

Study on Optimizing Combustion Process for Marine Diesel Engines

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Abstract: Regarding the power, the efficiency and the emission of the low speed diesel engine, this paper has studied the matching and optimizing technique in the diesel engine combustion process emphatically, proposed the electrically controlled fuel injecting system with the high-pressured common rail as well as the humid air motor method and the system plan. The practice proved that the fuel injecting system with the high-pressured common rail and the humid air motor system can improve the combustion process most efficiently, thus enhance the diesel engine's performance, and reduce the pollutant discharge. In response to the increasingly stringent diesel emission regulations, the paper analyzes the relationship of the low-speed marine diesel engine's emission with the combustion process, the fuel injection law, the exhaust recirculation and the SCR. Then the scheme of the fuel injection system with the high-pressure common rail for the low-speed diesel engine is proposed, and the test system for the diesel engine's emission performance is established. Through the experimental research, the optimization and matching technology for the diesel combustion process based on the emission control is analyzed, and the best injection law of the diesel engine is revealed under the different conditions. That will provide the technical support for the design and operating management of the diesel engine.
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1. Introduction

The low-speed two-stroke marine diesel engine is composed by the fixed part, the moving part, the distribution system, the fuel system, the lubrication system, the cooling system, the starting system, the speed regulation device, the reversing arrangement, and the supercharging system. As a result of its good power performance, the fuel efficiency and the reliability, the modern merchant ship takes generally it to directly drive the propeller as a main propulsion

system. Its performance has decided the entire ship's power performance and economical performance [1].

Internationally the low speed diesel engine's brand is mainly MAN B&W and Wartsila. The MAN's intellectualized ME series of the low speed diesel engines, can control the air starting valve, control the starting, advancing and reversing process, replace the speed governor, and implement the optimized control to the low speed auxiliary air compressor, the feed timing and rule, the exhaust gate and the spraying rate of the lubricating oil on the

cylinder wall and so on. They may achieve a lower oil consumption rate and the performance optimization in the entire operating mode and can satisfy the various requirements [2]. For example, the optimized formation of the injection pressure and rule, the lower NO_x discharge and the smokeless characteristic, the operating pattern transferred easily to a low oil consumption or a low NO_x, the mechanism and system's simplification, the heat load and balance control in the various cylinders, the lowest stable speed, the best accelerating, advancing and reversing characteristic and the emergency stop performance, the optimized control to the cylinder wall lubrication, as well as easy adaptation to the operating characteristic optimization of various ships. Wartsila Corporation expanded the RT-flex serial products with the electrically controlled fuel injecting system of the high-pressured common rail on the RTA series' foundation, and on the applying foundation in the small cylinder diameter RT-flex 50 and RT-flex60C, developed the larger cylinder diameter RT-flex84T-D and RTflex96C with the electrically controlled fuel injecting system of the high-pressured common rail IV.

The marine diesel engine's power and harmful emission are enormous. Moreover, the marine diesel engine burns generally the heavy fuel oil that is complicated in composition and heavy in harmful substance. In the same circumstances, it brings about the more harmful things. In order to prevent, reduce and control the air pollution caused by the ship operation, the International Maritime Organization (IMO) established the emission control rule of the marine diesel engine's nitrogen oxide (referred to as the NO_x Technical Code). With the continuous strict emission regulations, the research on the emission control technology for the marine diesel engine is more important. The marine diesel engine is low in speed, stable in load, large in power, low in fuel consumption rate, large in available installation space, etc. In order to reduce the NO_x emission, the SCR technology and the watered fuel technology can be used. The marine diesel emission control is related to regulations, standards, test methods and equipments, measuring instruments and their evaluation methods and other aspects. It is a systematic project.

A major factor impacting the nitrogen oxide's (NO_x) generation is the combustion process in the diesel engine's cylinder. It is related with the engine's structure, the working process parameters, the operating conditions, and the working quality of the auxiliary equipments and systems. The methods reducing the nitrogen oxide's (NO_x) emissions are the pre-processing, the processing inside the engine and the cleaning outside the engine. The key of the processing approach inside the engine is to control effectively the combustion process. Currently the main way is to develop the direct-injection combustion chamber with the low emission as to improve the engine's thermal efficiency while meeting the emission standards. In addition, the

methods of the delayed fuel injection, the exhaust gas recirculation (EGR), the variable control mechanism and the water injection inside the cylinder can also reach the emission standards currently specified, but will decrease the thermal efficiency of the diesel engine and deteriorate the running economy.

