$$

where CN_{H} is the equivalent cetane number of the blended fuel, while CN_{i} is the measured cetane number of each component.

(2) Oxygen content

Table 1
Measured physiochemical properties of tested fuels.

	Density (kg/m^3)	Oxygen content (wt%)	Carbon content (wt%)	Hydrogen content (wt%)	Cetane number	Low heating Value (kJ/kg)	Sulfur content (ppm)	T90 (°C)	Boiling point (°C)	20 °C Viscosity (mm^2/s)
Test method	GB/T 2540	Element analyser	SH/T 0656	SH/T 0656	GB/T 386	GB/T 384	SH/T 0253	GB/T 6536	GB/T 6536	GB/T 265
D	830	0.00	86.43	13.57	55.6	43,140	160	318.4	–	3.763
PB	878	11.14	76.55	12.40	63.8	40,063	2	334.9	–	7.114
AB	877	10.79	76.38	11.98	51.1	38,674	35	344.2	–	6.631
WB	870	11.16	76.32	12.18	55.6	40,055	7	342.5	–	6.897
Ethanol	794	34.80	52.20	13.00	8.0	27,000	0	–	78	1.06
DMC	1070	53.30	40.00	6.70	36.0	15,780	0	–	91	0.63
DMM	860	42.10	46.20	11.70	30.0	22,400	0	–	43	0.34
SD	810	0.00	84.80	15.20	62.0	43,711	0	–		3.34

Table 2
Caculated physiochemical properties of blend fuels.

	Density (kg/m^3)	Oxygen content (wt%)	Carbon content (wt%)	Hydrogen content (wt%)	Cetane number	Low heating value (kJ/kg)	Sulfur content (ppm)
D90PB10	835	1.17	85.39	13.45	56.5	42,816	143
D80PB20	840	2.33	84.36	13.33	57.3	42,496	127
D50PB50	854	5.73	81.35	12.97	59.8	41,558	79
D20PB80	868	9.01	78.44	12.62	62.2	40,651	32
PB90E10	870	13.30	74.33	12.45	58.7	38,870	2
PB80E20	861	15.50	72.06	12.51	53.5	37,654	2
PB70E30	853	17.75	69.75	12.57	48.2	36,414	1
WB90C10	890	16.23	71.95	11.52	53.2	37,137	6
WB80C20	910	21.07	67.78	10.89	51.0	34,346	5
WB90M10	869	14.20	73.55	11.64	53.1	38,308	6
WB80M20	868	17.27	70.54	11.09	50.5	36,557	6
AB90C10	890	16.58	71.98	11.53	49.2	35,941	31
AB80C20	910	21.35	67.83	10.90	47.5	33,323	27
AB50SD35C15	885	15.46	72.40	12.06	51.8	36,149	17
AB50D35C15	890	15.34	73.07	11.65	49.8	36,002	70
AB10D80C10	859	7.83	79.61	12.57	52.7	39,275	127

$$C_H = \frac{\sum_i \rho_i * x_i * C_i}{\sum_i \rho_i * x_i} \tag{2}$$

where C_H is the oxygen content of the blended fuel, while C_i is the oxygen content of each constituent.

The density of the blended fuel is calculated with a formula similar to Eq. (1). The carbon, hydrogen, and sulfur contents and the lower headings values are calculated with formulas similar to Eq. (2). With the above formulas, the physiochemical properties of all the oxygenated blends could be determined as shown in Table 2.

3.2. Test engines and apparatus

Fig. 1 shows the schematic diagram of the engine bench. The tests were conducted on two platforms of Cummins heavy-duty diesel engines. The engine specification is shown in Table 3. The Cummins ISBe6 engine can meet Euro III emission standard without any after-treatment devices. The Cummins ISB2007 adopts the pilot injection and EGR (with intercooler) technology and can meet the USA EPA 2007 emission standard when equipped with a diesel particulate filter (DPF). However, the DPF device is not used in this study.

The regulated gaseous emissions including NO_x were measured with an AVL CEB-II exhaust gas analyzer. The mass based total PM is obtained from an AVL SPC-472 partial flow dilution smart sampler. Thereafter, the SOF was extracted from the total PM with dichloromethane (CH_2Cl_2) as the extraction solvent. The residuary matter was considered as DS, because the sulfur content of the tested fuels were all very low.

