Numerical simulation of a new district cooling system in cogeneration plants

Zhang Tiantian\textsuperscript{a}, Tan Yufei\textsuperscript{a}, Bai Li\textsuperscript{b,a*}

\textsuperscript{a}School of Municipal and Environmental Engineering, Harbin Institute of Technology, Harbin 150090, PR China
\textsuperscript{b}Jilin Architectural and Civil Engineering Institute, Jilin 130119, PR China

Abstract

In allusion to the problem that the superheated steam need to be cooled down by a temperature and pressure reduction device if its pressure exceeds the requirement of a absorption refrigerator, based on the cascaded utilization of energy and the theories of compression refrigeration and absorption refrigeration, a new type of district cooling system driven by surplus steam is introduced. Calculation model for the new combined cycle system is developed. The thermodynamic calculations of the absorption cooling program and combined cycle cooling program are processed upon a practical example. The amounts of surplus steam consumption are obtained and the effects of chilled water temperature, cooling water temperature and transfer efficiency of the industrial turbine are studied and analyzed. The result shows, compared to absorption systems, combined cycle systems have the advantage in energy conservation and steam-consumption saving. This research provides technical support for district cooling in a cogeneration plant.

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Keywords: District cooling; Surplus steam; Industrial turbine; Energy conservation;

1. Introduction

The most protruding question in cogeneration plants is that the loads in summer and in winter are unbalanced. Changing the imbalance is one of key techniques in improving energy efficiency of a power plant. Introducing district cooling into a cogeneration plant can make the plant run in an economic may both in summer and winter [1]. On the one hand, it can improve the equipment utilization and increase generating capacity of the cogeneration plant. On the other hand, the cooling effect in summer can mitigate the adverse impacts of the high air conditioning load and balance the peak-valley power load [2].

* Corresponding author. Tel.: +8613766808235;
E-mail address: x418298537@163.com.

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In many power plants, district cooling is carried out by a steam-driving absorption refrigerator recently. But absorption systems have a very prominent defect; a certain requirement of steam quality. Absorption refrigerator can only use saturated steam with the steam pressure of 0.4MPa~0.8MPa. But the steam produced by the power plant is usually superheated, so it is necessary to cool down the superheated steam by a temperature and pressure reduction device for the refrigerator’s utilization[3-5]. The cooling process wastes a large amount of energy. This thesis focuses on the reusing of the waste energy in the cooling process.

Industrial turbine can supply mechanical force or work by consuming the heat energy of the steam[6]. We may use an industrial turbine to drive the compression refrigerator in cogeneration plants in summer. Based on the cascaded utilization of energy, this paper presents a new type of district cooling system driven by an industrial turbine and compares it with the traditional absorption cooling system. This research provides technical support for district cooling in a cogeneration plant.

2. The propose of the combined cycle system

Fig.1 shows the operation principle of this new combined cycle system. In the combined cycle system, the temperature and pressure reduction device is replaced by an industrial turbine and a superheated steam saturator. Superheated steam from the power plant expands in the industrial to do work and drive the compressor of the compression refrigerator. After the pressure of the steam is cooled down to a level at which an absorption refrigerator can use, it is sent into the superheated steam saturator. Here’s how it works: the superheated steam from the power plant goes into the industrial turbine through a steam pipe,
then the waste steam of the industrial turbine is saturated by a superheated steam saturator, the saturated steam goes into the absorption refrigerator; The industrial turbine and the compressor of the compression refrigerator are coaxially set, the compression refrigerator is driven by the industrial turbine; The chilled water pipe and cooling water pipe are both connected in a overlap mode. The cooling effect includes two parts: the absorption cooling and the compression cooling.

![Diagram](image)


Fig. 1. Elementary diagram of the new combined cycle system

3. Mathematical model and physical model

The process of the calculation should rely on the equations of the compression refrigeration cycle, the equations of absorption refrigeration cycle as well as mass balance equation and energy balance equation in the superheated steam saturator [7].

