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Research on Organic Rankine Cycle-Based Industrial Circulating Water Cogeneration System

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Author's contribution

The sole author designed, analyzed, interpreted and prepared the manuscript.

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ABSTRACT

A fertilizer plant wastewater recycling as a research object, the establishment of ORC (Organic Rankine Cycle, referred to as ORC) cogeneration system, using MATLAB software to simulate the operation of the system was found to change the evaporation temperature, condensing temperature, superheat and subcooling degree of the four factors will have an impact on the performance of the system, in which the evaporation temperature and degree of superheat to improve the performance of the system, the condensing temperature and degree of subcooling have a negative effect on the system efficiency. The evaporation temperature and superheat are favorable factors for improving the system performance, while the condensation temperature and subcooling degree adversely affect the system efficiency. Through the verification calculation of specific working conditions, under the conditions of evaporating temperature 110℃, condensing temperature 27℃, superheating degree 8℃ and subcooling degree 3℃, the thermal efficiency of the system can reach about 25%, and the energy efficiency reaches about 45%. The experimental results show that this designed ORC cogeneration system is able to recycle industrial waste heat to a greater extent, which is of great significance to improve the efficiency of energy utilization.

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Keywords: Combined heat and power (CHP); organic rankine cycle; thermal efficiency; energy – efficiency.

1. INTRODUCTION

The organic Rankine cycle (ORC) power generation system is based on a simple steam power cycle known as the organic Rankine cycle. This cycle involves several steps. First, a low-temperature organic mass is pressurized and its physical properties, such as boiling point and flow, are modified using a mass pump. Then, under the influence of the pump, the circulating mass in the system absorbs heat at medium pressure in the evaporator, causing it to vaporize and form saturated steam [1-4].This steam then transforms into high-temperature and high-pressure gases. Finally, these gases are further heated by the superheater. After transforming into superheated steam, the steam enters the expander, undergoes expansion, and performs work. This work drives the generator, enabling power generation and the production of a significant amount of usable power. The spent steam is then discharged after expansion [5-8]. Although its temperature is slightly higher than the surrounding environment, it is still significantly cooler than when it was superheated. The discharged steam is condensed back into liquid by the condenser and cooling water. This condensed liquid then continues to participate in the cycle, forming the power generation system's central element [9-11].

2. SYSTEM WORKING PRINCIPLE AND SELECTION OF CIRCULATING MEDIUM

ORC cogeneration system mainly contains three systems, the heat source system is connected to the power generation system, and the power generation system is connected to the heat supply system to realize the multiple utilization of energy, and the waste heat resources of the heat source in the output of electricity and heat through the cogeneration system. This system ORC power generation system in the selection of organic work mass needs to follow the relevant selection principles and consider the impact of various factors [12-13].

2.1 How Cogeneration Systems Work

ORC system is mainly composed of organic mass, evaporator, turbine, condenser and mass pump, the power consumption rate of the mass pump increases with the lowering of the temperature of the heat source, the enthalpy drop of the expander used in the ORC system is relatively low, one-stage or two-stage expansion can be designed to achieve the purpose of the manufacture is relatively inexpensive, the organic Rankine cycle of the organic mass of the gas phase and the liquid phase of the density gap between the smaller, the evaporation process has a more stable Heat transfer properties, so the ORC system used in the structure of the evaporator can be designed relatively simple, the condenser can be positive pressure (refers to the gas pressure than atmospheric pressure (that is, often referred to as an atmospheric pressure) of the gas state) work, such as R245fa (Pentafluoropropane is a colorless, transparent, easy-to-flow liquid with volatility and a boiling point of 15.3°C, stable at room temperature and pressure.) [14-16], condensing pressure at room temperature than the atmospheric pressure, the organic Rankine cycle of the workpiece has a more appropriate pressure, the sealing of the equipment requires less, low cost, and Safer. Organic mass first through the mass pump pressurization to reach a certain pressure value and then into the evaporator, in the low-temperature hot water (145°C -120°C) under the action of the evaporation of organic gases, and then in the turbine expander to do the work, the low taste of heat energy into a high grade of electricity, after doing the work of the discharged gas and enter the condenser, through the water-cooled to form the organic mass liquids, and then repeat to participate in the cycle.

In the condenser, the heat energy in the organic medium is transferred to the cooling circulating water, which then absorbs heat to reach the temperature at which heating can be provided, and the water supply circulating pump pumps the hot water into the user's home, and then releases the heat and then back to the condenser, which continues to participate in the condensation of the organic medium and completes the cycle of the heating system.

