Research on the Ultimate Performance of Organic Rankine Cycle Experimental System

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Abstract. At present, fossil energy is depleted and environmental pollution is severe. Based on this context, renewable energy has begun to be paid attention to, among which ocean thermal energy conversion (OTEC) has received more and more attention. In this paper, the organic Rankine cycle (ORC) wasted heat power generation system is built. Through the experimental method of controlling variables, the effects of the temperature of the heat source and the flow rate of the working fluid on system performance are explored. The results show that: when the flow rate of the working fluid is constant, as the temperature of the heat source gradually increases, the generating power of the ORC system increases rapidly first and then increases slowly. When the temperature of the heat source remains unchanged and the flow of working fluid gradually increases, the generating power of the ORC system increases first and then decreases. At different temperatures, there is a corresponding optimal working fluid flow that maximizes the system output power, and the higher the temperature, the greater the system output power. Through experiments, it is found that the maximum generating power of the ORC system is 667.55W, the corresponding heat source temperature is 120°C, the working fluid flow is 470.64 kg/h, and the frequency is 90 Hz. The experiment also found that the relationship between the pulse damper frequency and the working fluid flow is linear.

Keywords: Renewable energy, Ocean thermal energy conversion, organic Rankine cycle.

1. Introduction
Energy is an important material basis for human survival, economic development, and social activities. With the improvement of production and living standards, humans have consumed huge amounts of energy and caused great pollution to the environment, so adjusting the energy structure is urgent. With the depletion of fossil energy and the increasing awareness of ecological protection, the development and utilization of Ocean Thermal Energy Conversion (OTEC) has gradually become a hot spot for new energy development. Organic Rankine Cycle (ORC) is an indirect efficient waste heat utilization model, which has been widely paid attention to in recent years. Maximizing the generating power of the organic Rankine cycle system is more helpful for the application it in industrial production. A lot of research has been done by domestic and foreign scholars on the power generation of the ORC system.
Roy [1] analyzes the non-regenerative organic Rankine cycle. The results show that: R123 can produce maximum efficiency and turbo work output under constant and variable heat source temperature conditions with the minimum irreversibility. Jiang [2] et al. studied the performance of a small pumpless ORC system driven by a low-temperature heat source, obtaining that at 95 °C hot water inlet temperature, the maximum output power is 232W. Zhou [3] studied the performance of the organic Rankine cycle (ORC) power generation system operated by refrigerant R245 when the heat source temperature was lower than 200°C. The results showed that as the temperature of the heat source increases, the thermal efficiency of the system increases. Hou Zhonglan [4] compared the thermodynamic properties of systems and main equipment with different analysis boundaries at different heat source temperatures. The results show that: expander output work and ORC subsystem net output work both increase with the increase of heat source temperature and circulating water flow. Han Jiangtao [5] studied the influence of heat source temperature on centripetal turbines and system performance. The results show that the pressure drop and expansion work of the turboexpander increase with the increase of the heat source temperature, and the system thermal efficiency increases first and then decreases with the increase of the heat source temperature. Zhong Shaogeng [6] et al. built an experimental platform of ORC power generation system to study the changes in ORC performance caused by heat source temperature changes. The results show that the increase of the heat source temperature increases the circulating evaporating pressure, the expander inlet temperature and pressure, and the system cycle thermal efficiency and power generation efficiency increase.

Feng [7] conducted experiments and analysis of the operating characteristics of the organic Rankine cycle using R123 and vortex expander, obtaining that the heat content showed a slight downward trend with the increase of mass flow. Zhang Hongguang [8] and others explored the performance of the ORC waste heat recovery system from the multi-stage centrifugal pump speed and working fluid flow. The results of the study show that the ORC waste heat recovery system for vehicles is in the high-speed region, and the effect of the working fluid flow on the system evaporation pressure and the input power of the multistage centrifugal pump is significantly increased. Sun [9] et al. defined the temperature utilization rate of the heat source to evaluate the energy utilization rate of the organic Rankine cycle. The results show that the temperature utilization rate at the beginning of expansion remains basically unchanged, but with the increase of the mass flow rate of the working fluid, the net power output efficiency is significantly reduced. Zhang Fengge [10] studied the effect of working fluid flow on the performance of the expander. The results show that different working fluid flows correspond to different optimal heat source temperatures and inlet temperatures, and there is an optimal working fluid flow that maximizes the output power of the expander.