3.3. Test method

The PM emissions were measured on the Cummins ISBe6 engine with each of the fuel blends under various engine loads, i.e., the maximum torque speed of the engine. The European Steady Cycle tests for heavy-duty diesel engines were conducted on the Cummins ISB2007 engine in order to measure the NO_x and PM

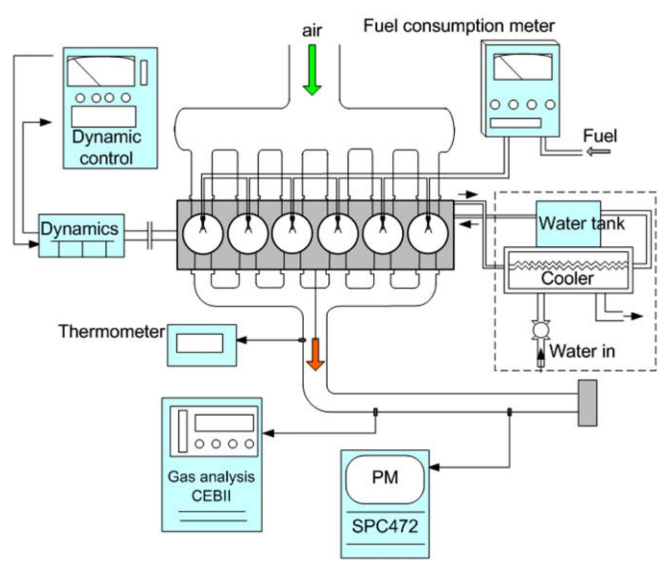

Fig. 1. Test cell schematic.

Table 3
Engine specifications of Cummins ISBe6.

Engine type	Cummins ISBe6, 4-stroke, direct injection, turbo-charging, intercooling, high pressure common rail	Cummins ISB2007, 4-stroke, direct injection, turbo-charging, intercooling, high pressure common rail
EGR	No	External EGR with cooler
Cylinder number	6	6
Displacement	5.9 l	6.7 l
Bore × Stroke	102 mm × 120 mm	106 mm × 124 mm
Compress ratio	17.5	17.5
Bowl geometry type	ω	ω
Number of orifices on each injector	8	8
Injection pressure level	160 MPa	120 MPa
Rated power/speed	136 kW/2500 rpm	192 kW/2600 rpm
Max toque/speed	670 N m/1500 rpm	840 N m/1500 rpm

emissions. The specific mode, sequence and weighting factor of the ESC test are shown in Fig. 2. The test cycle is comprised of the most common 13 modes of European heavy-duty diesel engine driving conditions, which is a comprehensive evaluation method for emissions characteristics. The A, B, and C speeds in ESC test are determined by the following formula:

$$A = n_{lo} + 0.25(n_{hi} - n_{lo}); B = n_{lo} + 0.50(n_{hi} - n_{lo});$$
$$C = n_{lo} + 0.75(n_{hi} - n_{lo}) \quad (3)$$

where n_{hi} is the high speed, determined by the 70% of the rated power speed; n_{lo} is the low speed, determined by the 50% of the rated power speed.

4. Test results

4.1. Total PM and the ratio of SOF

Fig. 3 shows the PM emission from the ISBe6 engine when fueled with the baseline diesel fuel and the waste cooking oil biodiesel. Compared to the diesel fuel, the biodiesel produced various extents of PM reduction, ranging from 37% to 81%, and the higher the load the greater the reduction. The extent of DS reduction being 70–87% is higher than that of PM; and the higher the load the greater the reduction. The SOF produced with the biodiesel is slightly higher than with the baseline diesel fuel while their respective percentages in PM differ significantly. The SOF constituents produced with both fuels are higher at low loads.

Fig. 4 shows the percentage of SOF in PM at different loads. It was obvious that the use of biodiesel produced a SOF percentage

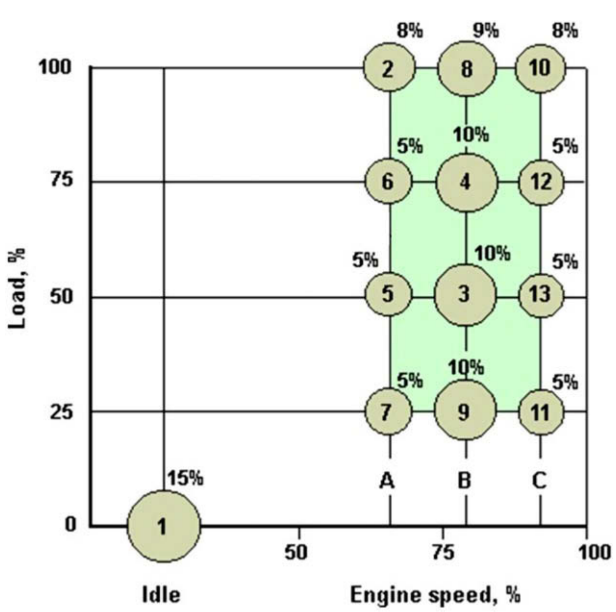

Fig. 2. Modes, sequence and weight factor of ESC cycle test (from www.dieselnet.com).

