WASTE HEAT RECOVERY AND REUSE FOR SHIP HYDRAULIC OIL TEMPERATURE CONTROL SYSTEM

by

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Original scientific paper
https://doi.org/10.2298/TSCI2302257C

In order to solve the problems of high energy consumption and serious waste of heat energy in the traditional oil cooler of Marine hydraulic system, the waste heat recovery and reuse of Marine hydraulic oil temperature control system is proposed. The hydraulic system waste heat recovery test platform has been established, the influence of electrical load, oil flow rate and working medium flow rate on system operation and energy characteristics is studied. The experimental results show that under the same working condition, compared with the oil cooler of the same specification, the maximum thermal efficiency of the proposed organic Rankine cycle waste heat recovery system is increased to 2.56%. The expander pressure ratio and system thermal efficiency increase with the increase of electric load and oil flow. The experimental results analyzed the energy saving effect of waste heat recovery system on hydraulic system, and obtained the rule of system operation efficiency.

Key words: *hydraulic system, waste heat recovery, organic Rankine cycle, experimental research, operating characteristics*

Introduction

It has been reported that the energy demand of various industries has increased rapidly in recent decades, further expanding the energy crisis. Under the background of the reduction of energy efficiency, the deterioration of ecological environment and the concept of energy conservation and reduction, logistics, as a kind of clean and inexpensive transportation mode, is essential to expand the economy [1]. Despite the continuous improvement of equipment quality and operation technology, the energy invested in the production process is still not fully utilized and transformed. Therefore, how to reduce transportation energy consumption effectively brings unprecedented challenges to researchers and enterprises. The group issued a series of stringent measures, such as improving the quality and price of fuel, and curbing emissions of sulphur, NO_x and GHG. It is imperative to save energy and reduce emissions [2].

Ships consume a lot of fuel during operation, but less than half of the heat energy is converted into useful materials to drive the ship's daily operation. The rest of the heat energy is discharged into the environment in the form of flue gas, liner cooling water and lubricant cooling water. This waste heat presents a great opportunity for researchers and manufacturers: good recovery and utilization of this waste heat can improve the overall thermal efficiency of Marine engines, reducing fuel consumption and pollution. With the help of waste heat recovery technology, waste heat can be converted into other forms of useful energy without adding

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additional power, which is regarded as an important measure for various industries to achieve green and sustainable development mode [3]. Therefore, deep and comprehensive exploration of waste heat recovery has become an important research topic at present. The author built the waste heat test platform of organic Rankine recycling hydraulic system, in order to study the operation effect and characteristics of the system under the action of low temperature heat source, the influence law of the hydraulic system and ORC parameters on the system performance is obtained, which provides a reference for the application of ORC in hydraulic system cooling. The waste heat recovery test platform of Marine hydraulic system mainly includes hydraulic circuit as heat source, ORC working medium circuit, mechanical transmission part and measurement and control signal, and is equipped with lubrication circuit. The hydraulic pump station is used to simulate the working process of the hydraulic system on the test platform, the three-phase asynchronous motor drives the hydraulic pump as the power source, and the relief valve is used as the load of the hydraulic system, after the overflow loss, the hydraulic energy is converted into heat energy, and the oil temperature rises. The oil flow is controlled by a variable pump and the oil temperature is controlled by adjusting the working pressure of the load valve. When the hydraulic oil reaches a certain temperature, the ORC system is gradually started. The heated hydraulic oil enters the evaporator and transfers heat to the working medium. At this point, the hot oil is cooled, and the working medium endothermic evaporation into a certain pressure of gas. The gas working medium drives the expander to rotate, and then drives the generator through the belt drive, which generates electricity and supplies the electrical load. Figure 1 shows the technical scheme of an energy saving refrigeration system based on waste heat recovery [4].

