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Effects of Fuel Quality on Euro IV Diesel Engine With SCR Aftertreatment

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ABSTRACT

Beijing will implement the 4th stage emission regulations (equivalent to Euro IV) in 2008 ahead of other provinces or cites in China. Beijing Environmental Protection Bureau (EPB) organized petroleum corporations, automobile and engine manufactories as well as research institutes to test the adaptability of the fuels from Chinese refineries to the modern vehicles or engines on the road running conditions in China. In this paper, the effects of diesel fuel quality on combustion and emission of an Euro IV heavy-duty diesel engine as one part of the program were studied to provide technical data to stipulate the feasible diesel fuel standard, which should guarantee modern vehicles or engines to meet the 4th stage regulations.

Eight kinds of diesel fuels with different properties, such as cetane number, distillation temperature (T90) and sulfur content, were tested on the Euro IV Cummins heavy-duty diesel engine with urea SCR after-treatment. Engine power, fuel economy, and ESC cycle emissions (NOx, CO, HC) before and after SCR were measured. The gaseous SO_2, total PM and SOF, DS, sulfate in PM were analyzed. Heat release rates were calculated to analyze in-cylinder combustion variation resulting from the changes of the fuel properties.

The test results show that diesel properties have little effect on power, fuel consumption, and heat release rate of the engine; sulfate in PM and gaseous SO_2 emission increase linearly with sulfur content; with the increase of cetane number, BSFC and PM decrease slightly, while NOx slightly increases; with the decrease of T90, NOx decreases, and PM shows trend of slight decrease.

Base on the experimental data from ESC cycle, the empirical formula of NOx and PM emissions before SCR changing with the sulfur content, cetane number, aromatics and T90 were obtained using the linear regression method.

INTRODUCTION

With the issue of more and more stringent automobile emission standards, more attention is being paid to the effects of fuel quality on engine performance. In the United States, Europe, and Japan, the governments have been funding oil related programs and organizing petroleum corporations, automobile and engine manufactories to study the effects from 1990s to the present. Also a lot of independent research institutes, automobile and engine manufactories, and petroleum corporations have their own researches on the correlation of fuel quality and engine performance. The researches mainly focus on some important properties of diesel fuel, such as sulfur content, cetane number, T90/T95, aromatics, and so on. Based on the test results, automobile and engine manufactories published serial versions of Worldwide Fuel Chapter[1], which show a good reference for stipulating the fuel standard. But all of the programs and results did not cover the fuels refined in China and its match with vehicles and engines on the road running conditions in China.

In China, the 3rd stage national emission standards will start from July 1st 2008 (delayed one year) and the 4th stage standards will begin from July 1st 2010. And Beijing will implement the 4th stage emission standard (equivalent to Euro IV) from 2008 in advance in China, but the corresponding diesel and gasoline fuel standards have to be set down before 2008. Therefore, Beijing Municipal Science & Technology Commission funded a project “Research of Relationship Between Beijing 4th Stage Fuel Properties and Emissions”, also known as China “Auto-Oil” program and entrusted Beijing EPB to organize petroleum corporations, automobile and engine manufactories, universities and institutes working together for the program, to analyze the effects of fuel properties on modern engines and after-treatments. Tsinghua University was in charge of the study of relationship between the fuel quality and emissions through engine bench test.

In this paper, on the basis of review of existed test results in the world, the effects of sulfur content, cetane number, and T90 on power, fuel consumption, emissions, and in-cylinder combustion process were studied on the Euro IV Cummins heavy-duty diesel engine with urea SCR after-treatment. Also the empirical formula of NOx and PM emission before SCR changing with sulfur content, cetane number, aromatics and T90 were deduced using the linear regression method.

LITERATURE REVIEW

Influence of the fuel properties on diesel engine performance is quite complicated due to the fact that these properties tend to be strongly inter-correlated. To get effective data, care must be taken to decouple the change in a particular fuel property from other properties. And different tests show different effects of the fuel properties on engine performance with different technologies and different test cycles,

Sulfur — Sulfur exists naturally in crude oil. Generally, sulfur has no effect on gaseous emissions [2,3], but sulfur can form sulfate particulate matter in the exhaust and atmosphere. No matter how much sulfur is, what kind of sulfur form exists and what type of engine is, 1%~3%[1,4,5,6] of the sulfur in diesel fuel would be converted into sulfate as one part of PM. Nearly all sulfur in fuel is oxidized to SO_2 during combustion, and about 50% of the SO_2 is again oxidized in atmosphere to form the secondary atmospheric sulfate [4], increasing total particulates in the air.

Cetane Number — For diesel engines with high NOx emission, the NOx reduces with the increase of cetane number [7,8]. But for the engines with low NOx, cetane number has little effect on NOx[7,9,10,11,12,13]. Effects of cetane number on PM is different for different engines, and cetane number shows little effects on PM in most programs [9,10,11,13]. In some research, PM shows a trend of increase [7] with the increase of cetane number, but in some research, it shows a trend of decrease[10]. The increase of cetane number per unit causes 0.5% decrease of NOx in average (changing range: -1% to + 1%), and 1% decrease of PM in average (changing range: -3% to +2%). The Worldwide Fuel Chapter concluded that cetane number has significant influence on NOx [1], showing that the increase of cetane number from 50 to 58 causes less than 10% decrease of NOx,.

