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Regulated and unregulated emissions from a light-duty diesel engine with different sulfur content fuels

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ABSTRACT

Five different sulfur content fuels were used on a light-duty diesel engine to study the effect of fuel sulfur on emissions. Four regulated emissions: smoke, nitrogen oxide (NO_x), unburned hydrocarbon (HC) and carbon monoxide (CO) emissions of the engine were investigated, as well as three unregulated emissions: formaldehyde (HCHO), acetaldehyde (MECHO) and sulfur dioxide (SO_2). The smoke emission decreases continuously and remarkably with the fuel sulfur content, and the fuel sulfur has more influence on smoke emission at lower engine load. The concentration of NO_x emissions did not change significantly with the different sulfur content fuels. As the fuel sulfur content decreases, the concentrations of HC and CO emissions have distinct reduction. The HCHO emission values are very low. The MECHO emission decreases with increasing engine load, and it continuously decreases with the fuel sulfur content and it could not be detected at higher engine load with 50 ppm sulfur fuel. The SO_2 emission increases continuously with the engine load, and obviously decreases with the fuel sulfur contents.

1. Introduction

In order to meet the stringent emission standards for modern diesel engines, a single technical solution will be no longer sufficient. Complex technologies, such as improvements in combustion strategies, air handling system, fuel injection system, exhaust emission aftertreatment system, and fuel quality are necessary [1]. Physical and chemical properties of fuel have important influence on exhaust emissions from diesel engines. Sulfur content is one important parameter among diesel fuel properties, and is one key controlled factor of fuel standard [2].

Fuel sulfur directly affects particulate matter (PM) emissions from diesel engines. In addition to fuel sulfur, the sulfur from additives in the lubricating oil will also affect the PM emissions. In this paper, effects of fuel sulfur on PM emission of diesel engines were study. Experiments confirmed the significant influence of the sulfur content of diesel fuel on particulate emissions. Compared with baseline diesel fuel, low sulfur diesel (LSD) fuel produced low PM emissions [3–5]. The PM emission of the engine with a 350 ppm sulfur fuel is about 20% lower than a 2000 ppm sulfur fuel [3]. A fuel (sulfur content less than 10 ppm) decreases PM emissions by 28% comparing to a reference fuel (sulfur content 206 ppm) [4]. Compared to the baseline diesel fuel (48 ppm sulfur content), the PM emission with lower sulfur diesel fuel (13 ppm sulfur content) had a small reduction rate of about 2% [5]. Fuel sulfur has significant influence on PM particle size and distribution from diesel engines. The concentration of nuclei-mode particles emitted increases with the fuel sulfur content [6–8]. When using 350 ppm sulfur fuel, an engine with an oxidation catalyst had more nuclei-mode particles emission than with a 4 ppm sulfur fuel [6]. The mean particle number emission rate of buses, in the size range 8–400 nm, using ULS (50 ppm) diesel fuel was 31–59% lower than the rate using LS (500 ppm) diesel fuel in all four modes [7]. The reduction of fuel sulfur from 50 to 10 ppm has had a significant effect on the production of the nucleation particles [8].

Steady state results show reasonable agreement with previous studies, while transient results show a large reduction of nuclei-mode particles with the use of ultra-low sulfur diesel (ULSD) fuel compared to LSD during testing with the higher primary dilution [9].

Fuel sulfur also has different effects on other exhaust emissions of diesel engines. With the use of lower sulfur diesel fuels in a diesel engine, more technologies could be used for reducing PM and nitrogen oxide (NO_x) emissions simultaneously [10]. Mode–averaged NO_x emissions decreased with ultra-low sulfur (15 ppm) diesel fuel compared to low sulfur (325 ppm) diesel fuel, as well as a 20% PM reduction [11]. A diesel fuel produced with a conventional sulfur removal process reduced PM emissions substantially, and the PM reductions level could be observed for NO_x emissions by using higher levels of exhaust gas recirculation [12].

Fuel sulfur content has distinct effects on advanced engine aftertreatment systems. The fuel sulfur content affects the performance of the DPF, LNT and SCR technologies [13–15]. Fuel sulfur content is crucial for the DPF application, especially for catalytic DPF. Low sulfur content fuel improves the DPF performance [16].