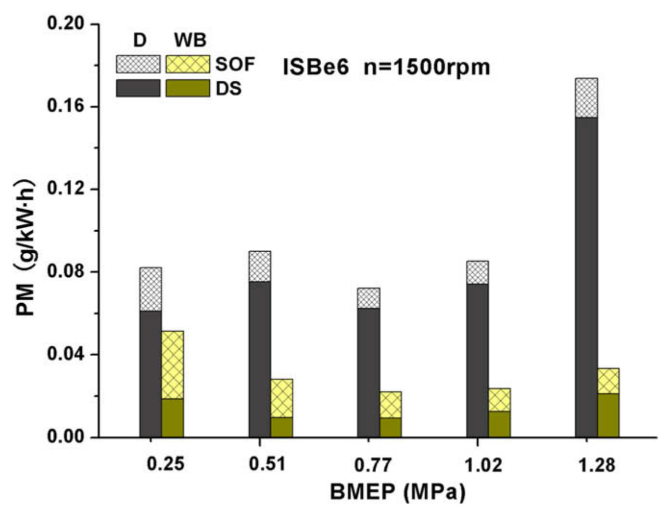

Fig. 3. Test results with diesel and biodiesel at different loads on ISBe6 engine.

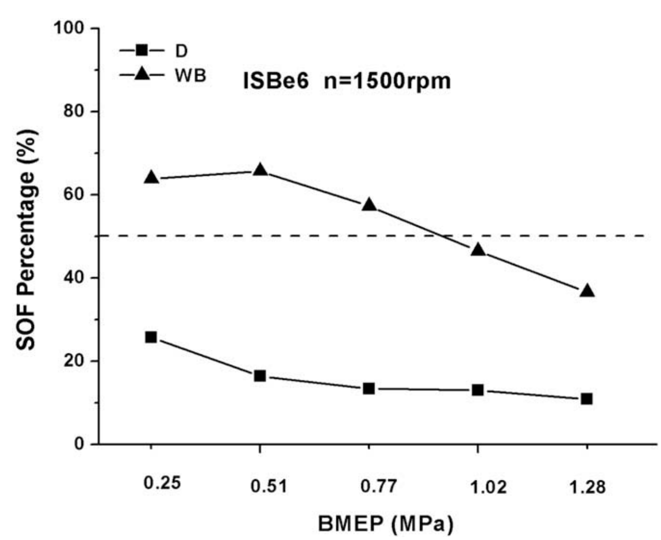

Fig. 4. SOF percentage in PM with diesel and biodiesel.

higher than 40% and mostly higher than 50% across the different loads, which was higher than the sub-30% of SOF produced with the baseline diesel. This indicated that SOF was a major constituent of PM for biodiesel.

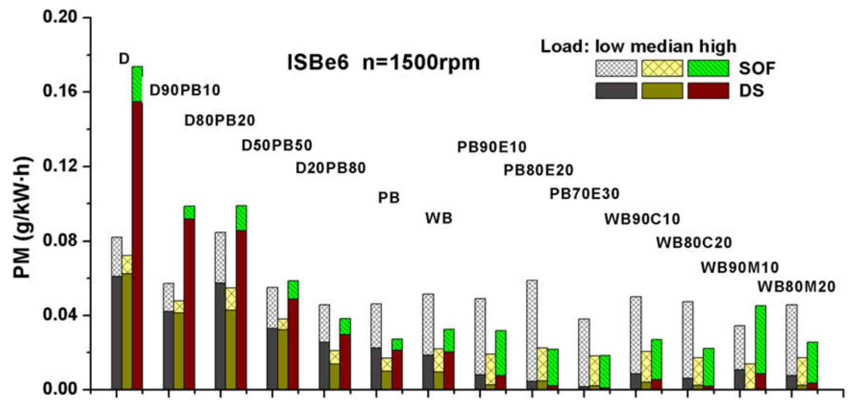

Fig. 5. Test results at $n = 1500$ rpm with all fuels on ISBe6 engine.