In this project, the process hot water in a fertilizer company is used as the heat source, and three systems are generated, which are the heat source system, the ORC power generation system and the heat supply system. The heat source system is directly connected to the process waste heat wastewater, and the heat exchange with the ORC power generation system occurs at the evaporator, and under the interaction of the hot water pump, it enters into the evaporator through the pipeline, and exchanges the heat with the organic workmasses therein, and then continues to return to the water to be used in the process when the process After the hot water releases its heat, it can be returned to the process to complete the cycle. The second system is the ORC power generation system, ORC system in the evaporator from the heat source in the hot water to absorb heat, from the work of the pump pressurized organic matter to absorb heat and evaporation into the turbine expander, the expander work to make the organic matter depressurization, and then enter the condenser and condensing circulating water heat exchange, at this time to start the third heating subsystem of the cycle, the heating system in the condenser to absorb the work of the organic matter remaining heat, and in the hot water pump, the heat pump, and then continue to return to the process water to be used to complete the cycle. The heat supply system absorbs the remaining heat of the organic mass in the condenser after doing work, and then enters the user's home under the action of the hot water pump to realize heating.The entire ORC cogeneration system is more adequate use of energy, the use of three systems will be the use of energy cycle after cycle, the study of each system can maximize the efficiency, reduce the loss of hot water pumps and industrial pumps can improve the performance and efficiency of the system, the three systems can complete the use of wastewater, industrial power generation and heating, can be said to be a three-in-one, very much of the analysis of the value of the design value.as follows Fig. 1. Shown in the cogeneration system schematic diagram [17]. Among them, the heat source system is the source of industrial waste heat for the cogeneration system, and the heat supply system is to transfer the industrial waste heat to the users to realize the reuse of energy.

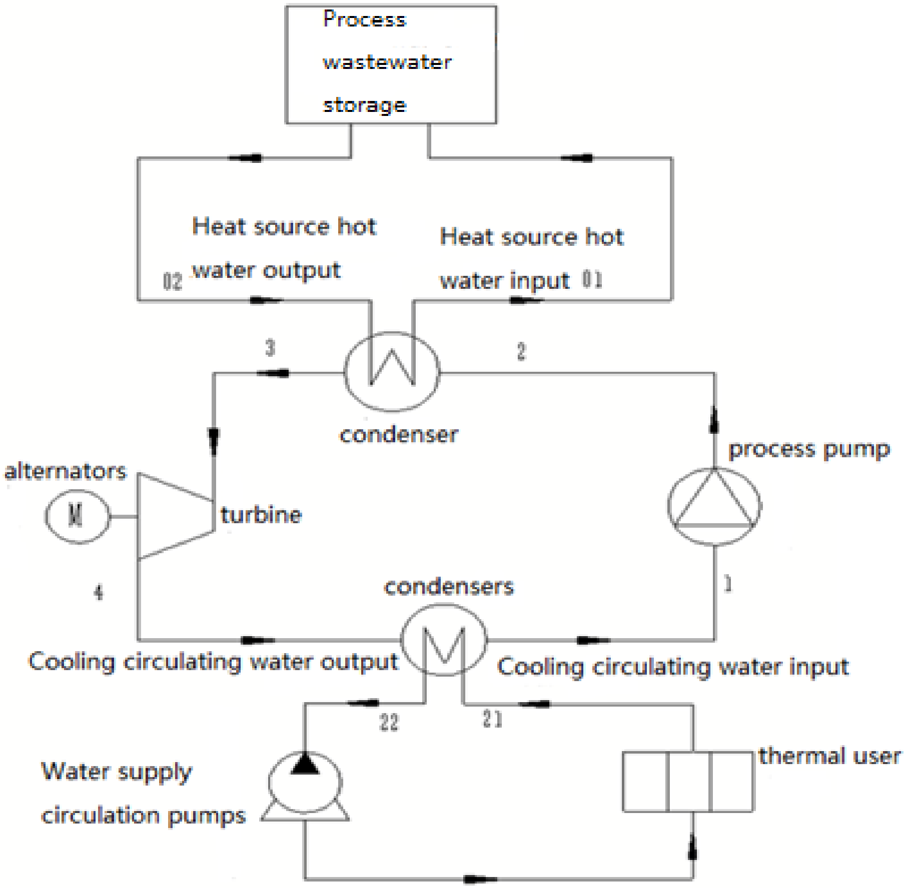


Fig. 1. Schematic diagram of cogeneration system

Table 1. Indicators for R245fa (pentafluoropropane)

industrial quality	R245fa
molecular mass	134
Boiling point (1atm), °C	15.14
Critical temperature, °C	134
Critical pressure, kPa	3651
Saturated vapor pressure (25°C), kPa	150
Heat of vaporization/latent heat of evaporation (below boiling point), kJ/kg	197
Ozone Depletion Potential (ODP)	0
Global Warming Potential (GWP, 100yr)	1030
ASHRAE Safety Levels	B1 (toxic non-combustible)

