RELIABILITY OPTIMIZATION DESIGN OF INTELLIGENT MECHANICAL STRUCTURE FOR WASTE HEAT RECOVERY

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In order to solve the problems of high energy consumption and serious waste of heat energy in the cooling of traditional oil cooler in hydraulic system, the author proposed the reliability optimization design of intelligent mechanical structure for waste heat recovery. The author has built a waste heat recovery test platform for hydraulic system, 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 rate. With the increase of the flow rate of the working medium, the superheat of the working medium at the inlet of the expander decreases significantly, while the heat exchange of the evaporator and the output power of the expander increase. Under the test condition, the maximum heat exchange of evaporator is 4.18 kW, and the maximum output power of expander is 356 W. The energy saving effect of waste heat recovery system of hydraulic system is obtained, and the influence law of operation parameters on system performance is obtained.

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

Introduction

When a large number of industrial devices are in normal operation, low temperature waste heat will be generated, at present, this part of heat source has not been effectively recycled, which not only wastes energy, increases the energy consumption of the device, but also leads to serious thermal pollution. At present, the methods of low temperature waste heat recovery are mainly organic Rankine circulation system and low pressure turbine recovery system. Organic Rankine cycle (ORC) is a closed circulation system using liquid material with low boiling point as the working medium, that is, the liquid working medium is heated by heat source, and the heat is absorbed and evaporated into steam, the working medium steam drives the turbine machinery to generate electricity or directly drives other mechanical equipment to realize the conversion of heat and mechanical energy [1]. The ORC is a closed cycle using low boiling point organic matter as the working medium, that is, using low boiling point, high vapor pressure organic working medium, when heated by a low temperature heat source, it generates a higher vapor pressure to drive an organic working medium turbine or directly drive other mechanical equipment, organic Rankine circulation system can realize waste heat recovery and

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power generation, and the minimum temperature of waste heat resource can reach 80 °C, which greatly expands the range of waste heat resources that can be recovered for power generation.

In the low temperature waste heat recovery system, the working medium expander is the main energy conversion equipment, whose function is to expand the high pressure working medium steam to the low pressure steam, converting the internal energy of working medium steam into mechanical energy recycling is the core mechanical equipment of this system, the technical level and capacity scale of working medium expander determine the technical level and economy of waste heat recovery system Rankine cycle. At present, expanders applied to organic working medium mainly include screw expander, stream-flow expander and axial flow expander*, etc.*, while low pressure steam inlet steam turbine can only be used for steam medium [2].

Hydraulic transmission system is widely used in high power mobile equipment and industrial equipment because of its large power to mass ratio. Hydraulic excavator as a typical mobile hydraulic equipment, according to the statistics of the Construction Machinery Industry Association, its possession has reached 1.495 million to 1.620 million at the end of 2017. Due to the throttling loss and overflow loss in the process of hydraulic energy conversion and transmission, the average efficiency of the system is only 22%, and almost all of the lost energy is converted into heat energy to make the oil temperature rise [3, 4]. Excessive oil temperature will produce a series of adverse effects, such as increasing leakage, accelerating oil oxidation and deterioration, accelerating the aging of sealing elements*, etc.* In order to prevent the oil temperature in the hydraulic system from being too high, an oil cooler is generally added to the system, and the fan introduces ambient air to the hydraulic oil for forced convective heat transfer.

Methods

Test system

The waste heat recovery test platform of hydraulic system based on ORC is built, and its feasibility and operation characteristics are studied through experiments. At the same time, the experimental results can provide a basis for the calibration and verification of the simulation model.

System introduction

The hydraulic system waste heat recovery test platform mainly includes hydraulic circuit as heat source, ORC working medium circuit, mechanical transmission part and measurement and control signal, and equipped with lubrication circuit, its principle is shown in fig. 1. 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 [5, 6]. 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. 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. Experiment tests, using dSPACE company DS1103 hardware in loop test system for control and measurement related signals [7-9]. In this test, R123 was used as the working medium of ORC system, the safety level was B1.