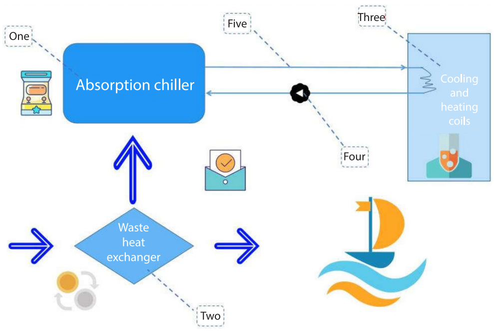

Figure 1. Technical scheme of energy saving refrigeration system based on waste heat recovery

Research methods

System introduction

The waste heat recovery test platform of Marine hydraulic system mainly includes hydraulic circuit as heat source, ORC working medium circuit, mechanical transmission part and measurement and control signal, and is equipped with lubrication circuit. The hydraulic pump station is used to simulate the working process of the hydraulic system on the test platform, the three-phase asynchronous motor drives the hydraulic pump as the power source, and the relief valve is used as the load of the hydraulic system, after the overflow loss, the hydraulic energy is converted into heat energy, and the oil temperature rises [5, 6]. The oil flow is controlled by a variable pump and the oil temperature is controlled by adjusting the working pressure of the load valve. When the hydraulic oil reaches a certain temperature, the ORC system is gradually started. The heated hydraulic oil enters the evaporator and transfers heat to the working medium. At this point, the hot oil is cooled, and the working medium endothermic evaporation into a certain pressure of gas. The gas working medium drives the expander to rotate, and then drives the generator through the belt drive, which generates electricity and supplies the electrical load [7]. After that, the working medium is condensed into liquid in the condenser and enters the liquid storage tank, which is again fed into the evaporator by the working medium pump to continue the next cycle. The lubricating circuit is mainly composed of oil pump, oil separator and oil storage tank to provide lubricating oil for the expansion machine. In the test, the DS1103 hardware of dSPACE company was used to control and measure the relevant signals in the loop test system. In this test, R123 was used as the working medium of ORC system, its boiling point was 27.82 °C, the critical temperature was 183.68 °C, the critical pressure was 3.66 MPa, and the safety level was B1 [8].

Test and calculation model

Experimental test

In addition, when the available energy generated by the ORC system is reused, its load power may also change. Therefore, the flow rate of hydraulic oil and the load power of the generator are taken as the input variables of the system. During the test, when other parameters are unchanged, adjust a variable, and dSPACE will collect and record the flow, pressure, temperature and other parameters of hydraulic oil and working medium in real time [9].

The state of each point in the thermal system is mainly calculated by measuring the pressure and temperature, and then combined with the mass-flow rate, the energy flow of each point can be calculated [10].

Calculation model

The working medium of the hydraulic pump station is L-HM46 hydraulic oil, and its density and specific constant pressure heat capacity can be expressed:

$$\rho_{\text{oil}} = 892 - 0.62T_{\text{oil}} \tag{1}$$

$$c_{p,\text{oil}} = 1940 + 3.4T_{\text{oil}} \tag{2}$$

where T_{oil} [°C] is the temperature of hydraulic oil.

The heat transfer in evaporator is shown:

$$\dot{Q}_{\text{evap}} = \dot{m}_{\text{wf}}\left(h_3 - h_2\right) = \rho_{\text{oil}} q_{\text{oil}} c_{p,\text{oil}}\left(T_5 - T_6\right) \tag{3}$$

The heat transfer in the condenser is shown:

$$\dot{Q}_{\text{cond}} = \dot{m}_{\text{wf}}\left(h_4 - h_1\right) = \rho_{\text{air}} q_{\text{air}} c_{p,\text{air}}\left(T_8 - T_7\right) \tag{4}$$

where $\dot{m}_{\text{wf}}$ [kgs^{-1}] is the mass-flow rate of working medium, ρ_{air} [1.29 kgm^{-3}] – the air density, $c_{p,\text{air}}$ [1005 Jkg^{-1}K^{-1}] – the specific heat capacity at constant pressure, q_{air} [m^{3}s^{-}1] – the air-flow rate, which is calculated from the wind speed and area, h [kJkg^{-}1] – the specific enthalpy of working medium, and T [°C] – the temperature [11].

The power consumed by the working medium pump is shown:

$$W_{\text{rp}} = \frac{\dot{m}_{\text{wf}}\left(h_2 - h_1\right)}{\eta_{\text{rp}}} \tag{5}$$

where η_{rp} is the working medium pump efficiency.

The cooling fan consumption power of the condenser and oil cooler is shown:

$$W_{\text{fan}} = \frac{\rho_{\text{air}} q_{\text{air}}}{\eta_{\text{fan}}} \tag{6}$$

where p_{air} [Pa] is the fan pressure drop and η_{fan} – the indicates the fan efficiency.