2.2 Selection of Organic Substances

The key to the success of the ORC system is the selection of the mass, in determining the heat source and cooling temperature, as far as possible to have a high thermoelectric conversion rate and power generation, the critical operating pressure, temperature, density and so on are influencing factors. Should be reasonable evaporation pressure, environmental protection ODP (ozone depletion), low GWP (greenhouse effect value), low toxicity, non-flammable and non-explosive [18].

There are many kinds of organic workmates, through the study of related literature, it is found that the more appropriate two organic workmates are R123 and R245fa, it is understood that R123, scientific name of Trifluoro-dichloroethane, molecular formula , is a kind of poisonous but non-combustible organic matter, usually used as a refrigerant, R123 and R245fa in the design of the parameter also has quite a lot of differences, so mutual replacement and common use are not very reasonable, R123 in reality is not optimistic, so only use R123 as a comparison of the subsequent organic work, and do not use R123 as the organic work of this system. Pentafluoropropane is a kind of colorless transparent easy flowing liquid with volatility, boiling point 15.3 ℃ stable at room temperature and pressure, mainly used in refrigerators, panels, polyurethane insulation material foam, etc. Its code name is R245fa [19].

Comprehensive consideration that R245fa is a more suitable organic work material, the production of R245fa is not restricted, the scope of application is also wider, the comprehensive performance of R245fa is also good, so the system design chooses to use R245fa as the organic work material of organic Rankine cycle power generation system.R245fa gasification temperature is 15.14 ℃, the latent heat of vaporization of organic work material (refers to the substance R245fa gasification temperature is 15.14℃, the latent heat of vaporization of organic workmass (refers to the heat absorbed or released from one phase to another under isothermal and isobaric conditions) is low, and the utilization rate of low-grade thermal energy is higher, and the utilization efficiency of ORC power generation system of waste heat is high when the temperature of the heat source is below 250 degrees Celsius, which is about 5% - 20% [20].

3. SYSTEM MODELING

This topic is simulated and analyzed by building a model, and this model is designed to analyze the net power generation of the power generation system, as well as the system thermal efficiency and energy efficiency of the cogeneration system, and to make the following assumptions: stable flow of the work mass in the piping of the various equipment within the device system. Pressure losses in all equipment such as preheater, evaporator, condenser, etc., as well as piping, valves, regulating valves, etc., connecting the equipment are neglected. The isentropic efficiency of the turbine expander is a constant value. The static pressure and flow resistance of the work mass in the work mass tank are negligible, and it is considered that the specific entropy and specific enthalpy of the work mass in and out of the work mass tank do not change.The ORC cogeneration system is based on the background of the low-temperature waste heat of a fertilizer company's process, and it is understood that the temperature of the wastewater from a fertilizer company's process can be up to 145°C with a pressure of 1.1 MPa, and that the temperature of the return water is 120°C with a pressure of 1.0 MPa, and a flow rate of 300t/h.

