

Effect of SME biodiesel blends on PM_{2.5} emission from a heavy-duty engine

Jie Zhang, Kebin He*, Xiaoyan Shi, Yu Zhao

Department of Environmental Science and Engineering, Tsinghua University, Beijing 100084, China

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ABSTRACT

To explore the effect of biodiesel and sulfur content on PM_{2.5} emissions, engine dynamometer tests were performed on a Euro II engine to compare the PM_{2.5} emissions from four fuels: two petroleum diesel fuels with sulfur contents of 50 and 100 ppm respectively, and two B20 fuels in which soy methyl ester (SME) biodiesel was added to each of the above mentioned petroleum diesel fuels (v/v: 80%/20% for petroleum diesel and SME respectively). Gaseous pollutants and PM_{2.5} emissions were sampled with an AVL AMA4000 and Model 130 High-Flow Impactor (MSP Corp). Measurements were made of the PM_{2.5} mass, organic carbon (OC), elemental carbon (EC) and the water-soluble ion distribution. The results showed that PM_{2.5} emissions decreased with lower sulfur content or blending with SME biodiesel, and the decrease would be more by applying both two methods together. Particles of approximately 0.13 μm contributed 48–83% of PM_{2.5} emissions. The impact of sulfur content on this percentage was different for low and high engine speed. The majority of PM_{2.5} was comprised of OC and EC, and the carbon emission rate had the same trend as PM_{2.5}. Since the EC abatement of B20 was larger than OC, the OC/EC ratio of B20 was always larger than that of petroleum diesel. For petroleum diesel, the OC/EC increased with sulfur content, which was not the case for B20. The SO₄²⁻ had highest emission rate in the water-soluble ions of PM.

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1. Introduction

Diesel engines are installed in approximately 24% of all on-road vehicles in China. Their emissions, especially PM, contribute significantly to air pollution. Diesel trucks contribute 83% of the total vehicle tailpipe PM emissions in Beijing (Yao et al., 2006). This percentage is similar to the California PM contribution in 1996, in which heavy-duty diesel trucks were responsible for 75% of exhaust PM from on-road vehicles statewide (ARB, 1996).

Biodiesel can be used as a fuel for diesel engines without engine modification. Biodiesel is receiving increasing attention due to the pressure of diesel emission abatement and alternative fuels application. Researchers have tested the effect of using petroleum diesel, 100% biodiesel or their blends. Some reported a PM emission reduction with the biodiesel blend (Bagley et al., 1998; Jung et al., 2006; Canakci, 2007), while others did not find significant abatement (Turrio-Baldassarri et al., 2004; McCormick, 2005) or even found increasing emissions (Mazzoleni et al., 2007; Wu et al., 2007).

Diesel particles are harmful to public health, global climate and urban visibility. Menon et al. (2002) expected aerosol to have

a cooling effect in the atmosphere. Andreae et al. (2005) also discovered that precipitation and temperature would be changed by soot (black carbon). The PM contributes mostly to the common PAHs collected in an urban area (Rhead and Hardy, 2003; Valavanidis et al., 2006), where the population exposure to diesel particles is substantial (Davis et al., 2006; B.K. Lee et al., 2005). The main constituents of diesel particles are elemental carbon (EC) and organic carbon (OC), together accounting for over 95% by weight (Watson et al., 2001). Diesel emissions are the major source of atmospheric EC (U.S. EPA, 2002), and thus EC is used as an indicator for determining the contribution of diesel engines to ambient particulate concentration (Birch and Cary, 1996).

However, OC and EC emissions varied depending on fuel type, vehicle type, vehicle operation mode, and ambient temperature (Kerminen et al., 1997; Zielinska et al., 2004; Shah et al., 2004). Moreover, OC and EC emission factors could be influenced by diesel truck activity (Harley et al., 2005). Diesel particles contain water-soluble ions from lubricant oil in addition to carbonaceous species (Sodeman et al., 2005).

Lowering diesel sulfur content could decrease particle emissions (Ristovski et al., 2006). Although the sulfur content standard in China is currently 2000 ppm, Beijing lowered the sulfur standard to 350 ppm (Euro III) between December 2005 and March 2008 in order to control diesel emissions, and the value further decreased to 50 ppm (Euro IV) after March 2008. Biodiesel production is also

* Corresponding author. Tel.: +86 10 62781889.

