Experimentally economic analysis of ORC power plant with low-temperature waste heat recovery

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Abstract

Due to the low boiling point of organic fluids, the organic Rankine cycle (ORC) is an effective way to improve the recovery efficiency of low-temperature waste heat. An ORC power plant was established with an actual generating capacity of 16.3 kW. As the ORC technology is in the initial stage of commercial application, a technical and economic analysis has been conducted in this paper. Through analysis of each part investment of the power generation plant, it is found that the ORC system part accounts for 61% of the total initial investment, and the larger the power generation scale, the larger the proportion. An economic model has been proposed to study the economic feasibility of low-temperature industrial waste heat conversion in this plant. The influences of the installation of cooling water system, preheater, superheater, loan ratio, interest rate on electricity production cost (EPC) and profit are analyzed. According to the analysis, the lowest EPC of the plant is 0.46 Yuan/(kW • h).

Keywords: organic Rankine cycle; economic analysis; feasibility study; low-temperature power generation; electricity production cost;

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1. INTRODUCTION

In the process of energy utilization, thermal energy is one of the most widely used forms in the production and life. However, in the use of conventional energy, ~50% of the energy was wasted, and ~67% of the energy is discharged in industrial production; most of them are low-grade thermal energy [1–2]. The process energy efficiency is an urgent issue to be addressed.

Because the efficiency of traditional steam cycle to convert low-grade waste heat is very low, it is necessary to analyze other cycles to convert low-grade waste heat, such as organic Rankine cycle (ORC) [3–5]. In ORC, we use organic fluid instead of water as working medium. According to the heat source and application, the working fluid can be selected. Due to the low boiling point of organic fluids, low-level waste heat can be used as a heat source conversion in electricity without consuming other fossil fuel energy [6]. Overall, the application of ORC power system is an effective way to improve energy efficiency and reduce environmental pollution.

ORC can utilize solar energy [7], geothermal energy [8], biomass energy [9] and the bottom of water/steam Rankine cycle [10], in addition to low-level waste heat [11].

Yamamoto et al. [12] experimentally demonstrated that organic substances used in Rankine cycle can give higher turbine power than water when the turbine inlet temperature is below 120°C. With the development of ORC technology, more and more ORC power generation systems have been tested and gradually entered the commercial development stage [13].

In the past decades, researchers have done many experiments to promote the ORC technology. These experiments were mainly focused on working fluid selection [14–16], cycle design optimization[17–19] and expander technologies [20–22].

According to the different heat sources and different optimization objectives, Borsukiewicz-Gozdor et al. [14] recommended...
that several pure organic fluids is suitable for ORC system, such as R134a, R123, R245ca and R245fa.

Heberle et al. [15] presented several zeotropic mixtures used in ORC system. By comparison, it is found that mixtures lead to an efficiency increase up to 15% when heat source temperatures below 120°C. Mago et al. [16] proposed seven kinds of organic fluids performance in the different temperature ranges: R113 is suitable for system with heat source temperature higher than 430 K; isobutane has better performance for low-temperature heat source lower than 380 K; for low-grade heat source between 380 and 430 K, R123, R245ca and R245fa have better performance.

Yekoladio et al. [17] experimentally compared the regenerative organic Rankine cycles and the non-regenerative cycles and demonstrated that the power output increased exponentially with the geothermal resource temperature. In order to optimize the regenerative ORCs, the lower vapor specific heat capacity organic fluids is needed.

Branchini et al. [18] developed a performance calculation method for comparison of ORC variants, based on a thermodynamic property database. This method mainly considers cycle efficiency, specific work, recovery efficiency, ORC fluid-to-hot source mass flow ratio, turbine volumetric expansion ratio and heat exchangers size parameter and provides the useful guidelines to select the most appropriate fluid, the ORC configuration and operating parameters.

Shengjun et al. [19] compared the subcritical ORC and transcritical power cycle system for low-temperature geothermal power generation. Through the simulation and parameter optimization, R123 yields the maximum value of thermal efficiency and exergy efficiency in subcritical ORC system and R125 presents excellent economic performance in transcritical power cycle.