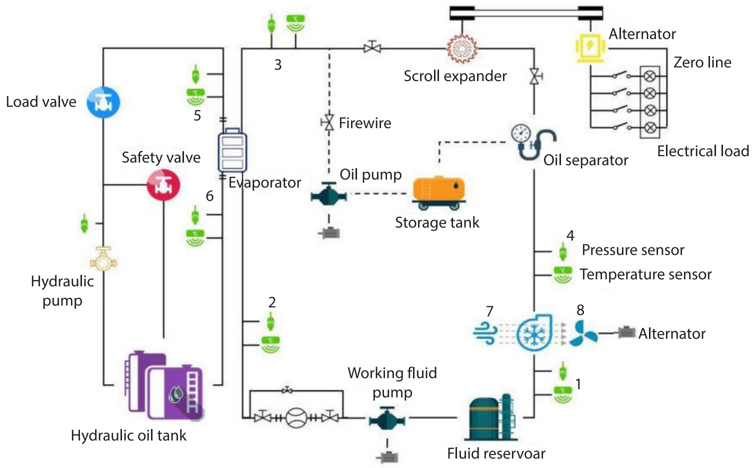

Figure 1. Schematic diagram of waste heat recovery test platform for hydraulic system; *1– working medium at condenser outlet, 2 – working medium at evaporator inlet, 3 – working medium state evaporator outlet, 4 – working medium state at condeser inlet, 5 – oil state at evaporator inlet, 6 – oil state at evaporator outlet, 7 – air state at condeser inlet, and 8 – working medium status at condenser outlet*

Main component parameters

The main components of the test platform of waste heat recovery system include hydraulic pump station, working medium pump, evaporator, expander, generator, liquid storage tank, condenser and corresponding sensor. There is insulation foam on the outside of the evaporator and the working medium line to reduce the heat loss of the working medium.

In the hydraulic pump station, the hydraulic pump used is a fully closed-loop electronic variable pump, its displacement is 71 mL/r, the speed is 1480 rpm. Hydraulic pump can realize the closed-loop control of displacement, and automatically control the change of displacement directly through the given flow rate, therefore, the flowmeter is not installed in the hydraulic circuit. According to the hydraulic fluid-flow measurement results.

In ORC system, plate heat exchanger and tube-fin heat exchanger are used for evaporator and condenser, respectively, the heat transfer area was 3120 m^2. The working medium is not diaphragm type metering pump, its maximum flow is 800 Lpm, the expander is transformed from a scroll compressor with an equivalent displacement of 106 mL/r and a built-in volume ratio of 21. By changing the working medium of plunger stroke length can be adjusted it, so as to change the working medium of the traffic. As a thermal power conversion device, the mechanical energy generated by the expander is transmitted to the single-phase permanent magnet synchronous generator by the belt wheel, and the electric energy is consumed by the bulb as the electrical load. Due to the adaptability of the positive displacement expander, even when the pressure ratio is very small and far below the design point, the scroll expander can still output mechanical energy.

Test

In the actual working process of the hydraulic system, the oil temperature changes slowly, and the oil return flow rate will change with the working condition. In addition, when the available energy generated by the 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. 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. The main sensors used in the test system are shown in tab. 1.

Table. 1 Precision and range of sensor used for measurement

Test parameters	Type of decoder	Range	Precision [%]
The temperature [°C]	PT100	–25-100	0.8
The oil pressure [MPa]	Relative pressure	0-1	1
Working medium and high pressure [MPa]	Absolute pressure	0-3	0.25
Working medium low pressure [MPa]	Absolute pressure	0.1-6	0.25
Working medium flow [th^{-1}]	Coriolis flowmeter	0.06-0.4	0.15
The wind speed [ms^{-1}]	Wind speed measuring instrument	0.3-45	3
Speed [rpm]	Photoelectric tachometer	10-99999	0.04

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} is the temperature of hydraulic oil.

The heat transfer in the evaporator:

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

The heat transfer in the condenser:

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

where $\dot{m}_{\text{wf}}$ [kgs^{-1}] is the mass-flow rate of the 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 by the wind speed and area, h [kJkg^{-1}] – the specific enthalpy of working medium, and T [°C] – the temperature. The lower corner marker 18, respectively, corresponds to the positions of corresponding numbers in fig. 1.

Working medium pump consumption power:

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

where η_{rp} is the working medium pump efficiency [10, 11].

The power consumed by the cooling fan of the condenser and oil cooler:

$$W_{\mathrm{fan}} = \frac{p_{\mathrm{air}} q_{\mathrm{air}}}{\eta_{\mathrm{fan}}} \tag{6}$$

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

The output power of the expander:

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

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

The compression ratio of the expander:

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

The system thermal efficiency:

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

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

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

Results and discussion

During the test, the indoor ambient temperature was measured as (18 ±1 °C). Keep the population oil temperature of the evaporator at 80 °C, and the oil flow rate increases from 50-80 Lpm in a gradient of 10 Lpm. The power of the electrical load varies according to 60 W, 120 W, 220 W, and 320 W.