T90/T95 — With the decrease of T90/T95, NOx and PM show different trends of decrease [9], or increase [9,13], or constant [9] for different programs. The decrease of T90/T95 per 10℃ causes 0.5% decrease of NOx in average (changing range: -1% to +1%), and 0.5% increase of PM in average (changing range: -2% to +3%). The Worldwide Fuel Chapter concluded that exhaust gas emissions from heavy duty diesel engines are not significantly influenced by T95-variations, but a trend of low NOx with low T95 was observed [1].

Aromatics — With the increase of aromatics in diesel fuel, NOx changes slightly [7,10,12,13,14], and shows a trend of increase in some researches [7,14]. PM mainly keeps constant [7,10,12,13,14], and in some researches shows the trends of increase [10,14] or decrease [7]. The increase of aromatics per 5% causes 3% increase of NOx in average (changing range: 0% to +15%), and 1% increase of PM in average (changing range: -9% to +15%). The Worldwide Fuel Chapter concluded that the decrease of aromatics could significantly lower NOx emission [1], showing that 5% decrease of NOx was achieved by the reduction of aromatics from 30% to 10%.

Modern technologies applied for heavy-duty diesel engines to meet Euro IV standard are high-pressure common rail multi-injection, turbo-charging, inter-cooling, EGR, combining with SCR or DPF after-treatments. But the test results above mentioned were obtained mainly on the diesel engines meeting Euro II or equivalent U.S. and Japan standards, little tests were based on Euro IV engines. There are significant differences of the technologies between Euro IV diesel engine and Euro II one, so the results from Euro II engines can't be used directly to analyze Euro IV diesel engines.

In the past, China had little research on the relationship between fuel properties and emissions, which brought a lot of difficulties for Chinese government to establish its own fuel standards reasonably.

EXPERIMENT SETUP

EXPERIMENTAL FACILITIES

The test engine is Cummins ISBe4 140 direct injection diesel engine with urea SCR after-treatment, meeting Euro IV standard. The engine specification is shown in Table 1.

Table 1 Engine specifications

Engine Model	Cummins ISBe4 140
Type	4-stroke, in-line, turbo-charging, intercooling, direct injection
Cylinder number	4
Displacement (L)	4.5
Compress ratio	17.3
Rated power/speed	103 kW / 2500 $r \cdot min^{-1}$
Max toque/speed	550 $N \cdot m$ /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, THC, CO, and CO_2 are measured by AVL CEB-II exhaust gas analyzer. SO_2 is measured by 43C pulsed fluorescence SO_2 analyzer of American Thermo Electron corporation. PM is sampled on filter paper (TX40HI20-WW of PALL Corporation) by AVL SPC-472 partial flow diluter smart sampler. The filter papers 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%. SOF and sulfate are extracted from PM using dichloromethane (CH_2Cl_2) and de-ionized water, separating the PM into three parts: SOF, sulfate and DS. In-cylinder pressure is measured using pressure sensor of Kistler and encoder, and the heat release rate is calculated using AVL Boost software.

TESTED FUELS

Eight different diesel fuels as shown in Table 2 were tested. 1# and 6# diesel fuels have the same fuel properties except cetane number and sulfur content, while 3# and 4# diesel fuels have the same fuel properties except T90 and sulfur. Sulfur in diesel fuel mainly influences sulfate in PM and gaseous SO_2

emission, but has no direct influence on power, fuel consumption and other gaseous emissions. Therefore, the effects of sulfur content, cetane number, and T90 on the engine performance can be analyzed directly from experimental results.

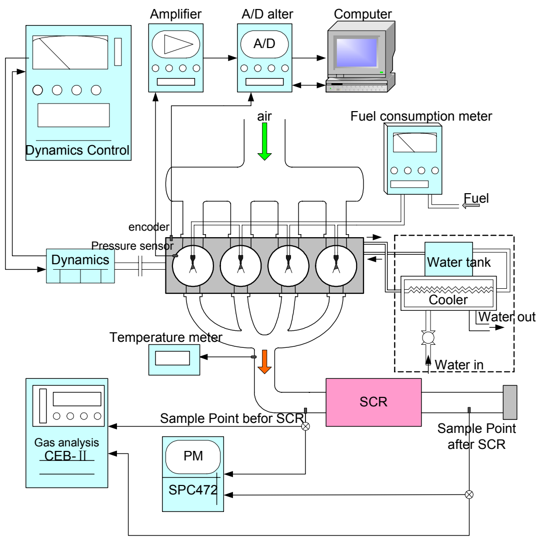


Figure 1 Schematic diagram of engine bench

TEST RESULTS

The engine performance under full load, part load at 1500r/min and ESC cycle using different fuels was tested without any adjustment of the engine.

POWER AND FUEL CONSUMPTION

The full load torque of the engine using different fuels is shown in Figure 2 and the brake specific fuel consumption (BSFC) of part load at 1500r/min is shown in Figure 3. From the figures, it can be seen that the power difference of the engine using fuels with different cetane number, aromatics, T90 is less than 1%, and the BSFC difference is less than 3%. This means that the fuel properties have little influence on power and fuel consumption of the Euro IV diesel engine.

