WORKING FLUID DISTRIBUTION OF A 315 KW ORGANIC RANKINE CYCLE SYSTEM IN THE OFF-DESIGN CONDITIONS

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1. INTRODUCTION

- Level of 300kW
  - Stability
  - Reliability
  - Safety

- The liquid level
  - The working fluid tank
  - The heat exchanger

- Operating state of the system

- Safe operation of the system
2. Introduction to the ORC test system

- **Main equipment:** Brazed plate heat exchanger (including evaporator, preheater and condenser), centrifugal working fluid pump, working fluid tank and radial turbine.

- **Working fluid:** R134a

- **Power generation:** 315 kW

<table>
<thead>
<tr>
<th>Code and meaning</th>
<th>Unit</th>
<th>Evaporator</th>
<th>Preheater</th>
<th>Condenser</th>
</tr>
</thead>
<tbody>
<tr>
<td>L (length of the heat exchanger)</td>
<td>m</td>
<td>0.83</td>
<td>0.83</td>
<td>1.232</td>
</tr>
<tr>
<td>A (width of the heat exchanger)</td>
<td>m</td>
<td>0.537</td>
<td>0.537</td>
<td>0.537</td>
</tr>
<tr>
<td>B (thickness of the heat exchanger)</td>
<td>m</td>
<td>0.778</td>
<td>0.324</td>
<td>0.881</td>
</tr>
<tr>
<td>n (Number of plates)</td>
<td></td>
<td>300</td>
<td>110</td>
<td>400</td>
</tr>
<tr>
<td>E (equivalent plate spacing)</td>
<td>m</td>
<td>0.00219</td>
<td>0.00219</td>
<td>0.0018</td>
</tr>
<tr>
<td>F (fouling coefficient)</td>
<td>m².°C/kW</td>
<td>0.049</td>
<td>0.049</td>
<td>0.19</td>
</tr>
</tbody>
</table>
The measuring range and accuracy of the measuring equipment used in the experiment

<table>
<thead>
<tr>
<th></th>
<th>Pressure Sensor</th>
<th>Temperature Sensor</th>
<th>R134a flowmeter</th>
<th>Water flowmeter</th>
<th>Level gauge</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Range</strong></td>
<td>0-2.5 MPa</td>
<td>0-125 °C</td>
<td>0.08-1.237 m³/min</td>
<td>0-10 m³/min</td>
<td>500 mm</td>
</tr>
<tr>
<td><strong>Accuracy</strong></td>
<td>±0.25%</td>
<td>±0.25%</td>
<td>±0.963%</td>
<td>±1%</td>
<td>±10 mm</td>
</tr>
</tbody>
</table>
3. Establishment and verification of heat exchanger simulation model

3.1 Model assumptions and simplifications

In order to speed up the calculation, the model is rationally simplified based on experimental experience.

- The system is well sealed, there is no leakage and no loss of working fluid.
- The model ignores the pressure drop.
- Ignores the change of the mass distribution caused by the change of the gas density.
- Ignores the fluid volume change caused by temperature.
3.2 Calculation of heat transfer coefficient

Empirical formulas were used to calculate the heat transfer criterion of each zone—$$\text{Nu}_f$$.

**Water side heat transfer**

$$\text{Nu}_f = 0.2121 R e_f^{0.78} P r_f^{1/3} (\frac{m_f}{m_w})^{0.14}$$

**Single-phase heat transfer**

$$\text{Nu}_f = 0.023 R e_f^{0.8} P r_f^{0.4} (\frac{m_f}{m_w})^{0.14}$$

**Boiling heat transfer**

$$\text{Nu}_f = 1.926 P r_f^{1/3} B o_{eq}^{0.3} R e_{eq}^{0.5} \left[ (1 - X) + X \left( \frac{r_f}{r_g} \right)^{0.5} \right]$$

**Condensation heat transfer**

$$\text{Nu}_f = 0.0143 \left( \frac{R e_{eq}}{H} \right)^{0.64} P r_f^{0.33} (\frac{r_f}{r_g})^{0.055}$$

References

Zhongzheng Wang, & Zhennan Zhao., 1993, Analysis of performance of steam condensation heat transfer and pressure drop in plate condensers.
3.3 Solution of the heat exchange area

Energy conservation equations were used to calculate the heat exchange area of each section—S

Energy conservation equation on the working side:

\[ Q = m(h_{in} - h_{out}) \]

Energy conservation equation on the water side:

\[ Q = \eta m_y C_p y (T_{out} - T_{in}) \]