The output power of the expander is shown:

$$W_{\exp} = \dot{m}_{\mathrm{wf}}\left(h_3 - h_4\right)\eta_{\exp} \tag{7}$$

where $\eta_{\exp}$ is the efficiency of the expander.

The compression ratio of the expander is shown:

$$r_{\exp} = \frac{p_3}{p_2} \tag{8}$$

The thermal efficiency of the system is shown:

$$\eta_{\mathrm{th,RRC}} = \frac{W_{\exp} - W_{\mathrm{rp}} - W_{\mathrm{fan}}}{Q_{\mathrm{evap}}} \tag{9}$$

Since the oil cooler only consumes power during cooling, its thermal efficiency is defined as the ratio of fan power consumption heat dissipation power, which is expressed:

$$\eta_{\mathrm{th,\ cooler}} = -\frac{W_{\mathrm{fan}}}{Q_{\mathrm{cooler}}} \tag{10}$$

Result analysis

Comparison of oil cooler and waste heat recovery system

Use ORC to reclaim waste heat from the hydraulic system, replace cooling oil with an evaporator in the oil return, and return the oil back from the hydraulic system to the oil tank after the evaporator [12]. The oil passed through the heater has a low pressure drop, which affects the lateral pressure of the hydraulic system. The lateral pressure of oil return will affect the motion stability and energy saving of hydraulic system. If the back pressure of the system is too low, the inability to impose immediate load is weakened, which will reduce the stable motion of the actuator. If the back pressure is too large, the power loss of the system increases and the efficiency decreases [13]. Therefore, it is necessary to compare the pressure drop of oil in evaporator and oil cooler.

Figures 2 and 3 shows when the inlet oil temperature is 80 °C, comparison of oil hydraulic drop and thermal efficiency between ORC system and similar oil cooler. According to the figure, the pressure drop of oil in the evaporator is slightly smaller than that in the oil cooler, and they are in the same order of magnitude [14]. Therefore, replacing the oil cooler with an evaporator in the oil return circuit of the hydraulic system will slightly reduce the system back pressure.

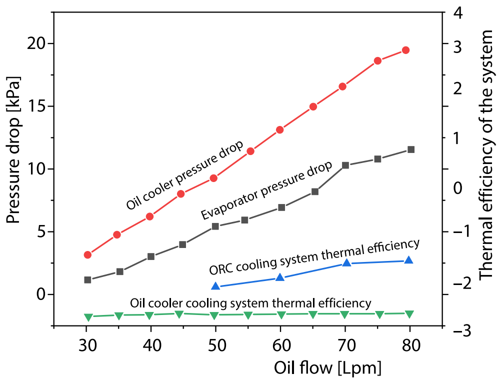

Figure 2. Comparison of pressure drop and system thermal efficiency between oil cooler and waste heat recovery system

The back pressure required by the system can be maintained by adjusting the parameters of the back pressure valve. The operating parameters of ORC system in the figure are: the load is 320 W, and the average operating efficiency is 16 g/s. It can be seen from the figure that the thermal efficiency of ORC air-conditioning system is good and increases with the increase of flow rate, with the maximum value of 2.56%. However, + the thermal efficiency of

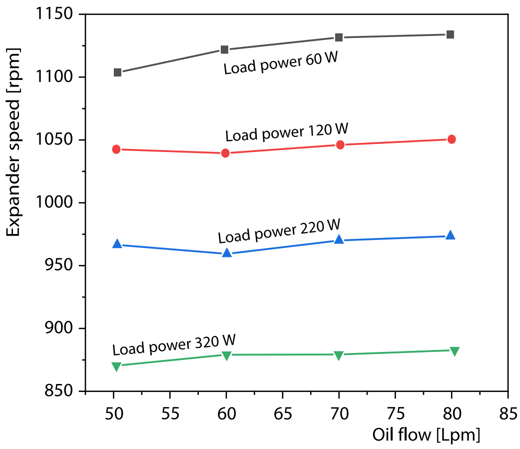

Figure 3. Influence of oil flow rate and electric load on the speed of expander

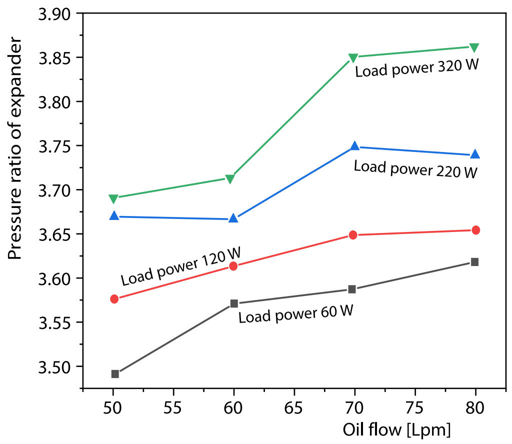

Figure 4. Influence of oil flow rate and electric load on pressure ratio of expander

