

Study on Air Intake and Cooling System for Marine Diesel Engine

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Abstract

Regarding the power, the efficiency and the discharge questions of the low-speed diesel engine, this article studied emphatically the Miller cycle, the analysis technology for the air intake system, and the matching technology for the intake and the exhaust. On the foundation of the twin inlet structure the paper analyzed the intake swirl control area and its influence to the gas charging efficiency, proposed the design scheme for the invariable intake swirl control system. By matching reasonably the intake, the exhaust, and the injection process of the diesel engine, the combustion process is further optimized to satisfy the target request for the complete machine's power, fuel oil efficiency and emission. Aiming at the high-power low-speed marine diesel engine, the paper analyzes the impact of the diesel engine's cooling to the power, economy and NOx's emission, studies the variable flow control method and system of the diesel engine cooling water and proposes the scheme setting up the intercooler system and the body cooling system independently in the diesel engine. The results show that the methods and systems are better to improve the engine power, reduce the fuel consumption and NOx's emission.

Keywords: air intake system, cooling system, marine diesel engine, matching control

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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. Controlling the intake swirl intensity is the principal means to solve the fuel oil efficiency and the emission question under the diesel engine's different speed condition. The invariable intake swirl system is applied in the low speed diesel engine to study the oil atomization in the cylinder and the combustion process to the intake swirl intensity's request under the different operating modes in order to realize the reasonable match of the intake swirl intensity with the fuel injection process. On the foundation of the twin inlet structure this paper analyzed the intake swirl control area and its influence to the gas charging efficiency, proposed the design scheme for the invariable intake swirl control system. By matching reasonably the intake, the exhaust, and the injection process of the diesel engine, the combustion process is further optimized to satisfy the target request for the complete machine's power, fuel oil efficiency and emission.

For the marine diesel engine, the fuel economy is one essential index. Currently, using the electronically controlled fuel injection system with the common rail and the variable intake swirl control system to optimize the cylinder combustion process, the engine achieves the minimum fuel consumption close to 170g/kWh. Improving the cylinder combustion process has no significant potential to reduce the fuel consumption. The power consumption of the engine's cooling system accounts for about 5% of the overall engine's power, so improving the whole economy has enormous potential. Controlling the heat dissipation capacity of the cooling process at the different heat conditions to achieve the optimum combustion chamber temperature can not only improve the reliability, but also reduce the heat loss of the burning process, and improve the thermal efficiency. Reducing the water flow of the cooling pump in the

partial load can lower the mechanical power loss of the cooling system to improve the whole economy.

In order to achieve the reasonable match of the cooling system with the whole engine, the working process of the low-speed diesel engine is analyzed to determine the optimum heat dissipation required for the different conditions. The cooling system is designed and the heat dissipation potential of the cooling system is analyzed in the different temperature and flow conditions to match reasonably the cooling system with the whole engine.

2. Miller Cycle

The low speed diesel engine uses generally the constant pressure turbo-charged technology to increase the inlet pressure, reduce the inlet temperature and enhance the power density. Matching the turbo-charged system with the intercooler system is the key aspect to affect the intake process.

Increasing the single-cylinder power brings a series of questions to raise the pollutant discharge and the key components' load, and needs to organize the combustion process reasonably. While the fuel feed is increased, the deflagration and the NO_x production are avoided, and the highest combustion temperature in the cylinder is reduced. To solve this problem in the existing low speed engine the method to reduce the inlet temperature and to increase the water content in the working substance is used, like increasing the water emulsion in the fuel oil, the inlet humidity, and the intercooling. To further improve the cylinder's combustion process and reduce the highest combustion temperature, the Mill cycle is considered to be used in the low speed diesel engine.