Energy conservation equation between the working fluid side and the water side:

\[ S = Q\left(\frac{1}{a_{water}} + \frac{d_w}{l_w} + 2F + \frac{1}{a}\right)(DT_m)^{-1} \]

\[ DT_m = \frac{DT_{max} - DT_{min}}{\ln DT_{max}/DT_{min}} \]

By using the above formula for simultaneous solution, the heat exchange area of each section can be obtained, thereby obtaining the distribution of the working fluid.
3.4 Model verification

Comparison of calculated and measured values of system liquid level distribution

$L_{\text{con}}$: Calculated liquid level of condenser
$L_{\text{eva}}$: Calculated liquid level of evaporator
$L_{\text{tank}\_\text{calculation}}$: Calculated liquid level of the working medium tank
$L_{\text{tank}\_\text{measuring}}$: Liquid level from meter measurement value

The calculated value of the liquid level of the working fluid tank is within the deviation range of $\pm 5\%$.
4. RESULTS AND DISCUSSIONS

Tested under different conditions
Evaporator outlet superheat: 13~21.5 °C
Condenser outlet subcooling: 4~11.5 °C
Working fluid pump flow rate: 2~20 kg/s
4.1 The change of working fluid distribution, superheat degree and supercooling degree during the change of working fluid flow

Superheat degree $\approx 18 \, ^{\circ}\mathrm{C}$
Supercooling degree $\approx 4.5 \, ^{\circ}\mathrm{C}$
The flow rate: $9 \, \text{kg/s} \rightarrow 18 \, \text{kg/s}$
The evaporator liquid level: $0.58 \, \text{m} \rightarrow 0.93 \rightarrow 0.88 \, \text{m}$
The condenser liquid level change $\approx 0.06 \, \text{m}$
The lowest level of the working fluid tank: $0.27 \, \text{m}$

- The working fluid flow rate determines the liquid level.
- As the flow increases, a large amount of working fluid moves to the evaporation system.
- Under the condition of sufficient cold source, the change of flow has little effect on the heat transfer of the condenser.
4.2 Effect of superheat change on working fluid distribution

- As the superheat increases, the working fluid moves toward the condenser and the working tank.
- Excessive superheating would waste the heat exchange area of the exchanger.

The cold source condition ≈ 5.3 °C
The working fluid pump frequency = 49 Hz
The system power generation → 315 kW
The superheat of the evaporator: 13 °C → 21.5 °C,
The evaporator liquid level: 0.075 m ↓
The condenser liquid level: 0.028 m ↑
The working fluid tank level: 0.16 m ↑
4.3 Operating characteristics of the condenser when the flow of cooling water changes

- Working pump frequency: 43 Hz
- The cooling water flow rate: 40 kg/s → 130 kg/s
- Outlet pressure $P_{out}$: 0.205 MPa
- Saturation temperature: 11 °C
- Degree of superheat $\Delta T_{sh}$: 3.3 °C
- Power generation: 66 kW
4.3 Operating characteristics of the condenser when the flow of cooling water changes

Temperature entropy diagram of working fluid in two states

![Diagram showing temperature entropy relationship]

- Working pump frequency: 43 Hz
- The cooling water flow rate: 40 kg/s → 130 kg/s
- The outlet pressure $P_{out}$: 0.205 MPa $\downarrow$
- The saturation temperature: 11 $^\circ$C $\downarrow$
- The degree of superheat $\Delta T_{sh}$: 3.3 $^\circ$C $\uparrow$
- Power generation: 66 kW $\uparrow$

- The degree of subcooling $\Delta T_{sc}$: 11.5 $^\circ$C $\rightarrow$ 4 $^\circ$C
- The heat exchange amount and area in the supercooled zone are reduced.
- The working fluid level drops.
CONCLUSIONS

- The increase of the flow causes the mass distribution to move to the evaporator. The increase of superheat reduces the working medium in the evaporator, and increases the working medium in the tank.

- Increasing the flow rate of the cooling water causes the pressure of the condenser to drop, which causes the subcooling to decrease. In this process, both the evaporator and the condenser liquid level are reduced, and the back pressure is lowered, which also increases the power generation. The sufficient cooling water flow is more conducive to efficient and stable operation of the system.

- The sufficient margin can ensure the overheated, enough margin can ensure more stable and safe operation, but the excessive superheat may cause waste.

- In the process, in order to avoid the pump cavitation, the superheat and the supercooling should be controlled within a reasonable range.
REFERENCES


Thank You!