E-mail address: hekb@tsinghua.edu.cn (K. He).

developing fast in China. A series of studies have been carried out on the PM emissions from diesel and biodiesel blends, but only a few of them measured the chemical composition of PM_{2.5} from the combustion of biodiesel blends (Mazzoleni et al., 2007; Wang et al., 2000). There were few investigations comparing the combined effects of biodiesel and low sulfur diesel. In this study, petroleum diesel with two sulfur content levels, and SME biodiesel, were chosen to explore fuel characteristics on PM emissions. Emissions using each of the two kinds of petroleum diesels and each blended with SME (B20) were tested on an engine dynamometer under a series of operating conditions. The comparative emission rates and composition of the exhaust collected from the engine were characterized, including PM_{2.5}, OC, EC and water-soluble ions.

2. Experimental method

2.1. Test conditions and fuel quality

The experiments were performed on a medium-duty, direct-injection, four-cylinder engine meeting Euro II emission standards. This four-stroke-cycle, turbocharged diesel engine is commonly used in Chinese trucks (China First Automobile Group Wuxi Diesel Engine Works 4CK). It had a 4.752 L displacement, with a peak power output of 117 kW at 2300 rpm and a peak torque output of 580 N m at 1400 rpm. Four modes from the 13-mode test cycle (ECE R49) were used in the investigation. The selected conditions were:

- (1) 1400 rpm, 50% load
- (2) 1400 rpm, 100% load
- (3) 2300 rpm, 25% load
- (4) 2300 rpm, 75% load

The power outputs were 42.5 kW, 85 kW, 25 kW and 75 kW for conditions (1), (2), (3) and (4) respectively, which had a power output order of (2) > (4) > (1) > (3).

The two kinds of petroleum diesel selected for this study were made by Fangyuan National Standard Oil Company in Liaoning Province in China. The SME biodiesel was from Xi'an Blue Sky Biological Engineering CO., LTD. The properties of the test fuels are listed in Table 1. The fuel properties were measured by a certified laboratory in RIPP (Research Institute of Petroleum Processing in China). The uncertainty for sulfur content test is ≤10%, for density is <0.1 kg m⁻³.

Two non-blended fuels and two blends were used:

- D(l) – Low sulfur petroleum diesel (50 ppm)
- D(h) – High sulfur petroleum diesel (100 ppm)
- B20(l) – Diesel/SME blend (v/v):80% D(l) + 20% biodiesel
- B20(h) – Diesel/SME blend (v/v):80% D(h) + 20% biodiesel

Table 1
Properties of petroleum diesel and SME biodiesel blends.

Fuel property	D(l)	D(h)	B20(l)	B20(h)	Method	Corresponding to ASTM
Sulfur content (ppm)	50	100	72	112	GB/T 380	ASTM D4294
Cetane number	52	52	54	54	GB/T 386	ASTM D6890
Density at 20 °C (kg m ⁻³)	841	841	848	848	GB/T 1884–1885	ASTM D1298/4052
Viscosity at 20 °C (10 ⁻⁶ m ² s ⁻¹)	4.0	4.0	4.6	4.6	GB/T 265	ASTM D445

The property of B20(l) and B20(h) is calculated from the property of D(l), D(h) and SME biodiesel.

Once the fuel was changed, the engine was operated for at least 1 h before the samples were collected in order to remove traces of the previous fuel.

The fuel was pumped into a tank before experiment. Since the fuel tank was put approximately 2 m above from the floor, fuel can flow into the engine with the gravity. The maximum fuel consumption of the engine is less than 30 L h⁻¹. The capacity of the tank is 100 L, which is enough for the 2 h sampling period. Once the fuel in the tank was not enough for another sampling period, fuel would be pumped in before the engine started.

2.2. Dilution and sampling system

Fig. 1 shows a schematic diagram for the engine, dilution system and sampling system. The engine was coupled to Schenck DYNAS HT350 dynamometer. The gaseous pollutants were detected by the AMA4000 from AVL. THC was monitored with a flame ionization detector (FID); NOx was monitored with a chemiluminescence detector; CO and CO₂ were monitored with a non-dispersive infrared analyzer; and O₂ was monitored with a paramagnetic O₂ analyzer.

