Working Fluids Optimization Based on Economical Performance and Thermodynamic Performance for 350kW ORC System

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Abstract. This paper established a 350kW level organic Rankine cycle (ORC) system with the 393.15K flue gas as heat source. Nine kinds of working fluids were selected based on comprehensive consideration of thermal physical properties, environmental performance and safety. The optimum one was selected from them by comparing and evaluating their thermodynamic performance and economic performance at different evaporation temperatures. The results show that the thermal efficiency of system using R236fa increased firstly and then decreased with the increase of evaporation temperature, while the exergy efficiency and economic performance increase gradually. The thermodynamic performance and economic performance of others increased with evaporation temperature increasing. When the exergy efficiency was taken as the evaluation index, isopentane was the best working fluid. However, the thermal efficiency, levelized electricity cost (LEC) and discounted payback period (DPP) of the system using butane better than others. Therefore, butane is considered to be the most appropriate working fluid for this system among the nine working fluids.

1. Introduction
There is a huge amount of low-temperature waste heat resources in China, and nearly 50% of industrial waste heat resources are directly discharged into the atmosphere[1], while the ORC has obvious advantages in recycling low-temperature waste heat below 200°C[2]. Therefore, using ORC power generation technology to recover low-temperature waste heat is an important way to save energy and reduce emissions. At present, the research on ORC focuses on system optimization, and the types of working fluids, actual working conditions and evaluation indexes will affect the system performance. Madhawa Hettiarachchi H.D. et al. studied four working fluids with the ratio of total heat transfer area to net work as the economic index, and found that the difference of objective function values of different working fluids may exceed twice[3]. Li Weiyi et al. studied 13 kinds of working fluids with the weighted sum of economy index and exergy efficiency as comprehensive index, and showed that R161 had the best comprehensive performance[4]. Wang Jianyong et al. found that the maximum net generating power increases with the increase of heat source temperature, and the system heat exchange area required by the minimum unit generating power decreases with the increase of heat source temperature for the same working fluid[5]. Han Zhonghe et al. found that the best thermodynamic condition of the same working fluid is different from the best economical condition[6].
Wang Zhiqi et al. took the heat exchanger area required for unit power and heat recovery efficiency as comprehensive indexes, and found that R123 had the best performance when the waste heat temperature was between 100°C and 180°C[7]. Dai Xiaoye et al. studied seven working fluids with expander size as economical index and thermal efficiency as thermodynamic index, and found that thermodynamic index is positively correlated with critical temperature of working fluid, while economical index is positively correlated with molecular complexity of working fluid[8].

The thermodynamic analysis of ORC system is mature, but the economical analysis is less. Therefore, this paper presents an investigation on a 350kW ORC system driven by low temperature flue gas at 120°C, the thermal efficiency and exergy efficiency are taken as the thermodynamic indexes, and LEC and DPP are taken as the economical indexes. Nine kinds of organic working fluids are selected according to its environmental and thermodynamic performance. Then the thermodynamic performance and economical performance of them are compared and analyzed to find the most suitable working fluid for this 350kW ORC system. The thermophysical properties of working fluids are shown in table1[9] and the initial calculation parameter of system are shown in table2.

### Table 1 Thermophysical properties of working fluids.

| Substance | type   | M (g mol⁻¹) | tbp (°C) | t crit (°C) | p crit (kPa) | ODP   | GWP   | Safety data |
|-----------|--------|-------------|----------|-------------|--------------|-------|-------|-------------|
| R141b     | CFC    | 116.95      | 32.05    | 204.35      | 4212.0       | 0.12  | 725   | A1          |
| R236ea    | HFC    | 152.04      | 6.17     | 139.29      | 3420.0       | 0     | 1370  | A3          |
| R123      | HCFC   | 152.93      | 27.82    | 183.68      | 3661.8       | 0.02  | 77    | A1          |
| R245fa    | HFC    | 134.05      | 15.14    | 154.01      | 3651.0       | 0     | 1030  | B1          |
| R245ca    | HFC    | 134.05      | 25.26    | 174.42      | 3940.7       | 0     | 693   | A1          |
| R236fa    | HFC    | 152.04      | -1.49    | 124.92      | 3200.0       | 0     | 9810  | A1          |
| butane    | HC     | 58.12       | -0.49    | 151.98      | 3796.0       | 0     | 约20  | A3          |
| isopentane| HC     | 72.15       | 27.83    | 187.20      | 3378.0       | 0     | 约20  | A3          |
| R365mfc   | HFC    | 148.07      | 40.15    | 186.85      | 3266.0       | 0.76  | 950   | A1          |

