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PERFORMANCE OPTIMIZATION ANALYSIS FOR SHIP CENTRAL COOLING SYSTEM BASED ON VARIABLE FREQUENCY CONTROL

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Abstract

Taking the central cooling system of an 8000TEU container ship as the research object, the equivalent model is established according to the conditions of each subsystem on the ship, and the subsystems are integrated to form the model of the ship's central cooling system. Matlab/Simulink is used as the simulation means to simulate the seawater variable flow, which compares the seawater flow saved under different loads and seawater temperature and speculates the percentage of energy saved by the pump according to the similarity theorem of centrifugal pump. The conclusion of this paper can be used as the reference for the design of the central cooling system of the ship in the future.

Key Words

Central cooling; centrifugal pump similarity theorem; frequency conversion; simulation; energy saving

1. Introduction

At present, all the motors on the ship or the equipment driven by the motor become the basic unit of the ship's maximum power consumption. Among them, the cooling water pump of the ship's central cooling system consumes the most power. The design of the seawater-cooling pump in the central cooling system of the ship is mostly to set the seawater inlet temperature at 32°C. To reach this temperature and flow, the seawater pump must be running at full speed. However, when the ship is sailing in different sea areas, the seawater temperature is often below 32°C. Thus, the actual required seawater flow is different with the sea area, resulting in increased power consumption of the ship and energy waste.

In the research of frequency conversion technology, Ponce and Pedro [1] apply the neural network to the speed observer/tachometer of direct torque control, which improved the accuracy of the observer. Based on fuzzy theory and direct torque control, Cazac and Vadim [2] optimize the parameters of the speed PID regulator to further improve the response of the speed control. Domestic researches on motor frequency conversion have also achieved preliminary results. On the basis of analysing the influence of controllable parameters on the dynamic performance of the system, He Xiaoran [3] brought forward an improved scheme on flux prediction and parameter optimization and analysed two predictive control schemes with different frequency standards to improve the stability of the direct torque control system under high dynamic torque response. Xiang Feng *et al.* [4] analysed the influence of the change of stator resistance on the system performance and used PI regulator to compensate the stator resistance to improve the original control system based on the space vector modulation theory on the problem of relatively large torque ripple in direct torque control. Chen Weizhi [5] took the central cooling system of a 57,000-ton bulk carrier as the research object and analysed the impact of using the seawater pump frequency conversion strategy on energy consumption. Li Binbin [6] studied the frequency conversion of the marine main seawater pump and explored the change of the seawater pump flow when the temperature of the main engine and the seawater inlet changed, and the focus was on the speed control of the frequency conversion motor.

On the basis of previous research, this paper takes the central cooling system of a certain ship as the research object, establishes the equivalent model of each subsystem, proposes a constant temperature control method based on improving the maximum operating point of the central cooling system, and carries out the simulation control of different flow rates of seawater in the central cooling system. The amount of seawater saved under different loads and seawater temperature is compared, and the percentage of energy that can be saved by the pump is inferred according to the similarity theorem of centrifugal pumps, ultimately achieving the purpose of energy conservation, emission reduction, and reduction of ship design costs.

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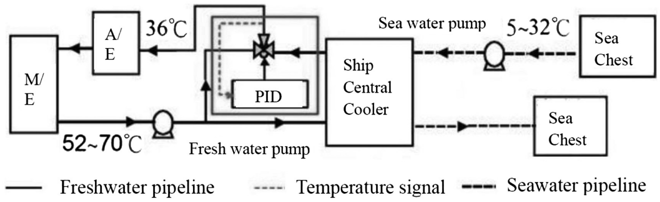

Figure 1. Central cooling system and structure diagram.

This paper is divided into six parts, the first part introduces the operation mode of the existing ship central cooling system, the second part establishes the mathematical model of the ship's central cooling system, and the third part proposes the energy-saving control of the central cooling system based on the constant temperature control method. The fourth part is the simulation control, the fifth part is the analysis of the simulation results under different loads and different temperatures, and the energy reduction of this energy-saving scheme is estimated, and the sixth part is the summary of this experiment.