The dilution system was a partial flow type and included two stages. The first stage was an injection dilution tunnel by Dekati Ltd. (Finland), which had a maximum flow of ~90 L min⁻¹. It is similar to the instrument described by Khalek et al. (2000). The second stage was designed and manufactured in accordance with the recommended type of partial flow dilution tunnel in the national standard for China (limits and measurement methods for exhaust pollutants from compression ignition and gas fueled positive ignition engines of vehicles (III, IV, V)). The second stage dilution tunnel supplemented the airflow to meet the need of the sampler (100 L min⁻¹). The temperature decreased from 120 °C at the inlet of the dilution tunnel to 25 °C at the inlet of Model 130 High-Flow Impactor (MSP Corp).

CO₂ concentration from the exhaust gas and diluted gas were measured and used to calculate the dilution rate of the system. The dilution ratio in the test was controlled in the range of 7–10 during the test. The method to calculate the dilution rate is defined as Eq. (1):

$$DR = \frac{(C_I - C_B) - (C_O - C_B)}{C_O - C_B} \quad (1)$$

where DR is the dilution rate, C_I is the CO₂ concentration at the inlet of the dilution system (exhaust gas), C_O is the CO₂ concentration at the outlet of the dilution system (after the pump), and C_B is the background of CO₂ concentration (intake air).

The fuel-based emission factor is the emission rate per unit of fuel used which could be calculated as Eq. (2):

$$EF_i = \frac{ER_i}{FC} \quad (2)$$

where EF_i (mg kg⁻¹) is defined as the fuel-based emission factor of the *i*th pollutant, ER_{*i*} (mg h⁻¹) is defined as emission rate of the *i*th pollutant, and FC (kg h⁻¹) is the fuel consumption rate.

The Model 130 High-Flow Impactor is a low-pressure-drop cascade impactor, which has six stages with nominal cutpoints of 10 μm, 2.5 μm, 1.4 μm, 0.77 μm, 0.44 μm, and 0.26 μm at 100 L min⁻¹ inlet volumetric flow rate. The corresponding midpoints of these stages are 6.25 μm, 1.95 μm, 1.09 μm, 0.60 μm, 0.35 μm and 0.13 μm respectively.

In each of the four modes, the testing time duration is 2 h. For the PM_{2.5} emission factors, the minimum total sample volume is 100 L min⁻¹, minimum sample time is 2 h. The minimum target

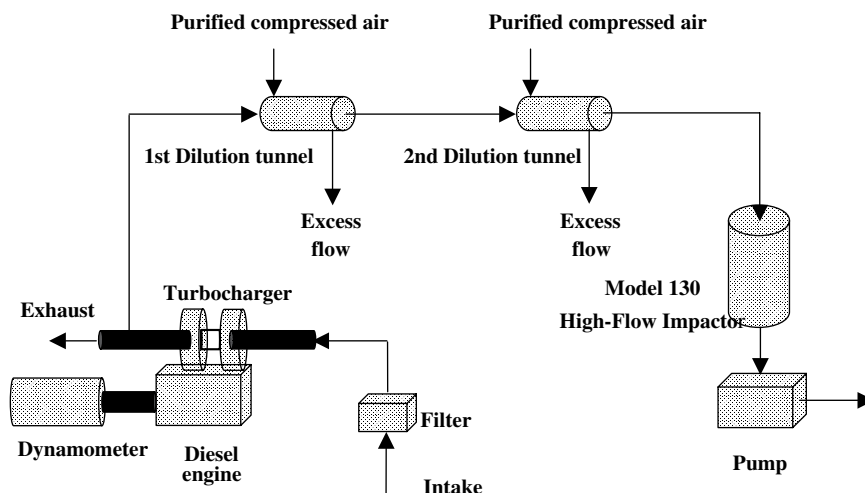


Fig. 1. The dilution and sampling system. The exhaust gas was mixed with compressed air in a two-stage dilution system before entering the sampler (Model 130 High-Flow Impactor). The pressure and flow rate of the purified compressed air were detected.

amount of PM mass collection is 0.1 mg based on the precise and sensitive level of the balance.

2.3. Filters and particle characteristics analysis

A Teflon filter (Shanghai Plastics Research Institute) was used for mass and water-soluble ion measurement, while a quartz filter (PALL #2500QAT2U) was used for OC and EC measurements.