Table 2 Properties of tested diesel fuels

	1#	2#	3#	4#	5#	6#	7#	8#
T90，℃	355	318.1	317.5	299.4	330	355	333.8	329
FBP，℃	365	343.3	343.8	340	342	365	346.5	343
Sulfur (ppm)	190	42	111	214	510	520	45	30
Cetane Number	51.9	64.3	64.8	65.1	47.9	55.9	50.1	51.2
Aromatics, %(v/v)	10	5.8	6.1	5.4	11	11	--	8.5
Density(20℃), kg/m^3	835.0	809.8	809.8	810.0	842.5	832.2	838.4	833.8

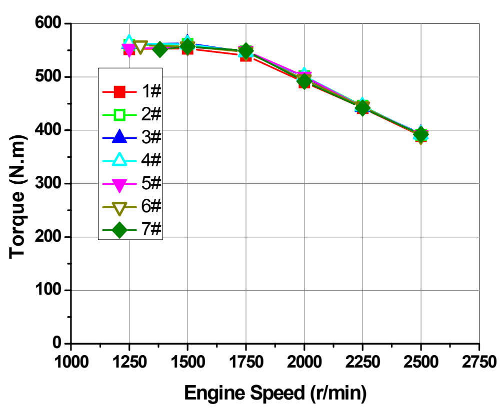


Figure 2 Full load torque with different fuels

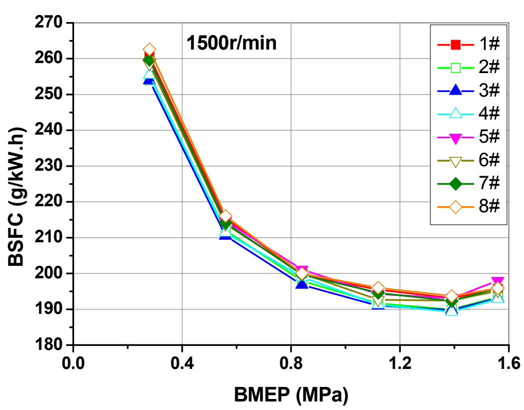


Figure 3 Fuel consumption with different fuels

SULFUR

Effects of sulfur on sulfate — Sulfur mainly influences sulfate in PM and gaseous SO_2 emission, and has no effect on power, fuel consumption and non-sulfur emissions of diesel engine. Since other fuel properties except sulfur have no direct effect on sulfate and SO_2, therefore sulfur can be actually decoupled with other properties and analyzed. PM emission of the engine in ESC cycle using different diesel fuels are shown in Figure 4. From the figure, it can be seen that PM increases with the increase of sulfur in fuels. SOF and DS in PM change slightly, while sulfate increases almost linearly with sulfur content.

The sulfate in PM changing with sulfur content in ESC cycle and at 1500r/min part loads before SCR are shown in Figure 5. The dot points in the figure are tested sulfate emissions, the lines are linearly regressed results of sulfate changing with sulfur in fuels under different conditions. It can also be observed that sulfate in PM increases linearly with sulfur in fuels. According to the data of ESC cycle, the sulfate emission of the fuel with 500ppm sulfur content is about 0.008g/kW.h, which takes 40% of Euro IV standard PM limit value.

The mass percentages of three PM components of 2# fuel with 42ppm sulfur and 5# fuel with 510ppm sulfur before SCR are shown in Figure 6. From the figure, it can be found that the sulfate percentage in PM rapidly increases with the increase of sulfur content. With the increase of sulfur content from 42ppm to 510ppm, the mass percentage of sulfate in PM increases from 4% to 24%.

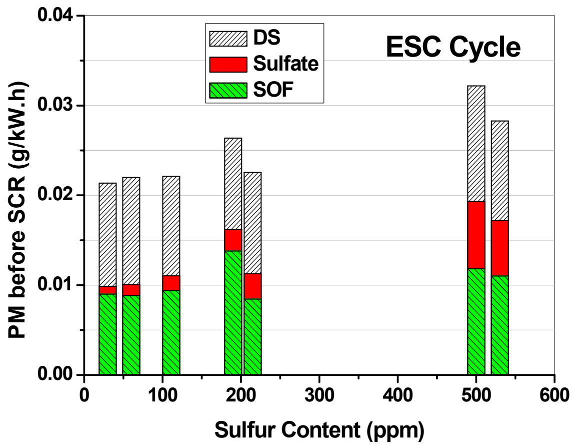


Figure 4 Sulfur's effect on PM emission (ESC cycle)

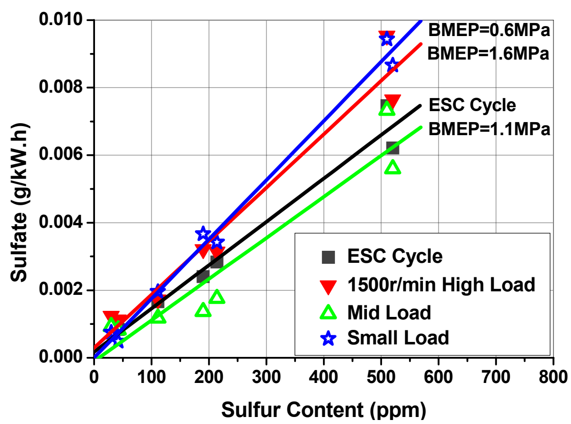
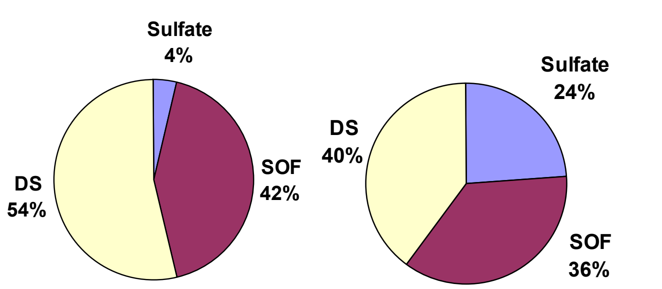