2. Overview of the Ship's Central Cooling System

The ship adopts a central cooling system, whose cooling fluid required for its main and auxiliary engines is currently replaced with fresh water, which improves the shortcomings of the shell-and-tube cooler in the traditional ship distributed cooling system, and is replaced by a plate cooler. The use of a large capacity seawater cooler in the unit instead of a small capacity individual one reduces the seawater line and uses the cooled fresh water as the cooling medium for the other heat exchangers. As each cooler is no longer in contact with seawater, the heat transfer surface of the central cooler is titanium, which can resist corrosion and reduce salt deposits.

The central cooling system consists of two parts: high temperature and low temperature fresh water. As shown in Fig. 1, the three-way valve mixes the high-temperature hot water flowing back from the main engine with the low-temperature fresh water controlled by the plate heat exchanger to control the output water temperature to 36°C [7], and then, it is distributed to each cooler. The high temperature part is a complete set of piping system to meet the high temperature requirements of the main engine and the auxiliary machine. Meanwhile, the high temperature fresh water is connected to the low temperature pipeline by the thermostatically controlled mixing valve to adjust the temperature of the liner cooling water.

3. Centrifugal Pump Similarity Theorem

The seawater pump generally uses a centrifugal pump to complete the predetermined function. The seawater pump system of the ship's central cooling system often uses two (or three) pumps of the same flow rate and one standby pump to provide cooling water. The centrifugal pump is connected by an induction motor, so it satisfies the similarity theorem of the centrifugal pump, that is, when the two geometrically similar pumps have a certain proportion in each part, the relationship between the pump speed and the flow rate, the head and the pump energy consumption is as follows [8]:

$$\frac{D_1}{D_2} = \frac{b_1}{b_2} \tag{1}$$

D is the impeller outer diameter; b is the impeller outlet breadth. It is known by the continuity equation that $Q = AV$ (Q is the pump flow in the equation). Therefore, in the same pump, the impeller has the same diameter and delivers the same fluid, that is, $D_1 = D_2$, then

$$\frac{Q_1}{Q_2} = \frac{N_1}{N_2} \tag{2}$$

N is the pump speed.

In addition, for example, the relationship between system head and pump energy consumption and pump speed, under the same pump impeller size, according to the similar theory of centrifugal pump, is

$$\frac{H_1}{H_2} = \left(\frac{N_1}{N_2}\right)^2 \tag{3}$$

$$\frac{P_1}{P_2} = \left(\frac{N_1}{N_2}\right)^3 \tag{4}$$

H is the head, and P is the power consumption.

4. Energy-Saving Strategy for Frequency Converting Control

When the ship is sailing in various sea areas, the sea temperature in each sea area will be different. For example, ocean current, latitude, and sunshine will affect the seawater temperature. According to the literature, the maximum seawater temperature will only reach 30°C. Therefore, the current seawater-cooling water temperature is set at 32°C [9]. When the entire central cooling system design is estimated from the total system maximum continuous output power (MCR) is 100% (The entire central cooling system design is estimated from the total system when the maximum continuous output power (Maximum Continuous Rating, hereinafter referred to as MCR) is 100%) and the heat output (H_f) of each main engine and the fresh water side (hot water side) of the plate heat exchanger output is set to 36°C, and the fresh water cooling water passes through the main engine, the full load temperature difference (ΔT_f) of the temperature rise is usually 12°C to 18°C. The known fresh water specific heat (C_f), together with $H_f = m_f C_f \Delta T_f$, can determine the fresh water side (hot water side) flow (m_f). Considering the above conditions m_f, ΔT_f and the set maximum seawater cooling water temperature of 32°C, etc., according to the seawater side flow rate (m_s) (usually slightly larger than m_f), with the design of the plate heat exchanger can determine the physical area (A) of the plate heat exchanger. Generally speaking, the heat exchange plate is more than 40 pieces, which determines the size of the plate heat exchanger, and then the seawater pump corresponding to the flow rate is designed according to the head loss of the pipeline system. The above is the design of the maximum working point of the central cooling system. That is, when the seawater temperature is 32°C, the output flow of the pump can be used to cool the high temperature cooling water on the fresh water side (hot water side) to 36°C after heat exchange.