Miao Zheng [11] analyzed the regularity of the output net work of saturated organic Rankine cycle power generation system with the temperature of condensing medium. The results show that when the temperature of the hot fluid is constant, the temperature of the condensing medium decreases and the net output work of the system increases. Liu Qiang [12] discussed the characteristics of the influence of cooling water temperature on the performance of geothermal ORC system. The results show that as the cooling water temperature increases, the net output power of the system decreases. Feibo Xie [13] studied the effect of cooling water temperature on the performance of ORC system. The results show that when the temperature of the heat source remains unchanged, as the temperature of the cooling water increases, the output electric power and thermal efficiency of the system decrease. Liu Qian [14] used the organic Rankine cycle system to study the influence of the change of cold and heat source parameters on the comprehensive objective function. The results show that the total heat transfer area and cycle heat efficiency required per unit of net power generation varies with the hot water inlet temperature. Increase and decrease. Pan [15] used experimental methods to study the performance of a small organic Rankine cycle (ORC) system combined with a radial flow turbine. It is obtained that when the evaporation pressure (temperature) is constant, the temperature of the cooling water outlet increases, and the cooling water mass flow decreases with the increase of the condensation pressure.

The above literature generally studies the effect of a variable on the performance of the ORC system, and few variables are associated together to comprehensively consider its impact on the power
generation of the ORC system and analyze the relationship between these variables. This paper introduces the ORC waste heat power generation system with R123 as the working medium. Through the experimental methods of control variables, the heat source temperature and working medium flow of the main equipment of the ORC power generation system under the maximum power generation are explored. The effects of cooling water temperature and expander inlet pressure on the power generation power of the ORC system are analyzed. The frequency of the control panel is related to the flow of working fluid, and the relevant expressions are derived, which provides an experimental reference basis for maximizing the power generation of the ORC system, and also lays the foundation for the future industrial production of the ORC power generation system.

2. ORC experiment system

2.1. Experimental device

The organic Rankine cycle power generation device built based on the thermodynamic principles of ocean temperature difference power generation is shown in Figure 1. The experimental device mainly includes four circulation systems, namely: organic Rankine circulation system, waste heat recovery system shown in Figure 6, cooling water circulation system shown in Figure 5 and lubricating oil circulation system. The working medium is first compressed in the refrigerant pump and heated by the heat exchanger, and then the high temperature and high pressure working medium expands in the expander to work to drive the generator to generate electricity. The pressure is reduced, and finally returned to the refrigerant pump, thereby completing a cycle.

2.2. Experimental process

In order to explore the maximum generating power of the ORC system, the experiment uses the method of controlling variables to keep any variable in the heat source temperature or working fluid flow unchanged and uniformly change the size of another variable. This will separately obtain the influence of heat source temperature and working fluid flow on the power generation power of the ORC system, which provides a basis for comprehensive consideration of the system's maximum power generation.

First, keep the working fluid flow constant, increase the temperature of the heat source from 60°C to 130°C with an interval of 10°C, and explore the effect of temperature on the power generation of the ORC system at each frequency. After keeping the temperature unchanged, increase the frequency from 20Hz to 100Hz, and the interval of each change is 5Hz. Explore the effect of frequency on the power generation of the ORC system at each temperature.

After the experiment, through the processing and analysis of the above experimental data, this paper will also draw the corresponding relationship between the frequency and the flow rate of the working fluid and the influence of the inlet pressure of the expander and the temperature of the cooling water on the system power generation.

In the experiment, R123 was selected as the working medium, the ambient temperature was 25°C, and the cooling water temperature was 15°C. The data collection interval is 1 second, and data is collected 300 times per test.

2.3. Experimental principle

By measuring the temperature and pressure values collected by the system, the corresponding enthalpy and entropy values of the organic working fluid at different temperatures and pressures are obtained. Based on thermodynamic principles, the performance parameters such as thermal efficiency and organic working fluid expansion ratio of the ORC system were calculated.
1: control panel to adjust the frequency; 2: pulse damper; 3: oil separator; 4: refrigerant pump; 5 lubricating oil pump; 6 cooling water pump; 7 scroll expander; 8 generator

**Figure 1.** Organic Rankine cycle power plant

**Figure 2.** Cooling water circulation device

**Figure 3.** Power meter
Figure 4. Waste heat recovery circulation device

The expansion work output of the working medium in the expander:

\[ W_{\text{exp}} = m_r (h_{\text{exp,in}} - h_{\text{exp,out}}) \]  
(1)

The theoretical output work of the working medium in the entropy expansion process of the expander:

\[ W_{\text{exp,t}} = m_r (h_{\text{exp,in}} - h_{\text{exp,outs}}) \]  
(2)