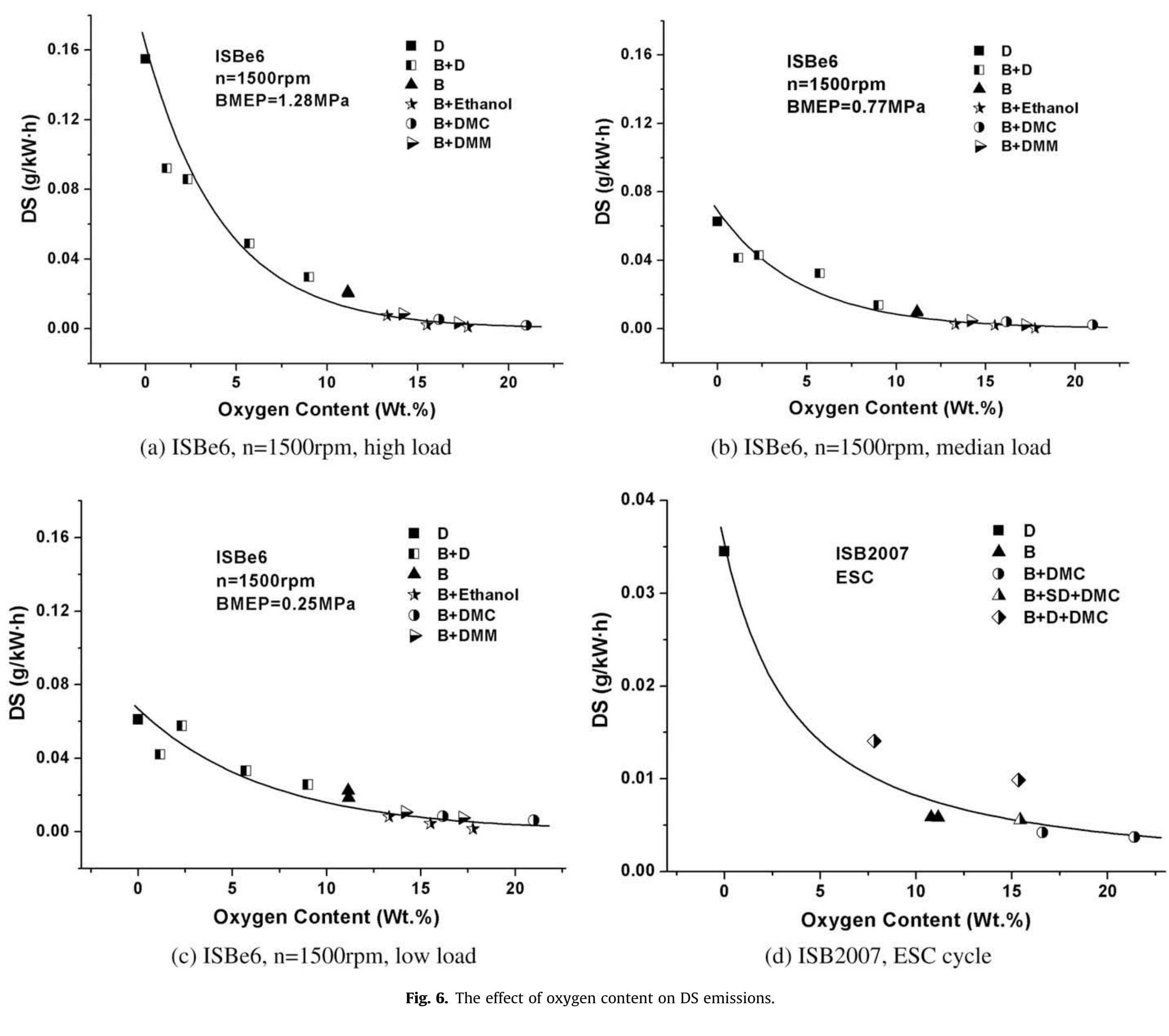

Fig. 6. The effect of oxygen content on DS emissions.

At the peak torque speed of 1500 rpm on the Cummins ISBe6 engine, three BMEP levels – 1.28 MPa, 0.77 MPa, and 0.25 Mpa – were selected to represent the high, median, and low load levels respectively, which correspond to 600 N·m, 361 N·m and 118 N·m in engine torque (the peak torque of the ISBe6 engine with diesel fuel is about 670 N·m). The PM, DS, and SOF emissions of the oxygenated blends as specified in Tables 1 and 2 were measured and demonstrated in Fig. 5. Overall, the adding of ethanol, DMC, and DMM into the biodiesel could reduce the DS emission drastically, exceeding 95%. However, the SOF constituent increased by different extents, which is more obvious at low loads. This led the total PM from the highly oxygenated blends to remain nearly the same, or even to increase slightly compared with the use of a neat biodiesel.

The above results indicate that the SOF may dominate the PM when fueling with the oxygenated blends. Therefore, in order to reduce the total PM, the DS and SOF constituents should be reduced simultaneously. In the following, the effects of the oxygen content and the cetane number on the productions of DS and SOF will be discussed, respectively.