The characteristic of the Mill cycle is that the effective expansion stroke is bigger than its compression stroke, namely the expansion ratio is bigger than the compression ratio. Mill proposed in 1940 that the early intake valve closed (EIVC) produces the cooling effect in the diesel engine's interior to reduce the diesel engine's compression power consumption. Afterward, Mill also proposed to make up the inlet reduction caused by the early intake valve closed (EIVC) using the turbo-charged technology. The cycle Mill proposed is to solve the deflagration caused by the unceasing enhance and strengthen of the diesel engine's performance. Its goal concentrates on raising the diesel engine's thermal efficiency. Using the Mill cycle can reduce the maximum temperature in the cylinder, and also the NO_x emission. But the request to the pressure ratio of the supercharger in the EIVC is higher than in the late intake valve closed (LIVC), when the pressure ratio of the supercharger is higher than 4.5. The optimized scope is narrow, therefore is in reality more difficult simultaneously to optimize the efficiency and to avoid the deflagration. Besides EIVC, the modern method of another kind of Mill cycles is the late intake valve closed (LIVC). The expansion ratio is bigger than the compression ratio. The different closure time of the intake valve is corresponding to the different degree of the Mill cycles. This way does not ask for much on the supercharger. Therefore, many researchers use the LICV now. The research on the Mill cycles is mainly to study the influence of the expansion ratio and the compression ratio on the preliminary stage of the combustion, the combustion duration, the combustion efficiency.

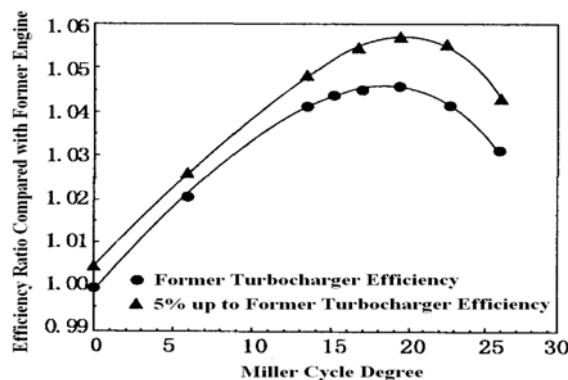


Figure 1. Effect of Miller Cycle to Efficiency

Postponing the time of the late intake valve closure can increase the degree of the Mill cycle and reduce the effective compression ratio to lower the thermal efficiency. But simultaneously the expansion ratio will increase, that is advantageous to the thermal efficiency's enhancement. Therefore how to choose the expansion ratio to make the Mill cycle's utilization rate to be the highest must be considered under the certain compression ratio's condition. As can be seen from Figure 1, the thermal efficiency is not increased along with the Mill cycle's increase. The reason is possibly the usage of the supercharger. In the turbo-charged diesel engine, obtaining how much energy from the exhaust is restricted, because the energy from the exhaust is used to actuate the air compressor. Under certain of the best expansion ratios, the energy extracted from the cylinder expansion process may happen to be equal to the additional pump loss. If the expansion ratio continues to be enhanced, the pump loss is to increase. That causes the system's overall efficiency to be reduced.

Therefore the turbo-charged diesel engine has a best expansion ratio. Matching reasonably the flow rate with the pressure ratio in the supercharger and controlling the exhaust timing may effectively reduce the combustion chamber's temperature under the small or medium load condition, lower the NOx emission, and enhance the fuel oil efficiency.

3. Analysis of Air Intake System

The marine diesel engine takes the combustion chamber structure of the direct injection type as a foundation. The development for the combustion system of the direct injection type is closely related to the carburetion process. In order to increase the air intake and reduce the pump loss, the marine high-power diesel engine mostly uses the four intake valve and double inlet structure. The double inlets use the spiral gas channel and the direct-current inlet separately, as shown in Figure 2. They produce the enough intake swirls in guaranteeing the intake efficiency. However, using the spiral gas channel may lead to be not enough in the swirl strength and inadequate in the mixed atomization in the low speed. To solve the swirl strength contradiction in the high and low speed, the intake deflector is increased to form a variable intake swirl system in the direct-current inlet. It is combined with the fuel injecting system of the high-pressured common rail to match best the intake swirl ratio with the fuel injection process in the working speed. So the emission is controlled, the fuel consumption is reduced, while not affecting the working stability and reliability of the engine.