The research at home and abroad indicates there are basically the two ways to control the NO_x emission. One is to fundamentally improve the combustion characteristics and reduce the sulfur content of fuel in order to not produce or to less produce the above harmful gases. By optimizing the structure or parameters of the components related with the fuel combustion, the maximum combustion temperature and duration is lowered, the Excess air factor in the high temperature area is reduced, and thereby the amount of the NO_x production is decreased to reach the emission requirements. The other is to reduce the degree of the exhaust gas directly into the atmosphere by post-processing the diesel exhaust. Through the technology post-processing the exhaust, the NO_x in the exhaust is decomposed, oxidized or reduced to reach the purpose lowering the diesel's NO_x emission [3-4].

As a member of the International Maritime Organization, China will strictly enforce the provisions of MARPOL Convention, Annex, and implement the nitrogen oxide (NO_x) control for the ship. China Classification Society constituted "the nitrogen oxide's emission testing and examination guide for the marine diesel engine" in accordance with the provisions of the Convention to direct the engine-making yard and the testing organization for the effective emission testing.

2. Electronically Controlled Fuel Injection System

Because the high-power low-speed diesel engine is excellent in performance, good in reliability, easy in maintenance, and can be fueled with the low-grade fuel, etc., it has become the main power for the large-size oil tanker, the large-size bulk carrier, the large-size container ship. The main brands of the low-speed diesel engines are internationally MAN B&W and Wartsila. All are the two-stroke low-speed diesel engines with the single valve's direct-current scavenging, the constant pressure supercharging, the long stroke, the high compression ratio, and the crosshead type structure close to isobaric combustion. The mean effective pressures of variety bore diesel engines (p_{me}) are 1.9 ~ 2.0 MPa. The maximum combustion pressures (p_{max}) are 15 ~ 16 MPa. The fuel consumption rates are 170 g / (kWh) or so. The new low-speed diesel engines in the structure have the non-cooled fuel injector, the variable injection timing pump, the long-size rod, the hydraulically-driven exhaust valve, the single valve's direct-current scavenging, the constant pressure supercharging, and the effective turbosupercharger. In terms of the

performance, the average effective pressure and the average piston speed is increased, the structural components are improved to increase their strength, the original level of the low fuel consumption is maintained, and the single-cylinder power and the service life is improved significantly. The electrohydraulic control system replaces the traditional mechanism driven by the mechanical cam to simplify the engine's design, reduce the cost, and optimize the operating control.

The current low-speed diesel engine's development is to increase the reliability, to extend the overhaul period, to improve the compactness of the engine, to reduce the fuel consumption rate and to control the emission. Especially in the increasingly strict emission requirements, as well as the better required economy under the low and high conditions, the intelligent diesel engine with the electronically controlled fuel injection system and the electronically controlled exhaust valves without the camshaft is developed and improved continuously. For example, MAN B&W increased the electronically controlled ME/ME-C series and productions on the basis of the MC/MC-C series. Wartsila extended the RTA series with the electronically controlled high-pressure common rail on the basis of the RT-flex series, and the RT-flex84T-D and RTflex96C low-speed engines with the large bore and the high-pressure common-rail type 4 were developed on the basis of the RT-flex 50 and RT-flex60C with the smaller bore.

The high-power low-speed diesel engine uses the scheme of the electrically controlled fuel injecting system with the high-pressured common rail, as shown in Fig. 1. The two-cylinder common rail made the high-power low-speed diesel engine small in structure against the engine with the high-pressured oil track. The high pressure oil circuit controlled by a high speed magnetic valve can avoid the low operational reliability which governing directly a fuel injector needle brings. The electrically controlled fuel injecting system with the high-pressured common rail, as shown in Fig. 1, has the good injection characteristics, can achieve the pre-injection, adjust the injection rate's shape, achieve the desired fuel injection law, optimize the combustion process, improve significantly the diesel engine's fuel consumption, smoke, noise, emission and other performance indicators, and help to improve the engine's torque characteristics.

It can achieve the high-pressure injection. The injection pressure is twice more than the general in-line pump system. The closed-loop control of the common rail's pressure is implemented with the common rail pressure sensor and the control algorithm. The optimum injection pressure is determined for the different load and speed. That is highly advantageous to improve the low-speed and the low-load performance of the diesel engine. The injection timing and the injection volume can be controlled accurately. Implementing the ideal fuel injection law of "the pre-injection, the low initial injection rate, the high main injection rate, the fast

stop speed of the post-injection" favors to reduce the NO_x emissions from the diesel engine.