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The NO_x reduction efficiency of the LNT is dominated by fuel sulfur effects [17]. With the SCR technology, the impact of sulfur was more significant on the NO_x activity of Cu/zeolite than that of Fe/zeolite SCR catalysts. The impact of sulfur on NO_x activity also changed with thermal aging on some catalysts, while remaining relatively unchanged for other catalysts [18].

In this work, the effects of varying the fuel sulfur content on the exhaust emissions of a light-duty diesel engine were studied through a series of tests. Regulated emissions (NO_x, HC, CO and smoke) were measured. Aldehydes are one of the most harmful incomplete combustion products from hydrocarbon-based fuels, and aldehydes from diesel engines usually include formaldehyde (HCHO) and acetaldehyde (MECHO). As there are growing environment concerns for other unregulated diesel engine emissions, namely HCHO, MECHO and SO_2, it was decided to also test and investigate these unregulated emissions in this study.

2. Experimental methodology

2.1. Test fuels

Five diesel fuels with different sulfur concentrations were used in the study. Now, special regulations of vehicle emissions and fuels exist in China. From 2007, the national regulations (China III stage) about emissions from light-duty vehicles and heavy-duty diesel engines have been carried out, and these emission limit values are the same as the Euro III standards. Therefore, the new light-duty vehicles and heavy-duty diesel engines in China market meet the Euro III standards. However, the fuel standards are not similar to the vehicle emissions in China. Up to now, the sulfur content limit of the national diesel fuel standard in China is 2000 ppm. In different cities, the sulfur content limit is different because of different local diesel fuel standard. The sulfur content limit of the diesel fuel in Beijing is 50 ppm (because of 2008 Olympic Games), and 500 ppm in Shanghai, China. So, the fuel sulfur content is below 2000 ppm in this study, and the fuel sulfur contents were 47 ppm (fuel code: S50), 324 ppm (S350), 469 ppm (S500), 786 ppm (S800) and 1473 ppm (S1500), respectively. Other basic physical and chemical properties of these fuels are listed in Table 1. Except for the different sulfur content, the cetane number and the aromatic content of the five fuels are also a little different. These different fuel properties could also affect the emissions of some pollutant compounds.

2.2. Test engine

The test engine is a turbocharged and intercooled direct injection diesel engine that meets Euro III emission standards, and with electronic control high pressure fuel unit-injector, exhaust gas recirculation and diesel oxidation catalyst. The test diesel engine specifications are listed in Table 2.

Table 1
Basic physical and chemical properties of test fuels.

Fuel code	S50	S350	S500	S800	S1500
Sulfur content (ppm, m/m)	47	324	469	786	1473
Density, 20 °C (kg/m^3)	831.6	831.4	831.6	833.7	835.6
Cetane number	54.2	54.2	52.8	52.8	52.0
Polycyclic aromatic (%, v/v)	3.4	6.0	6.1	6.2	8.3
Total aromatic (%, v/v)	15.0	18.0	18.2	19.1	19.8
Cloud point (°C)	−18	−8	−8	−8	−10
Cold filter plugging point (°C)	−13	−4	−4	−5	−7
Flash point (°C)	91	83	82	82	80
Viscosity, 20 °C (mm^2/s)	5.272	4.992	5.105	5.306	5.408
Viscosity, 40 °C (mm^2/s)	3.242	3.12	3.164	3.285	3.353
Distillstion T10 (°C)	235.8	232.3	229.3	233.3	234.4
Distillstion T50 (°C)	276.8	276.8	275.3	278.8	278.3
Distillstion T90 (°C)	320.0	329.0	332.0	334.0	331.5
Distillstion T95 (°C)	330.0	343.0	350.0	349.5	347.0

Table 2
Test diesel engine specifications.

Engine type	Direct injection 4-stroke, 4-cylinder
Displacement	1.896 l
Compression ratio	19.0
Cylinder bore	126 mm
Stroke	130 mm
Rated power	96 kW/4000 rpm
Peak torque	285 Nm/1900 rpm

2.3. Test equipments

An AVL PUMA open test bed automation system was used for the engine test. Exhaust emissions were measured using a AVL-PEUS multi-component gas analyzer capable of measuring over 25 gaseous component in the diesel engine exhaust, including regulated emissions (NO_x, HC and CO), as well as unregulated emissions (HCHO, MECHO and SO_2). Exhaust smoke was measured using an AVL 415 smoke meter.