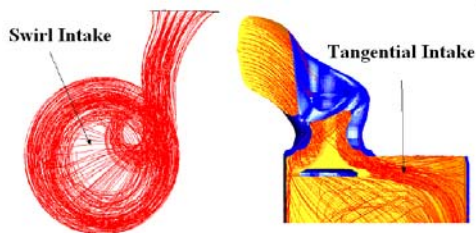


Figure 2. Double Inlet Structure

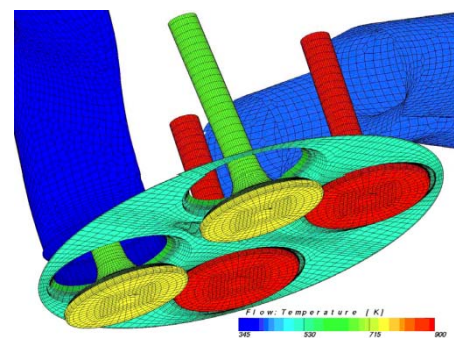


Figure 3. Three-dimensional Flow Simulation Model

The air inflow of the low-speed marine diesel engine is large. So the air flow sensors and the flow pumps are difficult to meet the requirements of the airway simulation. Therefore, using the combination of the flow field simulation with the overall testing method analyzes the inlet flow conditions to complete the matching and optimal control of the intake swirl. In the overall testing, the parameters of the intake pressure, temperature and flow in the parts of the intake system are measured to provide the calculation boundary conditions and verification basis for the simulation of the intake flow field. When the inlet flow conditions in the actual work process of the diesel engine are analyzed using one-dimensional simulation model, the three-

dimensional flow simulation model is constructed near the airway and the intake valve to analyze the inlet swirl strength for the basis on the variable intake swirl control, as shown in Figure 3.

4. Matching Control Technology of Intake and Exhaust Process

In order to better optimize the diesel combustion process, improve the engine's performance and reduce the exhaust emission, the improved design method for the parts of the cylinder head, intake manifold and valve mechanism is proposed on the foundation of the existing intake and exhaust system. The scheme of "the spiral airway of the small swirl ratio + the tangential airway + the blade controlled by the swirl strength" is used to meet the different requirements of different combustion processes to the intake efficiency and swirl strength, as shown in Figure 4.

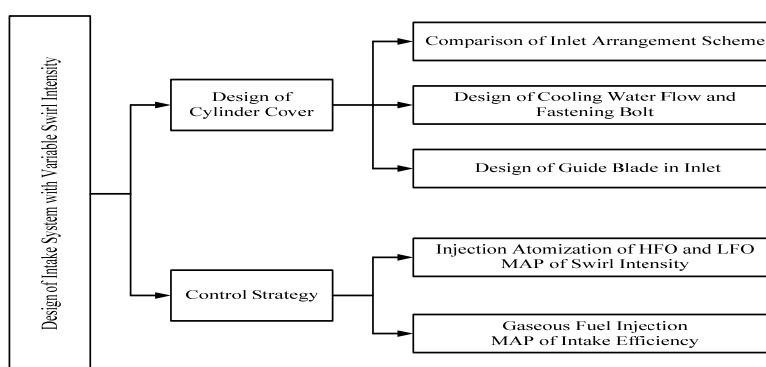


Figure 4. Matching Control Scheme of Intake and Exhaust System

By optimizing the swirl and tangential airway of the medium-small diesel engine's cylinder head, the intake efficiency and swirl ratio of the excellent power, economy and emission are obtained. By studying the influence of the inlet turning vane's structure to the inlet swirl strength and the flow resistance, the design scheme of the control system for the inlet swirl ratio is proposed. By researching the influence of the intake flow resistance and the swirl strength to the LFO, HFO fuel atomization of different liquids, the intake swirl control model and MAP are established to meet the requirements of the different conditions and the different liquid fuel's atomization.