The sample mass was determined by weighing the filters on a Mettler AE 240, model Toledo A6 balance of sensitivity 0.01 mg (0.1 mg accuracy). Ten inorganic ions (SO_4^{2-} , NO_3^- , F^- , Cl^- , NO_2^- , NH_4^+ , Na^+ , K^+ , Ca^{2+} , and Mg^{2+}) were analyzed by an Ion Chromatography Dionex 600.

OC and EC were analyzed with a DRI Model 2001 Thermal/Optical Carbon Analyzer, using the IMPROVE (Interagency Monitoring of Protected Visual Environments) protocol (Chow et al., 2001). The quartz filter was heated stepwise to temperatures of 120 °C (OC1), 250 °C (OC2), 450 °C (OC3), and 550 °C (OC4) in a pure helium environment. Then the environment was shifted to 2% O_2 /98% He, and the filter continuously heated stepwise to 550 °C (EC1), 700 °C (EC2) and 800 °C (EC3).

3. Results

3.1. $\text{PM}_{2.5}$ and gaseous pollutants emission rate

The fuel-based $\text{PM}_{2.5}$ emission factors obtained from Model 130 High-Flow Impactor measurements are summarized in Fig. 2. The engine performed well with B20, and no fuel-related problems were observed during the tests. The power output and fuel consumption rate were almost the same with these four fuels. This could be due to similar chemical and thermodynamics characteristics of SME and diesel. Both were made up of long chains that contain the methylene (CH_2) group (Wang et al., 2000). The fuel-based $\text{PM}_{2.5}$ emission factor (g kg^{-1} fuel) did not have the same trend as the power output. The rpm/load condition (3) always had the highest fuel-based emission factor, followed by condition (4). Rpm/load conditions (1) and (2) always had the lowest emission factor.

As listed in Table 2, the order of $\text{PM}_{2.5}$ emission rate (mg min^{-1}) for these four conditions was (4) > (3) > (2) > (1). Highest emissions were observed for D(h) (unblended high sulfur diesel) and lowest emissions for B20(l).

Compared with unblended diesel fuel D(h), the $\text{PM}_{2.5}$ emission rate from D(l) (unblended low sulfur diesel) decreased by 10%, –53%, 28% and 26% for condition (1), (2), (3) and (4) respectively. When D(h) was blended with biodiesel to form B20(h), the $\text{PM}_{2.5}$ emission rate decreased 20%, 9%, 33% and 15% for the (1), (2), (3) and (4) conditions respectively. $\text{PM}_{2.5}$ emissions could be reduced by both decreasing the sulfur content and adding 20% SME biodiesel. Considering these two effects together, compared to D(h), the emission from B20(l) decreased by 24%, 35%, 54% and 22% each for condition (1), (2), (3) and (4), showing a more significant benefit than that from B20(h) and D(l).

The mass distribution of $\text{PM}_{2.5}$ is presented in Fig. 3. The 0.13 μm particles contributed 48%–83% of the $\text{PM}_{2.5}$ from all test fuels and the contribution decreased as the diameter increased. The percentage of 0.13 μm particles from B20(h) was 24% higher than that from B20(l) at low engine speed, but 24% lower for B20(h) than that from B20(l) at high engine speed.

The emission rates of gaseous pollutants (NO_x , CO and THC) are listed in Table 2. THC and CO in diesel emission could be lowered by applying B20 under some conditions. For example, at condition (2), THC emission rate decreases from 0.5×10^3 to 0.4×10^3 mg m^{-3} when substitute D(l) with B20(l); at condition (3), THC emission

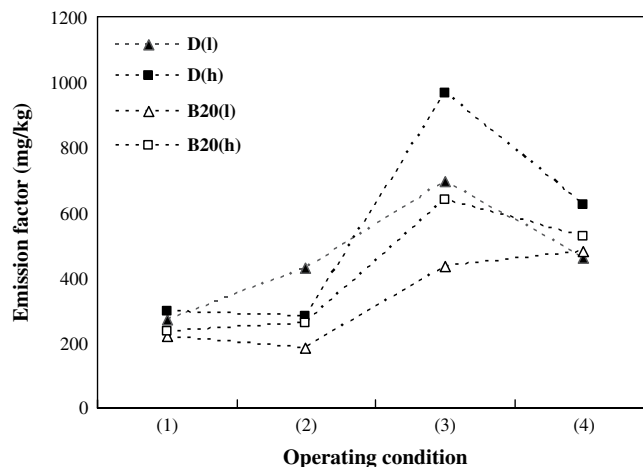


Fig. 2. Fuel-based emission factor of $\text{PM}_{2.5}$ with different fuel and operating conditions.