Heat absorption of working medium in evaporator:

\[ Q_{\text{evap}} = m_r (h_{\text{evap,out}} - h_{\text{evap,in}}) \]  
(3)

Heat release of working medium in condenser:

\[ Q_{\text{cond}} = m_r (h_{\text{cond,inn}} - h_{\text{cond,out}}) \]  
(4)

Expander pressure ratio before and after:

\[ \gamma_p = \frac{p_{\text{exp,in}}}{p_{\text{exp,out}}} \]  
(5)

Thermal efficiency of the system:

\[ \eta_{\text{ele}} = \frac{W_{\text{ele}}}{Q_{\text{eva}}} \]  
(6)

Among them:
- \( h \) — enthalpy, \( \text{kJ} \cdot \text{kg}^{-1} \)
- \( m \) — flow, \( \text{kg} \cdot \text{h}^{-1} \)
- \( p \) — pressure, \( \text{kpa} \)
- \( Q \) — heat exchange capacity of evaporator or condenser, \( \text{W} \)
- \( W \) — power, \( \text{W} \)
- \( \gamma \) — ratio
- \( \eta \) — efficiency

Subscript
- \( \text{exp} \) — expander
- \( \text{evap} \) — evaporator
- \( \text{cond} \) — condenser
- \( \text{ele} \) — output electric power
- \( r \) — working fluid
- \( p \) — pressure
- \( \text{in} \) — entrance
- \( \text{out} \) — export
- \( s \) — theoretical value
3. Experimental results and analysis

3.1. Effect of heat source temperature on power generation

Figure 5 is the change of the power generation power of the ORC system with the temperature of the heat source at different frequencies under other conditions unchanged. Change the frequency from 50 Hz to 100 Hz with an interval of 10 Hz. After changing the frequency each time, keep the frequency unchanged, change the heat source temperature uniformly from 80°C to 105°C, the interval is 5°C, the data collection interval is 1 second, and collect data 300 times per test. Figure 1 shows the variation of the power generated by the ORC system with the temperature of the heat source at different frequencies.

![Figure 5. The influence of heat source temperature on the power generation of ORC system](image)

It can be seen from Figure 5 that the power generated by the ORC system increases as the temperature of the heat source increases. But at the same frequency, when the temperature of the heat source rises evenly, the increase in the power generation of the ORC system is fluctuating. According to the analysis, after the frequency is fixed in the experiment, the temperature of the circulating water in the cooling tower rises due to the continuous increase of the temperature of the heat source and the increase of the experiment time. Affected by the increase in the temperature of the heat source, the cooling water circulates for a long time, which reduces its cooling capacity. It can no longer provide a good cooling function for the heated working medium, resulting in fluctuations in each group of curves.

For the curves of different frequencies, the graph does not reflect the law that the ORC power generation increases with the increase of frequency. Conversely, as the frequency reaches maximum values such as 90 and 100 Hz, the power generated by the ORC system has decreased compared to before.

When the frequency does not change and the temperature of the heat source gradually increases, the power generation power of the ORC system first increases rapidly. After reaching a certain value, the power generation power of the system increases slowly with the increase of the temperature of the heat source. The thermal efficiency of the system increases rapidly and then slowly. At a frequency of 90 Hz, when the temperature of the heat source increases from 80°C to 120°C, the thermal efficiency of the system increases from 0.38% to a maximum value of 3.55%; when the temperature of the heat source reaches 130°C, the thermal efficiency of the system increased to 3.99%. It can be seen from the formula that the thermal efficiency of the system is affected by the net output power of the system and the heat absorption of the evaporator. When the temperature of the heat source increases from 120°C to 130°C, the net output of the system increases slowly and the heat absorption of the evaporator increases linearly with the frequency Increase, so the system thermal efficiency tends to increase rapidly and then slowly.

3.2. Effect of frequency on generating power

Figure 6 is the variation rule of the power generated by the ORC system with frequency. As the frequency increases, the power generated by the ORC system increases first and then decreases at each temperature. At different temperatures, the power generated by the ORC system will have a maximum value with increasing frequency. And the higher the heat source temperature, the higher the frequency
corresponding to the maximum power generation in the curve. When the temperature of the heat source increases, more working medium can be heated to steam for expansion work in the expander, which increases the power generation power of the ORC system. Therefore, the higher the maximum power generation power of the ORC system, the higher the corresponding frequency will be. When the temperature is constant, as the frequency continues to increase, the flow rate of the working fluid continues to increase. When the working fluid flow is too large, the limited heat source temperature cannot heat the excess working fluid to steam, and the liquid-vapor mixture enters the expander to reduce the efficiency of steam expansion work. Therefore, when the temperature is constant, the power generated by the ORC system increases first and then decreases as the frequency increases.