2.4. Experimental procedure

Engine tests were performed without any modification to the engine fuel and air supply systems. The fuels were tested in the following sequence: S50, S350, S500, S800 and S1500. Tests at two typical speeds, i.e., 4000 rpm at rated power, and 1900 rpm at peak torque, were performed with a gradual load increase from 0% to 100% (0%, 25%, 50%, 75% and 100%). Regulated emissions (smoke, NO_x, HC and CO) and unregulated emissions (HCHO, MECHO and SO_2) were measured under these operating conditions.

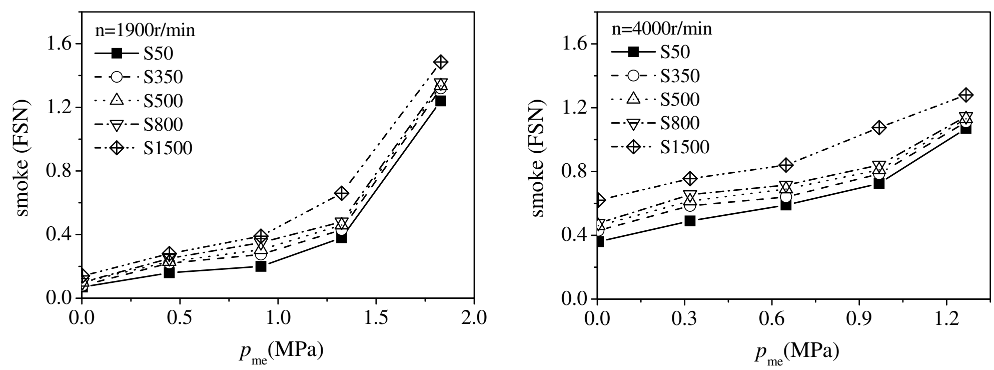
3. Results and discussion

3.1. Regulated emissions

Smoke, NO_x, HC and CO emission data measured during the diesel engine tests are shown in Figs. 1–5.

3.1.1. Smoke

Fig. 1 shows that smoke emission increases with engine load at the two engine speeds (1900 and 4000 rpm). At 1900 rpm engine speed, the smoke number increase rate is low in the low to intermediate load region, but smoke rises quickly from intermediate to high load. When the load increases from 1.32 (75% load) to 1.83 MPa (100% load), the smoke emission rises sharply. In general, the final soot emission of diesel engines goes through two processes: primary soot and soot oxidation. The primary soot formation in the gas phase is based on the molecular rate of collisions and the concentrations of fuel fragments. In this way, active radical nuclei from fuel molecules aggregate to form bigger nuclei. The process of soot oxidation also depends on gas phase collisions, similar to the soot primary formation, but the molecules contain carbon and oxygen. Oxygen, or OH radicals, penetrate the particle with internal burning and decrease the particle diameter. In addition to temperature, the local concentration of fuel vapor is crucial for the formation rate of soot, and the local concentration of oxygen substantially influences the rate of soot oxidation [19]. The soot thresholds depend on the equivalence ratio and the gas temperature inside the engine cylinder. In general, high temperature of the gas and lack of oxygen in the cylinder may cause high soot formation rates. As the load of the diesel engine increases from 75%



(a) n=1900r/min (b) n=4000r/min

Fig. 1. Smoke emission.

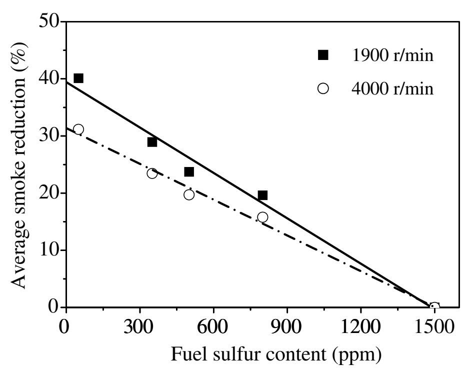


Fig. 2. Smoke reduction and fuel sulfur content.

load to full load at 1900 rpm (the full load at 1900 rpm is the peak torque operating condition), larger fuel injection combined to lack of oxygen in the cylinder contribute to a very quick rise in smoke emission.

At 4000 rpm engine speed, the smoke increase rate is low from low to high load, and the smoke at no-load is higher than at 1900 rpm, but the smoke at high engine load is lower than that at 1900 rpm.

