Performances of a Steam Generation System by the Heat Utilization of Mesothermal Solar

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Abstract: A 310kW steam generation system by the heat utilization of mesothermal solar was built and the thermodynamic model of main parts-solar collector and heat transformer were developed. In different conditions, the impact of solar radiation intensity, recycle ratio of condensate water and ambient temperature on thermal efficiency and heating power was investigated and the relationship of collecting temperature between system property was discussed. The result shows that the system property enhances significantly with the rise of solar radiation intensity. Recycling condensate water could escalate heating power while having little effect on thermal efficiency. The system property enhances first and then drops with the rise of ambient temperature. The system has the optimum collecting temperature which increases with the rise of solar radiation intensity and ambient temperature.

Introduction

As one of the important means to replace fossil energy and promote sustainable development, solar energy heat utilization technology is an effective way to realize energy saving and energy substitution[1]. At present, solar heat utilization technology can be divided into three kinds according to the range of output temperature: low temperature technology (<90°C) is mainly used in the production of domestic hot water and low temperature heating; high temperature utilization technology (>130°C) mainly concentrates on the field of thermal power generation; medium temperature utilization (90~130°C) is mainly used in the form of low pressure steam, which is widely used in the field of life and industry[2].Absorption heat transformer (AHT) is a heat transfer device which can promote low-grade thermal energy to utilization.The solar collector combined with AHT is an effective heat utilization mode, which theoretically can obtain low pressure steam which is more than 100°C[3].

At present, the integration of solar collector and AHT has been studied at home and abroad.Gommed demonstrated theoretically the possibility of producing industrial steam using solar energy AHT system[4,5]. Jiang Junzhi and Pei Gang studied the medium temperature steam

generation system which was combined by parabolic solar collector and AHT, analyzed the heat transfer characteristics and transmission power, obtained comprehensive evaluation of derived heat transfer enhancement criterion[6,7].Gormi and Liu Xiaohua designed a device that included flat plate solar collector and AHT to desalinate sea water. Based on this, the operating characteristics of each part of the system were modeled and analyzed under different operating conditions[8,9].Tao Yubing and He Zhibing established model for heat transfer process of the collector and heat conversion in the system. Energy flux density distribution were studied by numerical simulation and the heat loss was measured[10,11].

In this paper, a set of medium temperature steam system of solar energy heat utilization was established. The system was composed of solar collector array and AHT. The thermodynamic models were established respectively and the energy balance equations of all the system parts were given. Based on these, the thermodynamic analysis of the system was carried out, the influence on the system performance from environmental parameters and process parameters under the design conditions and variable conditions was studied.

System model

The medium temperature solar heating system is mainly composed of two modules, solar collector array and thermal converter (AHT). The system principle is shown in figure 1.
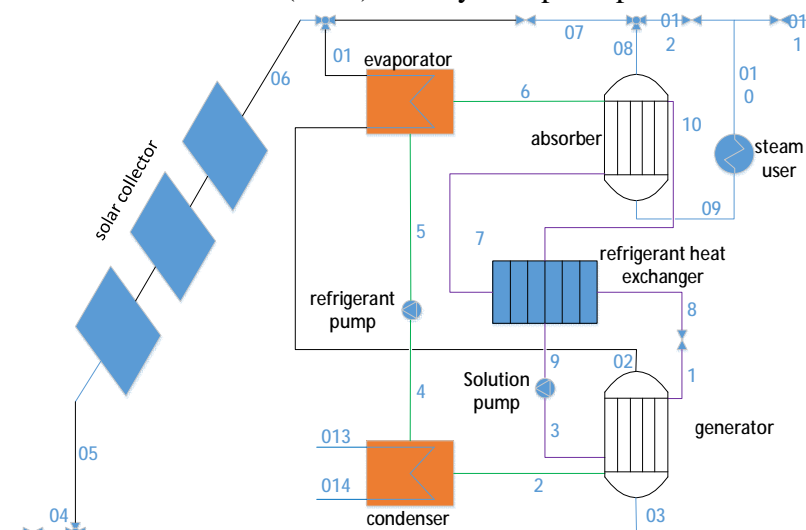

Fig.1 Principle diagram of the system

In the process of generating steam, feedwater (04) converting to steam (09) undergones two endothermic processes. In the first stage, feedwater (04) is preheated in solar collector array and is heated to hot water (06) whose temperature has been significantly improved. Part of the hot water (01) which flows past the flow valve is used as driving source of AHT system.In the second stage, the other part of the hot water (07) and condensed water (012) are mixed into the heated water (08), which absorbs heat and tures into low pressure steam (09) for users.

