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Effect of Nozzle Structure Parameters on Steady Emission Characteristics in an Opposed-Piston Two-Stroke Diesel Engine

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Abstract. According to 8-Mode cycle of measurement methods for non-road diesel engine of China III from GB20891-2014, the effects of the injection parameters on steady emission characteristics were researched on an opposed-piston two-stroke(OP2S) diesel engine. Test results show that nozzle-tip-protrusion(NTP) can't make a big influence on emission characteristics, but all of the CO, NOx and PM emissions decrease obviously with the increase of injector hole diameter. Moreover, there exists an optimal nozzle hole cone angle, which can lead to a least composite rate emission. Compared with the original engine, the gross emissions of NOx and HC decrease approximately by 17.2% for improved OP2S engine after nozzle parameters optimization matching, and the improved OP2S engine is able to meet non-road diesel engine of China III emission requirement.

1. Introduction

With the strengthening of people's environmental awareness, engine emission standards are becoming more and more strict. At present, in the development and production of non-road vehicles, the concept of developing "green" automobile products has been gradually concerned by the international community. Under the pressure of environmental protection, the emission regulations of non-road vehicles in many countries and regions limit the emission of different harmful emissions. In 2014, China III emission standard of non-road mobile machinery diesel engines made stricter provisions on the total emission limit of "NOx+HC"[1].

In the current power products, OP2S diesel engine has been considered as a third compromise in addition to hybrid and clean diesel engine. Advanced propulsion technologies of California has demonstrated how to improve the smoke emission of OP2S diesel engines[2]. The research of Chinese scholars on OP2S diesel engine mainly focuses on the design of key parts, in-cylinder scavenging, in-cylinder gas flow, in-cylinder combustion and other aspects[3-6], while the research on the emission characteristics of OP2S diesel engine has not been involved.

Fuel injection quality has a very important influence on engine combustion and engine performance[7]. Studies show that among the many factors that affect the combustion and emission characteristics of diesel engines, 60%~70% come from fuel injection, so the improvement of fuel injection system is the key to reduce the emission of diesel engines. Due to the particularity of the combustion chamber structure of OP2S diesel engine, its fuel injection and atomization process is different from the middle arrangement structure of single injector of traditional diesel engine. Therefore, when studying the combustion and emission characteristics of OP2S diesel engine, the influence of fuel injection system parameters should be fully considered.

In this paper, the impact of nozzle parameters on the emission characteristics of OP2S diesel engine will be tested, and through the comprehensive optimization of nozzle parameters, the emission index of engine in steady state condition will meet the emission standards of non-road diesel engines in China, which will lay a foundation for the emission upgrading and performance improvement of OP2S diesel engine in the future.

2. Test System

The test was carried out on a 1.2L OP2S diesel engine. The nominal power of the diesel engine is 32kW, the nominal speed is 1800r/min, and the geometric compression ratio is 22:1. The engine adopts single-pump and double-common rail oil supply system. According to the opening of the pressure regulating electromagnetic valve on the pump, the high-pressure oil pump provides quantitative and constant pressure high-pressure oil, which is fed into two common rail pipes through the three-way valve. The two injectors connected with each common rail pipe are arranged relatively around the cylinder and perpendicular to the center line of the cylinder. The three nozzle holes of the injector are arranged uniformly around the nozzle, and the elliptical combustion chamber composed of internal and external piston tops forms a combined jet combustion structure, as shown in figure 1.

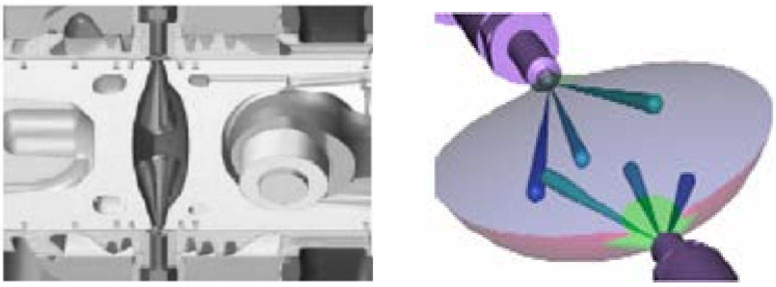

Figure 1. Combustion chamber of OP2S engine.