The smoke curve trends of the engine using the five different fuels are similar. The smoke emission has a downward trend with fuel sulfur content for the same engine operating condition. The smoke values with the five fuels at low load are low, so differences among these smoke values are small in vision. Compared to the S1500 fuel, the smoke reduction percentage of the S50 fuel is 49.7% (no-load), 47.5% (at 0.446 MPa, 25% load) and 18.2% (at 1.83 MPa, full load) at 1900 rpm, respectively, and 41.9% (no-load), 35.1% (at 0.319 MPa, 25% load) and 16.5% (at 1.27 MPa, full load) at 4000 rpm, respectively. It indicates that fuel sulfur has more effect on the smoke emission at lower engine load, whereas fuel injection quantity and cylinder temperature dominate the smoke emission at higher engine load.

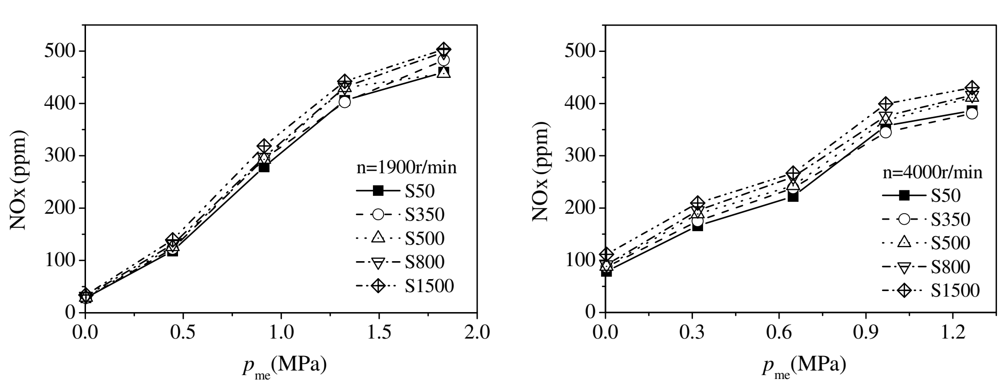
In order to understand the effect of fuel sulfur on the smoke emission, average reduction percentages of engine smoke with different fuels were calculated using the S1500 fuel as a base reference. The calculation method is as follows: for example, comparing the S50 fuel to the S1500 fuel, the smoke reduction ratios at five different loads (0%, 25%, 50%, 75% and 100%, 1900 rpm) with the S50 fuel are 49.7%, 47.5%, 43.7%, 41.8% and 18.2%, respectively. Comparing with the base fuel, the average smoke reduction extent of engine under S50 fuel is the average value of above the five smoke reduction ratios: 40.2%. So, average reduction extents of other fuels (S350, S500 and S800) can be calculated.

The result is shown in Fig. 2. It shows that the smoke value decreases linearly with the fuel sulfur content at 1900 and 4000 rpm of engine speed. It indicates the fuel sulfur content has a direct effect on the engine smoke emission.

3.1.2. NO_x emission

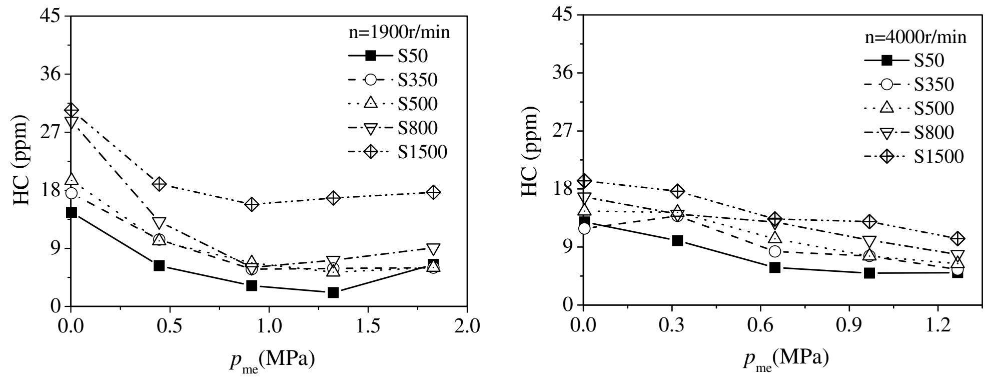
Fig. 3 shows the NO_x emission data of the engine tested with the different fuels. The NO_x emission increases with engine load at the two engine speeds, and the rate of increase at 1900 rpm is higher than that at 4000 rpm.

