Economic Analysis of Two Heat Pumps to Recover Heat from Circulating Water

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Abstract: The use of heat pump to recover the condensing heat of the unit can realize the cascade utilization of energy, improve the utilization efficiency of energy, not only can effectively increase the heating capacity of the unit, but also can improve the use efficiency of heating extraction steam, so as to improve the economy of the thermal power plant. Heat pumps suitable for use in power plants can be divided into absorption heat pumps and compression heat pumps. Which type of heat pump is more economical needs specific judgment for the specific application environment. In this paper, a specific example is used to compare the economy of the two heat pump systems. The calculation results show that the economy of the compressed heat pump is better than that of the absorption heat pump only when the COP of the compressed heat pump is greater than the critical value, and the waste heat recovery ability and water saving performance of the compressed heat pump are better.

Key word: absorption heat pump; compression heat pump; heating capacity; evaporation loss; economic analysis.

1. Introduction

Central heating is the steam and hot water produced by the central heat source, which supplies the heat needed by production, heating and life of a city or part of the area through the pipe network. Combined heat and power generation is a production method that thermal power plants use the steam that has done work in the steam turbine to heat users while producing electric energy. Combined heat and power plants are important heat sources for central heating. Regulating steam extraction heating unit is the main unit of cogeneration. Part of the steam that has done work in the steam turbine is extracted and sent to the first station of the heat network. It is used to heat the circulating water of the heat network in the heater of the heat network. The heat carried by the steam is transferred to the heat user through the medium of the circulating water of the heat network. A large amount of waste heat will still be generated in the process of regulating the extraction type heating unit. The usual treatment is to release this waste heat to the natural environment through the condenser and cooling tower, which is the cold source loss of the steam turbine. The amount of waste heat in this part is very large, but the grade is very low. It is usually impossible to obtain mechanical work from this part of waste heat, but this part of waste heat can be used for heating and heating, so as to realize the cascade utilization of energy and improve the utilization efficiency of energy. Heat pump technology plays an important role in the utilization of waste heat.

The working principle of heat pump is based on the inverse "Carnot cycle", which consumes a small amount of circulating net work, extracts heat from the circulating cooling water of the self-condenser, and sends it to the circulating water of the heat network to realize the purpose of waste heat utilization. Using heat pump heat recovery of condenser circulating water is used for heating of the heat on the one hand, can be improved by recycling waste heat heating system of heating capacity, on the other hand can improve the heat supply network water temperature of the heater, heater heat transfer temperature difference, reduce the network heater irreversible loss reduce network so as to improve the efficiency of heating extraction. The heat recovered from the circulating water of the condenser can be used for heat supply by either lithium bromide absorption heat pump or compression heat pump [1-2]. Absorption characteristics of the lithium bromide absorption heat pump units using the lithium bromide solution, based on the latent heat of vaporization of steam drive energy drive low temperature low pressure of water vapor in the evaporator condenser cooling water to extract the heat, the two parts of heat combined into absorption heat pump system to heat, and the water vapor carry heat to heat supply network in the condenser circulating water. The working medium of the compression heat pump absorbs the heat from the condenser circulating cooling water in the evaporator, flows through the heat pump compressor to absorb the compression work, and is cooled by the circulating water of the heat network in the
condenser, condenses into liquid, releases the latent heat of vaporization, heats the circulating water of the heat network, and then enters the evaporator for the next cycle. The most important performance index of heat pump is the heating coefficient, represented by the symbol COP, which is defined as the ratio of the energy obtained by the user to the energy consumed by the driving heat pump. According to the working principle of heat pump, the COP of compression heat pump and absorption heat pump is always greater than 1. Under current technical conditions, the COP of compression heat pump is generally around 3 ~ 6, while that of absorption heat pump is generally around 1.65 ~ 1.85 [3]. In reference [4-6], the equivalent heat drop method is used to analyze the economy of electrically driven compression heat pump system, steam driven compression heat pump system and absorption heat pump system respectively. Reference [7-9] illustrates the contribution of absorption heat pump system to energy saving and emission reduction based on actual cases. It can be seen that the energy saving benefit of both absorption heat pump system and compression heat pump system is far greater than that of direct extraction heat supply production mode.