Figure 5 Sulfur's effect on sulfate in PM (before SCR)



(a) S42 (b) S510

Figure 6 Sulfur's effect on mass percentage of PM components (ESC Cycle, before SCR)

The literature [4] considered that the sulfate form in PM from diesel engines is equivalent to $H_2SO_4 \cdot 5.3H_2O$, so the conversion rate of sulfur to sulfate can be calculated according to equation (1) as follows. Where, 6 is the weight increase factor of sulfur to sulfate.

$$\text{Conversion Rate} = \text{Sulfate} / (\text{BSFC} \times \text{Sulfur Content} \times 6) \tag{1}$$

The conversion rates under 1500r/min part load conditions are calculated to be 1%~2% according to sulfate in PM, BSFC, and sulfur content of fuels. The conversion rate keeps constant for each condition.

Effect of sulfur on SO_2 — Gaseous SO_2 emissions of three different diesel fuels (2#, 3#, and 4# diesel fuel) under 1500r/min part load conditions were tested by the pulsed fluorescence SO_2 analyzer, and test results are linearly regressed as shown in Figure 7. From the figure, it can be seen that SO_2 before SCR increases linearly with the increase of sulfur content, but the regressed lines don't pass zero point of the ordinate, which may be caused by the error of measurement. The increase of gaseous SO_2 emission can result in an increase of secondary atmospheric sulfate particulate.

From the figure, we can also see that SO_2 emission reduces with the increase of engine load. Since 98% of sulfur in fuels is emitted to atmosphere as gaseous SO_2, thus SO_2 emission is proportional to BSFC. As shown in Figure 3, BSFCs of three SO_2 measure conditions decrease with the increase of BMEP, which means SO_2 emission is reduced with the increase of load..

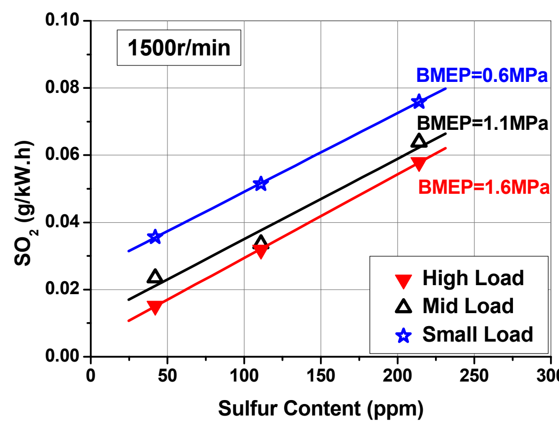


Figure 7 Sulfur effect on gaseous SO_2 (before SCR)

Forecast of sulfur's effects on engine-out and secondary atmospheric sulfate particulates — The conversion rate of sulfur in fuels to sulfate in PM is about 1%~3%. The effect of diesel sulfur content on sulfate in PM from diesel engines in ESC cycle can be forecasted according to equation (2). Averaged BSFC of ESC cycle is taken to be 250g/kW.h, the forecast of sulfate emission in ESC cycle changing with sulfur content is shown in Figure 8.

$$\text{Sulfate} = \text{Conversion Rate} \times \text{BSFC} \times \text{Sulfur Content} \times 6 \tag{2}$$

As shown in Figure 8, the sulfate emission of the diesel fuel with 670ppm sulfur would be 0.02g/kW.h, which is the PM limit value of Euro IV and Euro V standard. For Chinese national 3rd stage standard of diesel fuel with 350ppm sulfur, the sulfate emission in ESC cycle would be 0.01g/kW.h in average, which is about 50% of PM limit value in Euro IV standard. For Euro IV diesel fuel with 50ppm sulfur, the sulfate emission in ESC cycle is about 0.0015g/kW.h, less than 10% of Euro IV standard's PM limit value.

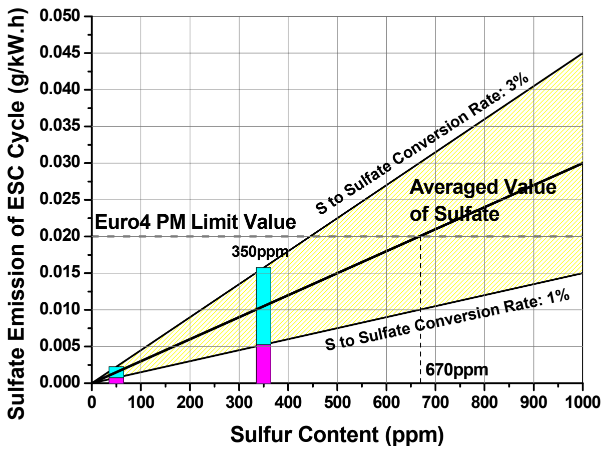


Figure 8 Forecast of sulfur's effect on sulfate emission (ESC Cycle)

As we know, 98% of sulfur in diesel fuel is emitted into atmosphere as gaseous SO_2, about 50% of which forms secondary atmospheric sulfate particulate through chemical reactions. The total mass of secondary sulfate is about 25 times that of engine-out sulfate. Similar to equation (2), the secondary sulfate particulate can be estimated by equation (3).

$$\text{Secondary Sulfate} = 50\% \times \text{BSFC} \times \text{Sulfur Content} \times 6 \tag{3}$$

The engine-out and secondary atmospheric sulfates in ESC cycle can be forecasted according to equation (2) and (3), as shown in Figure 9. Including the secondary atmospheric sulfate caused by sulfur in fuels, the total sulfate emission of diesel fuel with 150ppm sulfur would exceed the PM limit value (0.1g/kW.h) of Euro III standard.