The NO_x emission curves of the engine using the five different fuels show similar tendency. The NO_x emission has a little downward trend with the fuel sulfur content. The change in NO_x emission



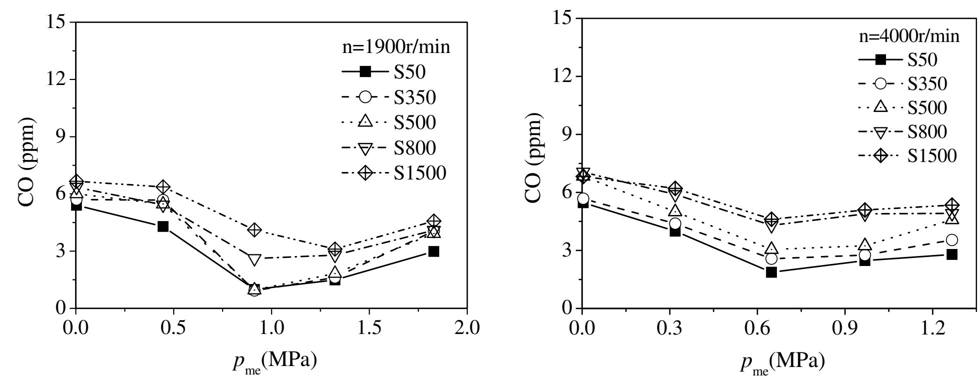
(a) n=1900r/min (b) n=4000r/min

Fig. 3. NO_x emission.



(a) n=1900r/min (b) n=4000r/min

Fig. 4. HC emission.



(a) n=1900r/min (b) n=4000r/min

Fig. 5. CO emission.

is not distinct while fuel sulfur is lower than 500 ppm when compared to the S1500 fuel, and the maximum decrease rate of NO_x emission for the other fuels is 11.2% at 1900 rpm, and 9.1% at 4000 rpm. The reduction could be due to the high cetane number of the S50 fuels that leads to lower combustion premixed phase. This result indicates that the fuel sulfur content has little effect on the NO_x emission.

3.1.3. HC emission

Fig. 4 shows the HC emission of the engine. The HC emission data display valley values with increasing engine load at 1900 rpm. The HC emission is lowest at the intermediate engine load value whereas it increases at the lower and higher engine loads. Under the 50% engine load (n = 1900 rpm), S350, S800 and S1500 fuels show valley values: 5.78, 6.04 and 15.82 ppm, respectively, and under the 75% engine load (n = 1900 rpm), S50 and S500 fuels show valley values: 2.14 and 5.31 ppm, respectively. Compared to the S1500 fuel, the HC reduction ratios of the S50 fuel under the five loads (0%, 25%, 50%, 75% and 100%, 1900 rpm) are 52.1%, 66.7%, 79.6%, 87.2% and 63.3%, respectively. Under lower engine load, fuel injection quantity is small. So, lean fuel–air mixture regions may escape into the exhaust because of poor fuel distribution, large amounts of excess air, and low cylinder temperature. Under higher engine load, the fuel injection quantity is larger, and the fuel–air mixture is too rich to burn at the time of autoignition. It will burn later with additional mixing and provided that the gases are hot enough. However, some hydrocarbons are produced because some of this fuel is not in a stoichiometric air–fuel ratio to burn until late in the expansion stroke. Therefore, the HC emission also increases.

The HC emission decreases with increasing engine load at 4000 rpm. The fuel injection quantity between intermediate and high loads varies less than at 1900 rpm, and the fuel–air mixture and cylinder temperature are more suitable for the combustion process. Therefore, the HC emissions of the engine continuously decrease from intermediate to high load.

The HC emission curves of the engine using the five different fuels are similar. The HC emissions decrease with the fuel sulfur content. Compared to the S1500 fuel, the average reduction ratio of HC emission under the S50 fuel at 1900 rpm is higher than that at 4000 rpm. Maximum HC reduction percentage of the S50 fuel are 87.2% at 1900 rpm and 67.1% at 4000 rpm, with average HC decrease rates of 69.8% and 49.2% respectively. This suggests that the lower the fuel sulfur content, the lower the HC emissions. Maybe it is related to the engine exhaust aftertreatment DOC technology. Lower fuel sulfur content is beneficial to the DOC performance, and could lead to more HC oxidation conversion of the engine.

