Correlation study of fuel injection strategies on engine emission and lubricating oil performance

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Abstract. Based on different fuel injection strategies, this paper analyzes the factors such as engine original emission smoke, exhaust temperature, soot content, wear spot diameter and kinematic viscosity. The study found that delaying injection timing, increased afterburn, engine original soot emissions, exhaust gas temperature increase, but will increase the thermal load of the parts. At the same time, the growth rate of lubricant soot and kinematic viscosity increased; The wear spot diameter at the same soot content is reduced, and the wear is reduced. In the end, the paper finally selects 1°CA BTDC as the optimal fuel injection strategy to achieve rapid aging of engine lubricating oil in order to complete the assessment of the anti-wear performance of lubricating oil.

1 Background

The lubricating oil performance of each friction pair in the engine has an important influence on the vehicle's emission, economy and durability. However, at present, there is little research on the engine's original discharge and lubricating oil performance. There is a lack of methods for the rapid generation of lubricating oil soot and evaluating the anti-wear performance of lubricating oil. The friction speed, temperature and load of the friction pairs in the engine are changing with time. So the lubrication oil state of the engine is also changing constantly. The internal combustion engine is developing towards high power and high torque. The temperature and pressure in the cylinder are increasing continuously, which leads to the worse working environment[1]. Poor lubrication oil performance will not only cause excessive friction and wear, but also increase fuel consumption. In severe cases, it will cause excessive wear of engine wear parts and even lead to engine cylinder pulling. According to the actual operation characteristics of the engine, the selection of suitable lubricating oil has a direct effect on the performance of the engine. At present, domestic diesel engine lubricating oil specification uses the American Petroleum Institute (API) specification[2-8]. OEM proposes that the US API specifications are no longer suitable for the needs of domestic diesel engine manufacturers for long oil change intervals, user convenience, and reduced maintenance costs. Therefore, it is of great significance to establish and perfect the standard system of Chinese autonomous lubricating oil, according

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to the characteristics of engine, post-treatment technology, road working condition and fuel oil in China[9-15].

The EGR technology is widely used in China and overseas to make the content of lubricating oil soot increase rapidly. As shown in Table 1, the Mack T11 in the US API specifications and the Cummins ISM and ISB engines both use increased EGR rates to achieve rapid soot growth. But domestic heavy-duty diesel engines do not use EGR technology[16-18].

Table 1. Selected bench tests of American API engines.

Project	CI-4	CJ-4
Piston ring - cylinder liner wear	Mack T10(EGR)	Mack-T12
Viscosity increases due to the soot	Mack T8E	Mack T11(EGR)
Low Temperature Performance of Used Oil	Mack T10A	Mack T11A
Sludge/tappet wear/filtration	Cummins M11(EGR)	-
Sludge/tappet wear/filtration	-	Cummins ISM (EGR+DPF)
Wear of rolling and sliding valves	-	Cummins ISB (EGR+DPF)
High temperature oxidation	IIIF	IIIF/IIIG
Rolling follower corrosion	RFWT	RFWT
Air release	EQAT	EQAT

In this paper, the engine bench test was used to simulate the state of engine lubricant when the vehicle traveled to 100,000 kilometers,by changing the injection strategy to achieve the accelerated generation of engine soot. In the lubricating oil bench test, the lubricating oil was sampled at regular intervals, and the physicochemical analysis of the soot content and lubricating oil viscosity was performed. In addition, some oil samples were also subjected to wear spot wear test. Through the wear spot test to simulate the wear state of the entire engine, the state of the wear parts such as the bearing bush, piston ring and cylinder liner in the engine is simulated and explored.

Finally, the optimal fuel injection strategy is selected to form a method for quickly generating lubricant soot, which is used to quickly assess the ability of the lubricant to resist wear.

2 Test equipments

A turbocharged intercooled diesel engine, which meets National V emission standard in the WP13 series, produced by Weichai Power Company. The engine occupies an important share in the heavy vehicle market, and its main parameters are shown in Table 2.

Table 2. WP13 Engine parameters.

Parameters/units	Parameters
Air intake form	Supercharged Medium Cold
Number of cylinders	6
Cylinder arrangement	Inline
Emission standards	National V emission standard
Emission control mode	Electronic High Voltage Common +SCR
Bore x stroke/mm	127x165
Total displacement of piston/L	12.54
Calibration power/ kW	368(1900 r/min)
Maximum torque/(N·m)	2400(1000-1400r/min)

Fig .1. Engine bench and main test equipment.