Reduction of diesel fuel's sulfur content can decrease not only the engine-out PM but also the secondary atmospheric sulfate particulate, which will have a great contribution to the improvement of atmosphere environment.

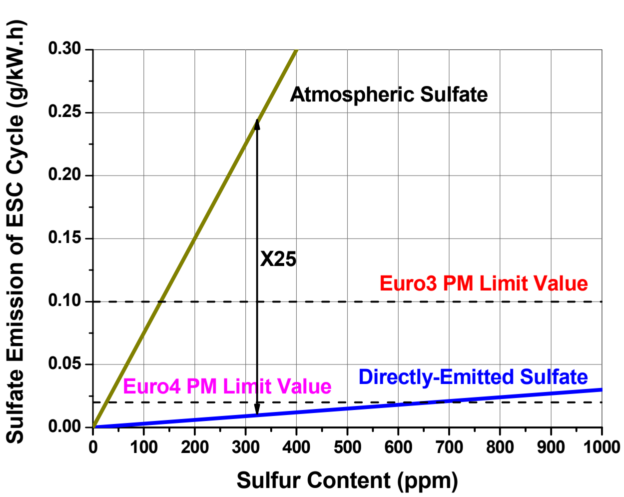


Figure 9 Forecast of sulfur's effect on engine-out and atmospheric sulfate emissions (ESC Cycle)

CETANE NUMBER

Fuel Consumption — The fuel consumptions of two diesel fuels with cetane number of 52 and 56 respectively (cetane number is decoupled with other fuel properties) at 1500r/min part load are shown in Figure 10. The BSFC of 1# diesel fuel with cetane number of 52 is slightly higher than that of 6# diesel fuel with cetane number of 56.

The fuel consumptions of seven diesel fuels with different cetane numbers at 1500r/min part load are shown in Figure 11, the points are test results and the lines are linearly regressed results. From the figure, it can be seen that the increase of cetane number from 48 to 65 causes about 3% decrease of BSFC, which means the increase of cetane number per unit will cause about 0.2% reduction of BSFC of the Euro IV diesel engine in average.

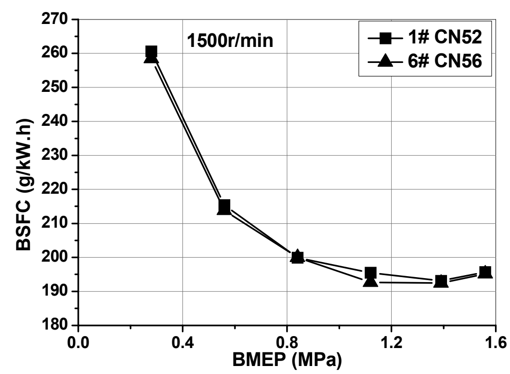


Figure 10 BSFC of fuels with different cetane numbers

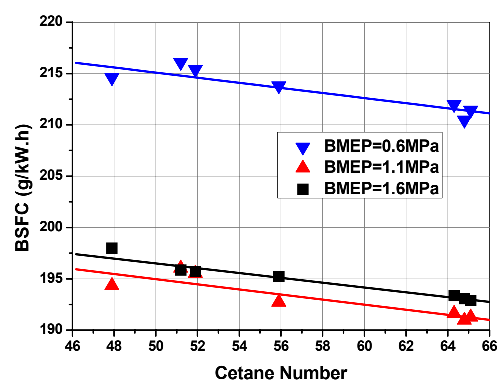


Figure 11 Cetane number's effect on BSFC

Emissions — NOx and PM emissions of 1# and 6# diesel fuels with cetane number of 52 and 56 respectively in ESC cycle before SCR are shown in Figure 12. When cetane number increases from 52 to 56 while other fuel properties keep constant, NOx of the engine slightly increases (about 2%) and PM decreases about 5% for same fuel sulfur content due to the 20% decrease of SOF. The increase of cetane number per unit causes about 0.5% increase of NOx, and about 1% decrease of PM in average. These trends are agreed well with the test results of completed programs. Our test results on Cummins ISBe6 Euro III diesel engine also show that, with the increase of cetane number, PM increases while NOx changes slightly without obvious trend [15]. The influence of cetane number on Euro IV and Euro III diesel engine isn't uniform for their different calibration strategies.