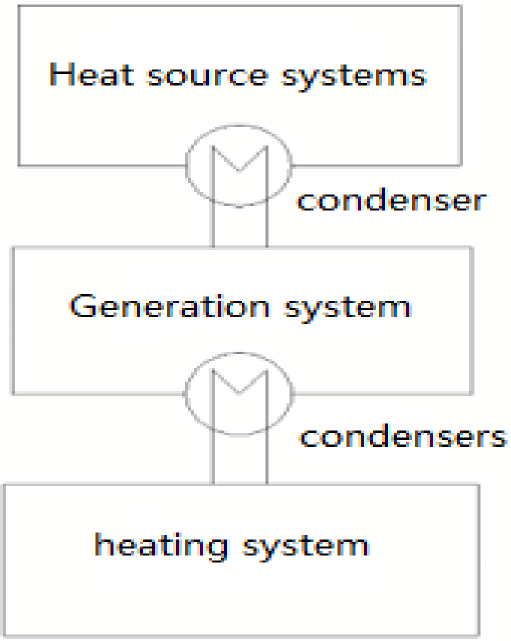


Fig. 2. Schematic diagram of the cogeneration system

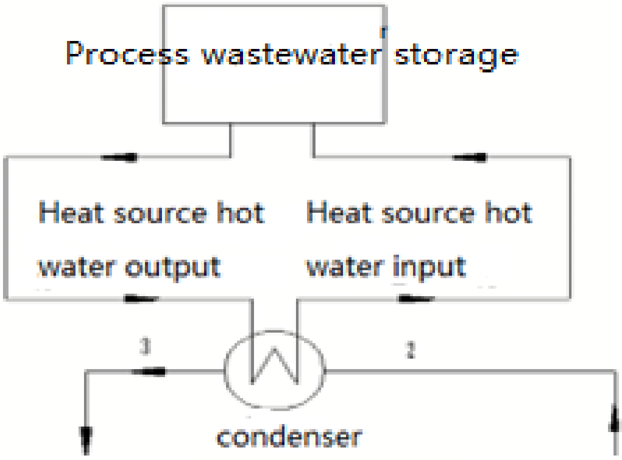


Fig. 3. Flow chart of heat source system

3.1 Heat Source System Modeling

From the fertilizer process wastewater storage discharged from the high-conditioned water (120 ℃ -145 ℃) through the pipeline into the hot water pump, under the action of several pumps to form a certain pressure and temperature of the hot water, the water supply temperature of 145 ℃, the pressure of 1.1 MPa, into the evaporator so that the organic workpiece heat-absorbing evaporation, discharged back to the temperature of 120 ℃, the pressure of 1.0 MPa, and then out of the evaporator and then into the Cyclic fertilizer manufacturing process is used, and the cycle is repeated [21].

Some of the thermodynamic terms are used in the following calculations, and these terms are explained in the following table, as shown in Table 2.

Table 2. Introduction to the thermodynamic part of the terminology

Terminology	hidden meaning
h	A parameter that expresses the thermodynamic properties of a substance and is numerically equal to the internal energy contained in the system plus the product of pressure and volume in joules.
s	Physics refers to the quotient of heat energy divided by temperature, marking the degree to which heat is converted into work
$\eta_{sys,ex}$	Process or the whole system, according to a variety of logistics and energy flow calculation of the input and output of the total effective energy ratio, which measures the effective energy utilization of the thermodynamic degree of perfection

The power consumption of the pump in winter:

$$W_{Bp0} = 2880 \times (m_{Bp} \times H_{Bp} / \eta_{Bp}) \times 9.8/1000 \tag{3.1}$$

Among them:

W_{Bp0} is the winter pump power consumption, kWh;

m_{Bp} is the flow rate of the water supply circulation pump, kg/s;

H_{Bp} is the head of the water supply circulation pump, m;

η_{Bp} is the efficiency reference value for water supply circulating pumps;

2880 Winter power consumption often, h;

9.8 is the acceleration of gravity on the ground $\mathrm{m/s^2}$;

Output heat:

$$q_0 = m_w (h_{01} - h_{02}) \tag{3.2}$$

Among them:

q_0 is the additional heat output in winter, kW;

m_w is the heat source hot water flow rate, 300t/h;

h_{01} is the enthalpy of hot water at the inlet of the evaporator, kJ/kg;

h_{02} is the enthalpy of hot water at the outlet of the evaporator, kJ/kg;

Added output Energy:

$$e_0 = m_w [h_{01} - h_{02} - T_0 (s_{01} - s_{02})] \tag{3.3}$$

Among them:

s_{01} is the entropy of hot water at the inlet of the evaporator $\mathrm{kJ/kg \cdot K^{-1}}$;

s_{02} is the entropy of hot water at the outlet of the evaporator $\mathrm{kJ/kg \cdot K^{-1}}$;

T_0: Ambient temperature 10°C, 283.15 K;

Net output in winter net output energy efficiency

$$E_0 = 2880e_0 - 2880W_{Bp0} \qquad (3.4)$$

Where:

E_0 is defined as the net winter output energy, kWh;

3.2 Power Generation System Modeling

Organic combination of the work pump, evaporator, turbine expander and condenser, it consists of the main part of the organic Rankine cycle power generation system, this subsection will be the integration of the system calculation formula, the evaporator at the organic work heat absorption for the overall energy input, and then in the turbine expander as the output of the power generation system to do the work, remove the loss of power consumption of the work pump, it is the system's net output of the work, and then calculate the value of the system's thermal efficiency and the Energy Then calculate the value of thermal efficiency and energy efficiency of the system [22].
Net system output power:

$$W_{rank} = W_t - W_p \qquad (3.5)$$

Net winter generation:

$$W_{el} = 2880 \times W_{rank} \qquad (3.6)$$

The thermal efficiency of the system cycle is:

$$\eta_{sys} = \frac{h_3 - h_4 - (h_2 - h_1)}{h_3 - h_2} \qquad (3.7)$$

Energyefficiency for:

$$\eta_{sys,ex} = \frac{m_f\left(h_3 - h_4 - (h_2 - h_1)\right)}{m_{w0}\left[h_{01} - h_{02} - T_0\left(s_{01} - s_{02}\right)\right]} \qquad (3.8)$$