5. Engine's Cooling Analysis

With the development of the design level, the low-speed diesel engine's intensified indices are continuously enhanced. Currently, the diesel engine's mean effective pressure (pme) is 1.9~2.0MPa, the maximum combustion pressure (pmax) is 15~16MPa, the fuel consumption rate is 164~170g/(kW • h) or so, and the single-cylinder power is close to or more than 5000kW. But the cooling system which takes away about a third of the fuel energy still uses the two-cycle approach of the high-low temperature to cool the engine. It does not make much progress.

The diesel engine's thermal state is an important basis for the diesel engine's design, and also is an important factor for designing the cooling system in the marine power cabin. The diesel's combustion heat is partly transferred into the effective work (about 40%). The remainder is taken away by the cooling medium (about 30%) and the exhaust (about 30%), as shown in Figure 5. The valve, cylinder wall, cylinder, piston and cylinder head, etc. are contacted directly with the hot gas. Their temperatures increase rapidly. The reliable working temperature range of the components is limited.

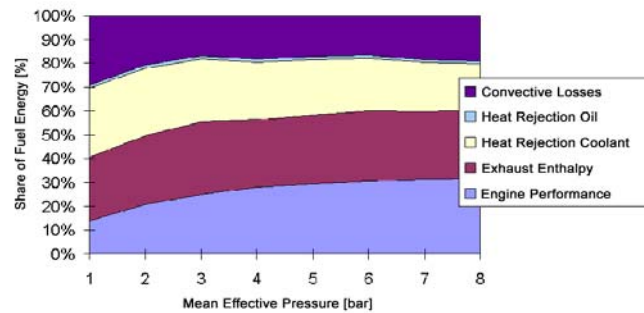


Figure 5. Engine's Thermal Equilibrium

Inadequate cooling will lead to the following series of phenomena. The volumetric factor decreases. Burning is not normal. The power output lowers. Rough work leads to the extra impact loads on the engine body. The normal gaps of the moving parts are disrupted to result in the cylinder score and even the piston melting due to thermal expansion. The mechanical stiffness and strength of the engine body will greatly decrease to bring about descending the mechanical performances or even damaging. The lubricant viscosity reducing, deterioration or consolidation makes the lubrication system's work poor, accelerating the mechanical wear and tear of the parts.

Over-cooling can also cause the following series of phenomenon. The fuel atomization is poor. The fuel consumption is increased, and the emission is increased. The fuel into the crankcase dilutes lubricant to lower the lubricating performance. The power output decreases to result in the inadequate driving ability. The sulfide in the exhaust gas generates the sulfurous acid across water to corrode the body surface. If the lubricant viscosity is too large, the friction of the moving parts and the diesel engine's friction losses are increased. So the primary task of the diesel engine's cooling system is to ensure the proper cooling and to make the heat of the key components in the temperature range of the safe work.

6. Matching and Optimization of Cooling System

The traditional low-speed diesel engine's cooling system uses the static matching method that calculates the required cooling water taking the rated power point as the maximum load point of the cooling system and checks the water in the maximum torque point. The design method can guarantee the heat emission under the diesel engine's rated power. Although the use of a thermostat valve and other measures can ensure the water temperature, but the pump's speed is too high, the cooling water is excessive, and the diesel engine leads easily to the over-cooled phenomenon in the small and medium load. On the one hand the excessive cooling takes away too much of the diesel combustion heat, resulting in decreasing the output power and increasing the fuel consumption. On the other hand that leads to increasing the pump and auxiliary system's power consumption. With the development of the low-speed diesel engine's design technology, to reduce the fuel consumption by optimizing the combustion process has been very difficult. The power consumption in the cooling systems accounts for about 5% of the diesel engine's power output, and the heat taken away by the cooling water accounts for about 30% of the combustion heat release. So to reduce the fuel consumption through matching and optimizing the cooling system has a great potential.