### Table 2 Calculation parameter settings.

| Parameters                | Value   | Parameters               | Value   |
|---------------------------|---------|--------------------------|---------|
| flue gas inlet temperature/K | 393.15   | pump efficiency/ %        | 80      |
| evaporation temperature/K  | 340–370  | expander efficiency / %   | 80      |
| cooling water inlet temperature/K | 283.15   | expander power/ kW        | 350     |
| expansion ratio/           | 4       | enviromental temperature/K | 293.15 |

### 2. Mathematical model

Figure 1. is the circulation structure and T-S schematic diagram of ORC system. The working fluid is pressurized from saturation point 1 to point 2 by pump, then enters the evaporator to be heated to point 4 by the heat source at constant pressure, then enters the expander to output electric power, and finally enters the condenser from point 5 to release heat to saturation point 1 at constant pressure.
2.1. Thermodynamic model

In order to evaluate the degree of energy conversion and irreversibility of the system, the change of thermal efficiency and exergy efficiency with evaporation temperature is analyzed basing the first and second laws of thermodynamics, and the equation are as follows (1)–(2).

\[ \eta_1 = \frac{W_t - W_p}{Q_t} \]  
\[ \eta_2 = \frac{E_{ex,all} - (I_e + I_t + I_c + I_p)}{E_{ex,all}} \]  

In the above equations, \( W \) represents work; \( Q \) represents heat exchange; \( I \) represents irreversible loss; \( \eta \) represents evaporator, expander, condenser and pump respectively; \( E_{ex,all} \) represent total exergy system input.

2.2. Economical model

In this paper, \( LEC \) and \( DPP \) are used as economical indexes[5], and the calculation formulas are as equation (4) , (5), and equation (3) is to calculate the total investment cost of the system in 2017.

\[ \text{Cost}_{2017} = \frac{\text{Cost}_{2001} \times CEPCI_{2017}}{CEPCI_{2001}} \]  
\[ \text{LEC} = \frac{CRF \times \text{Cost}_{2017} + \text{COMs} \times S}{(W_t - W_p) \times OP} \]  
\[ \text{DPP} = \frac{\ln \left( \frac{NE - \text{COMs} - ICost_{2017}}{NE - \text{COMs}} \right)}{\ln (1+i)} \]  

In the above formulas, \( CEPCI \) is the chemical cost index, with \( CEPCI_{2017} = 623 \) and \( CEPCI_{2001} = 394 \)[10]; \( CRF \) is the investment recovery factor; \( i \) is the annual interest rate, taking 6%; \( \text{COMs} \) is the system management operation cost; \( S \) is the exchange rate of RMB against US dollar, taking \( 1 \$ \approx 6.8 \text{¥} \); \( NE \) is the annual net income.

3. Method validation

To verify the calculation method in this paper, the \( LEC \) of R245fa in literature[11] is calculated by using it and the maximum error between them is 1.1%, which means that the method adopted in this paper is accurate enough and can be used for economical analysis of ORC system.
4. Result and Discuss

4.1 Thermodynamic analysis

The effect of evaporation temperature on the system thermal efficiency of the nine working fluids is shown in Figure 3. When R236fa is working fluid, the system thermal efficiency first increases and then decreases with the increase of evaporation temperature, while the system thermal efficiency of other working fluids increases with the increase of evaporation temperature. At the same evaporation temperature, the efficiency of this eight working fluids is in the order of butane>R141b>isopentane>R123>R236ea>R245fa>R245ca>r365mfc. The comparison of the maximum thermal efficiency of each working fluid at the optimum evaporation temperature is shown in Figure 4. Among these working fluids, r365mfc has the lowest efficiency value of 8.67%, butane has the highest value of 10.29%, which is 19% higher than r365mfc. That means butane has the higher utilization efficiency for 120°C heat source.

The effect of evaporation temperature on the system exergy efficiency of the nine working fluids is shown in Figure 5. The exergy efficiency of these working fluids increase with the increase of evaporation temperature. Exergy efficiency of all working fluids is significantly different when the evaporation temperature was low. As the evaporation temperature increased gradually, the difference was become smaller. The exergy efficiency increase rates of the nine working fluids are ranked follows r365mfc>isopentane>R123>R236ea>R245ca>R141b>R236fa>R245fa>butane. The comparison of the maximum exergy efficiency of each working fluid at the optimum evaporation temperature is shown in Figure 6. Among these working fluids, R236fa has the lowest efficiency value of 49.27%, isopentane has the highest value of 52.22%, which is 6% higher than r365mfc.