The ORC is used to recover the waste heat of the hydraulic system, and the oil cooler is replaced by evaporator in the oil return circuit, the returned oil of the hydraulic system is returned to the tank after the evaporator. There is a pressure drop of the oil through the heat exchanger, which affects the back pressure of the hydraulic system, and the back pressure of the back oil will affect the stable motion and energy saving of the hydraulic system [12]. If the rear height of the system is too small, the buffering capacity of the sudden load is weak, which will reduce the motion stationarity of the actuator. If the back pressure is too large. Therefore, it is necessary to compare the pressure drop of oil in the evaporator and oil cooler.

Figure 2 shows the comparison of oil hydraulic drop and thermal efficiency between ORC system and similar oil cooler when the inlet oil temperature is 80 °C. It can be seen from the figure that the pressure drop of oil in the evaporator is slightly smaller than that in the oil cooler, and the two are in the same order of magnitude. Therefore, replacing the oil cooler with an evaporator in the oil return circuit of the hydraulic system will slightly reduce the system back pressure. The back pressure required by the system can be maintained by adjusting the

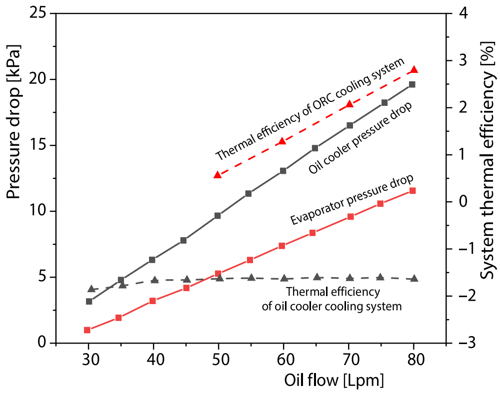

Figure 2. Comparison of pressure drop and system thermal efficiency between oil cooler and waste heat recovery system

parameters of the back pressure valve. The performance of the ORC system in the picture is: the load is 320 W, and the average operating speed is 16 g/s. It can be seen that the flow rate has a greater impact on the thermal efficiency of the ORC 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 [13].

Figures 3 and 4 show the effect of gas-flow and electrical load on the velocity and pressure ratio of the expansion. The speed and pressure ratio of the expander increases slowly with the increase of the oil flow, while the speed of the expander increases more with the decrease of the load. This is because with the increase in gas-flow, the working fluid absorbs more heat in the evaporator, and the enthalpy increases when entering the expansion machine, so that the speed of the expansion wide increase slowly. As the electric load increases, the output voltage of the expander increases, thus reducing the speed of the expander and increasing the height ratio. During the measurement, the speed difference of the expansion is 866-1128 rpm, and the pressure difference is 3.49-3.87.

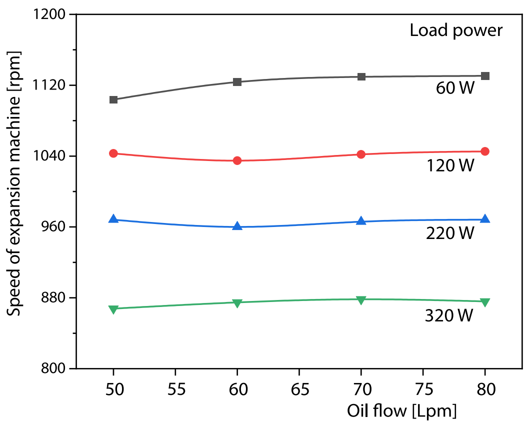

Figure 3. Influence of oil flow rate and electric load on the speed of expander

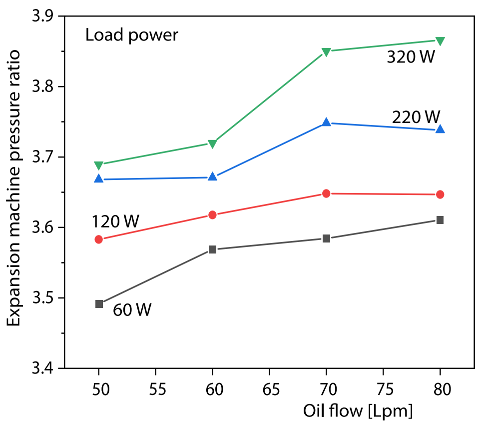

Figure 4. Influence of oil flow rate and electric load on pressure ratio of expander