3.1.4. CO emission

Fig. 5 shows the CO emission of the engine. The CO emission data display valley values with increasing engine load at 1900 and 4000 rpm. The CO emission is lowest at intermediate engine load, and it increases at high and low engine loads. CO emission is an incomplete combustion product. It is generated in diesel engines when operated with a fuel-rich equivalence ratio at high engine load. When there is not enough oxygen to convert all carbon to carbon dioxide (CO_2), some fuel does not get fully burned and some carbon ends up emitted as CO. Local low cylinder temperature and lean fuel–air mixture regions at low engine load may lead to more CO formation and emission.

The CO emission curves of the engine using the five different fuels are alike. The CO emission trends downward with the fuel sulfur content. Compared to the S1500 fuel, the maximum CO reduction rates of the S50 fuel are 75.9% at 1900 rpm and 59.5% at 4000 rpm, with an average CO reduction rates of 45.9% and 42.6%, respectively. This suggests that the lower sulfur content fuel leads to lower CO emission.

3.2. Unregulated emissions

The HCHO, MECHO and SO_2 emissions of the diesel engine are shown in Figs. 6–8.

3.2.1. HCHO emission

HCHO emission could only be measured at no-load operation condition, and its values are very low, most are lower than 1 ppm. It could not be measured over 25% engine load. This indicates that low cylinder temperature leads to HCHO formation. HCHO is an intermediate combustion product, and it decreases sharply as the load and cylinder temperature reaches over a certain threshold value.

3.2.2. MECHO emission

Fig. 6 shows the MECHO emission measured during the engine tests. It is higher than the HCHO emission, and its curve parallels those of the HC emission. The MECHO emission has a valley value

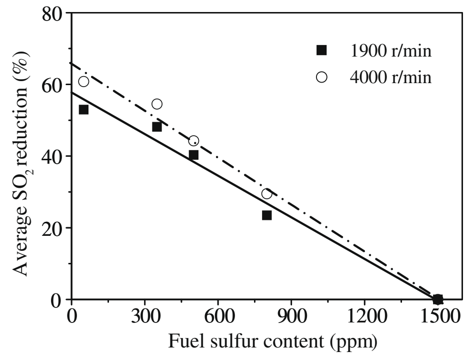
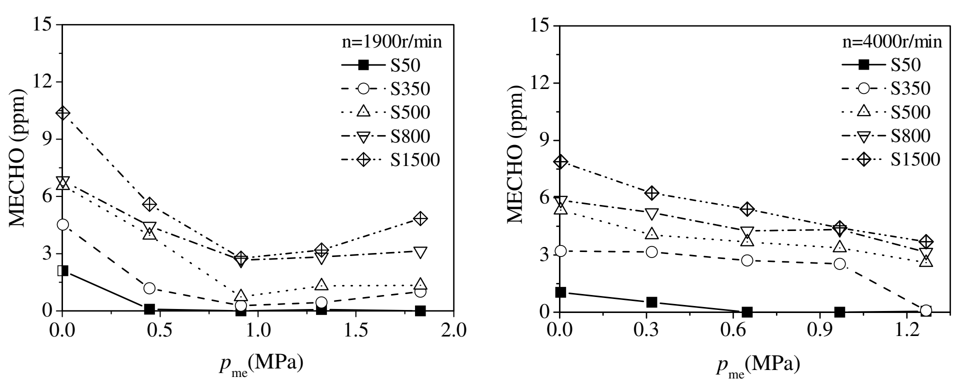


Fig. 8. SO_2 reduction and fuel sulfur content.

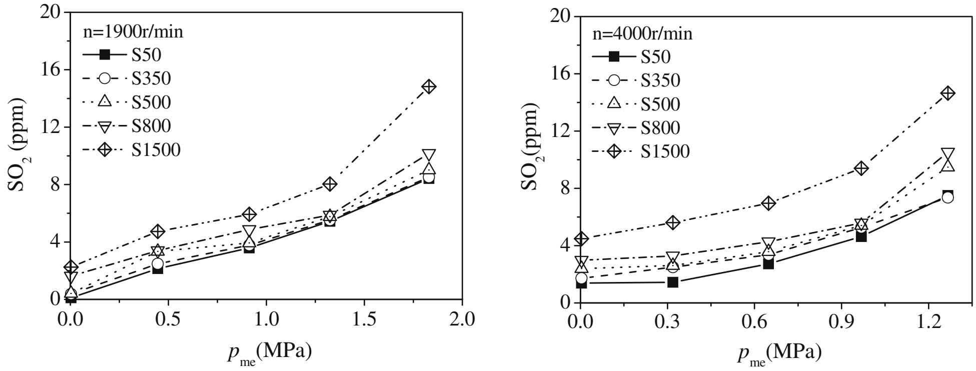
with increasing engine load at 1900 rpm. The MECHO emission is lowest at intermediate engine load, and it increases at high and low engine loads. Low cylinder temperature and lean fuel–air mixture regions at low load may lead to formation of more MECHO. When increasing the engine load, the cylinder temperature rises, combustion is improved, and the MECHO emission decreases. With the engine load continuously increasing, the amount of fuel injected gets larger and richer fuel–air mixture could lead to more MECHO formation [20].