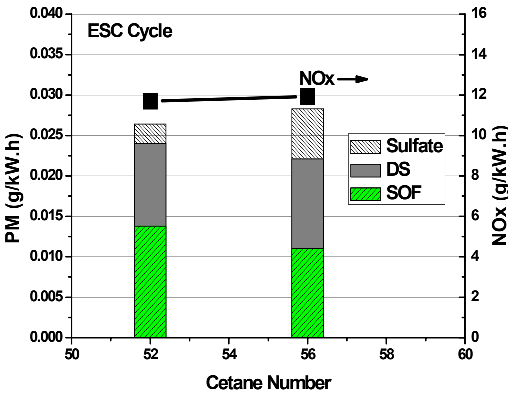
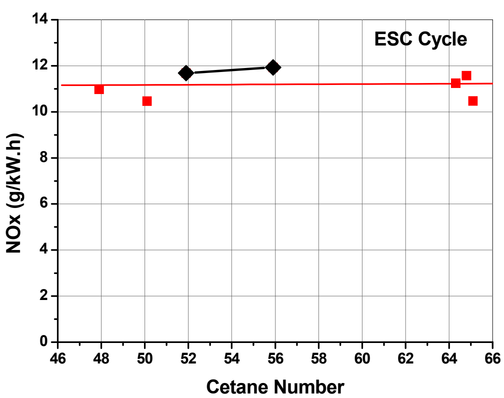
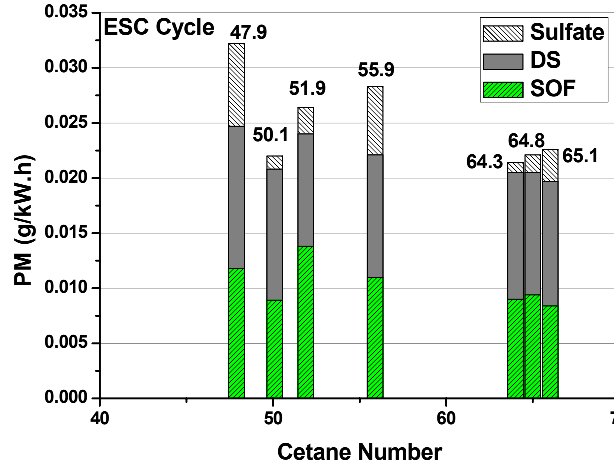


Figure 12 Cetane number's effects on NOx and PM (ESC Cycle)

Figure 13 shows NOx and PM emissions of seven diesel fuels with different cetane number in ESC cycle before SCR. The points in the figure are test results while the lines are linearly regressed results. Generally, the increase of cetane number has no obvious effects on NOx. The NOx emission can be decreased with the increase of cetane number in theory. The tested NOx changing trend may be caused by pilot injection technology, and the influence of cetane number on NOx is different for different diesel engines.



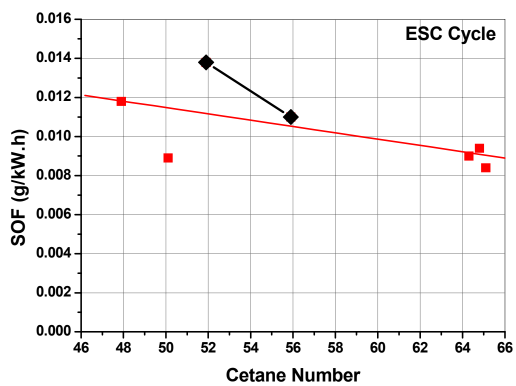
(a) Cetane number's effect on NOx



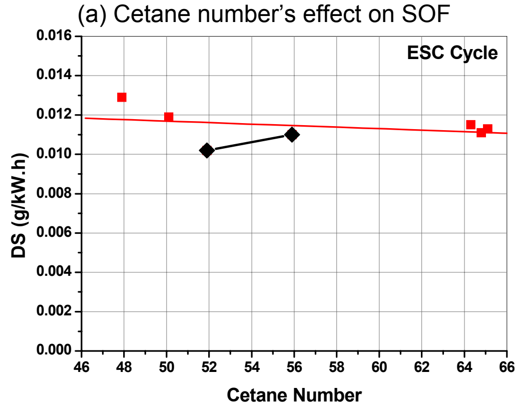
(b) Cetane number effect on PM

Figure 13 Cetane number's effects on main emissions of Euro IV diesel engine (ESC Cycle)

PM decreases with the increase of cetane number generally, but in Figure 13 the sulfur content difference of seven tested diesel fuels causes the variation of sulfate in PM, which influences of the changing trend of PM with cetane number. For further analysis, cetane number's effects on SOF and DS emissions are shown in Figure 14. With the increase of cetane number, SOF in PM decreases while DS basically keeps constant, so non-sulfate PM reduces.



(a) Cetane number's effect on SOF



(b) Cetane number's effect on DS

Figure 14 Cetane number's effects on SOF and DS (ESC Cycle)

Rate of Heat Release — In-cylinder pressure of seven diesel fuels was sampled under 1500r/min mid load condition, and processed to get the heat release rate. In-cylinder pressure, rate of heat release, and accumulated heat release of four diesel fuels with obviously different cetane numbers (64, 56, 52 and 48) are shown in Figure 15. The pilot-injection stage is obviously observed with the first peak of ROHR in the figure. Also it can be seen that the ignition point of pilot-injection is advanced for diesel fuels with higher cetane number. The pilot-injection ignition point of diesel fuel with cetane number of 64 advances 0.5~1°CA compared to the fuel with cetane number of 52 and 56, and advances 1~1.5°CA compared to the fuel with cetane number of 48. It seems the cetane number has little effect on ignition point of main combustion process, combustion duration, and shape of heat release.

