Operation Analysis of Organic Rankine Cycle under Variable Conditions and Comparison confirmation of simulation calculation

Chen Xiaoqing¹, Jiang Weiting¹, Cao Xianchang², Zhang Li'ang¹, Chen Chi², Chen Zhiliang², Yang Yiqing¹ and Pan Weiguo¹

¹Shanghai University of Electric Power, Shanghai, China

²Shanghai Baosteel Energy Technology Company, Shanghai, China

Abstract. The initial simulation calculation of the ORC power generation system was carried out using the software Aspen Plus, and the simulation data matched with the design conditions were obtained. According to the specific structure of the evaporator and superheater in the ORC power generation system and the characteristics of the software Aspen EDR, a new simulation calculation method is proposed: structural simulation calculation method. The calculation method and the direct simulation calculation method are used to carry out simulation comparison to find out the regularity of the change of waste heat resources, and it is convenient to further analyze and control the ORC power generation system.

1 Introduction

The researches of the Organic Rankine Cycle (ORC) technology began in 1924^[1]. In the 1960s, some test prototypes were developed. In the 1970s, due to the outbreak of the oil crisis, a lot of researches on this technology were carried out. However, the market size of this technology was small (mainly used in waste heat recovery and new energy fields), and until the late 1990s, ORC power generation systems began to be widely used.

In an organic Rankine cycle power generation system, it is important to select the right organic working fluid because the difference in organic working fluid affects the entire system. In view of this aspect: Michele Tavano^[2] compared the mixed working fluid with the pure working fluid, and the results show that the optimized mechanical power can increase the recovered mechanical power by about 3 percentage points. Heberle^[3] studied and compared the thermal properties of R227ea/R245fa and isobutylene/isopentane. The conclusion shows that the performance of R227ea/R245fa mixed working fluid is better under the working condition of 80°C- 180°C. Lecompte^[4] analyzed that the power output of the binary mixture increased by 30% compared to the pure fluid, and in some cases the thermal efficiency increased by more than 15%. Heberle et al. ^[5] had also shown that anisotropic mixtures can improve the efficiency of organic Rankine cycle systems. Papadopoulos^[6], Lampe^[7] developed and applied advanced computer-aided molecular design (CAMD)

methods to identify or design optimal fluids for ORC systems. Andreasen, J.G^[8] studied the thermodynamic properties of mixture working fluids, developed and utilized genetic algorithms, and selected suitable organic mixed working fluids from the composition database. Markus P^[9] studied the thermal degradation characteristics of organic matter MM. At 300 °C, the annual degradation rate of organic working medium MM is less than 3.5%.

On the other hand, researches on ORC power generation technology focuses on the design and optimization of expanders. In 1987, Verneau^[10] used FC75 as the working fluid, designed a single/two-stage axial flow turbine. Kang^[11] proposed a high-speed radial turbine with R245fa as the working fluid. The measured output power can reach 32.7kw and the turbine efficiency can reach 78.7%. T.Z. Kaczmarczyk^[12] established an organic Rankine cycle system test bench with a miniature radial turbine with HFE7100 as the working fluid. A.P. Weiß^[13] studied various turbines and considered that single-stage axial flow turbines can meet the requirements of small volume and high expansion ratio. P. R. Fernandez^[14] proposed a complete method for shape optimization of ORC turbine blades. Kiyarash Rahbar^[15] proposed a method for achieving maximum efficiency optimization of a radial ORC turbine using mean-line modeling and genetic algorithm (GA). Enrico Rinaldi^[16] first studied the single-stage high expansion ratio ORC radial turbine under non-design conditions using quasi-three-dimensional numerical simulation method, and proposed a kind of unstable CFD simulation.

While conducting experimental researches on the organic Rankine cycle, some scientists have studied their practical applications. Christopher R^[17] have been working on the application of organic Rankine cycle power generation systems on heavy duty road trucks. D. Serrano^[18] used the organic Rankine cycle to recover the exhaust heat of the train. Yari^[19] studied the efficiency of different ways of organic Rankine cycle for gas turbine waste heat recovery. Gao^[20] proposed a method for recovering exhaust heat from a turbocharged diesel engine using an organic Rankine cycle power generation system. Kévin R^[21] studied the application of small turbines in the waste heat recovery of automotive internal combustion engines. John H^[22] studied the application of the organic Rankine cycle in natural gas plants. Jan Wajs^[23] proposed a new small shell-and-tube type annular microchannel heat exchanger as a condenser for domestic micro-thermal power plant research.

Due to the fact that there is less actual simulation of the running organic Rankine cycle power generation system in the mainstream research direction, the accuracy of the organic Rankine cycle simulation system under variable operating conditions is rarely considered. This topic used Aspen Plus to selected a factory's ORC power generation system as the object to model, simulated its data changes under variable working conditions, and compared the actual data to draw conclusions. The ORC system is a Rankine cycle with organic matter as the working fluid. It consists of four basic components: evaporator, turboexpander, condenser, and working fluid pump ^[24].