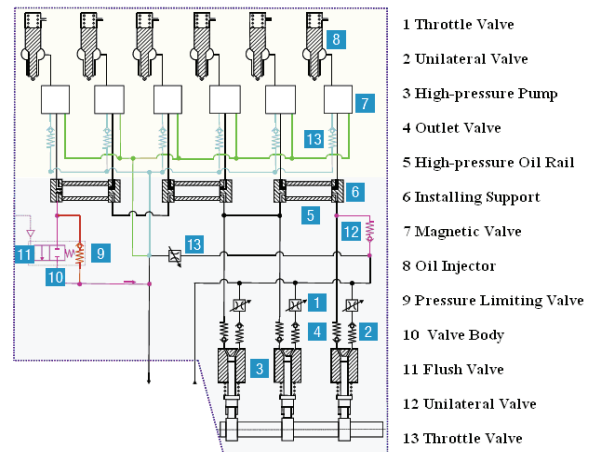


Fig. 1. The electrically controlled fuel injecting system with the high-pressured common rail.

3. Optimization of Diesel Engine's Combustion Process

In the low speed diesel engine design, the combustion process optimization mainly solves the carbon smoke and the NO_x emission. Regarding the high-power marine diesel engine's emission, what most mainly must be solved is the carbon smoke discharge in the slow-speed and the low operating mode. Firstly, in the entire operating mode, the black smoke that the naked eyes can see should not be produced including the starting mode. The emission value of the marine diesel engine is easy to be satisfied according to the IMO's NO_x stipulation. Fig. 2 is a group of curves. They are obtained on the experimental contrast in the Wartsila46 medium-speed engine. As can be seen from the figure, when the electrically controlled fuel injecting system with the high-pressured common rail is used, in the entire operating condition, the smoke is below FSN0.15. That is, the smoke color does not be seen, and is below the guarantee FSN0.4. But with the conventional oil supply system, for the entire operating mode the smoke surpasses the guarantee value in the load below 45%. But the biggest value is FSN0.9, also not too high. If the supplement air measure is taken in the low operating mode, the FSN value also possibly is below the guarantee value. If the requested NO_x is below 70% of the IMO standard value, the FSN value has surpassed the guarantee value in the load below 60%.

The high-power low-speed diesel engine uses the scheme of the electrically controlled fuel injecting system with the high-pressured common rail. The two-cylinder common rail made the high-power low-speed diesel engine small in structure against the engine with the high-pressured oil track. The high pressure oil circuit controlled by a high speed

magnetic valve can avoid the low operational reliability which governing directly a fuel injector needle brings.

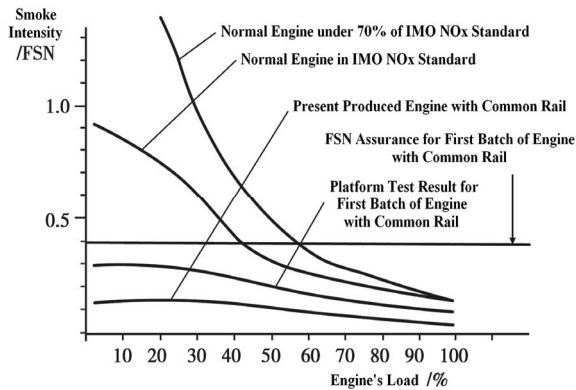


Fig. 2. The influence of the electrically controlled high-pressure common rail to the smoke intensity.

In the electrically controlled fuel injecting system with the high-pressure common rail, the high-pressure oil feed pump provides the pressured oil to the common rail, but the injection discharge and injection timing is controlled by the high speed magnetic valve in the fuel injector. The electronic control unit (ECU) of the fuel injection system acts according to the operator's order and the operating condition of the diesel engine, and controls the injection start point and the injection end point as well as the injection times by controlling the fuel pressure and the magnetic valve's operating time in the common rail. Thus it can be seen, the electrically controlled fuel injecting system with the high-pressure common rail may control independently the system injection pressure, the injection timing, the injection discharge and the injection rule. In comparison with the mechanical type fuel injection system, its superiority lies in: realizing the high-pressure injection; guaranteeing the accurate injection timing; implementing the optimized control of the fuel injection rate; setting the parameter freely and flexibly; optimizing the combustion process.

3.1. Realizing the High-pressure Injection

One of the most remarkable characteristics for the fuel injecting system with the high-pressure common rail is to realize the high-pressure injection. The high injection pressure may guarantee the good fuel atomization, thus can reduce the PM, CO, and HC emission. The injection pressure of the mechanical type fuel injection system is adjusted through the speed and the injection discharge. Because the mechanical type cannot guarantee the high-pressure injection, it causes easily the bad atomization, thus makes the PM, CO, and HC emission to increase. For example the diesel engine

produces easily two times of injection under the high speed and the high load. The fuel oil in the two times of injection comes into the cylinder by the very low pressure, and causes the fume discharge to increase.