Figure 5 shows the influence of gas-flow and electrical load on the system thermal efficiency. According to the figure, with the increase of gas-flow rate and electricity load, the thermal efficiency of the system increases. When the load power is 320 W and the oil flow is 80 Lpm, the system thermal efficiency reaches the maximum value of 2.56. The effect of the load on the ORC system can be identified from the temperature entropy diagram shown in fig. 6, where the red line represents the change of the temperature entropy diagram after the load increases. When the load increases, the speed of expansion decreases, so that the evaporation pressure and evaporation temperature of the working medium increase. Therefore, the heat transfer in the preheating area of the medium work in the evaporator increases, while the heat transfer in the evaporation area and the superheated area continues to decrease, and the total heat transfer work increases. The output power of expansion increases, so the thermal efficiency of the system increases. As the gas-flow increases, the pressure and temperature of the working medium at the outlet of the evaporator increases, and the heat absorption of the evaporator and the output of the expansion both increase, because that the latter increases more, the thermal efficiency of the system also increases.

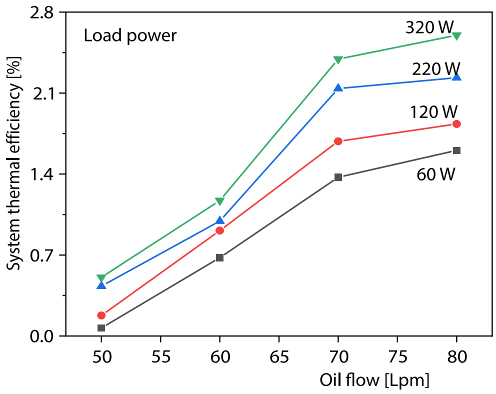

Figure 5. Influence of oil flow rate and electrical load on system thermal efficiency

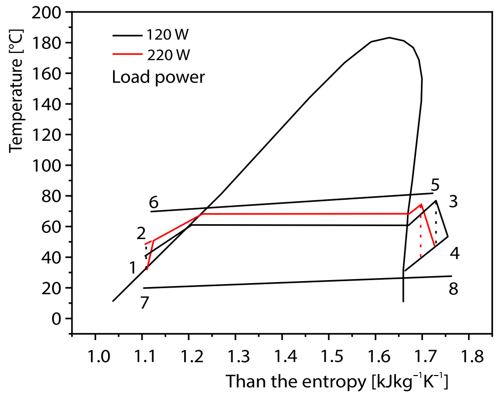

Figure 6. Impact of load on ORC system

The working medium of ORC system is pressurized and transported by the working medium stone, and the flow of working medium directly affects the operating characteristics of the system. In the test, the load power was kept at 320 W, and the mass-flow rates of working medium were 16 g/s and 21 g/s, respectively, to observe the system performance changes [14, 15].

Conclusions

The author put forward the hope for the scientific development of intelligent technology for waste heat recovery, the author conducted a study on the waste heat of the hydraulic return process, pressure drop and thermal efficiency of oil cooler and system were compared, and the effect of oil flow rate, electric load and working medium flow on the performance of the system was studied, the main conclusions are as follows.

- The pressure drop of the hydraulic oil in the evaporator is smaller than that in the cooling oil of the same specification. Those, the thermal efficiency of the oil cooler is –1.63, while the thermal efficiency of the ORC system can be positive and increase with the increase of the oil flow.
- The gas-flow and load have a great impact on the performance of the system, and the increase of the two will improve the pressure ratio of the expansion and the system thermal efficiency. When the load power is 320 W and the oil flow is 80 Lpm, the system thermal efficiency can reach 2.56.
- The increase of the flow of the working medium can increase the temperature change of the evaporator and the output power of the expansion machine, but it will reduce the superheat of the working medium. When the mass-flow of the working medium is 21g/s and the gas-

flow is 80 Lpm, the heat transfer power of the evaporator is 4.18 kW and the output power of the expansion is 356 W. Those, because of the small scale of the design time, the heat transfer power in the evaporator and the power output of the expansion machine is also small, but it can still identify the energy saving of waste heat recovery from the hydraulic system.

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