Style:

W_{rank} is the net system output power, kW;

η_{sys} It is the thermal efficiency of the system circulation;

$\eta_{sys,ex}$ It is the energy efficiency of the power generation system;

h_3 is the necessary enthalpy of the inlet mass of the turbine expander, kJ/kg;

h_4 is the specific enthalpy of the outlet mass of the turbine expander, kJ/kg ;

h_{01}、 h_{02} is the enthalpy of hot water inlet and outlet of the evaporator kJ/kg;

s_{01}、 s_{02}: is the entropy of hot water at the inlet and outlet of the evaporator $\mathrm{kJ/kg \cdot K^{-1}}$;

3.3 Overall Efficiency Analysis of the ORC Cogeneration System

Use the heat source system input as the overall input:

Thermal input

$$q_0 = m_w\left(h_{01} - h_{02}\right);$$

Energy Enter

$$e_0 = m_{w0}\left[h_{01} - h_{02} - T_0\left(s_{01} - s_{02}\right)\right]$$;

ORC Power Generation System

Output heat:

$$q_{sys} = m_f\left[h_3 - h_4 - \left(h_2 - h_1\right)\right]$$.;

Output energy:

$$e_{sys} = m_f\left[h_3 - h_4 - \left(h_2 - h_1\right)\right]$$.;

heating system

Output heat: $q_1 = m_{w1}\left(h_{22} - h_{21}\right)$;

Output:

$$e = m_{w1}\left[\left(h_{22} - T_0 s_{22}\right) - \left(h_{21} - T_0 s_{21}\right)\right]$$;

Thermal efficiency of cogeneration systems:

$$\eta_{Qall} = \frac{q_{sys} + q_1}{q_0} = \frac{m_f\left[h_3 - h_4 - \left(h_2 - h_1\right)\right] + m_{w1}\left(h_{22} - h_{21}\right)}{m_w\left(h_{01} - h_{02}\right)} \tag{3.9}$$

Cogeneration systems ï¼š:

$$\eta_{Eall} = \frac{e_{sys} + e}{e_0} = \frac{m_f\left[h_3 - h_4 - \left(h_2 - h_1\right)\right] + m_{w1}\left[h_{22} - h_{21} - T_0\left(s_{22} - s_{11}\right)\right]}{m_{w0}\left[h_{01} - h_{02} - T_0\left(s_{01} - s_{02}\right)\right]} \tag{3.10}$$

3.4 Typical Working Condition Model Validation

Within reasonable limits, the following assumptions are made, ORC power generation system evaporating temperature 110°C, superheat 8°C, subcooling 3°C, condensing temperature 25°C, condenser inlet cooling circulating water temperature 25°C, pressure 0.5MPa, condenser outlet cooling circulating water temperature, 45°C, pressure 0.4MPa, and using this as the initial conditions, the following calculations are performed:

available from the rest of this chapter:

Specific enthalpy of the inlet and outlet of the work pump:

$$h_1 = 231.14\text{kJ/kg}$$.;

$$h_2 = 232.7\text{kJ/kg}$$.;

Specific enthalpy of the organic work mass at the outlet of the evaporator:

$$h_3 = 491.06\text{kJ/kg}$$.;

Specific enthalpy of hot water from the heat source at the inlet and outlet of the evaporator:

$$h_{01} = 611.07\text{kJ/kg}$$.;

$$h_{02} = 504.38\text{kJ/kg}$$.;

Specific entropy of hot water from heat source at the inlet and outlet of the evaporator:

$s_{01} = 1.7900\,\mathrm{kJ/kg \cdot K^{-1}}$.;

$s_{02} = 1.5272\,\mathrm{kJ/kg \cdot K^{-1}}$.;

Specific enthalpy at the outlet of a turbine expander:

$h_4 = 455.46\,\mathrm{kJ/kg}$.;

Specific enthalpy of cooling circulating water at the inlet and outlet of the condenser:

$h_{21} = 105.29\,\mathrm{kJ/kg}$.;

$h_{22} = 188.78\,\mathrm{kJ/kg}$.;

Condenser inlet and outlet cooling circulating water than entropy:

$s_{21} = 0.36710\,\mathrm{kJ/kg \cdot K^{-1}}$.;

$s_{22} = 0.63845\,\mathrm{kJ/kg \cdot K^{-1}}$.;