Lemort et al. [20] experimentally studied the performance of the closed scroll expander using R245fa as the working fluid. The experimental results show that the maximum output power is 2.2 kW and the expander efficiency is up to 71.03%. Hu et al. [21] investigated the performance of a twin-screw expander. Experiments indicate that with the increase of rotational speed, the greater the loss of suction pressure and the indicated efficiency. When the suction pressure varies from 550 to 750 kPa, the indicated efficiency increases first and then decreases and has a peak value of 0.815. Kang [22] uses the radial turbine as the expander and R245fa as the working fluid in the ORC system. The experimental results show that the output power of the system can reach 32.7 kW and the system efficiency and the turbine efficiency can reach 5.22% and 78.7%, respectively.

Owing to the rapid development of ORC power generation technology, its commercial applications have been in the initial stage. Therefore, in order to make it easier for enterprises to make decision on whether to adopt ORC system to recover waste heat, it is necessary to find out the appropriate organic fluid, rationally configure the ORC system and analyze its economy. In this paper, the economic analysis model is established by taking the minimum electricity production cost (EPC) as the objective function. By changing the waste heat mass flow $m_w$ and the evaporator pinch temperature $\Delta T_P$, the objective function value of different organic fluids can be analyzed. Based on that, an ORC power generation system is designed and built; then its profit and payback cycle can be analyzed.

2. THE ORC POWER PLANT

In this paper, the system includes the basic components of the ORC: evaporator, condenser, expansion device, pump, preheater and superheater. The heat transfer process was calculated and simulated, and the expansion device was selected and calculated.

2.1. Heat transfer process

Generally, in the ORC system of waste heat power generation, the heat transfer process between the heat source and organic fluid can be divided into three periods: preheating period, evaporation period and superheating period, as shown in Figure 1. The condensation process of organic fluids is similar, except that the heat source is replaced by the cooling water.

The heat source and the organic fluid flow in reverse direction, and heat exchange is carried out in the flow. $T_5$ is the inlet temperature of the waste heat source, and $T_8$ is the outlet temperature; $T_1$ is the inlet temperature of organic fluid, and $T_4$ is the outlet temperature. The NIST software was used to determine the enthalpy of different state points according to temperature and pressure. The heat transfer of organic fluid in this process can be calculated by Equation (1).

\[ Q_e = m_f (h_4 - h_1), \]

where $m_f$ is the mass flow of organic fluid and $h_1$ and $h_4$ are the enthalpy of organic fluid at the exchanger inlet and outlet.

The organic fluid with a temperature of $T_1$ from the pump outlet is heated to a saturated liquid with a temperature of $T_2$, and at the same time, the temperature of the heat source decreases from $T_5$ to $T_8$, where $T_2$ is equal to the evaporation temperature $T_e$. In Figure 1, $\Delta T_P$ is the pinch point temperature of the evapo-
rator, and the minimum value is 3–7°C [23]. If the heat source is adequate, the pinch point temperature can be appropriately increased, in order to reduce the heat exchange area with lower production cost [13].

In the heat transfer process between the heat source and the organic fluid, the exergy loss ratio of the system is the largest. In order to improve the system economy and reliability, preheater, evaporator and superheater are adopted to heat organic fluid [24]. The installation of preheater can not only improve the economy of the system but also improve the stability of the system. In the preheater, the temperature of organic fluid rises rapidly. When entering the evaporator, the fluid is not supercooled. Therefore, the gas in the evaporator can be evaporated stably, so as to ensure the stability of power generation. The superheater is usually installed in front of the expander in order to overheat organic fluid and prevent liquid hammer from appearing in expander.