In order to meet the low-speed diesel's power and economy requirements, the variable flow method and system is applied to control the diesel engine's cooling water, as shown in Figure 6. The air through the exhaust-gas-turbo-supercharger of the diesel engine 11 is cooled by the intercooler 4 into the diesel engine's scavenge box. The intercooler 4 is cooled by the high and low temperature heat exchanger 2 with the sea water pump 1 and the fresh water pump 3. The cooling water in the diesel engine's body is cooled by the high and low temperature heat exchanger 6 with the sea water pump 5 and the fresh water pump 7. The lubricating oil of the diesel engine is cooled by the lubricating oil cooler 9 with the lubricating oil pump 10 and the flow control valve 8. The dynamometer 12 is used for measuring the engine's

power output. Unlike the conventional cooling system, the new cooling system uses the pump driven by the variable speed motor to regulate the cooling water flow, and then to control the engine's cooling capacity. In order to reduce the NOx emission, the design's requirement is that the air temperature after the intercooler is below 60°C. The use of the body's cooling water is difficult to achieve the requirement. So the body's cooling system and the intercooler is set separately. The separate cooling system is used to cool air.

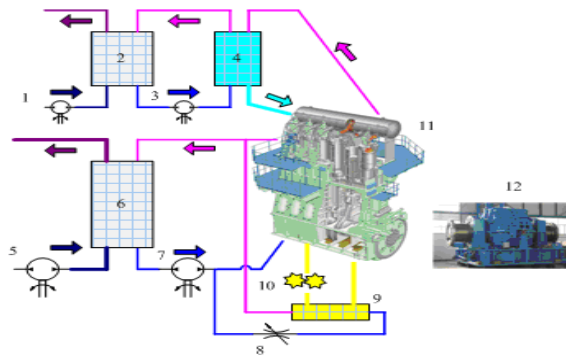


Figure 6. Structure of Cooling System

According to the engine's load, the cooling water flow in the body and the intercooler is separately adjusted to match and optimize the low-speed diesel engine's cooling system. By controlling the cooling capacity, the following functions are realized.

- (1) When the engine starts warming up, the heat dissipation for the cooling is reduced to accelerate the warm-up process.
- (2) In the medium-low load, the heat taken away by the cooling water is reduced to make the components in the best working temperature. That can reduce the fuel consumption and improve the overall reliability, and meantime lower the power consumption driven for the pump.
- (3) The intake cooling is independently controlled to avoid the mutual influence of the body's cooling system and the intercooler for stabilizing the intake temperature and reducing the NOx emission.
- (4) The heat dissipation of the lubricating oil is controlled oil in the best working temperature to optimize the lubrication conditions of the key parts.

7. Optimization of Combustion Process

The difficulty of the diesel's emission control lies in the mutual checks of the NOx's formation and the carbon black's formation. The emissions of the NOx 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 NOx 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 NOx 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.

8. Conclusion

In order to meet the increasing requirements for the power, economy and emission of the high-power low-speed marine diesel engine, the variable flow method is applied to control the cooling water for matching and optimizing the cooling system in the different operating conditions of the diesel engine. Controlling the heat release for the cooling at the different conditions to obtain the best combustion chamber temperature can not only improve the overall reliability, but also reduce the burning heat loss, and improve thermal efficiency. To lower the flow of the cooling water pump in the partial load can reduce the mechanical power loss of the cooling system to improve the whole economy. In order to reduce the No_x emission, using an independent set in the intercooler and the body cooling system to avoid the interaction with each other makes the air temperature after the intercooler equal to or lower than 60°C, and the inlet temperature maintains to be stable.

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