The main technical parameters of the oil supply system are shown in table 1.

Table 1. Key technical parameters of the oil supply system.

Element	Index
Nozzle orifice number	3
Nozzle diameter	0.29mm
Nozzle angles	17°
NTP(nozzle-tip-protrusion)	2.7mm
Injection pressure	160MPa
Common rails volume(a single pipe)	75ml

Layout of the emissions test system is shown in figure 2: the eddy current dynamic dynamometer, control cabinet and KAMA-4000 fuel consumption meter produced by AVL company in Austria are adopted; 7613C-KiBOX explosion pressure sensor is used to measure the explosion pressure in the cylinder; The DIGAS-4000 emission analyzer produced by AVL in Austria is used to measure NOx, HC and CO in exhaust gas. The smoke is measured by AVL-439 extinction type smoke meter.

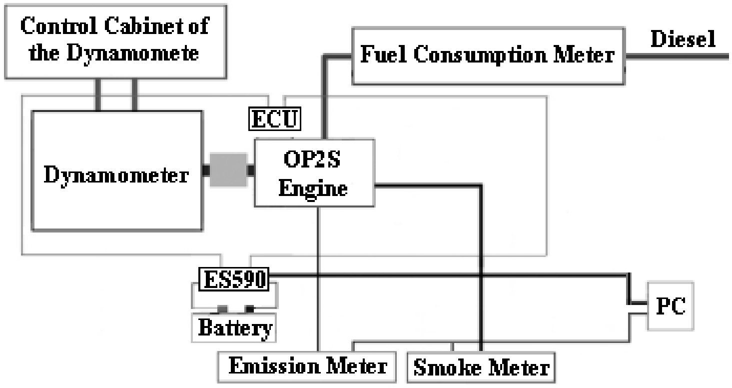

Figure 2. Schematic diagram of emission test system.

In order to ensure the reliability of test data, test boundary conditions and test process parameters should be strictly controlled, including the following parameters:

- Engine fuel temperature is about 35°C~40°C;
- Inlet temperature is about 50°C~80°C;
- Water temperature difference between inlet and return is not more than 8°C;
- Exhaust temperature is not more than 650°C;
- Maximum combustion pressure in cylinder is not more than 10.5MPa.

3. Emission Test Method

The emission test was carried out by using non-road diesel engine of China III emission requirement. The maximum permissible error of rotation speed is controlled within 50r/min, and the maximum error of torque is controlled within 2% by "8-Mode" test method. Run in each condition for 6 min, and complete the condition conversion within 1 min; Exhaust measurement including PM sample collection, 5 min in total. Test conditions and weighting coefficients are shown in table 2.

Table 2. Emission test condition cycle of OP2S diesel engine.

Test Condition Number	Speed	Load Percentage	Weighting Coefficient
1	Nominal Speed	100%	0.15
2	(1800r/min)	75%	0.15
3		50%	0.15
4		10%	0.1
5	Middle Speed	100%	0.1
6	(900r/min)	75%	0.1
7		50%	0.1
8	Idle Speed(700r/min)	0	0.15

"8-Mode method" uses the weighted ratio emission to evaluate the emission level of diesel engine. The weighted ratio emission of a certain harmful substance X is defined as:

$$X = \frac{\sum_{i=1}^{8} [X_{mass}]_i \cdot WF_i}{\sum_{i=1}^{8} Pe_i \cdot WF_i} \tag{1}$$

Where, X_{mass} is the weighted emission mass flow of the harmful substance; WF_i is the weighting coefficient; i is the operating condition serial number; Pe is the effective power.

4. Test Results and Analysis

4.1. Effect of Nozzle Diameter on Emission

The nozzle diameter determines the flow characteristics of nozzle when the number of nozzle orifice and back pressure of nozzle are constant. If the total flow area of the jet hole is too large, it will reduce the injection pressure and injection rate, shorten the injection duration, deteriorate the atomization quality of injection. A small flow area of the jet orifice will lead to high injection pressure and abnormal injection. The total flow area is directly determined by the nozzle diameter when the needle valve lift rule is fixed, which affects the fuel injection rule and ultimately affects the combustion characteristics and emissions of the engine. Figure 3 is the test result of the influence of nozzle diameter on the engine emission under eight working conditions.