The cost of the heat exchangers can be calculated by the following equations:

\[
lg C_b = R_1 + R_2 + R_3(\lg AR)^2
\]

\[
C_{BM} = C_b (B_1 + B_2 F_m F_p)
\]

\[
lg F_p = C_1 + C_2 \frac{lg P + C_3 (lg p)^2}{\Delta t_m}
\]

where \( R_1, R_2, R_3, B_1, B_2, C_1, C_2 \) and \( C_3 \) are constant coefficients, \( AR \) is the heat exchange area, \( C_b \) is equipment costs in accordance with the RMB purchase capacity, (1 US dollars = 6.67 Yuan conversion), \( F_m \) and \( F_p \) are the correction coefficients of the heat exchanger material and the pressure, respectively, and \( C_{BM} \) is the total acquisition cost for heat exchangers [25].

AR required by the heat exchanger can be calculated by Equation (5).

\[
AR = \frac{Q}{K \Delta t_m}
\]

where \( K \) is the total coefficient of the heat transfer and \( \Delta t_m \) is the average heat exchange temperature difference.

In engineering calculation, Equation (6) is used to correct \( \Delta t_m \) between two kinds of fluid:

\[
\Delta t_m = \frac{\Delta t_1 - \Delta t_2}{\ln (\Delta t_1/\Delta t_2)}
\]

where \( \Delta t_1 \) is the temperature difference between the two fluids at the inlet of the heat exchanger and \( \Delta t_2 \) is the temperature difference between the two fluids at the outlet of the heat exchanger.

2.2. The expansion device

The ideal expansion process of an expansion device is isentropic expansion. However, there exist irreversible losses in the process of actual expansion. Equation (7) is used to define the expansion device efficiency:

\[
\eta_{exp} = \frac{h_2 - h_1}{h_{2s} - h_1} \times 100\%, \quad (7)
\]

where \( h_1, h_2 \) and \( h_{2s} \) are the inlet, outlet enthalpy of an expansion device and the outlet enthalpy of isentropic expansion, respectively. During the operation of the ORC system, \( \eta_{exp} \) varies with the pressure, temperature and other parameters. The expansion device power output is obtained using Equation (8):

\[
W_s = m_f (h_2 - h_1) = m_f \eta_{exp} (h_{2s} - h_1). \quad (8)
\]

At present, the expansion device is usually modified in two ways:

(1) By modifying the compressor used for air conditioning, such as screw, scroll and piston compressor, which can be transformed into corresponding forms of expander. They have better sealing and lubricating properties and also applicability to organic fluids because the prototypes are air conditioning compressors.

(2) By modifying the steam turbines, gas turbines and other heat engines, such as radial and radial turbine. They are widely used in large-scale ORC power generation systems due to their compact structure, high speed and high efficiency.

Many studies have shown that the power scale has a great bearing on expander efficiency [26–32]. Figure 2 shows the expander efficiency varies with its power scale. According to the power scale, we can optimize the selection of high-efficiency expanders. Scroll expanders are more suitable for systems less than 5 kW, and screw expanders are suitable for scales of 5–50 kW. Turbines are widely used in large-scale systems, especially those larger than 10 kW. Rotary technology has lower efficiency than scroll in the same power scale.
According to Figure 2, combined with other technical parameters, the radial turbine is adopted as the expansion device. In order to improve efficiency, the expander and generator are coupled by a shaft and are totally enclosed, as shown in Figure 3.

### 2.3. ORC power plant design

The simplified process diagram of the ORC power plant is shown in Figure 4. In order to improve performance, preheater and superheater are installed on the original simple ORC. The plant uses the waste heat steam at the temperature of 90–150°C as the high-temperature heat source and the water at the temperature of 5–35°C as the low-temperature heat source. The main components include the preheater, the evaporator, the expander, the condenser, the refrigerant tank and the working fluid pump.

According to the type of fluids in the system, the circulation consists of three parts: the organic fluid cycle, the steam cycle and the cooling water cycle.

### 2.4. Results of the power plant building

The ORC power plant is built according to Figure 4. Figure 5 is the photograph of the ORC power plant. It should be noted that the cooling water cycle apparatus is not shown in Figure 5, which was placed on the top of the building. The system uses R245fa as the working fluid. When the system is operating under optimal operating conditions, it must remain stable for at least 30 days to allow data logging to assess the economics of the system. During this period, system power generation is about 11736 kW h, with an average power of 16.3 kW.