Since the Euro IV diesel engine uses pilot-injection technology, the cetane number changing in the range of 48 to 65 has little effect on in-cylinder heat release process, thus the cetane number has also little effect on power, fuel consumption, and NOx emission of the engine. The diesel fuel with higher cetane number has better ignition characteristics and makes combustion more complete, resulting in less HC and SOF emissions.

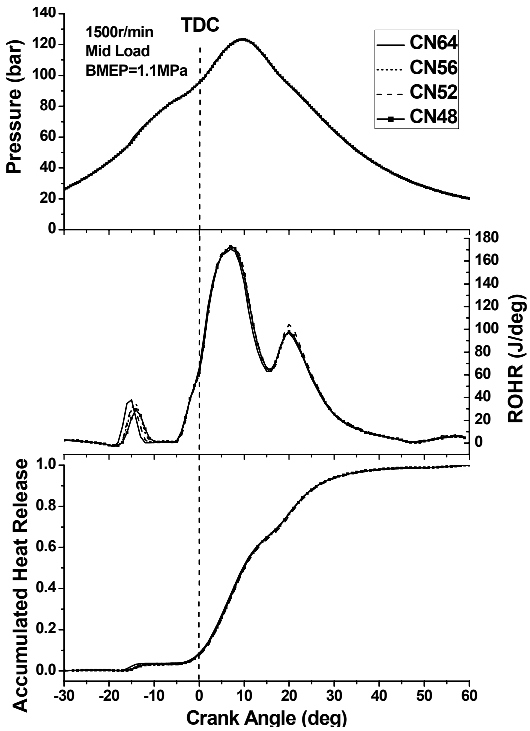


Figure 15 Cetane number's effects on in-cylinder pressure and ROHR

T90

The fuel consumptions of 3# and 4# diesel fuels with T90 of 318℃ and 300℃ at 1500r/min part load are shown in Figure 16. The BSFC variation of different T90s is less than 1%, and shows no obvious trend when T90 changes in the range of 300℃～318℃, which means that T90 has little effect on fuel consumption.

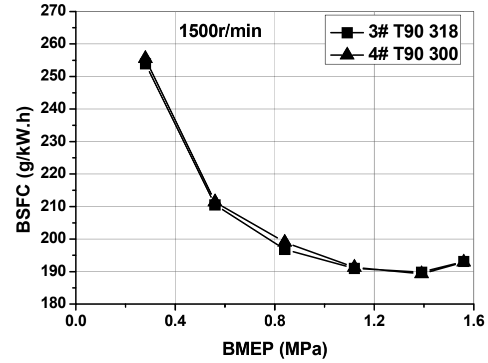


Figure 16 T90's effects on BSFC

Effects of T90 on NOx and PM of the engine in ESC cycle are shown in Figure17. The decrease of T90 from 318℃ to 300℃ causes 5% reduction of NOx and slightly decrease trend of PM. In PM, DS keeps constant while SOF shows trend of slightly reduction. The decrease of T90 per 10℃ causes 3% decrease of NOx and slightly decrease trend of PM. These trends are similar to the test results of completed programs.

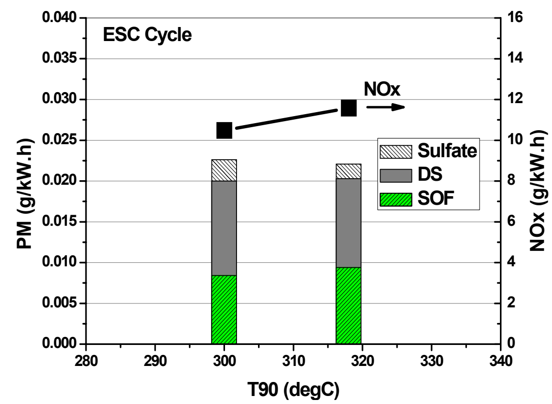
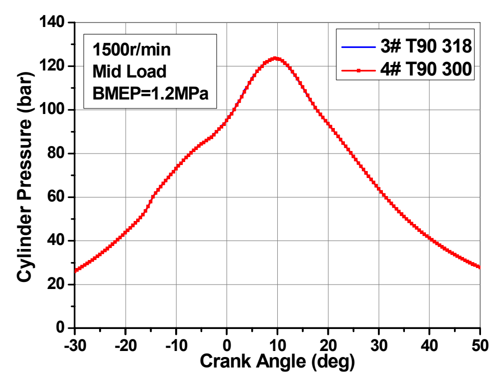


Figure 17 T90 effects on NOx and PM (ESC Cycle)

In-cylinder pressure and rate of heat release of diesel fuels with different T90s at 1500r/min mid load are shown in Figure 18. From the figure, it can be found that the decrease of T90 from 318℃ to 300℃ has little effect on ignition point, combustion duration and shape of heat release.