Table 3. Main test equipments.

Name of equipment	Type of equipment	Manufacturers
Engine Measurement and Control System	HORIBA systems	Japan HORIBA Corporation
Dynamometer	Power, hydraulic integration	Japan HORIBA Corporation
Filter paper soot meter	AVL 415S	Austria AVL Corporation
Non-transparent soot meter	AVL 439	Austria AVL Corporation
Thermogravimetric analyzer	TGA/DGC3+	METTLER company
Four ball friction Testing machine	MS-10A	Xiamen Tianji Automation Co., Ltd.

The engine bench is shown in Figure 1. The main test equipment is shown in Table 3, This article uses the electric and hydraulic integrated dynamometer and its measurement and control system produced by Japan HORIBA company, which can not only measure the heavy torque of heavy engine, but also ensure that the system has a fast working condition response. The filter paper soot meter AVL 415S and the non-transparent soot meter of Austria AVL Company AVL 439 were used to measure the emission of soot. The Swiss METTLER TGA/DGC3+ thermogravimetric analyzer is used to accurately determine the soot content in the lubricant. The MS-10A four-ball friction test machine of Xiamen Tianji Automation Co., Ltd. is selected to evaluate the anti-wear properties of the lubricating oil

3 Effect of oil injection strategies on original emission

3.1 Effect of fuel injection strategies on original soot emission

Figure 2 is the original soot emission chart of the external characteristics of the engine. As shown in Figure 2, AVL 439 opaque soot and AVL415 filter paper soot measurements have a consistent trend, so AVL 439 soot meter is used uniformly in subsequent measurements. However, the maximum value of the original soot emission of the engine is 0.015 1/m (at 1800r/min), which is not enough to generate more soot content, to further distinguish the advantages and disadvantages of the dispersion performance of the lubricant soot. This requires recalibration and adjustment of ECU control parameters. In this paper, the strategy of changing the fuel injection timing is used to change the combustion situation, thereby changing the original soot emission of the engine.

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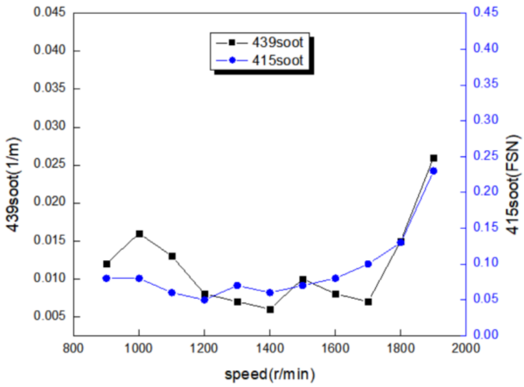

Fig. 2. Original soot emission from engine external characteristics.

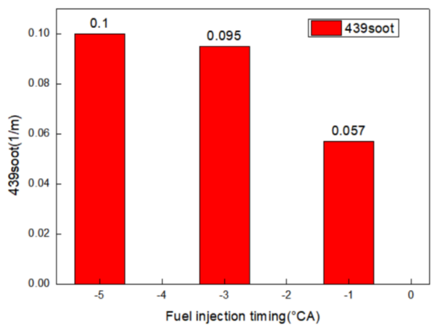

Fig. 3. The soot of the engine under the same injection strategy.

In the figure, -5, -3, and -1 indicate different injection strategies when the injection timing is 5°CA, 3°CA , and 1°CA ATDC. As can be seen from Figure 3, when the engine fuel injection timing is gradually delayed from 1°CA ATDC to 5°CA ATDC, the soot in the original emission increases rapidly to 0.1 1/m ,about 2 times the soot value of 0.057 1/md at 1°CA BTDC. As the injection timing is postponed, the engine's capacity decreases, and the post-combustion portion increases when the tissue is burned in the cylinder, resulting in an increase in the original soot emission caused by insufficient fuel combustion.

