Performance analysis of ORC low temperature waste heat power generation system

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Abstract: For 90~180℃ low temperature waste heat resources, three different types of organic working fluids, benzene, isopentane and R245fa are selected from the perspectives of safety, environmental protection and physical properties of working fluid. The mathematical models of the system are established through MATLAB and REFPROP and the influence of the evaporation temperature on the performance of the ORC low temperature waste heat power generation system is studied. The results show that the thermal efficiency and net output power of the system increase with the increase of evaporation temperature; the evaporation pressure of CFC-type working fluids is relatively low; the net output power and thermal efficiency of HFC and HC-type working fluids are generally relatively low. The evaporator has the largest irreversible loss in the system, followed by the condenser and expander while the working fluid pump has the smallest irreversible loss.

1. Introduction

At present, ORC low temperature waste heat power generation technology has been applied in many fields at home and abroad, and some fields have mature technologies and wide commercial applications[1]. In recent years, however, the research and application of ORC low-temperature waste heat power generation technology that use scroll expander as energy conversion device have gradually developed. The system has broad application prospects[2].

Wang Zhi et al. [3] selected R601 and R245ca as working fluids and studied the relationship between the reheat pressure ratio and the performance of the ORC system, but the objective function of this study was only the net output power; Wang Chenfang et al. [4] used Aspen Plus software to establish a thermodynamic model of the ORC system and analyzed the influence of the maximum evaporation pressure and working temperature which together determined the selection of the best working fluid for the system effect; Giuffrida A et al. [5] used hydrofluorocarbons and hydrocarbons to replace R245fa as the working medium, and analyzed the relationship between the efficiency of the ORC system and the cycle temperature. The research results provided a reference for the matching of heat source temperature and working fluid; Bo Zemin et al. [6] used R600a as the working fluid required for research, and optimized the cycle characteristics of the system, which was of great significance to the recovery of low-grade heat energy and improvement of the efficiency of the ORC system; Xu Z et al. [7] selected 6 kinds of working media as objects and proposed a simplified grey correlation method that can be used for the evaluation of working fluids and realized the common system optimization of ORC system exergy efficiency and economic performance; Liu Jie [8] established a thermodynamic model of the ORC system, the system efficiency of the organic working fluid R245fa reached its maximum value, but only the overall efficiency of the power generation load.
was related to it, and had nothing to do with the cycle efficiency.

2. The selection of working fluid in cyclic process
According to the slope of the saturated gasification curve of the working fluid in Fig. 1. When the wet working fluid passes through the outlet of the expander, the water vapor contains some droplets which will seriously damage the blades of the entire expander and directly affect the relative efficiency of the expander. Considering the requirement of the lowest drying temperature, isentropic working medium, dry working medium, and heat transfer working medium with large heat capacity, low viscosity, high density and high thermal conductivity should be selected that can obtain excellent heat transfer characteristics and small volume flow.

As a candidate working fluid for the Organic Rankine Cycle system, the working fluid with the following characteristics should be selected: low-GWP, corrosion-resistant, non-toxic, non-flammable, non-irritating and easily available working fluid. Considering comprehensively, the following working fluids are selected. The physical properties of which can be obtained from REFPROP9.0 developed by the NIST (National Institute of Standards and Technology) laboratory in the United States.

| Working fluid type | Working fluid type | Tcr/°C | Pcr/MPa | Ttp/°C | Tnb/°C | safety | ODP | GWP |
|--------------------|--------------------|--------|---------|--------|--------|--------|-----|-----|
| Benzene            | CFC                | 318.6  | 4.126   | -94.97 | 110.4  | A3     | 0   | -   |
| Isopentane         | HC                 | 187.2  | 3.37    | -160.5 | 27.86  | A3     | 0   | -   |
| R245fa             | HFC                | 154    | 3.651   | -102.1 | 15.19  | B1     | 0   | 950 |

3. The mathematical models of ORC System

3.1 Experimental principle
The basic structure of the ORC low-temperature waste heat power generation system can be seen in Fig. 2 clearly, which mainly consists of an evaporator, a condenser, a working fluid pump and an expander.

3.2 mathematical model of ORC system
4-5s is the isentropic expansion process of the working fluid in the expander, the expansion work of the system is calculated by:

$$ W_i = m_f\left(h_4 - h_{sg}\right)\eta_i $$(1) 

5-1 is the isostatic condensation process of the working fluid in the condenser, and the heat absorption of the working fluid in the condenser is calculated by:

$$ Q_c = m_f\left(h_s - h_1\right) $$ (2) 

1-2s is the medium entropy compression process of the working fluid in the working fluid pump, and the working fluid pump does work is calculated by:
\[ W_p = \frac{m_f (h_{2s} - h_i)}{\eta_p} \]  

2-3-4 is that the working fluid absorbs heat at equal pressure in the evaporator, then the heat absorption is calculated by:

\[ Q_e = m_f (h_4 - h_2) \]  

The net output power of the system is calculated by:

\[ W_{net} = W_i - W_p \]  

The thermal efficiency of the system is calculated by:

\[ \eta_e = \frac{W_{net}}{Q_e} \]  

The exergy loss of the evaporator is calculated by:

\[ I_i = E_i - E_a = T_m \left[ (s_i - s_a) - \frac{h_i - h_a}{T_0} \right] \]  

The exergy loss of the expander is calculated by:

\[ I_e = E_e - E_i = T_m \left[ (s_e - s_i) - \frac{h_e - h_i}{T_e} \right] \]  

The exergy loss of the condenser is calculated by:

\[ I_c = E_i - E_c = T_m \left[ (s_i - s_c) - \frac{h_i - h_c}{T_m} \right] \]  