As the temperature of the heat source increases, the working fluid flow corresponding to the maximum generating power of the ORC system also increases. When the heat source temperature is 90℃, the maximum system output power is 303.7W, and the corresponding working fluid flow is 213.85kg/h; when the heat source temperature is 100℃, the maximum system output work is 457.63W and the corresponding working fluid flow is 270.38kg/ h; when the heat source temperature is 110℃, the maximum system output power is 534.55W, corresponding to the working fluid flow is 347.56kg/h; when the heat source temperature is 120℃, the maximum system output work is 667.55W, the corresponding working fluid flow is 470.64 kg/h. The oil pump in this experimental device can only be heated up to 120°C in practice, so the maximum power generation of the ORC system is 667.55W, the corresponding heat source temperature is 120°C, the working fluid flow is 470.64kg/h, and the frequency is 90HZ.

When the temperature of the heat source remains unchanged and the flow rate of the working fluid gradually increases, the thermal efficiency of the ORC system first increases and then decreases. When the heat source temperature is 90 ℃, when the working fluid flow is increased from 109.12kg/h to 212.33kg/h, the system thermal efficiency increases from 2.61% to the maximum value of 4.6%; when the working fluid flow is increased to 445.66kg/h, the system thermal efficiency decreases to 1.20%. The thermal efficiency of the system is affected by the net output power of the system and the heat absorption of the evaporator. When the working fluid flow is gradually increased from 109.12 to 212.33kg/h, the net output of the system increases first and then decreases. The heat absorption of evaporator increases linearly with the increase of working fluid flow; hence the thermal efficiency of the system tends to increase rapidly and then slowly.

3.3. Correlation between hydraulic diaphragm pump frequency and working fluid flow

The flow of working fluid as a variable to explore the maximum power generation of the ORC system needs to be constantly changed. In the experiment, the working fluid flow is changed by changing the frequency through the control panel. There is a certain relationship between the working fluid flow and frequency.

Figure 7 shows the variation of working fluid flow with frequency at different temperatures. It can be seen from the figure that at different temperatures, the flow curve of the working fluid flow with frequency is almost the same, and the flow rate with frequency is independent of temperature. The working fluid flow and frequency have a linear relationship, the relationship expression is:

\[ Q = (5.09576 \pm 0.06897)t + (4.78324 \pm 0.044697) \]  

(7)
3.4. Effect of inlet pressure on power generation power of ORC system

Set the heat source temperature to 90 °C, 100 °C, 110 °C, at each temperature, adjust the frequency from 20 to 100 Hz, the data collection interval is 1 second, collect data 300 times per test. As shown in Figure 8, when the temperature remains unchanged, as the inlet pressure of the expander increases, the power generation power of the ORC system first increases, and after reaching the maximum power generation power, it shows a downward trend. And the higher the temperature, the greater the upper limit of the maximum power generation line, and the greater the corresponding inlet pressure. As the flow rate of the working fluid increases, the inlet pressure of the expander also increases, more working fluid is heated to become steam, expands in the expander to do work, and the power generation of the ORC system gradually increases. When the inlet pressure continues to increase, since the temperature of the heat source is constant, it is insufficient to vaporize more working fluid at the temperature of the heat source. As the inlet pressure increases, due to insufficient heat supply, the power generation of the ORC system gradually decreases.
Figure 8. The influence of the inlet pressure of the expander on the power generation of the ORC system

Figure 9 is the change curve of pressure with the flow of working fluid at various temperatures. When the temperature is constant, as the flow rate of the working fluid continues to rise, the inlet pressure of the expander first increases and then remains unchanged. The vaporization of the working fluid flow is limited by the temperature of the heat source. At a certain temperature, the pressure cannot continue to rise with the rising of the working fluid flow, and the inlet pressure remains unchanged after reaching a certain value. Consistent with the conclusion of Figure 8, at a certain heat source temperature, with the increase of the flow rate of the working fluid, the pressure at the inlet of the expander first rises and then remains unchanged; the power generation of the ORC system starts to increase with the increase of the pressure. The power generation of the ORC system reaches the maximum value when the inlet pressure reaches the maximum.