3.1. Single-stage compressed refrigeration cycle driven by a industrial turbine

1) Refrigerating capacity per weighing:

\[ q_e = \bar{h}_{ev,\text{out}} - \bar{h}_{ev,in} = \bar{h}_{ev,\text{out}} - \bar{h}_{co,\text{out}} \]  

2) Unit theoretical work:

\[ w_0 = \bar{h}_{\text{com,}\text{out}} - \bar{h}_{ev,\text{out}} \]  

3) Flow rate of refrigerant:

\[ m_g = \frac{Q_e}{q_e} \]  

4) Theoretical power:

\[ N_0 = m_g w_0 \]  

5) Indicated power:

\[ N_i = \frac{N_0}{\eta_i} \]  

6) Actual refrigeration coefficient:

\[ \varepsilon = \frac{Q_e}{N_i / \eta_m} \]  

7) Matching formula of industrial turbine and compressor:

\[ q_{mg} (\bar{h}_{it,\text{in}} - \bar{h}_{it,\text{out}}) \times \eta = N_i \]  

3.2. Double-effect Li-Br absorption refrigeration cycle

The mass balance equations and energy balance equations of all equipments are required in the thermodynamic calculation of the absorption system [8].
1) High pressure generator (HPG):

\[ Q_{bg} + m_1 h_{he,ds,out} = m_{D_1} h_{sc} + (m_1 - m_{D_1}) h_{bg,cs,out} \]  

(8)

2) Low pressure generator (LPG):

\[ Q_{lg} + m_2 h_{he,cs,out} = m_{D_2} h_{sa} + (m_2 - m_{D_2}) h_{lg,cs,out} \]  

(9)

3) Condenser:

\[ Q_{co} = m_{D_1} (h_{sc} - h_{sw,co}) + m_{D_2} (h_{sa} - h_{sw,ev}) - Q_{lg} \]  

(10)

4) Evaporator:

\[ Q_{ev} = m_{D} (h_{sc,ev} - h_{cw,ev}) \]  

(11)

5) Absorber:

\[ Q_{ab} = m_{D} (h_{sc} - h_{le,cs,out}) + q_{m,a} (h_{le,cs,out} - h_{ab,out}) \]  

(12)

6) High temperature heat exchanger (HTHE):

\[ Q_{he} = q_{m,a} (h_{he,ds,out} - h_{he,ds,in}) = (q_{m,a} - m_{D_1}) (h_{bg,cs,out} - h_{he,cs,out}) \]  

(13)

7) Low temperature heat exchanger (LTHE):

\[ Q_{le} = q_{m,a} (h_{he,ds,in} - h_{ab,out}) = (m_1 - m_{D_2}) (h_{lg,cs,out} - h_{le,cs,out}) \]  

(14)

3.3. Mass, energy balance equation in steam saturator

1) Mass balance equation:

\[ m_g + m_w = m_a \]  

(15)

2) Energy balance equation:

\[ m_g h_{sa,in} + m_w h_a = m_a h_{sa,out} \]  

(16)

3) Matching formula of refrigerating capacity:

\[ \overline{Q_e} + Q_{ev} = Q_e \]  

(17)

4. Case study

There are vast quantities of cooling requirements around Tushan Cogeneration Company, a power plant in Anhui province of China. The total cooling load of the company reaches the number of 69780kW while the amount of surplus steam quantities up to 240 ton per hour. The pressure of the surplus steam is 1.27Mpa, and the temperature is 304℃. We are going to design an absorption system and a combined cycle system respectively for district cooling in the power plant and then compare the results obtained.

In China's current industry standard, the driving steam of the double-effect Li-Br absorption refrigerator can be saturated steam at the pressure of 0.4MPa, 0.6MPa and 0.8MPa. We call the pressure at which the steam entering the absorption refrigerator as the mid-pressure, and we have to carry out the thermodynamic calculation of combined cycle systems with different mid-pressures. In the calculation, the total cooling load is divided into 20 units so that the capacity of each refrigerator is reasonable. The design conditions in the thermodynamic calculation are shown in table.1.