4.2. Effect of oxygen content

Fig. 6 shows the relationship of the DS emissions versus the oxygen content of the oxygenated blends. The tests were conducted on the ISBe6 engine at the specified low, median, and high loads and on the ISB2007 engine following the ESC cycle. From Fig. 6a–c, it is apparent that the DS emissions decrease with the increase in oxygen content and the DS decreases faster at high load than at low load. The above observation is attributed to that the higher DS emission produced by the richer mixture at high load is more sensitive to the oxygen content of the fuel blend. Additionally, the rate of DS reduction increases slower as the oxygen content further increases. When the oxygen content reaches 15% or higher, the reduction rate of DS on the ISBe6 engine apparently approaches 95%, 93%, and 83% at the high, median, and low loads respectively. When the oxygen content is 15%, the reduction of DS emission with the ESC cycle on the ISB2007 engine approximates 80%, i.e., the DS emission at about 0.005 g/kW h or 1/4 of the Euro IV limit of 0.02 g/kW h. When the oxygen content is high, the percentage of DS in the PM is very low and thus an additional increase in the oxygen content of the fuel blend would not benefit

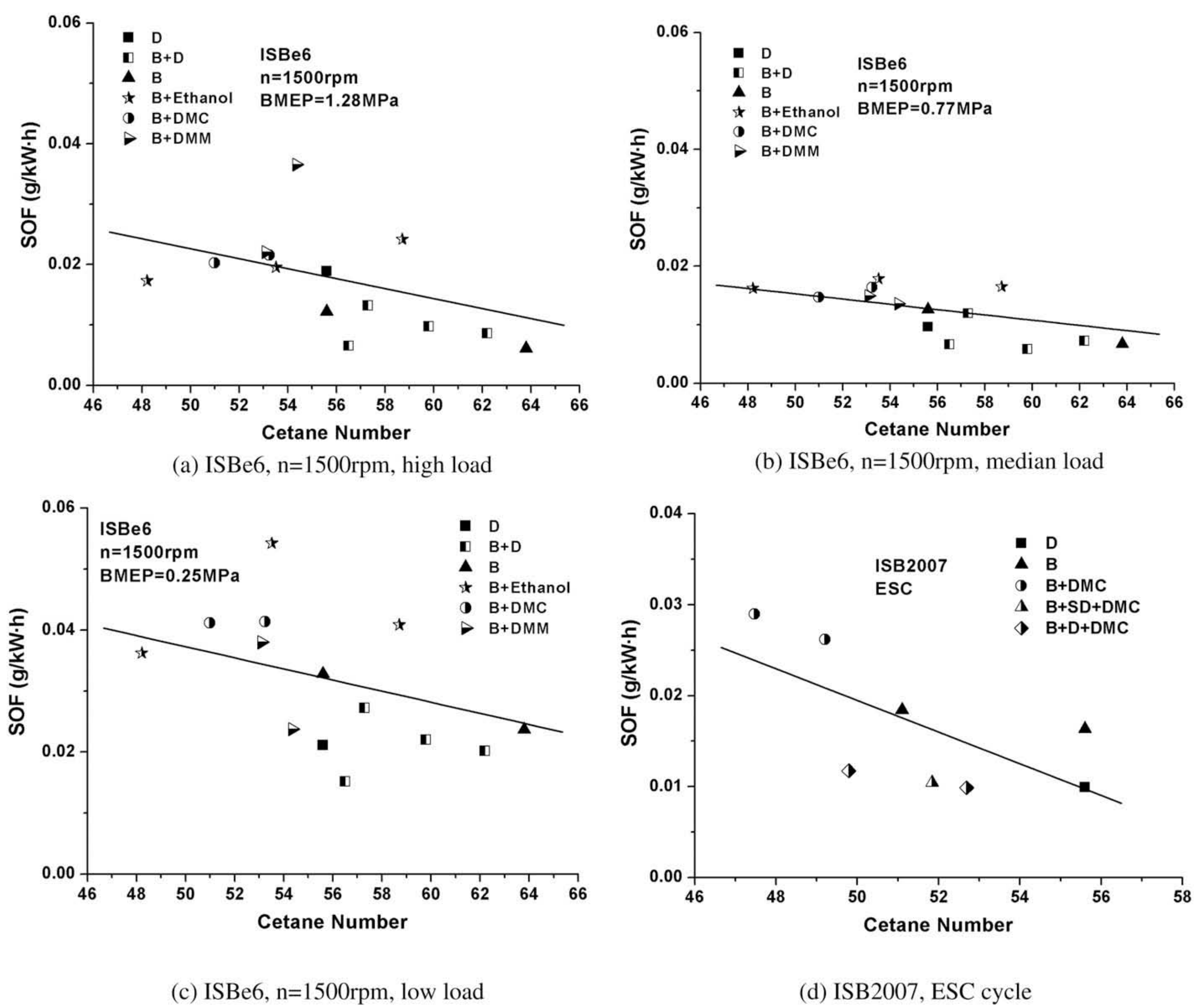

Fig. 7. The effect of cetane number on SOF emissions.