AHT cycle principle: hot water (01) works as heat source,which returns to the solar collector again after flowing through the evaporator and generator to complete to heat cycle.LiBr-H_2O is chosed as AHT refrigerant. After exchanging heat with hot water (012) in the AHT, LiBr-H_2O dilute solution becomes concentrated solution and refrigerant steam (2) is generated. The refrigerant steam (2) is condensed into saturated refrigerant water (4), then flowes into high-pressure evaporator through cooling pump. Saturated refrigerant water (4) driven by hot water (01) tures into high pressure refrigerant steam (6) in the high-pressure evaporator. High pressure refrigerant steam (6) is mixed with LiBr-H_2O concentrated solution. In the above progress, a lot of heat is absorbed by hot

water (08). The mixed LiBr-H$_2$O dilute solution(7) flows back to cycle.

Solar collector model

In order to establish the mathematical model of the solar collector, the following assumptions are made.

a. The solar radiation intensity and environmental temperature are constant;

b. The solar collector is studied as a whole, dust influence on collector efficiency is ignored;

c. The process of thermal cycle is stabe, without considering the heat loss of pipeline.

When the collector runs stably, the relationships of system effective heat collection Q_e, total

acceptance of solar radiation Q_s and heat collector efficiency are shown blow:

$$Q_e = Q_s \cdot h_c \tag{1}$$

$$Q_e = m_{05} C_p (T_{06} - T_{05}) \tag{2}$$

$$Q_s = A_c \cdot I_s \tag{3}$$

$$h_c = a_0 - a_1 \frac{T_{05} - T_a}{I_s} \tag{4}$$

Where:

m_{05}:is the flow rate of the working fluid (water) of a collector(kg/s)；C_p=4.18kJ/(kg·°C)，is

specific heat capacity of water at constant pressure; T_{06}:is heat collection temperature (i. e. collector

temperature)(°C)；T_{05}:is inlet temperature of thermodynamic mass(°C)；A_c:is effective area of plate

heat collector(m^2)；I_s:is solar radiation intensity(kW/m^2);T_a:is ambient temperature(°C);a_0:is

collector truncation efficiency(%)；a_1:is first correction factor of collector(kW/(m^2·°C)).

Absorption heat transformer model

In order to establish the mathematical model of heat converter, the following assumptions are made:

a. The heat transfer process is stable, without considering the heat loss and the flow resistance;

b. The refrigerant solution of generator and evaporator outlet are saturated, so as the refrigerant vapor of absorber and condenser outlet;

c. The differential pressure of refrigerant pump and ignore solution pump pressure is neglected.the enthalpy value remains unchanged before and after throttling.

The mathematical model of heat converter includs mass conservation equation and energy conservation equation of refrigerants.

The heat balance equations of converter components are shown in table 1.

Tab.1 Balance equation of heat transformer

Parts	Equations
Evaporator	$Q_{zf} = m_6 h_6 - m_5 h_5$
	$Q_{zf} = m_{01} h_{01} - m_{02} h_{02}$
Generator	$Q_{fs} = m_3 h_3 + m_2 h_2 - m_1 h_1$
	$Q_{fs} = m_{02} h_{02} - m_{03} h_{03}$
Absorber	$Q_{xs} = m_6 h_6 + m_{10} h_{10} - m_7 h_7$
	$Q_{xs} = m_{09} h_{09} - m_{08} h_{08}$
Condenser	$Q_{ln} = m_2 h_2 - m_4 h_4$
	$Q_{ln} = m_{014} h_{014} - m_{013} h_{013}$
Heat exchanger	$Q_{hr} = m_{10} h_{10} - m_9 h_9$
	$Q_{hr} = m_7 h_7 - m_8 h_8$
Solution pump	$W_{P1} = m_3 (P_9 - P_3) / h_p$
Refrigerant pump	$W_{P2} = m_4 (P_5 - P_4) / h_p$