Flow rate of hot water from heat source: 83.33kg/s;
Organic work mass flow rate: 33.09kg/s;
Cooling circulating water flow rate: 13.89kg/s;
ORC Cogeneration System Thermal Efficiency:$\eta_{\mathrm{Qall}} = 0.2570$
ORC Cogeneration System Energy Efficiency: $\eta_{\mathrm{Eall}} = 0.4529$;

In this subsection, the overall efficiency of the cogeneration system is analyzed and the calculation is verified for a specific case of a working condition, and it is calculated that the thermal efficiency of the overall system is about 0.25, and the efficiency of the overall system Energy about 0.45 , which are both improved compared to the ORC power generation system, and the cogeneration system is superior to the separate ORC power generation system [23-24].

3.5 Variable Factor Analysis

There are four main variable factors that affect the ORC power generation system, which are evaporation temperature, condensation temperature, superheat and subcooling, and it is understood that the evaporation temperature and superheat have a positive impact on the system, while the condensation temperature and subcooling have a negative impact, and the next step will be to analyze the four influencing factors in multiple sets of cases, and the results of the calculations will be plotted, and a more intuitive point in Origin software. The results will be plotted in the Origin software to describe the changes of power generation and efficiency at different temperatures, and the results are shown in the following figure. Fig. 4 The results are shown in Fig. 4, Fig. 5. The results are shown in Fig. 5 and Fig. 6.

Through the analysis, it is found that the changes of the evaporation temperature and superheat degree of the organic matter have a positive influence on the system, with the increase of the evaporation temperature and superheat degree of the organic matter, the net power generation of the ORC cogeneration system, the overall thermal efficiency of the system, and the efficiency of the system are improved, while the changes of the condensation temperature and the degree of subcooling have a negative influence on the system, with the increase of the condensation temperature and the degree of subcooling, the system parameters are gradually reduced, so it is necessary to choose the appropriate evaporation temperature, superheat degree, condensation temperature and subcooling degree within a reasonable range to make the power generation system and heating system performance. As the condensing temperature and the degree of subcooling increase, all the parameters of the system gradually decrease, and the change of these four variables directly affects the performance of the power generation system and the heating system, so it is necessary to optimize the system performance by selecting the appropriate evaporation temperature, degree of superheat, condensing temperature and degree of subcooling within a reasonable range.