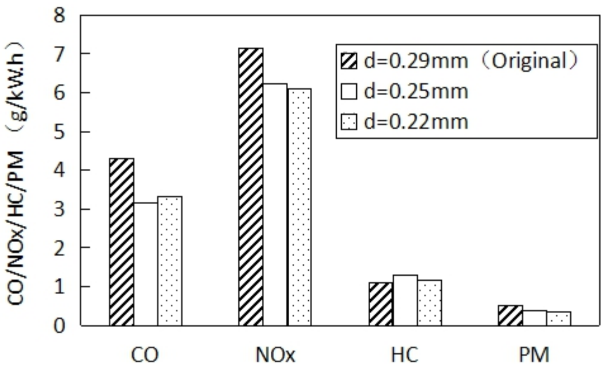

Figure 3. Influence of nozzle diameter on average specific discharge.

It can be seen from figure 3 that NOx, CO and PM emission are all decrease significantly with the decrease of nozzle diameter. This is because a smaller nozzle diameter will lead to a faster spray speed of fuel droplet, and the spray is evenly meticulous, and the same time the oil beam form around back-flow zone is strong, which can enhance the fuel vapor entrainment ability, and improve the utilization rate of air and fuel vapor heat utilization. In the end, the generation of CO and PM will reduce, but small diameter nozzle can reduce initial fuel injection quantity, and make the premixed combustion rate reduced. So the pressure rise rate and the maximum combustion temperature is reduced, thus effectively inhibits NOx generated; At the same time, the reduction of premix combustion ratio will increase the diffusion combustion ratio of fuel, and the inevitable collision between fuel injection and combustion chamber wall surface will intensify the cracking of small particle size fuel at higher wall temperature, thus causing HC emission to increase to a certain extent.

4.2. Effect of Angle of Nozzle on Emission

Nozzle angle is defined as the angle between the axis of nozzle orifice center and the center line of nozzle. It directly affects the position of the jet beam, and affects the subsequent combustion stability and emission characteristics. At the same time, the angle of nozzle orifice designed should be matched with the combustion chamber shapes.

To obtain a higher air utilization rate for OP2S diesel engine, the angle of nozzle orifice must be adjusted and optimized in order to matches the elliptic combustion chamber structure, the contrapuntal injector, the lateral combination injection cylinder liner. In addition, while the fuel beam penetrates through the external radial volume, it is necessary to prevent the fuel from condensing in the center of the combustion chamber and ensure that the fuel injection has less contact with the cylinder liner.

Figure 4 shows the test results of three different orifice angles(17°, 20°, 23°)on emission characteristics of OP2S diesel engine. As can be seen from the figure, the HC, CO and PM emission reached the lowest when the angle of the nozzle is 20°, while the NOx emission is the highest at this time.

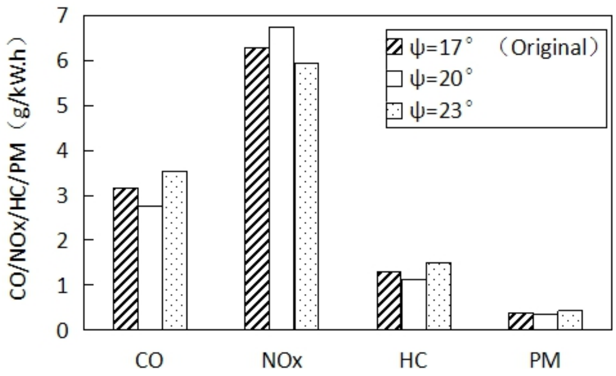

Figure 4. Influence of angle of nozzle on emission.

17°for nozzle angle, the jet oil mainly concentrates in the centre of the combustion chamber, oil beams barriers make it difficult to penetrate between external combustion chamber of transverse space. It is not conducive to the use of air to reach the best state of oil and gas mixing, which lead to an incomplete combustion, and HC, CO and PM emissions is increase. At the same time, the poor quality of oil and gas mixture made formed in the early years of the burning combustible mixture is less, so in the cross area of injection beam, the mixture of oxygen concentration is low, and reduce the burning zone NOx generation.