2 Preliminary simulation

2.1 Overview of ORC Units in Operation

The object of the simulation was the low-temperature waste heat ORC power generation system of the three-sinter ring cooler of a factory in Shanghai. The low-temperature section waste heat recovery process consists of a closed circulating hot water system, an ORC generator set and a cooling water circulation system. According to the actual ORC unit structure, a preliminary model structure was established in Aspen Plus as shown in Fig. 1.

Fig.1. Preliminary model structure

EVPI represents the evaporator, and the heat source used 220t/h and 150°C hot water; EVP2 represents overheating, The steam is used as a heat source of 10t/h and 180°C; the TUR represents a expander with an isentropic efficiency of 80% and a mechanical efficiency of 85%; CON stands for a condenser, and the cold source is about 23°C, 1620t/h normal temperature water; PUMP is a working fluid pump with an isentropic efficiency of 85% and a mechanical efficiency of 85%.

2.2 Simulated an already running unit with Aspen Plus

First, the global characteristics were set. In the process simulation, two kinds of fluids were involved: organic working fluid R245fa and water. The physical method chosen in this paper was the RK-SOAVE equation of state, which was often used in systems using organic working fluids.

Then input the logistics parameters and module parameters in the system, The mass flow rate of organic working fluid R245fa was 88kg/s, the evaporation pressure was set to 2.04MPa, the condensing pressure was set to 0.2MPa. Each of the external streams must input three of the specific parameters of temperature, pressure, dryness, and flow. Each model must entered different parameters that the module needs to enter.

After inputting the above data, the preliminary running simulation results can be obtained, and the simulation results of each module in each cycle were uniformly represented by using a table, as shown in Table 1.

Table 1. Simulation results of various components of the system

equipment	Inlet temperatur e (°C)	outlet temperature (°C)	Fluid flow rate (Kg/s)	Energy (MW)
evaporator	33.89	122.4	88	16.42
Superheater	122.4	126.13	88	5.77
Turbine	126.13	64.69	88	2.66
condenser	64.69	33	88	19.21
pump	33	33.89	88	0.17

Under the set condition parameters, the simulated thermal efficiency value was calculated according to Equation 1 as:

$$\eta_c = \frac{W_{\text{net}}}{Q_c} = \frac{2.66 - 0.17}{16.42 + 5.77} = 11.22\% \quad (1)$$

 η_c — Cyclic thermal efficiency, %;

W_{net} ——System power, MW;

Q_c ——System heat absorption, MW.

According to Equation 1, it can be concluded that the system cycle efficiency was 11.22% under normal

operating conditions. However, due to the instability of the waste heat resources in the industrial park, the ORC power generation system cannot meet the design conditions during normal operation, and was often operated at low load. In order to simulated the parameter changes during the operation of the ORC power generation system, the ORC simulation system needs to be further designed and calculated.

3 Comparison confirmation of simulation calculation

3.1 simulation calculation

3.1.1 Structural Simulation calculation

Since the Aspen Plus EDR does not have a structure similar to the actual running ORC system, the simulation results may be biased due to structural errors during the simulation of the superheater. if wanted to simulate the superheater in accordance with the actual situation, it need to obtained the specific parameters of the working point of the two exit points of the evaporator.

Although the software only gives a working fluid export parameter when simulating, that was, the working fluid parameters of the two export working fluids were mixed, the temperature of both outlets was not marked. However, the temperature of the two outlets of the housing can be seen on the analog interface, as shown in Figure 2. It can be seen from the figure that the temperature of the left working outlet point 1 was significantly higher than the right exit point 2 and also higher than the saturation temperature. Therefore, the working outlet of the left exited point 1 is saturated or superheated steam. The working fluid flow rate of the two outlets was regarded as half of the total flow rate, and the specific parameters of the two export working fluids, that was, the working temperature and dryness, can be obtained according to the mixed parameters.

Fig.2. Schematic diagram of fluid temperature in the evaporator housing

The total heat transfer of hot water can be obtained

by formula 2. According to formula 3, the total heat transfer of working fluid at outlet point 2 can be obtained by subtracting the heat transfer of working fluid at outlet point 1 from the total heat transfer. Finally, the enthalpy of the working fluid at outlet point 2 was obtained according to the working fluid 4. The enthalpy h of each point was obtained by software REFPROP.

$$Q_{\text{total}} = (h_{w\text{in}} - h_{w\text{out}}) m_w \quad (2)$$

$$Q_2 = Q_{\text{total}} - Q_1 = Q_{\text{total}} - \frac{(h_{\text{out1}} - h_{\text{in}}) m}{2} \quad (3)$$

$$Q_2 = \frac{(X - h_{\text{in}}) m}{2} \quad (4)$$

Q_{total} —total heat transfer of evaporator;

$h_{w\text{out}}$ —the enthalpy of hot water at the outlet of evaporator;

$h_{w\text{in}}$ —Enthalpy value of imported hot water of evaporator;

m_w —evaporator hot water flow, kg/s;

Q_1 —heat transfer of working fluid at outlet 1;

Q_2 —heat transfer of working fluid at outlet 2;

h_{out1} —Enthalpy value of working substance at exit point 1;

X —Enthalpy value of working substance for export point 2.