Table 2
Emission rate of PM_{2.5} and gaseous pollutants.

Fuel	No.	Engine speed (rpm), load (%)	Emission rate (mg min ⁻¹)			
			PM _{2.5}	THC	NOx	CO
D(l)	(1)	1400, 50	44	0.3 × 10 ³	4.5 × 10 ³	0.4 × 10 ³
	(2)	1400, 100	136	0.5 × 10 ³	7.3 × 10 ³	1.5 × 10 ³
	(3)	2300, 25	139	0.7 × 10 ³	2.3 × 10 ³	2.3 × 10 ³
	(4)	2300, 75	173	1.0 × 10 ³	6.2 × 10 ³	1.7 × 10 ³
D(h)	(1)	1400, 50	49	0.3 × 10 ³	4.4 × 10 ³	0.4 × 10 ³
	(2)	1400, 100	89	0.4 × 10 ³	7.1 × 10 ³	1.1 × 10 ³
	(3)	2300, 25	193	0.8 × 10 ³	2.3 × 10 ³	2.2 × 10 ³
	(4)	2300, 75	234	0.9 × 10 ³	6.2 × 10 ³	1.9 × 10 ³
B20(l)	(1)	1400, 50	37	0.2 × 10 ³	4.3 × 10 ³	0.4 × 10 ³
	(2)	1400, 100	58	0.4 × 10 ³	7.2 × 10 ³	0.8 × 10 ³
	(3)	2300, 25	88	0.8 × 10 ³	2.3 × 10 ³	2.5 × 10 ³
	(4)	2300, 75	182	0.8 × 10 ³	6.3 × 10 ³	1.8 × 10 ³
B20(h)	(1)	1400, 50	39	0.3 × 10 ³	4.6 × 10 ³	0.4 × 10 ³
	(2)	1400, 100	81	0.4 × 10 ³	7.2 × 10 ³	1.2 × 10 ³
	(3)	2300, 25	130	0.7 × 10 ³	2.3 × 10 ³	2.4 × 10 ³
	(4)	2300, 75	200	0.9 × 10 ³	6.3 × 10 ³	1.8 × 10 ³

rate decreases from 0.8 × 10³ to 0.7 × 10³ mg m⁻³ when substitute D(h) with B20(h); at condition (2), CO emission rate decreases from 1.5 × 10³ to 0.8 × 10³ mg m⁻³ when substitute D(l) with B20(l).

3.2. PM_{2.5} carbon emissions

As expected, the PM_{2.5} emissions at all conditions were almost all TC (total carbon), although the relative proportions of OC versus EC were quite variable depending on the engine operation and types of fuel. The emission rate of TC in PM_{2.5} had the same trend as PM_{2.5}, having the order as (4) > (3) > (2) > (1). It was different from the results of an IDI (indirect injection) engine, which had the total

carbon mass emissions increase with an increase of the power output (Alander et al., 2004). As shown in Fig. 4, OC and EC contributions to the total mass were influenced by biodiesel blend, fuel sulfur and engine operation.

At condition (1) (1400 rpm/50% load), OC contributed more to the total mass than EC. OC1, EC1 and OC2 contained the majority of the carbon. EC reduction was always more than that of OC when using B20 in all the other conditions. At condition (2), (1400 rpm/100% load), OC emissions of all the fuels remained at a similar level to condition (1), while EC increased sharply. Lower OC/EC ratios at higher load were observed both at the engine speed of 1400 rpm and 2300 rpm.

3.3. Water-soluble ions

Table 3 shows the emission rate of the water-soluble ions in PM_{2.5} measured from Teflon filters. The tested anions emission rates were higher than cations. Within these water-soluble ions, the highest emissions usually came from SO₄²⁻. Beside SO₄²⁻, Cl⁻ and NO₃⁻ also had a relatively large contribution to the emissions. Those three anions had higher emission rates from B20 than that from diesel. The sulfur content differences between D(l) and D(h) seemed to have little effect on the SO₄²⁻ emission rate similar to that of B20(l) and B20(h). This was different from the results of Wall et al. (1987), which reported that lowering fuel sulfur content could reduce emissions of both sulfur dioxide and particulate sulfate.