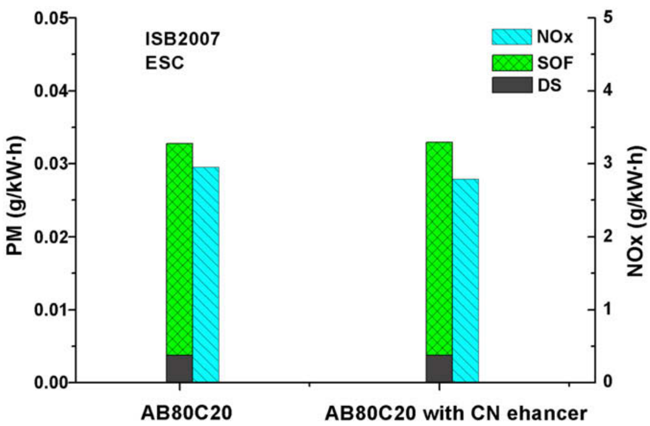

Fig. 8. The effect of cetane number enhancer on SOF emissions on the ISB2007 engine.

the DS emissions significantly as shown in Fig. 6d, and would, however, result in excessive power loss.

Furthermore, Fig. 6d indicates that the DS emissions produced from the ESC test on the ISB2007 engine are higher with the B + D + DMC blend than with the B + SD + DMC blend. The test results suggest that, converse to the straight-run diesel fuel, the presence of aromatics in a conventional diesel fuel will accelerate the soot formation process. Therefore, the aromatic content should be kept low in formulating an oxygenated fuel.

4.3. Effect of cetane number

Fig. 7 shows the effect of cetane number variation on the SOF emissions when using the same set of oxygenated blends and under the same testing conditions as discussed in Fig. 6. It is apparent from Fig. 7 that the SOF emission has a reducing trend with the increase in cetane number, although with relatively high data scattering. Based on the testing results from the ISBe6 engine, as shown in Fig. 7a–c, the regression line is steeper at the high and low loads than at the median load, because the SOF emission level is lower at the median load. This effect can also be observed from the results on the ISB2007 engine, i.e., an increase in cetane number by five units decrease the SOF emission by 0.01 g/kW h.

It was also apparent from the ISBe6 engine tests, as shown in Fig. 7a–c, that the biodiesel–diesel fuel blends produced the lowest SOF emissions, the DMC blends produced the medium SOF emissions, and the DMM or ethanol blends produced the highest. This indicates that the low cetane oxygenates will raise the SOF emissions. In addition, the ESC tests on the ISB2007 engine produced similar trends, i.e., the blended fuel, especially when blended with the high cetane straight-run diesel, reduced the SOF emissions.

In order to investigate the effect of cetane number enhancer on SOF reductions, 0.3% (volume content) of peroxide cetane number enhancer was added in the AB80C20 fuel that originally had a cetane number of 47.5, referring Table 2. The 0.3% enhancer constituent is sufficient to raise the cetane number by 5–10 units. However, the ESC tests indicated that the cetane enhancer did not cause a reduction in SOF, as shown in Fig. 8, which was con-