The heat converter efficiency is expressed as follows in stable operation condition:

$$h_{AHT} = \frac{Q_{xs}}{Q_{zf} + Q_{fs}} \tag{7}$$

The condensate recovery ratio e is expressed as the percentage of the total amount of condensate used in the recovery process, which is calculated as follows in this system:

$$e = m_{012} / m_{010} \times 100\% \tag{8}$$

The external heating power of the system:

$$Q_o = m_{09}(h_{09} - h_{010}) \tag{9}$$

System thermal efficiency：

$$h = \frac{Q_o}{Q_s} \tag{10}$$

System running state and performance analysis

Performance parameters in design conditions

On the basis of the established system thermodynamics model and the assumption condensate recovery ratio 0, the indexes of the system performance parameters were calculated which are shown in table 2 according to the temperature difference of each component.When the refrigerant heat grade is improved, the heat transfer efficiency is reduced, so it directly affects the thermal efficiency of the whole transport system.

Tab.2 Performances under designed condition

Parameters	Values
Radiation intensity I_s/(W·m^2)	800
Ambient temperature T_a/°C	25
Collector temperature T_{06}/°C	85
Reclaimed water temperature T_{03}/°C	75
Low pressure steam flow m_{09}/(kg·s^{-1})	0.278
Evaporator heat Q_{zf}/kW	352
Generator heat Q_{fs}/kW	323
Absorber heat Q_{xs}/kW	324
Condenser heat Q_{ln}/kW	704
Solar radiation Q_s/kW	1114
Heating power Q_o/kW	310
Collector efficiency η_c	63.9%
Heat converter efficiency η_{AHT}	47.9%
System thermal efficiency η	27.8%

System performance analysis under variable operating conditions

The influence on system performance from operation parameters including radiation intensity I_s, condensate recovery ratio e and ambient temperature T_a were studied. The import flow remained unchanged.

Figure 2 shows the influence on system performance of radiation intensity with the recycled water recovery ratio e and the ambient temperature T_a being design value when the recycled water T_{03} is 75°C.When I_s changes from 0.2kW/m^2 to 1.0kW/m^2, the collector efficiency increases from 28% to 71.2%, the system heat accumulation effectively increases.When the heat collecting temperature T_{06} increases, thermal converter circulating temperature is improved, circulation rate decreases, h_{AHT} increases about 3%.The heating power of the whole system Q_o increases by 11.8 times and the overall thermal efficiency of the system increases by 20%. It can be seen that the increase of radiation intensity has significantly improved the performance of the system.
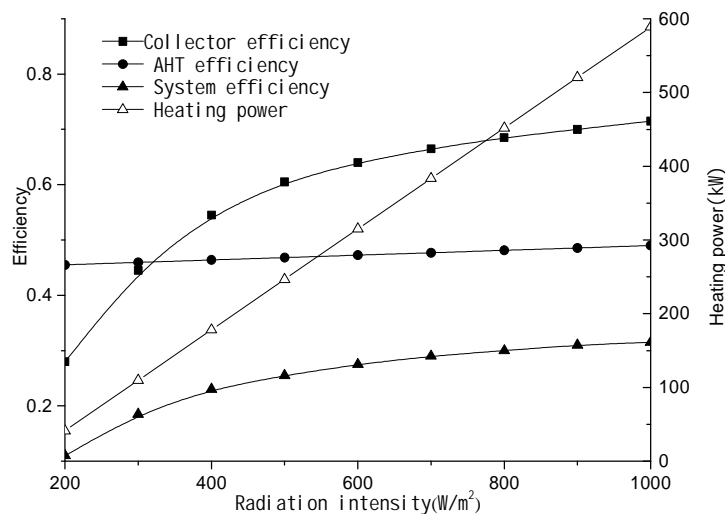

Fig.2 The rule of property changing with collecting temperature

Figure 2 shows the influence of the condensate recovery ratio e on the system performance when the radiation intensity and the ambient temperature are at designed values. It can be obtained

from the diagram that e has little influence on h_c and h_{AHT} .For the system, the condensate temperature is higher. When the condensate recovery flow increases, the collector heating is reduced, the thermal efficiency of the system is increased by 2% and the heating power is raised by 30kW.