4. Discussion

4.1. PM_{2.5} emission factor

In order to ensure the engine working under a steady state, smoke was sampled three times to check the engine condition.

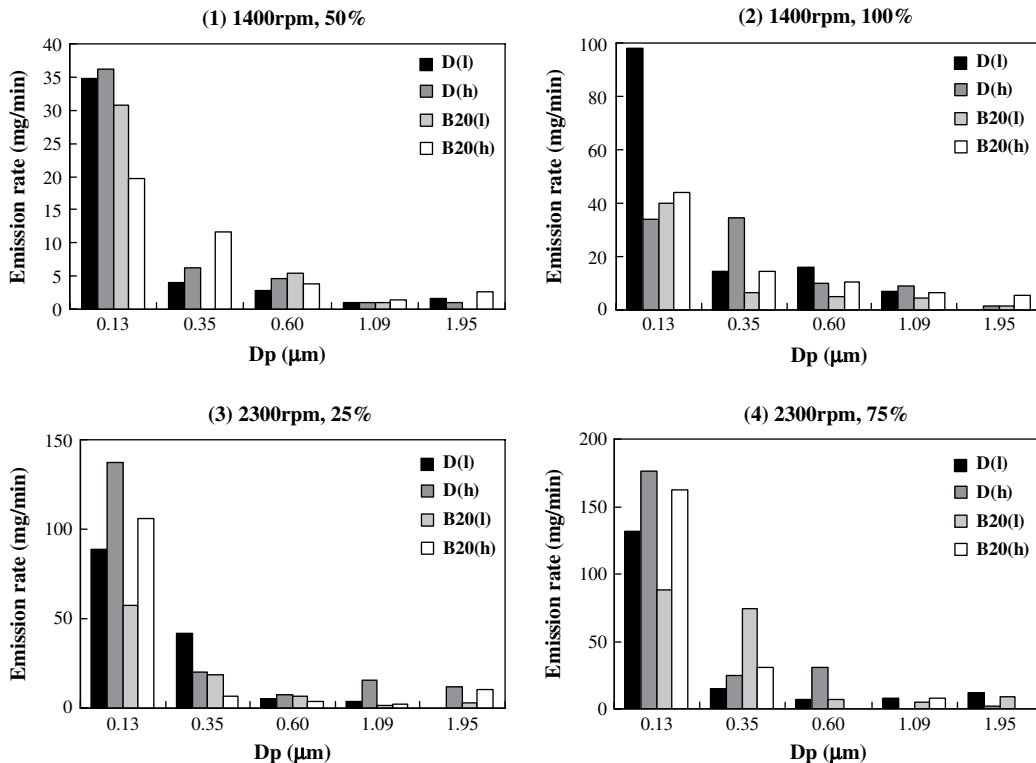


Fig. 3. Size distribution of PM_{2.5} from D(l), D(h), B20(l) and B20(h).