3.2. Guaranteeing the Accurate Injection Timing

To a great extent the injection timing is to affect the pollutant emission. Postponing the injection can cause the NOx emission to reduce, but possibly causes the CO and PM emission to increase. The injection timing also is very sensitive to the HC emission, and has the best value. The injection timing above or below the best value will possibly increase the HC emission. Therefore, choosing an accurate value of the injection timing is very important. It may enable the emission to achieve a best compromised value. However, the mechanical type fuel injection system adjusts the injection timing by the injection pump and the timing advance unit. Its setting range and the precision has been restricted. In the fuel injecting system with the high-pressure common rail, the injection timing is controlled by the ECU and the fuel injector. According to the electronic control signal from the ECU, the fuel injector takes the high-pressure fuel oil in the common rail to inject into the engine's combustion chamber by the best injection timing, the injection discharge, the injection rate and the atomization condition.

3.3. Implementing the Optimized Control of the Fuel Injection Rate

In the fuel injecting system with the high-pressure common rail, the injection start point and the duration time are decided by the command pulse, and they have nothing to do with the speed and the load. Therefore the injection time may be controlled freely. In addition the injection pressure may be controlled flexibly. So the ideal premix combustion can be formed. The pre-injecting start point, the main injecting start point and the injecting end point may be adjusted freely. The pressure in the pre-injecting section may be selected freely. The pressure rise rate after the main injecting start is suitable. The oil can be broken fast. The peak pressure of the injection may be chosen flexibly. The full combustion of the fuel oil may reduce the CO, HC, and PM emission. But the delay period reduced as far as possible can lower the NO_x emission.

3.4. Setting the Parameter Freely and Flexibly

In the fuel injecting system with the high-pressure common rail, the Injection nozzle

parameter and the other various parameters may be set freely. Each parameter may satisfy the corresponding request independently. The aspect in satisfying the request is not restrained, the flexibility is good. These are the essential conditions to atomize the fuel oil good and reduce the emission.

Matching reasonably the high-pressure fuel injection system and controlling the parameters of the fuel injection pressure and the injection time, are important to improve the internal combustion process, optimize the diesel engine's power, efficiency and emission.

3.5. Optimization of Combustion Process

The difficulty of the diesel's emission control lies in the mutual checks of the NO_x 's formation and the carbon black's formation. The emissions of the NO_x and the carbon black are mainly related with the combustion process in the diesel engine's combustion chamber. So reducing the diesel's emissions is carried out from improving the combustion process. In order to achieve the desired heat release curve and reach the desired purpose of reducing the emissions, the premixed combustion quantity is suppressed in the pre-mixed combustion phase to reduce the initial combustion temperature and the NO_x emissions. In the diffusion combustion period, the good mixing and the high combustion temperature is maintained to promote the diffusion combustion and to reduce the carbon black's emissions. That requires the good mix and match for the diesel fuel injection system, the combustion chamber shape, and the air movement. Improving the fuel injection system is the most important. From the fuel injection law to consider, it is important to reasonably allocate the fuel injection quantity in the various sections. Specifically, to reduce the amount of the pre-injection leads to reduce the NO_x emissions, and to strengthen the mixture of the main injection leads to reduce the carbon black's emissions. These put forward the higher requirements to the performance of the fuel injection system. Thus enabling the ideal fuel injection process is one of the keys to improve the diesel combustion process, improve the economy and reduce the harmful emissions.

The fuel injection system has a direct and decisive impact to the diesel engine's combustion and emissions. With the development for the diesel engine technology of the electronically controlled injection, the injection strategy has been an important breakthrough to reduce the NO_x and carbon black's emissions. By studying the different control strategies, comparing and analyzing the influence rules of the different main injection timing, the different pre-injection quantity and the different interval between the main injection and the pre-injection to the emission performance of the diesel engine, the best match on the different conditions can be obtained.

In order to study the influence laws of the different injection to the diesel engine's combustion process and emissions, the testing system of the diesel engine's emission performance is established, as shown in Fig. 3. Through the experimental research, the best injection law of the diesel engine is revealed under the different conditions to provide the technical support for the diesel engine's design and operation management.

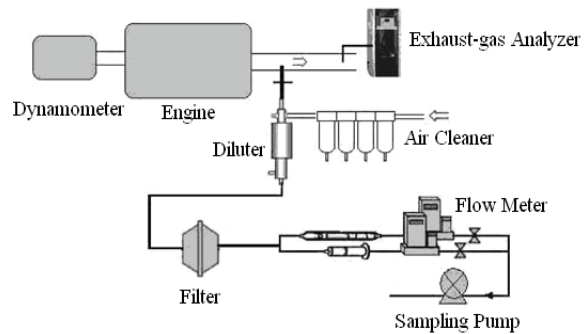


Fig. 3. The testing system of the diesel engine's emission performance.