Absorption heat pump system and compression heat pump system have their own applicable conditions and advantages and disadvantages. Single heat pump heating coefficient, the heating coefficient of compression heat pump is far higher than that of absorption heat pump, but electric compression heat pump in the process of production needs to consume large amounts of high grade of electricity, reference [10, 11], respectively, compared the COP is 1.7 absorption heat pump system and the COP is 4.5 and the COP for 6 electric compression heat pump system efficiency difference. It is concluded that the economy of absorption heat pump is better than that of compression heat pump. Combined with the analysis and comparison of actual operation parameters of power plants, reference [12] also draws the conclusion that the economy of absorption heat pump is better than that of electrically driven compression heat pump. Reference [3] compares the economic difference between the absorption heat pump and the electrically driven compression heat pump by introducing the electric energy conversion coefficient, and obtains the critical condition that the economy of the electrically driven compression heat pump system is higher than that of the absorption heat pump system. However, these analyses only consider the change of the heat pump system to the power generation of the system or the calculation is complex and not intuitive, and do not consider the contribution of the heat pump system in water saving, so it is not comprehensive enough. This paper comprehensively considers the differences of various heat pump systems in power generation, heating and water saving, comprehensively and intuitively compares the economy of electrically driven compression heat pump, steam driven compression heat pump and absorption heat pump, and discusses the economic difference between compression heat pump and absorption heat pump.

## 2. Economic analysis model

In the original system without the use of a heat pump, the heat required to heat the circulating water in the heat network is provided entirely by the heating extractor in the heat grid heater. Usually, the hot water outlet temperature produced by the heat pump cannot reach the required water supply temperature of the circulating water in the heat network. In the heat pump production mode listed in this paper, the heating system adopts the mode of heat pump and heat network heater running in series. The heat extraction steam from the medium pressure cylinder of the steam turbine further heats the hot water from the heat pump in the heat network heater to the required water supply temperature of the heat network and then supplies it to the municipal pipe network.

In order to compare the economy of compression heat pump and absorption heat pump more easily and intuitively, the following assumptions are made: the parameters of the turbo-generator set are consistent; The supply and return temperatures of the circulating water in the heat network are consistent; The flow of circulating water in the heat network is consistent; The heat of the heat pump is equal; After the condenser circulating cooling water flows through the evaporator of the heat pump, the temperature drop is 5°C. Generator efficiency ηd is 0.99.

Because the heat production of heat pumps is the same, the operation parameters of heat network heaters in all kinds of heat pump production methods are the same, so it is not necessary to consider the heat network heaters and the corresponding heat recovery system in the economic comparative analysis, thus simplifying the calculation.

### 2.1 Absorption heat pump

In the production mode of absorption heat pump heating, the steam source driving the heat pump is taken from the exhaust steam of the medium pressure cylinder, and the condensate water at the shaft plus outlet is used as the desuperheated water to reduce the temperature and decompress the exhaust steam from the medium pressure cylinder to saturation steam, and then it is sent to the generator of the absorption heat pump as the driving steam. The condensate generated after heat release in the generator flows through the water-water heater and is partially recovered by the condensate at the outlet of the shaft and returned to the condenser.

The temperature reduction water required for cooling 1 kg/s extraction steam is:

\[
f = \frac{h_{zp} - h_{bh}}{h_{bh} - h_{j2, out}}
\]  

(1)

Where: \( h_{zp}, h_{bh} \) and \( h_{j2, out} \) are the enthalpy of middle exhaust, saturated steam and axial added water, respectively.

Exhaust steam from 1 kg/s medium pressure cylinder will reduce the power generation:

\[
w_{1} = \left( h_{zp} - h_{c} \right) \cdot \eta_d
\]  

(2)

Where: \( h_{c} \) is the exhaust enthalpy of steam turbine.