When the nozzle angle increases to 23°, the oil beam arrives at the top of the piston earlier in middle fuel injection period, where more and more fuel accumulates. Since the temperature of piston top surface increases, the rate of fuel evaporation increases. At this time, fuel vapor will decompose and form incomplete oxidation products of unburned hydrocarbon and carbon smoke, leading to HC emission increase and PM increase. In addition, the “air stagnation zone” is formed between the two umbrella shaped oil bundles, which result in reducing air utilization in the middle of the combustion chamber and a lower concentration of oil-gas mixture, and it will also lead to more HC, CO and PM generation and less NOx generation after combustion.

When the nozzle angle is 20°, the oil beam collide at the middle section of the combustion chamber, further crushing the oil droplets, promoting the air disturbance and enhancing the atomization of fuel, so that the combustion is more complete and the maximum combustion temperature in the cylinder increases, so HC, CO and PM emissions decrease and NOx emissions increase.

4.3. The Effect of NTP on Emission

Nozzle angle and NTP directly affect the spatial distribution of fuel in the cylinder, and thus the concentration distribution of the mixture, combustion process and emission generation. As the air flow movement in the cylinder of OP2S diesel engine is very complicated, coupled with the reciprocating motion of the piston, the position of the injector nozzle in the cylinder will affect the distribution of the spray body in the combustion chamber to a certain extent, resulting in different combustion and emission characteristics.

By adjusting the number of gaskets, the protruding height of NTP is changed. Figure 5 shows the overall emission test results corresponding to different NTP.

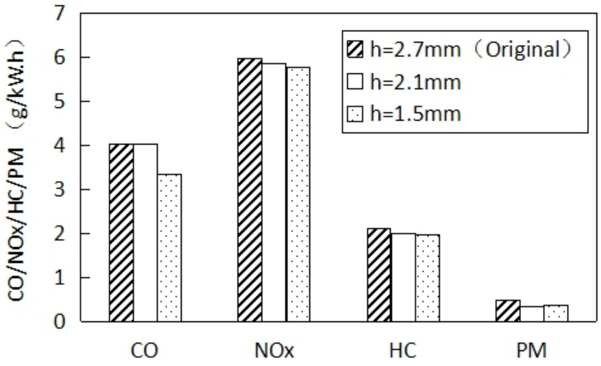

Figure 5. Influence of NTP on average specific emission.

As can be seen from figure 5, the smaller the NTP is, the less the CO emission, but the NOx, HC and PM emissions decrease unobviously in “8-Mode” test results. When NTP is 1.5mm, the emission characteristics of OP2S engine are the best.

5. Comprehensive Optimization of Nozzle Parameters

Because the emission standard of China III emission requirement for non-road mobile mechanical is the limit of NOx and HC emissions, so in order to make the OP2S diesel engine meet the regulatory standards, the above nozzle parameters need to be optimized. The final matched test scheme is: nozzle diameter is 0.22mm, nozzle angle is 20°, NTP is 1.5mm.

The test was carried out again according to the GB20891-2014 steady state test cycle test method, and the measured “8-Mode” average specific emission results are shown in table 3.

Table 3. Exhaust results before and after optimization of nozzle parameters.

Emissions	Phase III emission standards (g/kW.h)	Original machine emission value (g/kW.h)	Optimized engine emission value (g/kW.h)
CO	5.5	4.40	3.49
NOx	—	7.28	5.27
HC	—	1.11	1.68
NOx+HC	7.5	8.39	6.95
PM	0.60	—	0.37

From table 3 as you can see, compared with the original engine, the harmful emissions of OP2S diesel engine was effectively controlled after the nozzle parameters were optimized. In “8-Mode” test results, although the HC emissions increased, but the total emissions of “NOx + HC” decreased by 17.2%, and the improved emission levels of the machine can satisfy China III emission requirements of nor-road mobile machanical.

6. Conclusion

- The comprehensive specific emission of “8-Mode steady-state test” of OP2S diesel engine is more sensitive to the influence of nozzle diameter and nozzle angle, but less affected by NTP. By reducing the nozzle diameter, average specific emission of NOx, CO and PM can be reduced.
- The nozzle angle should match with the elliptical combustion chamber structure. When the nozzle angle is 20°, comprehensive emission of OP2S diesel engine is lowest in “8-Mode test” average specific emission results.
- After the optimization of nozzle parameters, the total emission of “NOx+HC” of OP2S diesel engine is reduced by 17.2% compared with that before optimization.

7. References

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