Figure 9. Effect of working fluid flow on inlet pressure of expander

3.5. The influence of cooling water temperature on the power generation of ORC system

In the experiment, the temperature of the heat source continuously heats the working medium, and the steam is condensed by the cooling water after expanding in the expander to perform work. As the experiment progressed, the cooling water temperature gradually increased. It can be seen from Figure 10 that the higher the temperature of the heat source, the higher the maximum temperature that the cooling water finally reaches. When the temperature is unchanged, the frequency is increased from 20 to 100 Hz, the data collection interval is 1 second, and data is collected 300 times per test. As the frequency increases, the temperature of the cooling water first increases and then remains unchanged. When the heat source temperature is 90°C, the cooling water temperature reaches a maximum of 34°C.
at a frequency of 50 Hz; when the heat source temperature is 100°C, the cooling water temperature reaches a maximum of 39°C at a frequency of 65 Hz; when the heat source temperature is 110°C, the cooling water temperature reaches a maximum of 43°C at a frequency of 80 Hz. The higher the heat source temperature, the higher the corresponding frequency of the cooling water temperature when it reaches the maximum value. Limited by the temperature of the heat source, when the flow rate of the working fluid increases, some of the working fluid cannot be vaporized due to insufficient heat supply. The heated working fluid that turns into steam works in the expander. Then the steam is condensed by the cooling water and forms liquid again, and the next cycle begins. The higher temperature of the heat source, the more heat is transferred to the cooling water during condensation, so the maximum temperature of the cooling water also increases.

Figure 10. Effect of frequency on cooling water temperature

As shown in Figure 11, changes in cooling water temperature have an impact on the power generation of the ORC system. When the temperature of the cooling water continuously increases to the maximum value, the power generated by the ORC system first increases, and then gradually decreases after reaching the maximum value. And the higher the temperature, the greater the maximum power generation of the ORC system, the higher the corresponding cooling water temperature. When the temperature of the heat source remains unchanged, as the flow rate of the working fluid increases, the power generation of the ORC system increases, and the temperature of the cooling water also rises accordingly. As the temperature of the cooling water continues to rise, the cooling capacity of the cooling water against steam continues to weaken. When the temperature of the cooling water rises to a certain value, the power generation of the ORC system begins to gradually decrease. The temperature of the cooling water continues to increase until it reaches the maximum value then remains constant, and the power generation of the ORC system gradually decreases. When the heat source temperature is 110°C, the cooling water temperature increases from 23.74°C to 41.4°C, the output electric power increases from 136 W to 534.55W. In the experiment, the flow rate of the working fluid is continuously increasing. Therefore, the generating power of the ORC system is mainly affected by the temperature of the heat source and the working fluid flow before reaching the maximum power generation. When the temperature of the cooling water continued to increase to 42.86°C, the output electric power decreased from 534.55W to 365.84W, which decreased by 34.87%. Since the temperature of the heat source remains unchanged and the heat supply is limited, when the heat supply reaches the maximum, the cooling water temperature begins to perform a major impact on the power generation of the ORC system, and the power generation of the ORC system drops rapidly.
4. Experimental conclusion

Using organic Rankine cycle and lubricating oil circulation equipment, the experiment studied the influence of heat source temperature and working fluid flow on the output performance of main equipment and system through the method of controlling variables, and obtained the following conclusions:

(1) When the flow rate of the working fluid remains unchanged, the greater the temperature of the heat source, the greater the power generated by the ORC system. However, when the temperature of the heat source reaches a certain value, the system power rises significantly slower.

(2) At different temperatures, there is a corresponding optimal working fluid flow that maximizes the system output power, and the higher the temperature, the greater the system output power. When the flow rate of the working fluid continues to rise, the heat source does not provide enough heat, and the pressure at the inlet of the expander and the temperature of the cooling water will remain unchanged after they reach the maximum value. The change of power generation power of the system in the early stage is mainly affected by the temperature of the heat source and the flow rate of the working medium. When the temperature of the heat source reaches the maximum flow rate of the working medium that can be heated, the temperature of the cooling water will have a greater impact on the power generation system of the system, and the gas-liquid mixture entering the expander causes the system's power generation to drop rapidly.

(3) The experiment shows that there is a linear relationship between the frequency of the pulsation damper and the flow rate of the working fluid. The relationship is expressed as: \( Q = (5.09576 \pm 0.06897) \times f + (4.78324 \pm 0.044697) \).

(4) Through experiments, the maximum power generation of the ORC system is 667.55W, the corresponding heat source temperature is 120℃, the working fluid flow is 470.64kg/h, and the frequency is 90Hz.

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