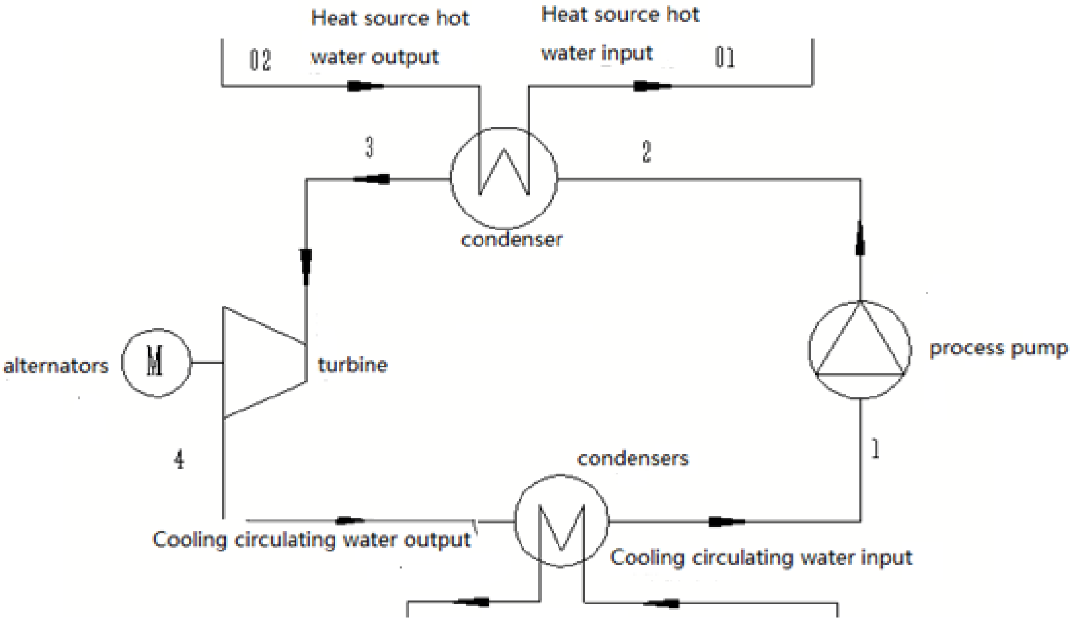
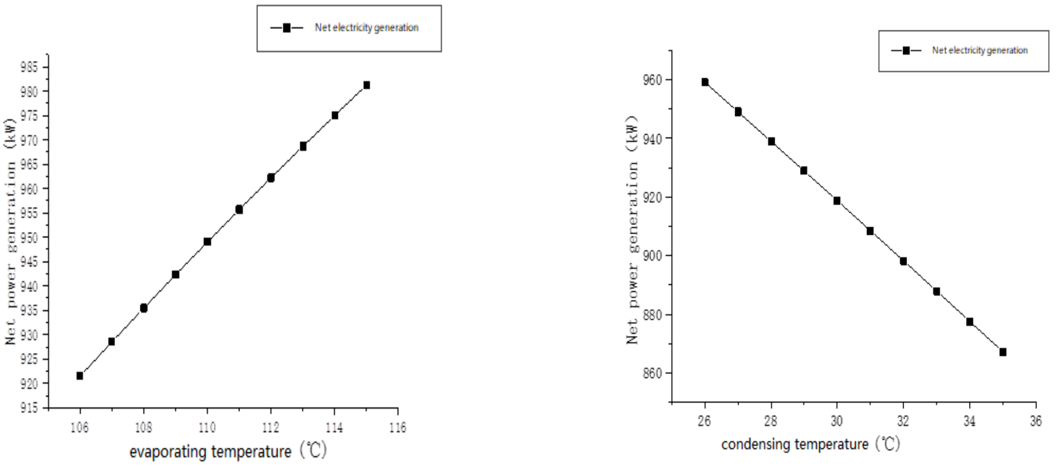
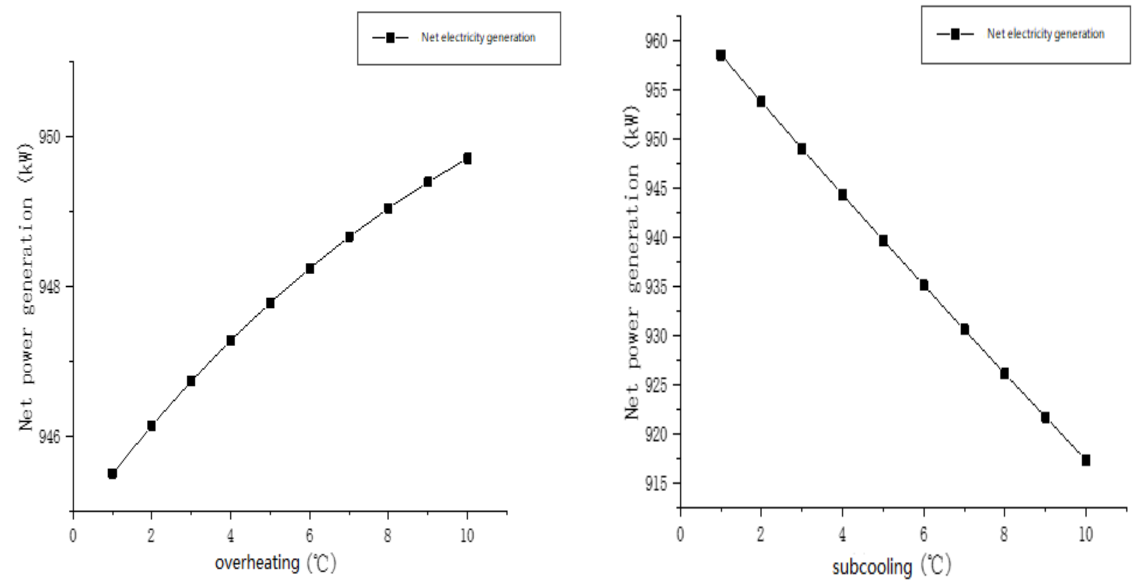