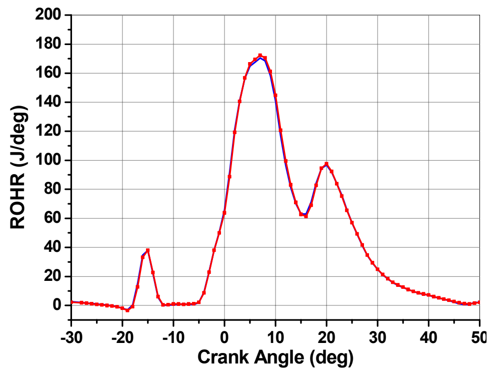


Figure 18 T90's effects on in-cylinder pressure and ROHR

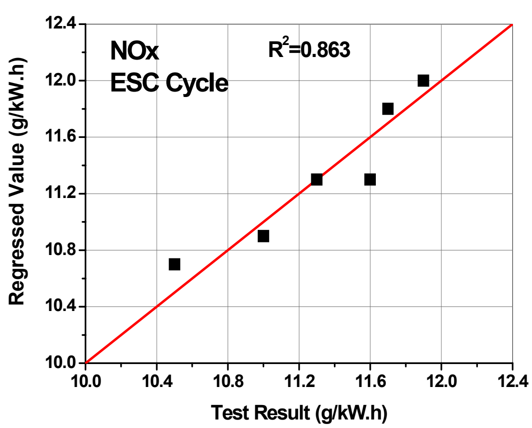
EMPIRICAL FORMULA OF EURO IV ENGINE EMISSION CHANGING WITH FUEL PROPERTIES

Based on the experimental data of the Euro IV diesel engine in ESC cycle, the empirical formula of the engine's NOx and PM emissions before SCR changing with sulfur content, cetane number, aromatics and T90 were obtained using the linear regression method. The formulas and correlation coefficient R^2 between regressed value and test result are shown as equation (4) and (5). Comparison of NOx and PM between tested results and regressed values are shown in Figure 19. It can be found that the regressed values are similar to tested results, and the correlation coefficients of R^2 are larger than 0.85.

$$NOx = -1.16 + 0.0137*Aro + 0.029*T90 + 0.0481*CN \quad R^2=0.863 \qquad (4)$$

$$PM = 0.027 + 0.00002*Aro + 0.000022*T90 - 0.000215*CN + 0.000013*S \quad R^2=0.95 \qquad (5)$$

Where, emissions' unit: (g/kW.h); CN: cetane number; S: sulfur content (ppm); Aro: aromatics content (%v/v); T90: 90% distillation temperature (℃).



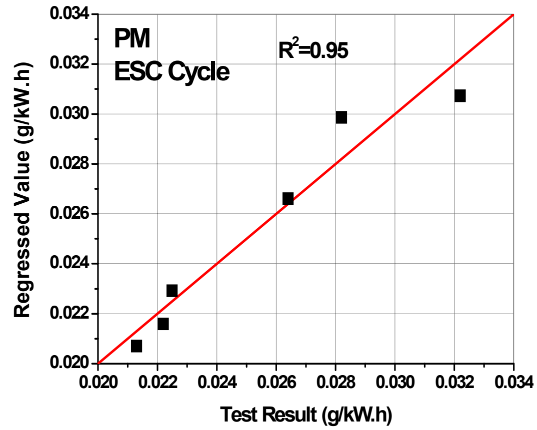


Figure 19 Comparison of NOx, PM test result and forecast value

It can be seen from the formula that, NOx increases with the increase of cetane number, T90 and aromatics; PM increases with the increase of sulfur content, T90, aromatics, and the decrease of cetane number. These trends agree well with engine bench's test results.

CONCLUSIONS

Effects of diesel fuel quality on power, fuel consumption, emissions, and in-cylinder combustion process of the Euro IV engine have been studied through engine bench experiments. Based on the test results, it can be concluded as follows:

(1) Influence of the variation of diesel fuel properties on power and fuel consumption is small within the range of 1% and 3% respectively.

(2) Sulfur has large effect on PM emission of the engine. The sulfate in PM and gaseous SO_2 emissions increase linearly with the increase of sulfur content in fuels. The conversion rate of sulfur into sulfate is about 1%~2%. The sulfate emission of the fuel with 500ppm sulfur in ESC cycle is about 40% of Euro IV PM limit value. The secondary atmospheric sulfate particulate is about 25 times that of engine-out. Considering the first and secondary sulfate together, the total sulfate of the fuel with 150ppm sulfur is larger than the PM limit value of Euro III. Therefore the sulfur content in fuels should be reduced greatly.

(3) With the increase of cetane number, the BSFC and PM of Euro IV diesel engine are slightly reduced, but NOx slightly increased. The increase of cetane number per unit causes 0.2% reduction of BSFC, 0.5% increase of NOx, 1% reduction of PM. DS in PM keeps constant while SOF reduces 2.5%. Higher cetane number makes more ignition advance of pilot injection, and has little effect on combustion duration and shape of heat release.

(4) With the decrease of T90, the BSFC of Euro IV diesel engine has no obvious variation, but NOx reduces, and PM shows the trend of slightly decrease. The decrease of T90 per 10℃ causes 3% reduction of NOx

emission. T90 has little effect on ignition point, combustion duration, and shape of heat release.

(5) Empirical formula of NOx and PM emissions from the Euro IV diesel engine before SCR changing with sulfur content, cetane number, aromatics and T90 were obtained using the linear regression method. The forecasted results show a good agreement with the test data.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

BMEP: Brake mean effective pressure

BSFC: Brake specific fuel consumption

DS: Dry soot

HC: Hydrocarbons

NOx: Nitrogen oxides

PM: Particulate matter

ROHR: Rate of heat release

SOF: Soluble organic fraction

TDC: Top dead center