The exergy loss of the working fluid pump is calculated by:

\[ I_p = W_p (E_p - E_i) = nT_i (s_i - s_p) \]  

### 4. Results and analysis of calculation

The organic working fluids benzene, isopentane and R245fa are selected as the research objects, the evaporation temperature is taken as variable to establish a mathematical model of the system and the performance of this system is analyzed. The operating parameters of the system are shown in Table 2.

| Parameter                                    | Set value |
|----------------------------------------------|-----------|
| inlet temperature of heat source /°C         | 90-180    |
| narrow point temperature difference of evaporator /°C | 5         |
| narrow point temperature difference of condenser /°C | 5         |
| ambient temperature /°C                       | 25        |
| inlet temperature of cooling water /°C       | 20        |
| efficiency of expander /%                    | 0.80      |
| efficiency of working fluid pump /%          | 0.85      |
| efficiency of generator /%                   | 0.95      |

#### 4.1 Thermodynamic properties

As shown in Fig. 3, the evaporation pressure of the working fluid increases as the temperature increases. At the same evaporation temperature, the relationship between the value of evaporation pressure is: R245fa > isopentane > benzene; in terms of pressure and temperature, when the saturation temperature of the working fluid is lower, the value of temperature of the remaining heat that can be recovered will become lower under the condition of reaching the same temperature. The evaporation pressure of HFC-type working fluids is generally higher than that of HC and CFC-type working fluids, excessive evaporation pressure will cause mechanical pressure problems. Therefore, from the perspective of safety, at the same evaporation temperature, a working fluid with a lower evaporation pressure is preferred, and can effectively reduce pumping labor consumption. However, the lower pressure may also affect the tightness of the system. Based the above analysis, The performance of isopentane is the best.
Different working fluids at the same evaporating temperature or the same working fluid at different evaporating temperatures will have a great performance of the system. As shown in Figure 4, when the condensing temperature is set to 30°C, the thermal efficiency of the working fluid system gradually increases with the increase of the evaporation temperature, and then the rate of increase gradually slows down, and R11>benzene>isopentane>R245fa. As can be seen from Figure 4, taking the working fluid benzene as an example, when the evaporation temperature is 90°C, the thermal efficiency is 10.14%; when the evaporation temperature reaches 150°C, the thermal efficiency will rapidly rise to 18.21%; the working fluid R245fa has the smallest thermal efficiency, at 150°C. When the thermal efficiency reaches the maximum of 16.95%, because the critical temperature of the working fluid R245fa is 154°C, the physical properties of the working fluid will change after the critical temperature; at 150°C, the thermal efficiency of isopentane is 15.66%, and the thermal efficiency of R245fa is the lowest of 14.9%. The latter is 4.85% lower than the former. Therefore, when the thermal efficiency is selected as the preferred index, the working fluid benzene is the best, and R245fa is the second.

It can be seen from Figure 6 that the net output power of the system gradually increases with the increase of the evaporation temperature, and benzene>isopentane>R245fa, the value of net output power of benzene is the highest, the value of net output power is 9.38kw when the value of temperature is 90°C; when the evaporation temperature reaches 150°C, the net output power rises to 19.92kw, and the net output power of R245fa is the lowest at 150°C, which is 6.78kw. The former is 65.96% higher than the latter.
Exergy loss is the main cause that affects the efficiency of the system's exergy. The greater the exergy loss, the lower the system's exergy efficiency. Figure 6 shows the exergy loss distribution of different components when the evaporation temperature of the three working fluids is 120°C. It can be seen from the figure that each working fluid has the largest proportion of exergy loss in the evaporator, the main reason is the temperature difference between the evaporator and the low-temperature heat source. The exergy loss of each component of the working fluid R245fa is the largest, and the exergy loss in the evaporator reaches 47.33kw. Therefore, in order to improve the exergy efficiency of the system, the optimization of the system is mainly focused on the structural parameters of the evaporator. For example, a large area evaporator can be used and the increase of the evaporation temperature can effectively reduce the exergy loss of the evaporator.

5. Conclusion
In this paper, the organic working fluids benzene, isopentane and R245fa are selected as the research objects, the properties of which are comprehensively evaluated combined with the thermodynamic properties, environmental protection and safety of the organic working fluids. Taking the evaporation temperature as a variable, the mathematical model of the system is established and analyzed. The results show that:

(1) In terms of thermodynamic characteristics, the evaporation pressure, thermal efficiency and net output power of the system all increase with the increase of the evaporation temperature; when the condensation temperature is a certain value, when the performance of whole system reaches the highest value through observing the performance curve, the best evaporation temperature appears in the range of 120~140°C; HFC-type organic working fluid has higher net output power and good environmental performance. The thermal efficiency of CFC-type organic working fluid is generally higher than that of other working fluids. Above all, benzene have relatively good performance, environmental protection and safety, which has the highest net output power, less exergy loss, low evaporation pressure and a good operational safety.

(2) Under the same working conditions, the largest exergy loss of working fluid is the evaporator while the working fluid pump has the minimum, which can be ignored among the system components. In order to improve the exergy efficiency of the system, the optimization of the system should mainly focus on the structural parameters of the evaporator.

Acknowledgments
This work was supported by the National Natural Science Foundation of China (Grant No.51675254, 51966009), the National Key Research and Development Program of China (Grant No. SQ2020YFF0420989), the Talent Innovation and Entrepreneurship Program of Lanzhou (Grant No.2020-RC-23), the Science and Technology Program of Gansu Province (Grant No.20YF8GA057).

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