Fig. 4. ORC Power Generation System Flowchart



a evaporating temperature

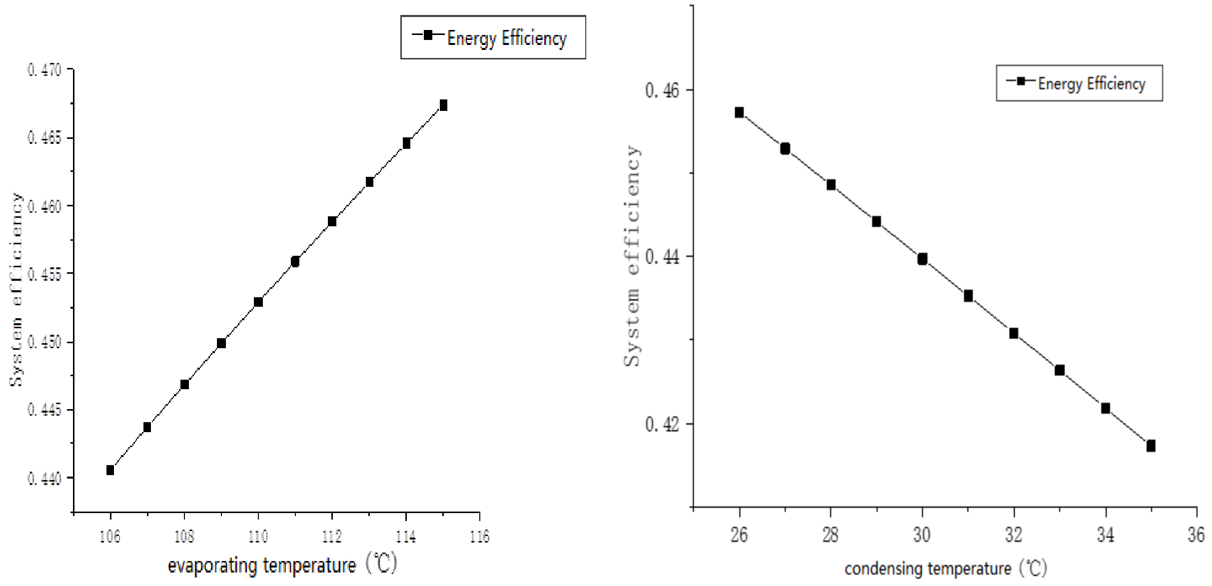
b condensing temperature



c overheating

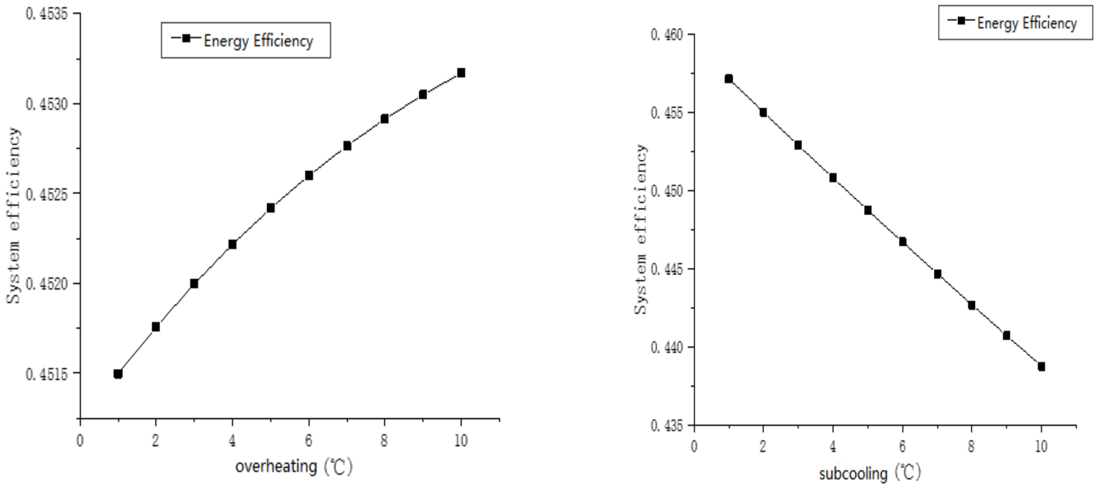
d subcooling

Fig. 5. Impact of variable factors on power generation



a evaporating temperature

b condensing temperature



c Overheating

d Subcooling

Fig. 6. Impact of variable factors on energy efficiency

4. CONCLUSION

The ORC power generation system in this cogeneration setup utilizes a fertilizer process wastewater with a temperature of 145 ℃ and pressure of 1.1 MPa. By analyzing and comparing different options, the circulating organic media R245fa is chosen, which results in good performance for the power generation system. This system then efficiently utilizes the waste heat by integrating it into the heating system, maximizing its secondary use. Through the establishment of an ORC cogeneration system model, it is observed that increasing the evaporation temperature and degree of superheat leads to a decrease in irreversible losses, an increase in system thermal efficiency, and higher output power from the expander. Conversely, increasing the degree of subcooling and reducing the condensing temperature results in increased irreversible losses and decreased system thermal efficiency. Further study of the factors influencing the system reveals that the power generation power can reach 949.05 kW, while the system thermal efficiency can reach approximately 0.25 kW. The cogeneration system demonstrates excellent performance in utilizing waste heat, with a thermal efficiency of about 0.25 and an energy efficiency of about 0.45. This highlights its significant potential for further development and utilization.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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