The MECHO emission decreases with increasing load at 4000 rpm. The fuel injection quantity that varies from intermediate to high load is smaller, and fuel–air mixture and cylinder temperature are helpful for the combustion process. Therefore, the MECHO emission continuously decreases from intermediate to high engine loads.



(a) n=1900r/min (b) n=4000r/min

Fig. 6. MECHO emission.



(a) n=1900r/min (b) n=4000r/min

Fig. 7. SO_2 emission.

The MECHO emission curves of the engine using the five different fuels are similar. The MECHO emission decreases with fuel sulfur content. Compared to the S1500 fuel, the average reduction ratio of MECHO emissions using the S50 fuel are high. Average MECHO reduction percentages of the S50 fuel are 95.2% at 1900 rpm and 95.4% at 4000 rpm, respectively. The MECHO emission at some engine operating conditions, using the S50 fuel could not be measured, indicating that the MECHO emission decreases sharply as the engine uses ultra-low sulfur fuel. The reason is similar to the HC emission properties with the five different fuels. The MECHO emission is more unsteady than HC emission, so ultra-low sulfur fuel leads to high performance of DOC that oxidates and reduces more MECHO emission.

3.2.3. SO_2 emission

Fig. 7 shows that the SO_2 emission increase with the engine load. This is obvious because that the small fuel quantity in the cylinder at low engine load leads to small sulfur concentration in the air–fuel mixture, and low SO_2 emission in the engine exhaust. The SO_2 emission would increase with more fuel injected in the cylinder.

The SO_2 emission curves of the engine using the five different fuels are similar. The SO_2 emissions decrease with the fuel sulfur content. Except for the S1500 fuel, the concentrations of the SO_2 emissions of the engine using the other four fuels are similar, especially at higher engine load at 1900 rpm. This is explained by the fact that the DOC also converts SO_2 emission to sulfate and its value decreases. From intermediate to high load at 1900 rpm, the high exhaust temperature of engine is helpful for the conversion of SO_2 emission. The SO_2 emission is converted to sulfate, and may lead to more PM or smoke emissions.

The average reduction extent of SO_2 emission with the five different fuels is calculated using the S1500 fuel as the base fuel. The same calculation method used for the smoke emission was used here. The result is shown in the Fig. 8. It shows that the SO_2 emission decreases linearly with descending fuel sulfur at 1900 and 4000 rpm. It indicates fuel sulfur directly effects on the engine SO_2 emission.

4. Conclusion

Five fuels with different sulfur content were used on a light-duty diesel engine. Emissions of regulated and unregulated pollutants of the engine using these five fuels were studied. The results show that:

(1) The engine smoke value significantly decreases and linearly with the fuel sulfur content. Fuel sulfur content has more effect on the smoke emission at lower engine load, but fuel injection quantity and cylinder temperature dominate the smoke emission at higher engine load.
(2) The fuel sulfur content has little effect on the NO_x emission.
(3) The concentrations of HC and CO emissions from the engine are lowered significantly with decreasing fuel sulfur content. Comparing to the S1500 fuel, the average reduction percentages of HC and CO emissions using the S50 fuel are both more than 40%.
(4) The concentrations of MECHO emission of the engine decrease with the fuel sulfur content. The HCHO emission could not be measured above 25% engine load with the five fuels. The MECHO emission pattern under the engine test conditions parallels that of the HC emission, and the MECHO emission at intermediate and high engine loads of the engine using the S50 fuel could not be measured.
(5) The SO_2 concentration increases with the engine load. The curve relating the SO_2 emission and engine load are similar for all the tested flues, and it decreases linearly with the fuel sulfur content.

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