In summary, recovery of condensate has little effect on the efficiency, but the influence on heating power is more obvious. In the condition of condensate water being recycled for heating occasions, increasing the pipeline equipment investment can get a good heating capacity upgrade.
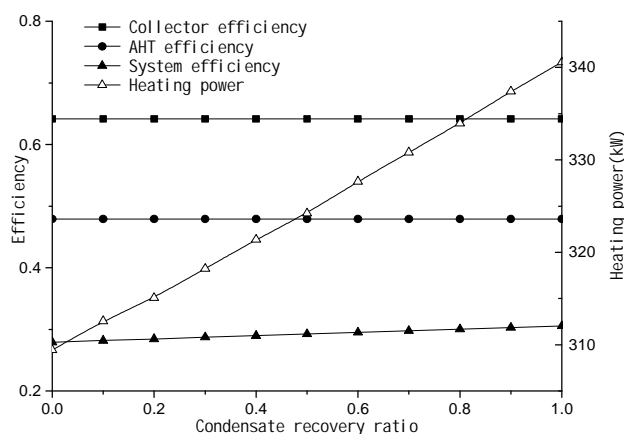

Fig.3 The rule of property changing with recycle ratio of condensate water

Figure 3 shows the influence of ambient temperature T_a on the system performance when the radiation intensity I_s and condensate recovery ratio e are at designed values.As the diagram shows, with the increase of the environmental temperature, the feedwater temperature and the input heat of the system increase, and heat loss of heat collector is reduced, and h_c is improved by 6.5%. For AHT, with working temperature of condenser heat rising, circulation rate increases, h_{AHT} decreases.But when the temperature is above 30°C , pressure difference of evaporation/occurrence process increases, there is a sudden drop in the saturation concentration of the refrigerant solution. The absorption capacity of concentrated solution decreases obviously, System heat transfer performance deteriorates, h_{AHT} decreases rapidly.Being affaected by AHT performance, the system thermal efficiency h and heating power Q_o first slowly rise and then decline rapidly in the experimental temperature range. Extreme point is obtained at 25°C.

The above analysis is based on the fact that the feedwater flow and heat source water are constant. When T_a is above 30°C, working temperatures of heat converter components are regulated by changing the heating water flow. Thus pressure difference of evaporation/occurrence process decreases, h_{AHT} changes moothly, system performance tends to be stable.
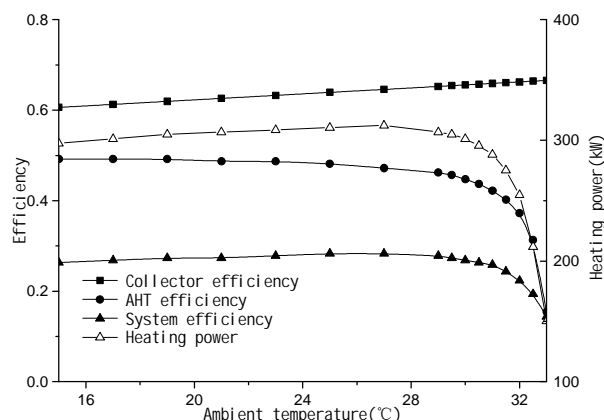
Fig.4 The rule of property changing with ambient temperature