In order to analyze the economics of the entire system, the ORC power plant is divided into five parts: ORC system part, cooling water circulation part, measurement system part, system control part and others. The main components and prices of each part are shown in Table 1. The ORC system part accounts for 61% of the total initial investment.

### 3. ECONOMIC SIMULATION

In order to analyze the economic feasibility of the ORC power plant, an economic model with the minimum EPC as the objective function is established. These analyses are based on the Chemical Engineering Plant Cost Index (CEPCI) economic model, and some parameters are modified. According to the reference materials, an economic calculation method was adopted to develop the model [33–37]. Furthermore, the total initial investment cost is input, in order to analyze the power plant economically.

#### 3.1. Electricity production cost

By calculating the EPC, the economy of the ORC power plant can be directly seen. According to the total initial investment cost, capital recovery rate (CRF), operation and management cost of ORC power plant and the cost of electricity production are calculated.
According to the EPC of the plant, combined with CEPCI, the economic model of the ORC power plant is established. The total cost of the plant can be calculated:

$$C_{2001} = CO_{2001} + CO_{tw} + CO_{ms} + CO_{cs} + CO_{oth} \quad (9)$$

$$C_{2014} = C_{2001} \times \frac{CEPCI_{2014}}{CEPCI_{2001}} \quad (10)$$

Considering the time value of capital, the initial investment is at a certain rate to bank loans or one-time payment made by company. The annual percentage rate of interest is $i$. The term of payment for the investment is defined as the life cycle of the equipment, denoted by $N$. Then, the CRF is equal to the average annual investment cost to the total initial investment ratio.

$$CRF = \frac{i(1+i)^N}{(1+i)^N - 1}. \quad (11)$$

Cost of operation and management can be calculated by Equation (12).

$$COM = 1.65\%C_{2014}. \quad (12)$$

Finally, EPC is calculated as shown in Equation (13).

$$EPC = \frac{C_{2014} \times CRF + COM}{W_{net} \times H} = \frac{C_{2014} \times \left[\frac{i(1+i)^N}{(1+i)^N - 1} + 1.65\%\right]}{W_{net} \times H}. \quad (13)$$

### Table 1. Price list of each part of the ORC power plant.

| No. | Nomenclature                        | Main includes                                                                 | Price (dollars) |
|-----|------------------------------------|-------------------------------------------------------------------------------|-----------------|
| 1   | ORC system part                    | Evaporator, condenser, preheater, superheater, working fluid pump, oil separator, mass flow meter, turbine expander, R245fa, lubricating oil, etc. | 68 660          |
| 2   | Cooling water circulation part     | Circulating water pump, electromagnetic flowmeter, cooling tower, etc.        | 11 690          |
| 3   | Measuring system part              | Computer, communication expansion board, data acquisition instrument, digital power measuring instrument, platinum resistor, temperature transmitter, pressure transmitter, frequency transmitter, etc. | 19 190          |
| 4   | Control system part                | Control/power cabinet, programmable logic controller, frequency converter, electric switch box, touch screen, etc. | 4500            |
| 5   | Other parts                        | Installation and debugging, software design, system design, taxes, etc.        | 9000            |
|     | Total initial investment           |                                                                               | 11 3040         |

3.2. Economic model

Equation (13) shows that EPC mainly depends on the total initial investment cost and the capacity output of the ORC power plant. Therefore, an economic model of the ORC power plant was established with those variables affecting EPC. The main variables that affect the minimum value of EPC are considered as follows [38–40]:

1. For the power generation of the plant, the evaporation temperature $T_0$ has an effect on the flow rate and specific enthalpy of organic fluid at the turbine inlet. Turbine power is equal to the product of the flow rate and enthalpy drop. Thus, the power generation of the plant is affected by evaporation temperature.
2. Because the cost of evaporator is mainly determined by its heat exchange area, the evaporator pinch temperature difference $\Delta T_p$ is directly related to its heat transfer area. The combination of preheater, evaporator and superheater is used to complete the heat transfer process of organic refrigerant and waste heat.