However, the difference in water temperature between ships in various areas of navigation can reach 10°C or so, and the main engines of the ship are light-loaded or heavy-loaded, which will affect the cooling efficiency (*i.e.* heat exchange capacity) of the central cooler, enabling the fresh water side (hot water side) output temperature is lower than 36°C, so the three-way valve is used to bypass the high-temperature fresh water flowing back from the main engine, which is mixed into the main engine and make the temperature is 36°C [10]. Due to the design of the system, the normal bypass of the three-way valve is large and the pump is running at full speed, which causes waste of energy. Therefore, it is necessary to design a system to change the pump speed to reduce the seawater flow according to the seawater temperature and the load of the main engine, which enable the fresh water side (hot water side) outlet 36°C.

Figure 2 is the schematic diagram of temperature control three-way valve system. According to the concept of the maximum working point, regardless of the light and heavy load of the main and auxiliary engine or the temperature of the seawater [11], the low temperature fresh water (T_{f2}) flowing out of the central cooler is maintained at 36°C; the temperature control of the three-way valve will fully close the bypass line. When the ship is sailing in a seawater temperature lower than the maximum operating point of 32°C, the cooling capacity of the central plate heat exchanger is increased at this time, or when the main and auxiliary engine is operated at light load, the cooling capacity of the central plate heat exchanger is excessive. If the pump continues to run at full speed to draw the same seawater flow (m_s) as the maximum operating point, T_{f2} will be lower than 36°C. To maintain the three-way valve outlet temperature at 36°C, the bypass will open below 36°C T_{f2} so that T_{f3} can be maintained at 36°C. If the motor still maintains the same workload as the maximum operating point, energy will be wasted. To save energy, it is necessary to reduce the seawater flow to solve the problem of increased and excessive cooling of the plate heat exchanger, so as to achieve the same effect as when the ship is working at the maximum working condition and achieve the effect of energy saving. The method is when T_{f2} is below 36°C. The T_{f2} temperature signal is fed back to the PID controller to control the seawater flow (m_s) to reduce seawater flow, which in turn changes the cooling capacity of the plate heat exchanger and make T_{f2} at 36°C. According to the seawater flow rate fed back by the PID controller, it can be known from the similarity theorem of the centrifugal pump that the motor speed is proportional to the pump flow rate, the frequency is proportional to the motor speed. In addition, the pump full load speed and its corresponding flow rate are given, the output frequency required by the converter is calculated, and then the pump is changed to the actual required flow rate to save energy.

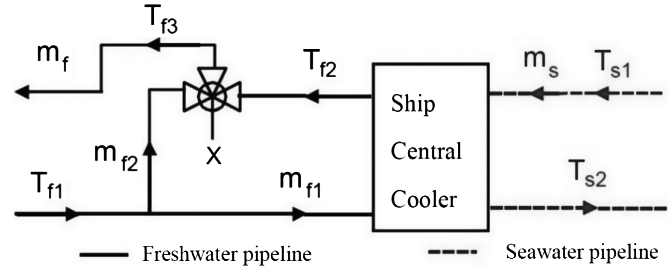

Figure 2. Definition of three-way valve parameters.

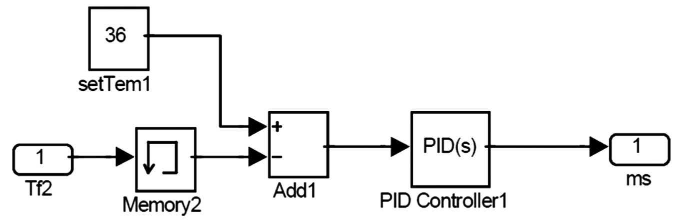

Figure 3. Simulink model for the seawater variable flow control of the ship's central cooling system.

m_s is the total flow of seawater pipeline, m_{f1} is the high temperature fresh water flowing into the central cooler, x is the opening of the three-way valve, m_{f2} is the high temperature fresh water flowing into the three-way valve bypass line, T_{f1} is the high temperature fresh water temperature flowing out of the main engine and flowing into the central cooler, T_{f2} is the low temperature fresh water temperature flowing out of the central cooler, T_{f3} is the fresh water temperature after mixing through a three-way valve, T_{s1} is the seawater temperature flowing into the central cooler, T_{s2} is the seawater temperature flowing out of the central cooler, h_2 is the total heat of fresh (hot) water side, and h_1 is the metabolizable heat of the sea (cold) water side.