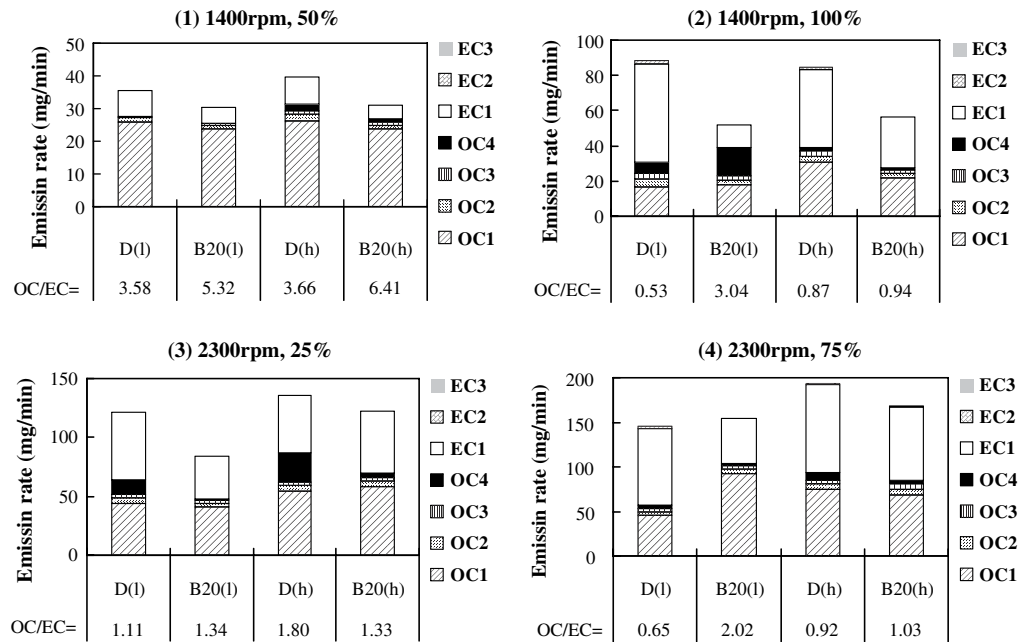


Fig. 4. OC1–OC4, EC1–EC3 emission rates and OC/EC ratios.

Smoke was tested by AVL 439 opacimeter, in which the loss of light intensity between a light source and a receiver is measured and from it the opacity of the exhaust gas is calculated based on the Beer–Lambert law. The error bars are less than 5.0%, implying the experimental condition was stable and the results were believable. For all the gaseous pollutants, the concentration was sample three times under each condition. The error bars for THC, NO_x and CO are 2.0%, 12% and 5.1% respectively.

As listed in Table 2, the NO_x emission rate in this study was positively correlated with engine load. It varied little with different types of fuel. The emission rate of PM_{2.5} was expected to decrease as the NO_x emission rate increased according to the trade-off relationship between these two pollutants (Cocker et al., 2004). However, in this study, the PM_{2.5} emission rate did not have a negative correlation with NO_x.

The average value of emission reduction was in the same order as prior research in which 75% commercial diesel and 25%

sunflower oil biodiesel were applied (Lapuerta et al., 2002). Durbin and Norbeck (2002) reported higher PM emission rates in four of the seven test vehicles, with comparable PM emission rates for the other three vehicles when changing the CARB fuel to the soy-based biodiesel blends. Some authors found increasing PM emissions with biodiesel compared with petroleum diesel (Peterson and Reece, 1996). The reduction of PM when using biodiesel blends was supposed to be due to the increase in oxygen content in the fuel which contributed to complete fuel oxidation even in locally rich zones, and more complete evaporation of the biodiesel (Lapuerta et al., 2002).

Leung et al. (2006) reported higher PM emission reduction at higher engine load, but there was no significant correlation between PM_{2.5} emissions with engine load in this study. Particles are mainly formed during diffusion combustion, and most of the combustion process is diffusive at high load. Therefore, the oxygen content of biodiesel could be effective in reducing PM (Leung et al.,

Table 3
Emission rate of the water-soluble ions in PM_{2.5}.

Fuel	No.	Engine speed (rpm), load (%)	Emission rate (mg h ⁻¹)									
			F ⁻	Cl ⁻	NO ₂	NO ₃	SO ₄ ²⁻	Na ⁺	NH ₄ ⁺	K ⁺	Mg ²⁺	Ca ²⁺
D(l)	(1)	1400, 50	4.03	6.64	–	6.75	39.39	0.02	–	0.01	0.01	0.03
D(l)	(2)	1400, 100	0.38	0.27	–	3.11	16.19	–	–	–	–	–
D(l)	(3)	2300, 25	–	–	0.97	2.54	–	0.02	–	0.01	0.01	0.02
D(l)	(4)	2300, 75	4.02	6.28	–	3.16	3.22	0.04	0.01	0.02	0.02	0.01
D(h)	(1)	1400, 50	2.39	3.98	–	1.91	15.58	0.03	0.01	0.01	0.01	0.02
D(h)	(2)	1400, 100	0.66	1.43	–	0.42	7.04	0.01	0.01	0.01	–	–
D(h)	(3)	2300, 25	0.22	–	–	3.31	1.35	0.04	–	0.01	0.01	0.01
D(h)	(4)	2300, 75	–	–	3.05	3.73	9.09	0.02	–	0.01	0.01	0.01
B20(l)	(1)	1400, 50	1.59	1.94	0.09	3.02	10.58	0.04	–	0.01	0.03	0.05
B20(l)	(2)	1400, 100	2.11	4.95	0.16	3.11	35.86	0.01	–	–	0.01	0.01
B20(l)	(3)	2300, 25	3.66	7.04	–	8.07	12.05	0.01	–	0.01	0.01	0.03
B20(l)	(4)	2300, 75	2.19	9.26	–	3.65	22.85	0.01	–	–	–	–
B20(h)	(1)	1400, 50	2.87	3.80	0.81	2.53	22.46	0.01	–	0.01	0.01	0.01
B20(h)	(2)	1400, 100	12.59	10.38	–	2.22	45.21	–	–	–	–	–
B20(h)	(3)	2300, 25	7.84	10.64	0.05	4.06	9.35	0.02	–	0.01	0.01	0.02
B20(h)	(4)	2300, 75	–	42.62	–	3.12	12.53	0.01	–	–	0.01	0.02