The heat release of driving steam in the generator is:
The heat absorption of the working medium in the evaporator is:
\[ Q_e = Q_c \times (\text{COP}_x - 1) \]  
(4)

The extraction efficiency of No.8 low pressure heater is \( \alpha_8 \), and the heat released by saturated water in water-water heater is used for No.8 low pressure heater. Due to the exclusion of part of No.8 pumping steam, the added value of turbine energy generation is:
\[ \eta = (1 + f) \times (h_{bh,x} - h_{gh}) \times \alpha_8 \times \eta_d \]  
(6)

Where: \( h_{gl} \) is the enthalpy of supercooled water.

After the exhaust steam of the medium pressure cylinder of 1 kg/s is extracted, the power generation reduction value of the unit is:
\[ w_2 = (1 + f) \times (h_{bh,x} - h_{gl}) \times \alpha_8 \times \eta_d \]  
(7)

The hourly evaporation loss of circulating water is reduced
\[ \frac{Q_c \times 3.6 \times \Delta t \times k_{zf} \times (\text{COP}_{y1} - 1)}{\text{COP}_{y1} \times \Delta t \times c_p} \]  
(15)

Where: \( k_{zf} \) is the evaporation loss coefficient, and its value is 0.001

\[ E_{x3} = e_s \times f_e \]  
(11)

Where: \( e_s \) is the industrial water price.

### 2.2 Compression heat pump

The production mode of compressed heat pump can be divided into two kinds: mode 1, extract part of the exhaust steam from the medium pressure cylinder to expand and do work in the condensing small steam turbine, the exhaust steam of the small steam turbine is recovered to the condenser, and the small steam turbine drives the compressor of the heat pump through the coupling; Method 2, the use of plant electricity to drive the compressor of the heat pump.

#### 2.2.1 Steam driven compression heat pump

The steam source of the condensing steam turbine driving the compression heat pump comes from the exhaust steam of the medium pressure cylinder. The exhaust steam volume of the medium pressure cylinder that is equal to that of the absorption heat pump is:
\[ f_{y1} = \frac{Q_c}{\text{COP}_{y1} \times (h_{dp} - h_{y,c})} \]  
(12)

Where: \( h_{xj,c} \) and \( \text{COP}_{y1} \) are the exhaust enthalpy of small machine and the heating coefficient of compression heat pump respectively.

The reduction value of turbine power generation is:
\[ w_{y1} = f_{y1} \times w_1 \]  
(13)

Decrease in electricity revenue
\[ E_{y2} = e_d \times w_{y1} \]  
(14)

The hourly evaporation loss of circulating water is reduced
\[ f_{y1} = \frac{Q_c \times 3.6 \times \Delta t \times k_{zf} \times (\text{COP}_{y1} - 1)}{\text{COP}_{y1} \times \Delta t \times c_p} \]  
(15)

Water cut
\[ E_{y3} = e_s \times f_{y1} \]  
(16)

#### 2.2.2 Electric energy driven compression heat pump

The electrical energy required to drive the heat pump is
\[ w_{y2} = \frac{Q_c}{\text{COP}_{y2}} \]  
(17)

Where: \( \text{COP}_{y2} \) is the heating coefficient of the compression heat pump.

Decrease in electricity revenue
\[ E_{y2} = e_d \times w_{y2} \]  
(18)

The hourly evaporation loss of circulating water is reduced
\[ f_{y2} = \frac{Q_c \times 3.6 \times \Delta t \times k_{zf} \times (\text{COP}_{y2} - 1)}{\text{COP}_{y2} \times \Delta t \times c_p} \]  
(19)

Water cut
\[ E_{y3} = e_s \times f_{y2} \]  
(20)

### 2.3 Revenue from heat pump systems

Under the premise of equal heat supply, the use of heat pump can reduce the flow of heating extraction steam. The contribution of heat pump to power plant revenue can be analyzed from the following three aspects:

Earnings 1: Power generation increased by crowding out heating extraction steam;
Earnings 2:Generation loss generated by driving heat pump;
Earnings 3:The evaporation loss of condenser circulating cooling water is reduced.
2.4 Economic comparison

Because the heat load of the system is equal and the heat produced by the heat pump is equal, the quantity of heating extraction steam is equal in the production mode of various heat pumps, and this part of steam returns to the turbine to do work, so the power generation increased by the system is equal.

\[ E_{x1} = E_{y1} = E'_{y1} \]  \hspace{1cm} (21)

Order

\[ E_{y} \geq E_{x} \]  \hspace{1cm} (22)

and

\[ E'_{y} \geq E_{x} \]  \hspace{1cm} (23)

Solving equations (21), (22) and (23) can obtain the corresponding critical COP value when the system revenue obtained by the compression heat pump production mode is greater than that obtained by the absorption heat pump production mode.

3. The calculation example

Taking an ultra-supercritical 600 MW unit as an example, the exhaust pressure of the medium pressure cylinder at rated load is 1.171Mpa, the temperature is 394.4 °C, the enthalpy value \( h_{zp} \) is 3249.7kJ /kg, the exhaust enthalpy of the steam turbine \( h_c \) is 2316.4kJ /kg, and the benchmark electricity price \( e_d \) is 0.4 yuan /kWh. The industrial water price \( e_s \) is 2 yuan/T. The relevant parameters required for calculation are as follows:

According to the relevant standards, the COP of the absorption heat pump used in the power plant shall not be lower than 1.7, and the COP of the absorption heat pump shall be 1.7. Put the value of COP and the value in the above table into equations (1) to (11) to obtain the relevant data of the absorption heat pump.

By substituting the values of \( Q_c \) and \( W_1 \) into equations (12) to (20), and further solving equations (21), (22) and (23) simultaneously, \( \text{COP}_{y1} \geq 5.67 \) and \( \text{COP}_{y2} \geq 4.98 \) are obtained.
By comparing the calculation, the compression heat pump for electricity, electricity only when the COP is greater than 4.98 gains the compression heat pump system is greater than the absorption heat pump system, and for small condensing steam turbine drive of compression heat pump system only when the COP is greater than 5.67 compression heat pump system of revenue is greater than the absorption heat pump system. The benefit of compressed heat pump driven by condensing steam turbine is not as good as that driven by electric energy because the former still has cold source loss. The above is just a case for illustration. The economic difference between the absorption heat pump and the compression heat pump is affected by the electricity price, water price, system connection mode and the heating coefficient of the heat pump.

4. Conclusion
Because of the heat pump COP is greater than 1, so from the perspective of energy use, no matter what type of driven heat pump recovery condenser cooling water waste heat can be implemented without increasing thermal power plant capacity expansion of capacity reduction of central heating energy consumption of heating purpose, relative to the direct extraction steam heating has good energy saving effect. At the same time, it can reduce the evaporation loss of condenser circulating cooling water, reduce the thermal pollution caused by thermal power plant to the environment, save water resources and protect the ecological environment. It has significant economic, social and environmental benefits, as well as significant energy saving and emission reduction effects, in line with the national energy saving and emission reduction policy requirements. The COP of the compression heat pump is larger than that of the absorption heat pump. Under the same heat production condition, the compression heat pump can recover more waste heat of the condenser circulating cooling water, and accordingly, the evaporation loss of the condenser circulating cooling water will be less. Therefore, the ability of compression heat pump to recover waste heat is stronger than that of absorption heat pump, and the amount of water saving is greater than that of absorption heat pump, which is of great significance for some areas lacking water resources. The operation cost of absorption heat pump is lower than that of compression heat pump. The structure of compression heat pump is simple and more convenient to control. In actual operation, with the change of the return water temperature of the heat network and the temperature of the condenser circulating cooling water, the performance of the heat pump will change, and the performance of the compression heat pump is more sensitive to the change of water temperature than that of the absorption heat pump. Therefore, the use of heat pump system in the field of district heating should be based on the actual production situation of the site to choose the most appropriate heat pump technology application scheme.

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