5. Simulation Control

Modeling with Matlab/Simulink and investing in the seawater variable flow simulation of the ship's central cooling system in the previous section, the temperature-controlled three-way valve in the fresh water reduces the bypass. The PID controller is used to control the seawater flow to maintain the fresh water outlet water temperature of the central cooler at 36°C [12]. Figure 3 is established as the Simulink model for the seawater variable flow control of the ship's central cooling system, which is put into the Simulink model for seawater variable flow control of the ship's central cooling system of Fig. 4 [13].

Figure 4 shows the Simulink model of seawater variable flow control in the central cooling system of the ship. The parameters are set and the three-way valve is fully open when the thermal load MCR% changes and the seawater temperature is changed at 32°C and 25°C, respectively [14]–[15]; the output fresh water temperature is maintained at 36°C. Then the seawater variable flow simulation is carried out and the relationship between seawater temperature and flow is observed.

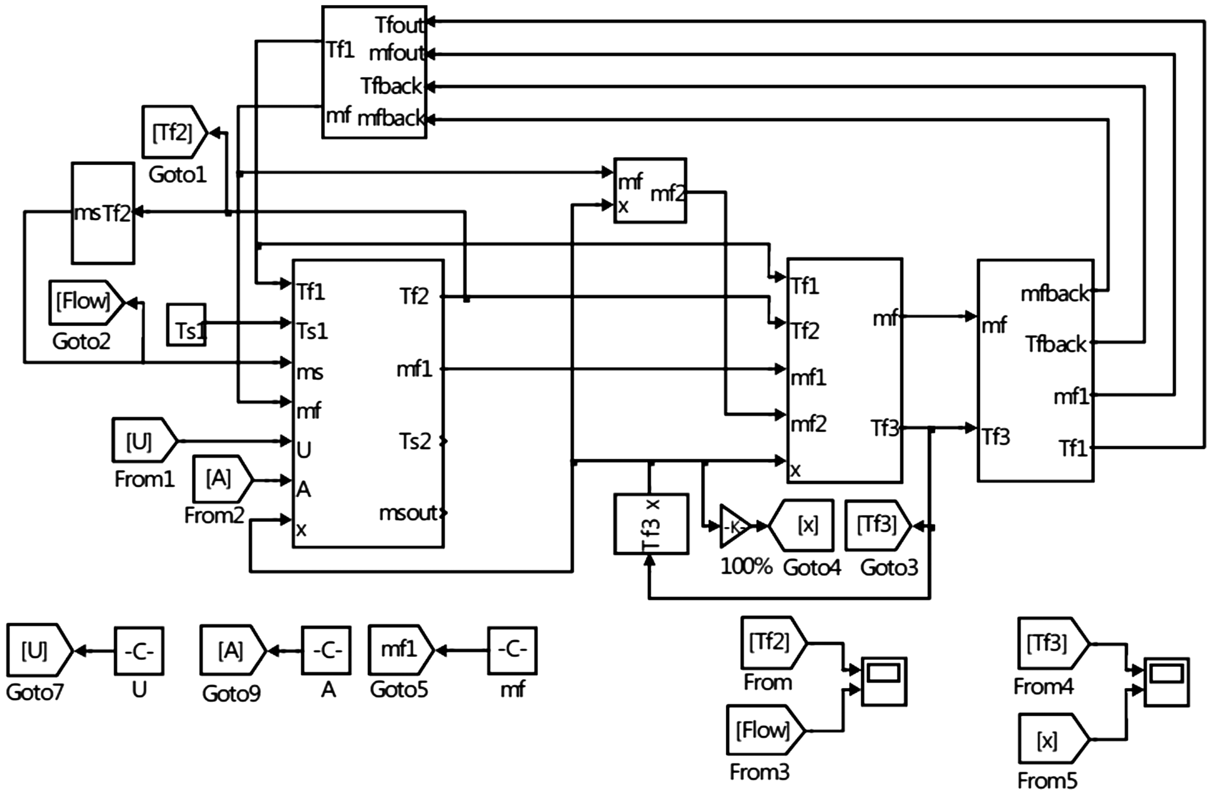

Figure 4. Simulink model for the seawater variable flow control of the ship's central cooling system.