3. Waste heat flow rate $m_w$ and cooling water flow rate $m_w$ affect the heat transfer performance and pressure drop of evaporator and condense, respectively, and then affect the cost of heat exchanger and the cost and power consumption of the water pump.

Therefore, select the waste heat flow rate $m_w$, cooling water flow rate $m_w$, the evaporation temperature $T_0$ and the evaporator pinch temperature difference $\Delta T_p$ as the variables; the calculation formula of objective function is obtained.

$$EPC_{min} = f (m_g, m_w, \Delta T_p, T_0). \quad (14)$$

In the economic analysis, use the Shanghai municipal government guidance electricity price in 2016 as the price 0.91 yuan/(kW \* h) or 0.136 dollars/(kW \* h). The difference between the electricity price and the EPC is the profit earned by the ORC plant, as shown in Equation (15). The profits here are assuming that the plant can operate normally for 20 years. As the operation life time increases, the lower the annual depreciation rate, the longer the payback time.

$$P = Pr \times \text{ele} - EPC. \quad (15)$$

4. **ECONOMIC ANALYSIS RESULTS**

In order to evaluate the economy of the plant comprehensively, the residual value of the whole plant assets should be considered. The residual value of the assets refers to the residual value that can be recovered when the equipment is scrapped or reaches to its useful life. The estimation of the residual value of the assets is a complex technical and economic problem, 3–5% of the original value of the assets is adopted [41].
The ORC power plant is applied to those factories where low-temperature heat sources can be produced continuously. However, we need to deduct the downtime caused by maintenance. Therefore, assuming that the plant running time is 7500 hours per year and the average output power is 16.3 kW, the annual output power is 122,250 kW·h.

The influence of installing cooling water system on EPC and the profit of the power plant is analyzed by economic model. The influence of the installation of preheater and superheater on EPC and the profit of the power plant with cooling water system is analyzed. Finally, from the economic point of view, the influence of interest rates, loan ratios on EPC and the profit of power plant with preheater, superheater and cooling water system is analyzed.

4.1. Influence of cooling water system
In water-scarce areas, cooling water systems are needed to cool organic fluids, while in water-rich areas, cooling water systems are not needed. In the economic analysis, the main difference between power plants with cooling water system and without cooling water system is that the initial total investment is different, which affects the profits of EPC and power plants. Figures 6 and 7 present the variation of EPC with the operation life time of the power plant without cooling water system and with cooling water system at different evaporation temperatures, respectively.

The longer the operating life, the smaller the EPC value; this change is non-linear. The minimum EPC value is 0.46 Yuan/(kW·h) when the maximum operating life time is 20 years, shown in Figure 6. The changing tendency of EPC versus operation life time of the power plant is similar to that of without cooling water system. Due to the cooling water system increases the total initial investment of the plant, the EPC of the power plant with cooling water system is larger than that of the power plant without cooling water system at the same period. The minimum EPC value of the power plant with cooling water system is 0.57 Yuan/(kW·h).

Figures 8 and 9 present the variation of profitability with the operation life time of the power plant without cooling water system and with cooling water system at different evaporation temperatures, respectively. As the operation life time increases from 1 year to 20 years, the profit of the power plant increases from −1.89 Yuan/(kW·h) to 0.45 Yuan/(kW·h). This can be explained that the longer the operation life time (the depreciation time), the greater the profitability. Negative value illustrates that
the value of EPC is greater than the electricity selling price, which represents the poor economic performance of the power plant. Compared with Figure 9, the profit of the power plant increased from $-2.29$ Yuan/(kW • h) to 0.34 Yuan/(kW • h). The main reason for the decrease is the increased initial investment in the cooling water system.