3.2 Effect of fuel injection strategies on exhaust temperature

It can be seen from Figure 4 that as the engine fuel injection timing is gradually delayed from 1°CA BTDC to 5°CA ATDC, the post-combustion portion of fuel increases, and excess fuel continues to burn in the exhaust pipe, which makes the exhaust temperature of each cylinder after vortex increase greatly. Especially at 5°CA ATDC, the exhaust temperature after turbocharger reaches 640℃, and the exhaust temperature of each cylinder is above 700℃. The parts such as the intake and exhaust valves and the supercharger are easily damaged under high temperature, which is not conducive to the long-term operation of the engine.

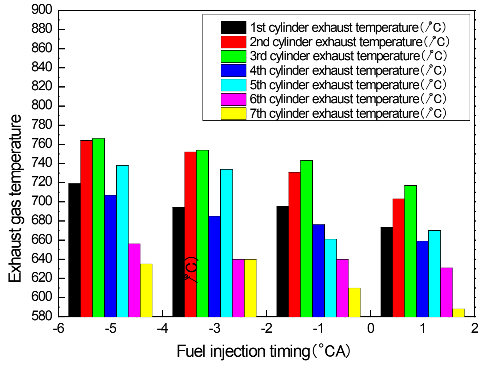

Fig. 4. Engine exhaust temperatures under different injection strategies.

4 Effect of oil injection strategies on lubricating oil performance

4.1 Effect of fuel injection strategies on soot content

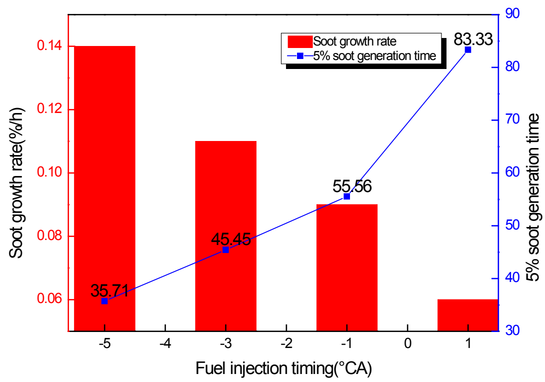

Fig. 5. Lubricant Soot Content under Different Fuel Injection Strategies.

Soot is a mixture of many substances. Its main component is graphitizing of carbon black. The soot is mainly caused by the incomplete combustion of fuel oil, and the part attached to the cylinder wall is eluted by lubricating oil, which exists in the lubricating oil in the form of solid insoluble matter.[19].

It can be seen from Figure 5 that as the injection timing is postponed, a small portion of the soot generated by the post-combustion of the fuel enters the lubricating oil to form soot, so that the growth rate of soot is 0.06%/h from 1°CA BTDC increase to 0.14%/h of 5°CA ATDC. The 5% soot generation time is also shortened from 83.33h at 1°CA BTDC to 35.7 hours at 5°CA ATDC, which has a faster soot generation rate.

4.2 Effect of fuel injection strategies on the diameter of wear spot

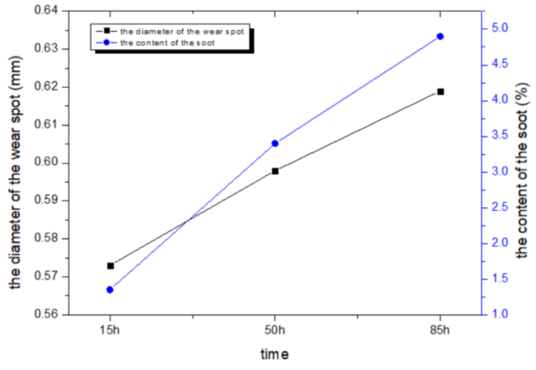

Fig. 6. Soot content and wear spot diameter change with time at 1°CA BTDC.

Under different injection strategies, the changes in soot content and wear spot diameter with engine operating time are similar, so only the injection of 1 °CA BTDC will be introduced. Fig.6 shows that the diameter of the wear spot and the content of the soot increase with the engine running time. The relationship between the diameter of the wear spot and the content of the soot is obvious. As the engine's running time accumulates, the generated soot is also accumulating. The increasing soot particles in the lubricating oil will lead to the deterioration of the lubrication oil state between the friction pairs in the wear spot test, thus causing the wear spot diameter to increase continuously with the running time.