<table>
<thead>
<tr>
<th>Refrigerating capacity(kW)</th>
<th>Inlet and outlet cooling water temperature (℃)</th>
<th>Inlet and outlet chilled water temperature (℃)</th>
<th>Transfer efficiency of the industrial turbine</th>
<th>Indicated efficiency of the compressor</th>
<th>Mechanical efficiency of the compressor</th>
</tr>
</thead>
<tbody>
<tr>
<td>3489</td>
<td>12/7</td>
<td>32/37</td>
<td>0.6</td>
<td>0.8</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Table.1 Design conditions

<table>
<thead>
<tr>
<th>Category</th>
<th>Synthetic refrigeration coefficient</th>
<th>Steam consumption(t/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absorption system</td>
<td>1.424</td>
<td>3.782</td>
</tr>
<tr>
<td>0.8MPa mid-pressure combined cycle system</td>
<td>1.488</td>
<td>3.619</td>
</tr>
<tr>
<td>0.6MPa mid-pressure combined cycle system</td>
<td>1.452</td>
<td>3.633</td>
</tr>
<tr>
<td>0.4MPa mid-pressure combined cycle system</td>
<td>1.407</td>
<td>3.649</td>
</tr>
</tbody>
</table>

Table.2 Results of thermodynamic calculation and the amounts of steam consumption

The result of thermodynamic calculation and the consumption of superheated steam under the designed working conditions are listed in table.2. Synthetic refrigeration coefficient means the refrigeration coefficient of the whole system: it is a combined action of absorption refrigerator and pressure reducer in an absorption system, while it is a combined action of compression refrigerator, superheated steam saturator and absorption refrigerator in a combined cycle system. It reflects the refrigeration capacity of the whole system. It can be observed that combined cycle system with the mid-
pressure of 0.8MPa has the strongest refrigeration capacity. As the transfer efficiency can reach up to 0.8 in actual operation, the energy conservation potential of combined cycle system can be predicted.

5. Discussion

5.1. Influence of outlet chilled water temperature

Fig.2 displays the influence of the temperature of outlet chilled water on each system. The superheated steam consumption decreases as the chilled water temperature increases, and the curves’ changing trend are basically equivalent. The rate of decline varies from 8 percent to 4 percent.

![Fig.2 Influence of outlet chilled water temperature](image1)

5.2. Influence of inlet cooling water temperature

Fig.3 illustrates the influence of the temperature of inlet cooling water upon all systems. The superheated steam consumption increases as the cooling water temperature increases, and the curves’ changing trend are basically equivalent. The rate of rise varies from 3 percent to 8 percent.

![Fig.3 Influence of inlet cooling water temperature](image2)

5.3. Influence of the transfer efficiency of the industrial turbine

The transfer efficiency of the industrial turbine is the most important influencing factor in the operation of the combined cycle system. The influence of the transfer efficiency of the industrial turbine on the two types of cooling systems is presented below in Fig.4.

![Fig.4 Influence of the transfer efficiency of the industrial turbine](image3)
The superheated steam consumption of combined system decreases as the transfer efficiency increases. Steam consumption of the combined cycle system with a mid-pressure at 0.8Mpa reduces by 3.18% as the transfer efficiency increases by 0.1, and the droop rates of the 0.6Mpa system and 0.4Mpa system are 2.15% and 1.23%. The combined cycle system with a higher mid-pressure consumes less steam than that with a lower mid-pressure when the transfer efficiency is in a lower level. However, if the transfer efficiency is maintained above 0.65, the lower mid-pressure system is more effective in saving energy in cogeneration plants. If the transfer efficiency reaches up to 0.8, compared with the absorption system, the combined cycle system with a mid-pressure at 0.4Mpa can reduce steam consumption by 9.164%, and 8.215%, 7.101% for the 0.6Mpa system and 0.8Mpa system.

Conclusion

In the condition of completing the same refrigerating capacity, compared with traditional absorption system, combined cycle system can save a large amount of steam consumption.

The influences of inlet cooling water temperature on the two types of systems are basically equivalent, and so does the outlet chilled water temperature. The superheated steam consumption decreases as the chilled water temperature increases, and increases as the chilled water temperature increases.

The superheated steam consumption decreases as the transfer efficiency increases. Steam consumption of the combined cycle system with a mid-pressure at 0.8Mpa reduces by 3.18% as the transfer efficiency increases by 0.1, and the droop rates of the 0.6Mpa system and 0.4Mpa system are 2.15% and 1.23%.

The combined cycle system with a higher mid-pressure consumes less steam than that with a lower mid-pressure when the transfer efficiency is in a lower level; If the transfer efficiency is maintained above 0.65, the lower mid-pressure system is more effective in saving energy in cogeneration plants.

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