### 4.2. Influence of preheater and superheater

The benefits of installing preheater and superheater for the ORC power plant performance are explained in the second part. In economic analysis, it is different from the cooling water system; its installation not only increases the total initial investment but also increases the power generation of the plant; thus, the EPC and profits are reduced. The simple ORC, the ORC with preheater and the ORC with preheater and superheater were compared to analyze the effect of preheater and superheater installation on EPC and profit. In all three cases, the ORC power plants have installed the cooling water systems.

Figure 10 presents the variation of EPC with the operation life time of the power plant. At the start of operation life time, the EPC value of the simple ORC power plant is minimal, followed by the ORC with preheater, and the ORC with preheater and superheater is maximal. With the operation of the plants, the EPC values of the ORC with preheater and the ORC with preheater and superheater are gradually close to that of the simple ORC. After 7 years of operation, the EPC values are smaller than that of the simple ORC due to the increase of the power generation. The EPC values of the plant with superheater are always higher than that of the plant with the preheater only but the difference is small. This indicates that the superheater installation is uneconomical. Due to the protective effect of superheater on the plant, installation of superheater is also necessary. It is obvious that the EPC value of the plant with the preheater only is minimum and

Figure 11 presents the variation of profitability with the operation life time of the power plant. The profits of the simple ORC and the ORC with preheater are almost positive at about 7 years, followed by the ORC with preheater and superheater. After 9 years of operation, the profits of the ORC with preheater and the ORC with preheater and superheater all exceed the profits of the simple ORC. After 20 years of operation, the ORC with preheater has the maximum profits value 0.38 Yuan/(kW • h).

### 4.3. Influence of loan ratio and loan interest rate

In the economic analysis of the ORC power plant, the loan problems need to be considered. The most previous research ignored the issue of loan. The influence of the ratio of loans to the total
initial investment and the interest rate on EPC and profits are analyzed in this paper. Figure 12 shows the variation of EPC with operation life time under loan ratios at 0, 20, 40, 60, 80 and 100%, which is based on the interest rate of 8%. After 20 years of operation, the EPC value increases from 0.56 Yuan/(kW • h) to 1.07 Yuan/(kW • h). The EPC decreases rapidly in the first 10 years and then decreases slowly and steadily. Figure 13 presents the variation of profitability with operation life time. After 20 years of operation, profit decreases from 0.34 Yuan/(kW • h) of loan ratio 0% to −0.16 Yuan/(kW • h) of loan ratio 100%.

Different regions and different periods have different interest rates. The influence of interest rates of 8%, 10%, 12%, 14% and 16% on EPC and profits are analyzed when the loan ratio is 30%. Figure 14 shows the variation of EPC with operation life time under different interest rates, in which the evaporation temperature is equivalent to 413 K. When interest rates change from 8% to 16%, the minimum EPC value increases increased by 12.7% from 0.735 Yuan/(kW • h) to 0.93 Yuan/(kW • h).

Figure 15 presents the variation of profitability with operation life time under different interest rates. With the increase in interest rates, profits decrease: at 8% interest rate the profit is 0.175 Yuan/(kW • h), while at 16% interest rate the profit is −0.02 Yuan/(kW • h).
5. CONCLUSIONS

The ORC power plant with an actual generating capacity of 16.3 kw has been built. The radial turbine is adopted as the expansion device. Through the analysis of the investment in each part of the power plant, it was found that the ORC system part accounts for 61% of the total initial investment, and the larger the power generation scale, the larger the proportion. An economic model for low-temperature industrial waste heat conversion in ORC power plant was established. The effects of cooling water system, preheater and superheater installation, loan ratio and interest rate on EPC and profit are analyzed.

Through the analysis, it is found that the installation of preheater and superheater are necessary, especially preheater. The paper analyzes the proportion of loan in the total initial investment and the influence of interest rate on EPC and profit. With regard to the investment, as the loan ratio and interest rate increase, EPC will increase with the loan ratio and the interest rate increase, while the profits will decrease due to the need to repay interest.

It is anticipated that the ORC power plant and its economic model can be used for the feasibility assessment of other ORC power plants. Project managers can use these conclusions and date to consider how to invest and build their ORC power plants.

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