Fig .7 shows that when the content of soot is the same, the diameter of wear spot increases with the advance of the fuel injection timing. The smaller the soot content, the faster the wear spot diameter increases. As the injection timing continues to advance, the particle concentration, mass concentration, surface area concentration, and volume concentration decrease. The peak of the particle size distribution curve shifts to the direction of small-diameter particles. The proportion of nuclear particles increases, and the proportion of accumulated particles decreases[20]. The shrinking particles have a higher relative hardness, and the larger the diameter of the wear spot generated during friction.

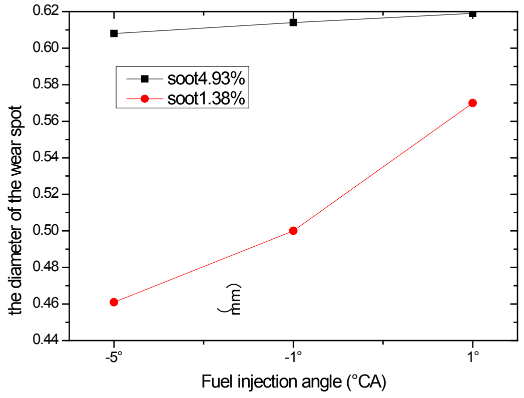

Fig. 7. The wear spot diameter under different injection strategies, when the soot content is the same.

When the soot content is 1.38%, with the advance of the fuel injection timing, the increase in the size of the wear spot is small. At this time, the growth rate of the proportion of nuclear particles in the original emission of the engine is large, and the initial wear spot diameter is small. Then, the diameter of the wear spot generated on the friction test prototype corresponding to the soot of the lubricating oil increases rapidly. On the contrary, when the soot content is 4.93%, the diameter of the wear spot advances with the injection timing, and the increase is smaller.

4.3 Effect of fuel injection strategies on kinematic viscosity of lubricating oil

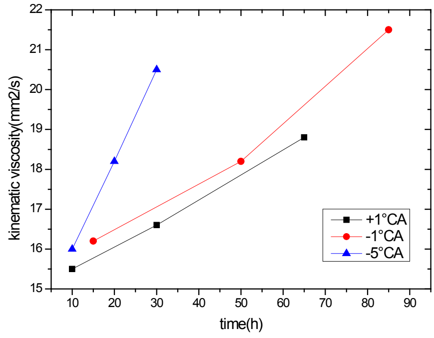

Fig. 8. Variation of lubricating oil kinematic viscosity over time.

In Fig.8, with the increase of engine running time, the kinematic viscosity of lubricating oil changes linearly with time. With the delay of injection timing, the linear trend is increasing continuously, showing an increasing trend. The increase in the kinematic viscosity of the lubricating oil is the fastest at 5°CA ATDC. Because at this time the soot in the lubricating oil is generated the fastest, and the generated soot causes the kinematic viscosity of the lubricating oil to increase continuously. The slowest increase in the kinematic viscosity at 1°CA BTDC, due to the slowest growth of soot relative to other injection moments. At 1°CA ATDC, the growth rate of kinematic viscosity is moderate. Between 5°CA ATDC and 1°CA BTDC, the growth rate of soot is also between the two, and the kinematic viscosity and soot present a significant positive correlation.

5 Summary and outlook

Based on different fuel injection strategies, this paper analyzes the original emission soot, exhaust temperature, soot content, wear spot diameter and kinematic viscosity, and draws the following conclusions:

(1) Postponement of fuel injection timing will increase post-combustion, the original soot emission and exhaust temperature of the engine, and will increase the heat load of the parts;

(2) Delaying the injection timing, the growth rate and kinematic viscosity of the soot of the lubricating oil increase, and the soot dispersion of the lubricating oil can be checked;

(3) When the content of soot is the same, the proportion of nuclear particles in the original particulate matter emission of the engine is delayed when the fuel injection timing is delayed, which reduces the diameter of the wear spot of the lubricating oil.

(4) In summary, the soot content of lubricating oil has a certain positive correlation with the original soot emission of the engine and the diameter of the wear spot of the lubricating oil.

In the end, 1°CA BTDC has a faster soot growth rate of 0.06%/h relative to the original machine, and has the largest wear spot diameter relative to 1°CA ATDC and 5°CA ATDC. In this paper, 1°CA BTDC is selected as the optimal fuel injection strategy to achieve rapid aging of engine lubricating oil, which can complete the evaluation of the anti-wear performance of lubricating oil.

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