2006). At low load, the lower temperature led to difficulties in evaporation and burning of heaviest hydrocarbons which could be ameliorated by biodiesel (Lapuerta et al., 2002).

4.2. OC and EC emissions

The OC/EC ratio of B20 was always larger than that of petroleum diesel. Since the air-to-fuel ratio of B20 was the same as that of diesel, the higher oxygen content in the B20 could contribute to more particle-bound volatile organic material. In most cases in this study, B20 reduced the EC emissions by over 30%. The soot formation mainly occurs in the fuel-rich zone at high temperatures and pressures. The biodiesel could reduce the local fuel-rich region and limit soot formation, for oxygenated fuels are expected to enable more complete combustion and promote the oxidation of already formed soot (Graboski and McCormic, 1998; Lapuerta et al., 2008).

The OC/EC ratio of petroleum diesel increased as the sulfur content increased, but the ratio of B20 did not show this trend. It is assumed that the B20 had higher kinematic viscosity, surface tension and cetane number which caused the atomization and combustion characteristics differences (C.S. Lee et al., 2005). Cocker et al. (2004) tested an HHDDT (Heavy heavy-duty diesel truck) and found that the OC/EC ratio varied from 0.8 for the creep mode to 1.3 for the cruise mode, which was usually lower than OC/EC in this investigation.

As shown in Fig. 4, in this experiment, using a direct-injection engine, the OC was composed mainly of the OC1 fraction, while OC4 was remarkable only under two instances: the B20(l) at condition (2) and D(h) at condition (3). Alander et al. (2004) reported that in the PM emitted from an IDI engine, the OC3 was the main composition of OC. Besides operating conditions and fuel property, engine type also influenced the carbon emissions. Further research is needed.

Zhang et al. (2007) used 1.2 as the OC/EC ratio for motor vehicles in Beijing, the lowest average value during an investigation under strong wind conditions in 2004. This value is less than 1.3, the lowest OC/EC in this research. First, OC/EC ratio from diesel-fueled vehicles is lower than that of gasoline. Watson et al. (1994) reported that OC/TC ratio of gasoline-fueled vehicle exhaust was higher than that of diesel-fueled vehicle, and this was further confirmed by Cadle et al. (1999). Second, the OC/EC ratio should be higher than the sampling result of Zhang et al. (2007). As shown in Fig. 4, OC/EC from petroleum diesel increased as the sulfur content increased. Since the sulfur content was 2000 ppm in 2004 and only 50 ppm or 100 ppm in this study, the OC/EC ratio in 2004 would have been expected to be higher than the result in this test.

4.3. Water-soluble ions

The SO_4^{2-} comprised the majority of the water-soluble ions, which was consistent with Zielinska et al. (2004). Lyyranen et al. (2002) suggested that sulfuric acid formed in the exhaust gases at a temperature lower than that in the engine. In this work, SO_4^{2-} was presumably formed mainly in the exhaust gas. The SO_4^{2-} emission rate is relatively higher at low engine speed. Under the same engine speed, however, the SO_4^{2-} emission rate increased as the engine load increased. The SO_4^{2-} emission rate of B20 is higher than that of pure diesel. B20(l) has SO_4^{2-} emission rate seven times higher than D(l) at condition (4), and B20(h) has SO_4^{2-} seven times higher than D(h) at condition (3).

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