6. Analysis for Simulation Results

According to the parameter setting of central cooler for the 8000TEU container ship, the freshwater flow rate is 3,280 m^3/h, the seawater water temperature is 32°C, 25°C and MCR100%, MCR90%, MCR25% thermal equipment, *etc.* [16], [17], and other information is input into the model of Fig. 4. Thus, the conclusion can be obtained from Fig. 5, which is the simulation result of outlet water temperature and valve opening of the three-way valve when the MCR is 100% and the seawater variable flow when the seawater temperature is at 25°C. Figure 6 shows the simulation result of the required seawater flow rate and the low temperature fresh water temperature flowing out of the central cooler when the MCR is 100% and the seawater variable flow when the seawater temperature is at 25°C.

As shown in Figs. 5 and 6, the controlled seawater flow rate is 2,000 m^3/h. It can be seen from the results that, compared with the seawater temperature of 32°C, the required seawater flow rate is reduced from 3,400 to 2,000 m^3/h, saving 41.2% of the flow rate. This confirms that the seawater flow is changed for constant temperature control, and the three-way valve is kept fully open, which solves the problem of increased and excessive cooling of the central plate heat exchanger due to the decrease of seawater temperature.

Figure 7 shows the relationship between the seawater temperature and the required seawater flow when the MCR is 100%, the three-way valve is fully open. As shown in the figure, when the seawater temperature is close to 10°C, the required seawater flow rate is less than 1,500 m^3/h, and the savings exceed more than half of the seawater flow.

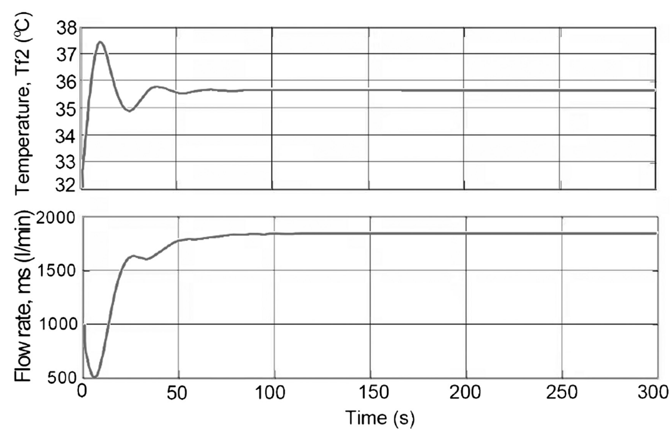

Figure 5. Simulation result of outlet water temperature and valve opening of the three-way valve when the MCR is 100% and seawater variable flow when the seawater temperature is at 25°C.

According to the cubic relationship between the flow rate and the energy consumption of the pump, and the simulation results of the seawater variable flow of the central cooling system of the ship, it is assumed that when the seawater pump runs at a constant flow rate, the energy consumption is 100%. Evaluation of the energy consumption of seawater variable flow pump is shown in Figs. 8 and 9.

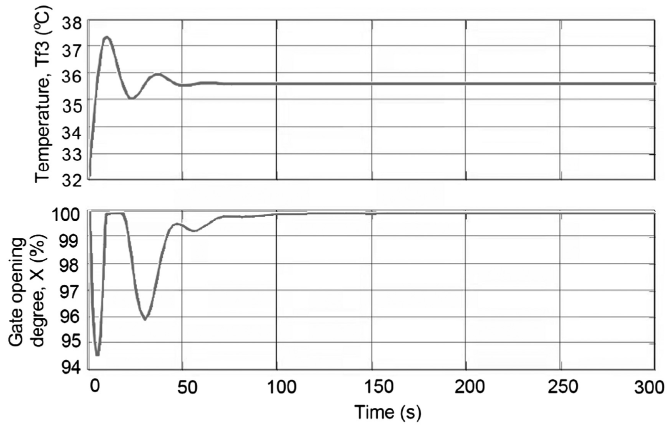

Figure 6. Simulation result of the required seawater flow rate and the low temperature fresh water temperature flowing out of the central cooler when the MCR is 100% and the seawater variable flow when the seawater temperature is at 25°C.