After the enthalpy value of the working substance at outlet 2 was obtained, it can be judged whether the working substance was in two-phase state or not. If it was in two-phase state, the dryness of the working substance can be calculated by formula 5.

$$h_{\text{gas}} Y + h_{\text{liquid}} (1 - Y) = X \quad (5)$$

Y —Dryness of working fluid at outlet point 2;

h_{gas} —the enthalpy of working substance at outlet point 2 when it is gaseous;

h_{liquid} —Enthalpy value at outlet point 2 when working fluid is liquid.

3.1.2 Direct simulation

The direct simulation calculation method is to select the heat exchanger structure consistent with the evaporator and superheater in the ORC power generation system, and directly input the parameters of the working fluid parameters of the evaporator outlet to the exit point of the superheater (This parameter was the working parameter of the two evaporator outlet point parameters.). Since the calculation method was relatively straightforward and did not take into account the connection mode of the evaporator and the superheater in actual operation, the method was called the direct simulation calculation method.

3.1.3 Comparison of direct simulation calculation and structural simulation calculation

The mixed superheater outlet working medium has reached a gaseous state. The temperature of the superheater outlet working fluid obtained by the two methods was compared, as shown in Table 2. It can be seen that when using the direct simulation calculation

method, the deviation value was small, and the fluctuation value was within +10%. When the structural simulation calculation method was used for the simulation calculation, the deviation value fluctuates greatly and fluctuates within $\pm 20\%$. Therefore, through the data comparison, it can be concluded that the direct simulation method can be used to obtain a more realistic value, and the value has a certain regularity.

Table 2. Comparison of two simulation algorithm parameters

Actual operation (°C)	Direct simulation n (°C)	Deviation (%)	Structural simulation n (°C)	Deviation (%)
128.8	133	3.26	122.5	-4.89
114.6	121	5.58	130	13.45
122	125	2.46	134	9.84
115	124	7.83	138	20

3.2 Analysis of simulation results of direct simulation calculation

Simulate calculations using direct simulation, the working fluid pump outlet data was input into the Aspen EDR, and the evaporator superheater module was simulated. The working fluid parameters of the superheater outlet were obtained and compared with the actual working fluid export parameters, as shown in Fig. 4. Then input the simulated superheater outlet working parameters into the turbine module in Aspen Plus, simulated the system power, and compared the results with the actual power.

The 20 sets of data selected in this simulation have a large span, the superheater outlet temperature was from 96 °C to 126 °C, and the attack power was from 1 MW to 1.9 MW. From the comparison of the simulated outlet temperature and the actual outlet temperature, the simulation of the turbine power and the actual work power: the error was within $\pm 10\%$, and presented a certain regularity. It can be concluded that the direct simulation calculation method in Aspen Plus can be used to simulate the ORC power generation system, and the simulation parameters which were in good agreement with the actual parameters can be obtained.

3.3 Simulate using direct simulation

As can be seen from Figure 3, the simulated heat exchanger outlet temperature and turbine work were higher than the actual data. Compared with the simulated turbine power, the simulation data of the heat exchanger outlet temperature fluctuates greatly. However, the power of the turbine was not only considering the outlet temperature, but also the pressure of the exporting work. Therefore, when simulated the power of the turbine, the error would decrease and it would show a certain linearity compared with the actual power. In future applications, the correction factor can be set according to the error between the simulated calculation parameters and the actual parameters, which can improved the stability of the simulation data.

Fig.3. Comparison of actual parameters and simulation parameters

4 Conclusion

(1) Using software Aspen Plus to carry out preliminary simulation study on low temperature waste heat ORC power generation system, using RK-SOAVE as physical method, the heat exchanger assembly adopts preliminary design, and does not design parameters such as heat exchanger size, number of tubes, length of pipe, etc. After inputting the basic parameters, it is found that the design conditions of the ORC power generation system are basically the same, that is, the software Aspen Plus has relatively high accuracy when designing the working condition of the ORC power generation system. It can be seen from the simulation results that under full load operation, the cycle efficiency of the ORC power generation system can reach 11.22%, and the design power of the turbine is 2.66MW.

(2) When the ORC power generation system was operated under variable operating conditions, the structure of the ORC power generation system needs to be further simulated. The software Aspen Plus was used to simulate the evaporator and superheater modules in the ORC power generation system. After the heat exchanger module was simulated, 20 sets of data with stable operation are selected, and the ORC power generation system was simulated by using the structural simulation calculation method and the direct simulation

calculation method. Compared the two calculation methods, it can be seen that the simulation data obtained by the direct simulation calculation was closer to the actual operation value. When the direct simulation calculation method was used to simulate the ORC power generation system under variable working conditions, the simulated data was compared with the real data deviation value within 10%, and a certain regularity was presented.

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