oil cooler is poor, and increases slowly with the increase of flow rate, the maximum value is –1.63%. The results show that ORC has obvious energy saving effect in recovery of waste heat from hydraulic system. With the increase of gas-flow rate, the thermal efficiency of gas cooler increases slowly, while the ORC cooling power increases obviously. It can be seen that gas-flow has a greater influence on the thermal efficiency of ORC system [10].

Influence of oil flow rate on performance of waste heat recovery system

Hydraulic system is the heat source of ORC system, the change of oil flow will affect the heat exchange of evaporator, and thus affect the performance of organic Rankine circulation system. In the test, the working medium pump displacement is kept unchanged, the oil flow rate and the electrical load power are changed, and the system performance changes are observed.

Figures 3 and 4 show the influence of oil flow rate and electric load on the speed and pressure ratio of expander, respectively. This is because with the increase of oil flow rate, the working medium absorbs more heat in the evaporator, and the enthalpy increases when entering the expansion machine, so that the speed of the expansion machine increases slowly. When the electrical load increases, the output torque of the expander increases, which reduces the speed of the expander and increases the pressure ratio. In the test, the speed of the expander varies from 866-1128 rpm, and the pressure ratio varies from 3.49-3.87 [15].

With the increase of oil flow rate and electrical load, the system thermal efficiency increases gradually. When the electrical load power is 320 W and the oil flow rate is 80 Lpm, the system thermal efficiency reaches the maximum value of 2.56%. The influence of load on ORC system can be analyzed by the temperature entropy diagram shown in fig. 5, where the red line represents the change of the tempera-

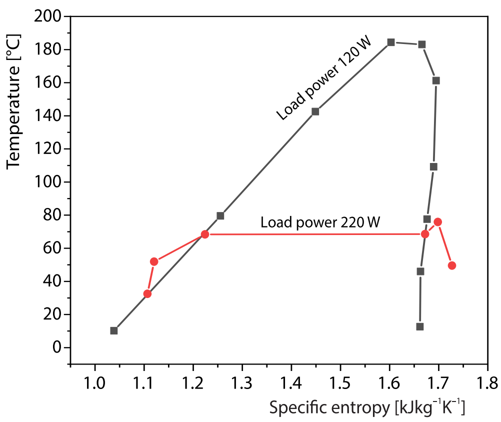

Figure 5. Impact of load on ORC system

ture entropy diagram after the load increases. When the load increases, the speed of expansion decreases, and the evaporation pressure and the temperature of the operating medium increases. Therefore, the heat transfer in the preheating area of the central evaporator is increased, the heat transfer in the evaporation area and the superheat area is also decreased, and the total heat transfer efficiency is improved a little. The output power of the expansion machine is increased, and the thermal efficiency of the system is improved. With the increase of gas-flow rate, the pressure and temperature of the evaporator working medium increase, the temperature of evaporator and the output voltage of expander increase. As the latter increases greatly, the thermal efficiency of the system also increases [16, 17].

Conclusion

The author has conducted an experimental study on the waste heat system of ORC recovery ship hydraulic system, compared the pressure drop and thermal efficiency of oil cooler and ORC system, and studied the influence of oil flow rate, electric load and working medium flow rate on ORC system performance, the main conclusions are as follows. The hydraulic pressure drop in the evaporator is a little lower than that in the cooling oil of the same specification. The thermal efficiency of oil cooler is –1.63%, while the thermal efficiency of ORC system can be optimized and increased with the increase of oil flow. The gas-flow and load have an important effect on the performance of the system, and the increase of both will improve the pressure ratio of the expander and the thermal efficiency of the system. When the power supply load is 320 W and the fuel flow is 80L/min, the thermal efficiency of the system can reach 2.56%.

Acknowledgment

This work was supported by the National Key Technology Support Program of china under Grant No. 2020YFB2103702.

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Paper submitted: September 27, 2022
Paper revised: November 26, 2022
Paper accepted: December 2, 2022