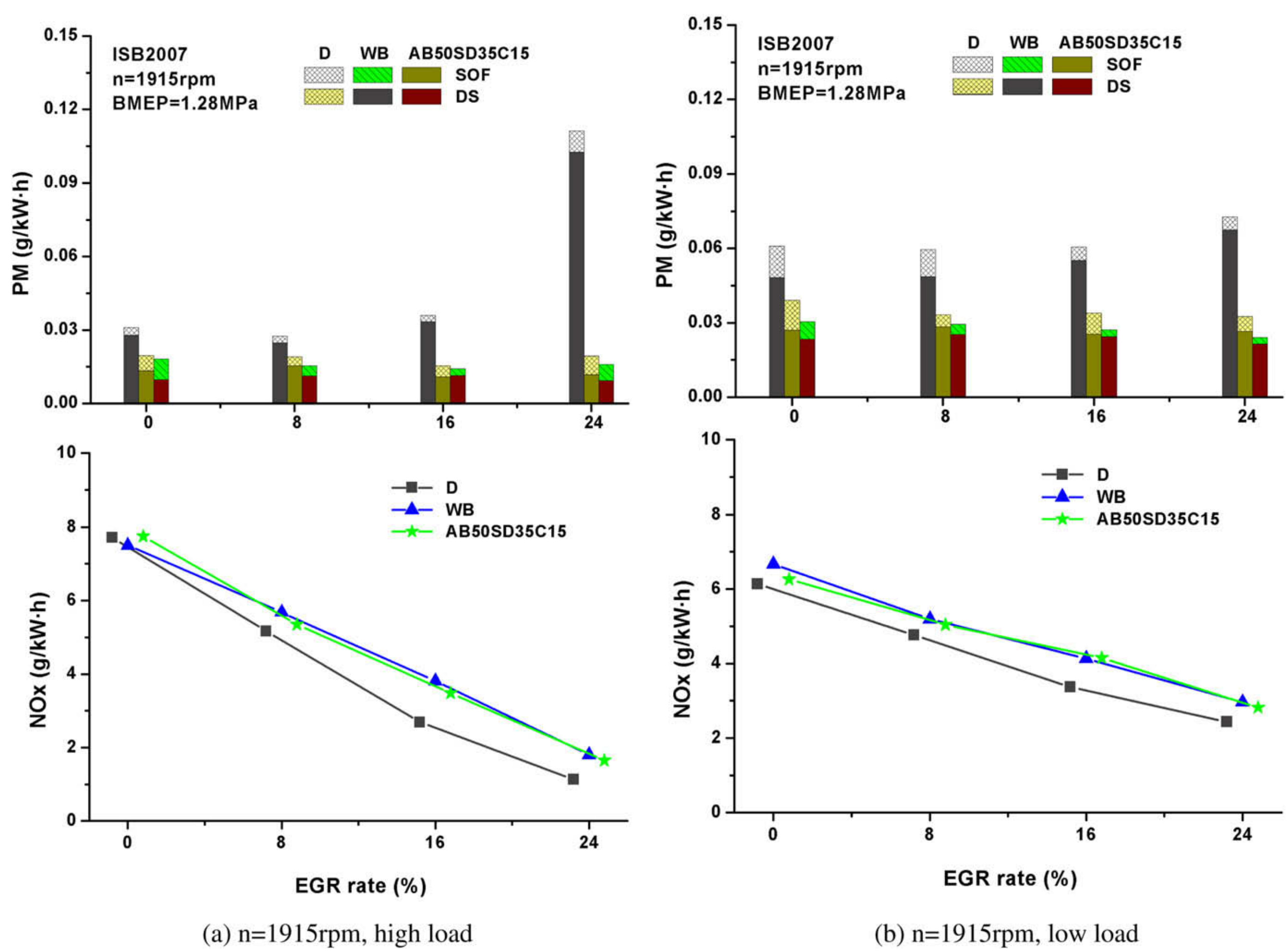

Fig. 9. Effect of EGR rate on PM emissions on ISB2007 engine.

tradicting to the cetane to SOF reduction mechanism observed in Fig. 7d. However, after the cetane number enhancer was added, the DS emission increased by about 1% and NO_x decreased by about 6%, which results were possibly attributed to the shortening of ignition delay. Therefore, although the cetane number enhancer could advance the combustion phase by making part of the fuel ignite earlier, the overall auto-ignition capability and the combustion readiness of the blended fuel had not been improved. Therefore, the SOF emission could not be reduced by using a cetane number enhancer.

4.4. Effect of EGR rate

Since oxygenated blends could greatly reduce PM emissions, it is possible to reduce PM and NO_x emissions simultaneously by the combined uses of oxygenated blends and the EGR technology. This paper investigates the effect of EGR rate on PM and NO_x emissions with the diesel, WB, and B50SD35C15 fuels on the ISB2007 engine. The testing results are shown in Fig. 9. For the diesel fuel, at high load the PM increased as the EGR rate increased and the rate of PM increase grew faster at high EGR rates; at low load the PM did not change significantly when the EGR rate varied from zero to 16%. However, the PM did start to increase when EGR rate was increased to 24%. For the biodiesel WB and the oxygenated blend B50SD35C15, the PM almost remained the same or even decreased slightly as the EGR rate increased. On the other hand, with the increase in EGR the NO_x emission of all the tested fuels decreased significantly, although the NO_x of the B50SD35C15 was 10–30% higher than the diesel fuel at fixed EGR rates.

Therefore, the high cetane and oxygenated blends have good pro-EGR characteristics. Such fuel blends therefore did not exhibit the trade-off relationship between PM and NO_x conventional to using a diesel fuel.

5. Verification of final plan and discussion

5.1. Final plan and its verification

According to the above testing results, the final design plan of the oxygenated blends is such determined: 50% biodiesel, 35% straight-run diesel fuel, and 15% DMC, which is named the AB50SD35C15 plan. As shown in Table 2, the oxygen content of this fuel blend is 15.46%, the equivalent cetane number is 51.8, the sulfur content is 17 ppm, and the aromatic content is approximately zero. This study commissioned a national certified automotive emission testing facility to perform the ESC and ETC tests on the Cummins ISB2007 engine with the AB50SD35C15 fuel. The test results are shown in Table 4. The PM and NO_x results of ESC tests are 75% and 85% of the Euro IV limits, while the PM and NO_x of ETC tests are 77% and 90% of the Euro IV limits, respectively. The results showed that by fueling the AB50SD35C15 fuel this engine could meet the Euro IV standards in ESC and ETC tests without resorting to an aftertreatment device.

Table 4
ESC and ETC test results with AB50SD35C15 fuel on ISB2007 engine.