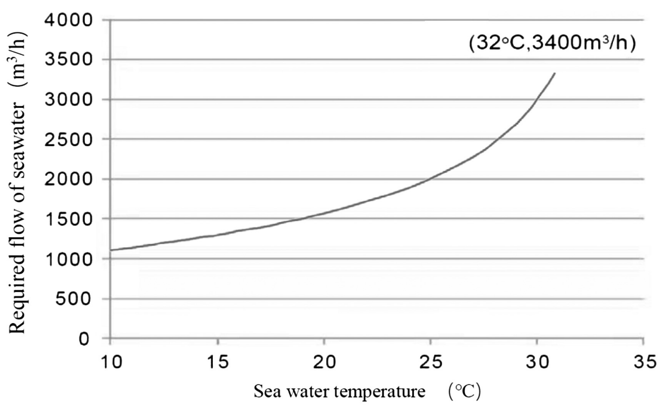

Figure 7. Relationship between seawater temperature and required seawater flow under variable frequency control.

Observing the change of the seawater temperature and the output of the main and auxiliary engines (MCR%), it can be found from Fig. 8 that when the seawater temperature is 25°C, the evaluated frequency converter needs to be adjusted to 35.4 Hz, but the curve shows that the energy consumption of seawater pump dramatically drops below 30%. Meanwhile, it can also be seen from Fig. 9 that when the seawater temperature is between 10 and 25°C, the energy saving is relatively limited, and considering the heat dissipation problem when the actual frequency converter controls the seawater pump motor at low frequency. Therefore, under the appropriate efficiency, if the flow rate at the lowest head of the ship's seawater pump is not considered, a minimum frequency of the converter can be limited as a reference value. In this scheme, it is set to 35 Hz to make it suitable for the application of the energy-saving strategy proposed in this paper [18]–[20].

Conclusion

When the seawater pump is running at full speed and the seawater temperature is gradually lower than the working point or the main and auxiliary engine is gradually smaller than the MCR 100%, the opening of the three-way valve bypass line will also increase.

When the seawater flow rate is changed, the cooling efficiency of the central plate heat exchanger can be controlled so that the bypass line of the three-way valve is fully closed when the fresh water outlet temperature is at 36°C.

The method of controlling the cooling capacity of the seawater variable flow can directly replace the use of the original three-way valve to avoid the phenomenon of chasing each other and solving the waste of cooling efficiency.

From the seawater variable flow simulation results, and based on the centrifugal pump similarity theorem, the energy consumption in the seawater variable flow rate and the corresponding frequency when the frequency converter is applied can be estimated.

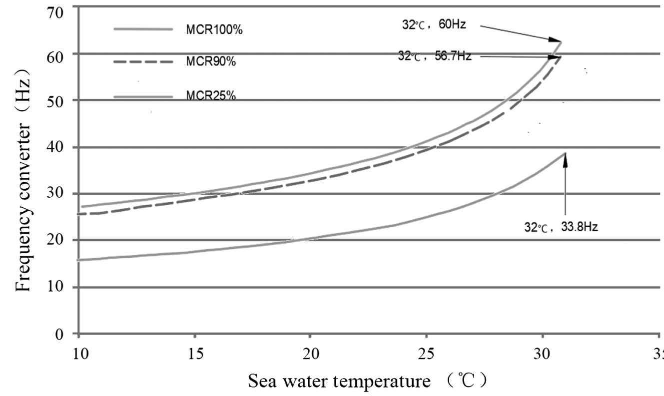

Figure 8. Simulation evaluation of variable frequency control of ship's seawater pump to adjust frequency of its converter.

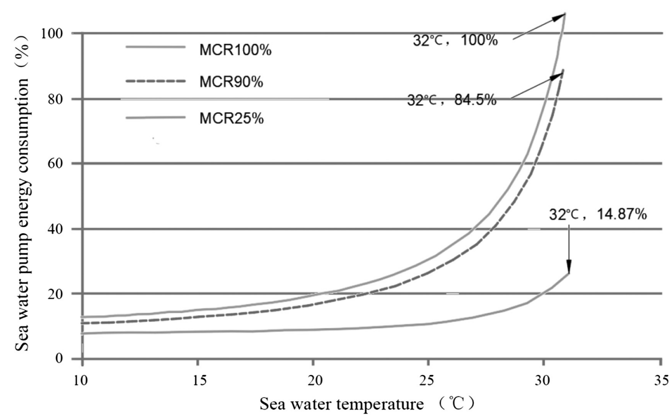

Figure 9. Energy consumption simulation evaluation of variable flow control of marine seawater pump.

Conflict of Interest

We all declare that we have no conflict of interest in this paper.

Availability of Data and Materials

All data generated or analysed during this study are included in this article.

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