Figure 2. The comparison about calculation results of this paper and reference[11]
4.2 Economical analysis

The effect of evaporation temperature on the system \( LEC \) of the nine working fluids is shown in Figure 7. The \( LEC \) of these working fluids decrease with the increase of evaporation temperature. Because the expander power is a fixed value and the work done by pump is very small, the net work of this system changes very little. That means the change trend of \( LEC \) depends on the change of total investment cost which is greatly influenced by the area of heat exchanger and the heat exchange capacity. Under the condition that the inlet temperature of heat source, inlet temperature of cold source and expansion ratio are unchanged, the condensation temperature increases gradually with the increase of evaporation temperature, while the heat exchange capacity and heat exchange area of the two heat exchangers decrease gradually, so the total investment cost and \( LEC \) of the system both decreases gradually. The comparison of the minimum \( LEC \) of each working fluid at the optimum evaporation temperature is shown in Figure 8. Among these working fluids, butane has the lowest \( LEC \) value of 0.34yuan/(kW·h), r365mfc has the highest value of 0.38yuan/(kW·h), which is 11% higher than butane. That is to say, the system has the better economical performance when using butane as working fluid.

The effect of evaporation temperature on the system \( DPP \) of the nine working fluids is shown in Figure 9. The \( DPP \) of these working fluids decrease with the increase of evaporation temperature. Among them, \( DPP \) of r365mfc is most affected by evaporation temperature, which decreases by 16% in the evaporation temperature range of 340-370K, while \( DPP \) of butane is less affected by evaporation temperature. At the same evaporation temperature, the \( DPP \) of r365mfc is obviously higher than others, and its economic performance is poor, while the \( DPP \) of butane is obviously lower than others, and its economical performance is better than others. The comparison of the minimum \( DPP \) of each working fluid at the optimum evaporation temperature is shown in Figure 10. Among
these working fluids, r365mfc has the highest \(DPP\) value of 109 months, while butane has the lowest value of 77 months, which is 29% lower than r365mfc.

Figure 9. Effect of evaporation temperature on \(DPP\)

Figure 10. Comparison of minimum \(DPP\) of different working medium

5. Conclusions

In this paper, the ORC system driven by 120\(^\circ\)C flue gas is taken as the research object. With the given power of expander and expansion ratio, the changes of thermodynamic performance and economic performance of nine working fluids with evaporation temperature are analyzed and compared. The results are as follows:

1. In the evaporation temperature range of 340-370K, the thermal efficiency of R236fa reaches a maximum value of 9.25% when the evaporation temperature is 355K, and the \(LEC\) reaches a minimum value of 0.37 yuan/(kw·h) when the evaporation temperature is 370K. The thermodynamic performance and economic performance of the other eight working fluids increase with the increase of evaporation temperature, that is, they have the same thermodynamic optimal working condition and economical optimal working condition when the evaporation temperature is 370K.

2. When the evaporation temperature is 370K, the every index of butane reaches the optimum, its maximum thermal efficiency and exergy efficiency are 10.29% and 50.19% respectively, while its minimum \(LEC\) and \(DPP\) is 0.34 yuan/(kW·h) and 77 months respectively. Moreover, the every index of butane is obviously higher than those of others in the range of evaporation temperature. Therefore, butane has the strongest utilization ability of 120\(^\circ\)C heat source, and it is the best choice with both economical and thermodynamic performance among the nine working fluids studied in this paper.

Acknowledgments

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Modification instructions

1. The second sentence of the second paragraph in the Introduction originally reads as follows: “Therefore, this paper present an investigation on a 350kW ORC system driven by low temperature flue gas at 120°C.”
   Now it be revised as “Therefore, this paper presents an investigation on a 350kW ORC system driven by low temperature flue gas at 120°C.”

2. The last sentence of Introduction originally reads as follows: “The thermophysical properties of working fluids are shown in table1[9]and the initial calculate parameter of system are shown in table2.”
   Now it be revised as “The thermophysical properties of working fluids are shown in table1[9]and the initial calculation parameter of system are shown in table2.”

3. The original figure 2 is not clear enough, see figure (1), Now it be revised as figure (2).

4. The first sentence of the second conclusion originally reads as follows: “When the evaporation temperature is 370K, the every index of butane reach the optimum, its maximum thermal efficiency and exergy efficiency are 10.29% and 50.19% respectively.”
   Now it be revised as “When the evaporation temperature is 370K, the every index of butane reaches the optimum, its maximum thermal efficiency and exergy efficiency are 10.29% and 50.19% respectively.”