Items		Units	Results	Euro IV limits
ESC	NO_x	g/kW·h	3.00	3.5
	PM	g/kW·h	0.015	0.02
	THC	g/kW·h	0.074	0.46
	CO	g/kW·h	0.405	1.5
ETC	NO_x	g/kW·h	3.16	3.5
	PM	g/kW·h	0.023	0.03
	THC	g/kW·h	0.074	0.55
	CO	g/kW·h	0.648	4.0

5.2. Design principles for oxygenated blends

In order to drastically reduce the diesel PM emission without using an aftertreatment device and thus to meet the Euro IV, i.e., Chinese Stage IV, emissions standards, the following formulation principles are proposed based on the research results presented in this paper:

(1) The fuel oxygen content should be controlled between 10% and 20% by mass concentration. When the fuel oxygen content is insufficiently high, the DS production could not be minimized effectively. Conversely, the power loss would be excessive and the maximal mileage shortened.
(2) The equivalent cetane number should be modulated between 50 and 60. A substantially lower cetane number would result in higher SOF, while excessively high cetane number would extravagantly shorten the ignition delay that would cause inadequate mixing and therefore increase the DS emission. It should be noted especially that the cetane number should be kept sufficiently high when EGR is applied.
(3) The sulfur content should be reduced as low as possible to prevent the sulfate production.
(4) The aromatic content should also be contained as low as possible because aromatics are precursors to the soot formation.
(5) The viscosity and surface tension should be close to those of a conventional diesel fuel, in order to ensure the spray characteristics and lubricity of the fuel blend.

5.3. Discussion

The technique of homogeneous mixing may also produce low PM or zero soot combustion, which is commonly referred as homogeneous charge compression ignition (HCCI) operation. Though being one of the focuses by the many, presently HCCI could only be implemented at partial loads. An alternative is to re-design the fuels. The current reported research by the authors demonstrated that the high oxygen content and high cetane number in the oxygenated fuel blends could reduce the PM emission to an extremely low level that is capable of meeting the Euro IV or even stricter emission standards without applying an aftertreatment device. Considering the sourcing constrains of the non-fossil based ingredients and other logistic issues, it is prudent to first apply the new fuel on the city bus or municipal vehicle fleets. Even if the oxygen content and/or the cetane number of the actual fuel blends are lower than the optimized fuel blend presented in this paper, the PM and smoke emissions from diesel vehicles could still be reduced significantly. The new fuel blends are therefore effective to reduce emissions for the in-use vehicles, which provide an alternative to the aftertreatment retrofitting technologies.

If all the diesel automobiles adopt the new oxygenated fuel blends in the future, it would be relatively easier to solve the diesel emission problems and thus the relevant aftertreatment technologies may be deferred to apply by $1 \sim 2$ phases in China and possibly in the world, which would greatly reduce the cost.

The design ideas of the oxygenated blends presented in this paper will benefit the diversification of the future automotive energy sources. New fuels can be formulated according to the combustion needs for high efficiency and low emissions by taking advantages of the different fuels or chemical materials. The disadvantages of the blending ingredients should be avoided or neutralized therein. Such designed fuels could be superior to the conventional diesel or gasoline fuels, which helped to promote the application of other non-petroleum based fuels.

Notwithstanding, there are also some problems that need to be settled when using this oxygenated fuel blend. For example, the fuel heat value decreases proportionally with the oxygen content, which will lower the maximal torque and power output. However this issue could be conveniently resolved by tuning up the maximum fuel supply from the fueling system. The loss in fuel heating value will also reduce the maximal mileage of the vehicle. However this could be easily compensated with a larger fuel tank. The consequent increase in total vehicle weight should still be less than the weight of an aftertreatment device. Additionally, the oxygenated blends will raise the local oxygen content of the flame that could produce approximately 20% increases in NO_x emissions. At present this is a most challenging problem, the only way available is to increase the EGR rate.

Moreover, further studies need to be conducted on the oxygenated blends to detail the characteristics of spray and mixture formation, the aromatic contents, and the distilling processes; and thus to understand their effects on the exhaust emissions. There are still potentials for further optimization in these aspects.

6. Conclusion

(1) When fueling oxygenated blends, the DS constituent in PM emissions decreases significantly as the fuel oxygen content increases. However, when the oxygen content reaches 15% or higher, reduction rate becomes obviously slow.
(2) When the PM emission is relatively low, the SOF emission may exceed the DS and become the main constituent of PM; overall, the SOF emission decreases with the increase in cetane number, which trend is not apparent when substituted with a cetane number enhancer.
(3) A set of design principles for oxygenated blends are proposed to drastically reduce PM emissions, which requires for the high oxygen content, high cetane number, low sulfur, low aromatics, and suitable viscosity.
(4) Based on the design principles proposed in this paper, an oxygenated blend containing 50% biodiesel, 15% DMC, and 35% diesel fuel was formulated to meet the Chinese 4th Stage Standard (equivalent to Euro IV) for heavy-duty engines without using any aftertreatment device.

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