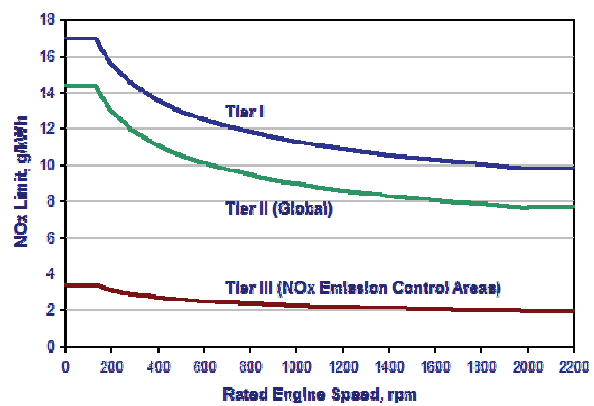


Fig. 4. The emission regulation of the marine diesel engine.

In the aspect of the control of the exhaust pollutants, the more strict emission regulation IMO Tier3 will be imposed in 2016, as shown in Fig. 4. Using the technology of the purification inside the engine about improving the combustion (such as the high-pressure injection, the injection duration shortening, the electronically controlled injection system with the common rail, the direct water injection and the exhaust recirculation system) and the exhaust's after-treatment technology is to meet the increasingly stringent emission standards. Using the high-pressure common-rail fuel injection technology to controlling the injection timing and the fuel injection quantity is the trend on the diesel engine's technology. This paper presents the scheme of the fuel injection system with the high-pressure common rail for the low-speed diesel engine, and the test system for the diesel engine's emission performance is established. Through the experimental

research, the optimization and matching technology for the diesel combustion process based on the emission control is analyzed, and the best injection law of the diesel engine is revealed under the different conditions. That will provide the technical support for the design and operating management of the diesel engine.

4. Humid Air Motor

In order to adapt to the more stricter request compared to the existing IMO's emission laws and regulations, as well as the local codes and regulations like Sweden and Norway, besides using the electrically controlled fuel injecting system, in the low-speed engine the other measures also considered. For example, MAN B&W uses the EGR method and the humid air motor (HAM) method. The water-in-oil emulsion is used in the 5 MAN B&W low-speed two-stroke diesel engines for the power plant. If water is sprayed in the air cylinders directly, the more refitment must be made in the structure, moreover the massive fresh water must be used. But with the HAM system, the water is injected into the high temperature air after the supercharger, and it can also play the cooling role. If the air temperature after cooling is 70 °C about, the HAM system may replace completely the intercooler.

With the HAM system, the diesel engine itself does not need to refit, moreover may use the sea water. Therefore it is a good choice. The HAM system was once experimented on the 4T50ME-X testing engine. The NO_x discharge drops by 25 % ~ 50 %, the oil consumption rate increases by 1.0 % ~ 1.5 %, the CO discharge increases some, the PM and HC discharge changes a little. Using the EGR in the two-stroke diesel engine may realize the cylinder's EGR through adjusting the exhaust timing. Moreover, MAN B&W uses the high-pressured EGR system, namely an air compressor presses the exhaust gas into a sea water bathing pool to purify and cool the exhaust gas. The experiment proved that the NO_x discharge may drop by 30 % ~ 50 %. The EGR and the HAM system further experimented in 2004 on the solid ship. Wartsila has also done the corresponding experimental study. The method combining the direct water injection (DWI) in the cylinder with the EGR

in the cylinder is called WaCoReG (Water Cooled Residual Gas). Testing in the 4RT-flex58T-B using the above method, may make the NO_x discharge lower than 50% of the limitation value by the IMO laws and regulations. In order to further improve the cylinder wall lubrication, lengthen the time between overhauls (TBO) and cut the lubricating oil consumption rate, Wartsila uses the anti-polishing rings in the two-stroke low-speed engine.

5. Conclusion

Matching and optimizing the low-speed diesel engine's combustion process has decided the engine's power, efficiency and emission. But the combustion process's optimization and match has more to do with the fuel injection rule, the intake swirl control, the Valve timing adjusting, the combustion chamber structure, and the operating condition. This article proposed the electrically controlled fuel injecting system with the high-pressured common rail as well as the humid air motor method and the system plan. They can improve the low-speed diesel engine's combustion process, thus enhance the diesel engine's performance, and reduce the pollutant discharge.

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