Influence of collector temperature on system performance

Under design conditions, when the collector temperature T_{06} rises from 82°C to 98°C, the performance of the system is shown in figure 5.With the rise of T_{06}, collector efficiency h_c declines, AHT efficiency h_{AHT} first increases rapidly then becomes stable.Affected by this, system thermal efficiency h and heating power Q_o first increase rapidly and then decrease slowly, and the maximum value is about 88 °C.Thus, there is optimum of the system performance with the collector temperature changing. It is called the optimum collector temperature T_M which is of great significance. The further analysis of the optimum collector temperature under different environmental conditions is made.
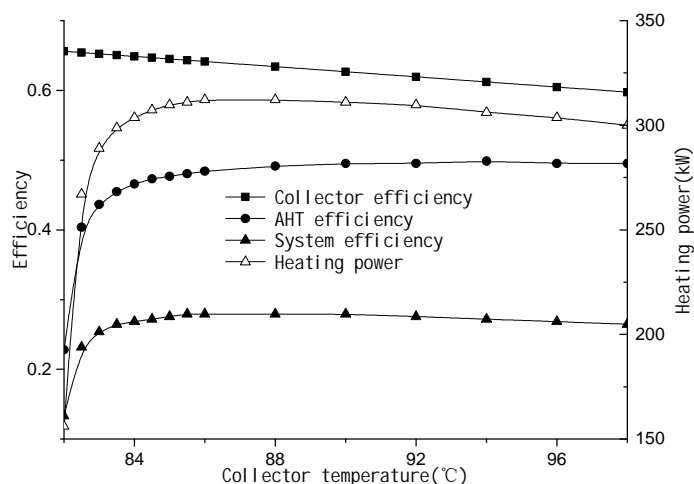

Fig.5 The rule of property changing with collecting temperature

Figure 6 shows the variation of the system thermal efficiency h and the heating power Q_o with the variation of collector temperature at different values of the radiation intensity I_s.When I_s increases from 0.3kW/m^2 to 0.9kW/m^2, T_M rises from 79 C to 94 C, h_{max} increases from 18.9% to

31%, $Q_{o\max}$ increases from 107kW to 518kW. And before T_{06} arrives at T_M, the system performance improves faster than exceeding T_M.It can be seen that in the given range, as I_s increases, the corresponding maximum collector temperature increases continuously with the maximum value of the heat increases accordingly.

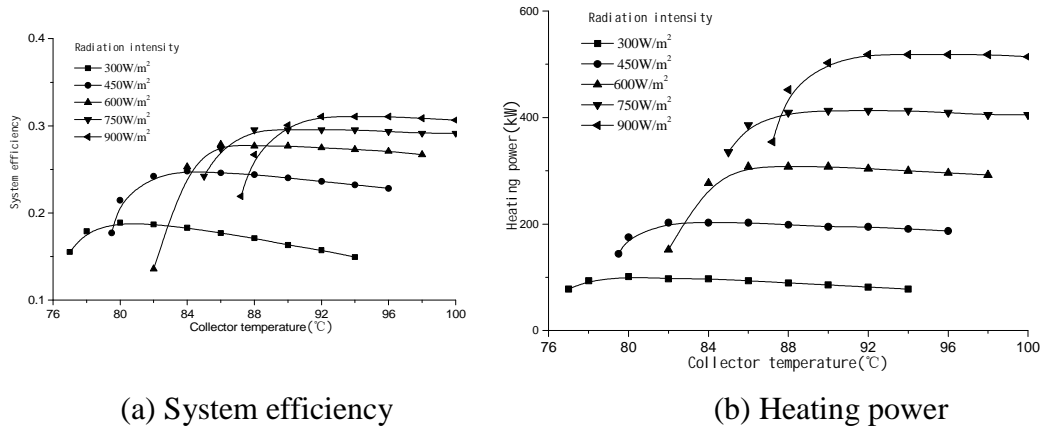(a) System efficiency   (b) Heating power

Fig.6 The rule between property and collecting temperature under different radiation intensity

Figure 7 shows the variation of system heat efficiency h and the heating power Q_o with the variation of collector temperature when the condensate recovery ratio is at different value.In the process of e changing from 0 to 1, T_M maintains at 88 degrees, $h_{\max}$ increases from 28% to 30.6%, $Q_{o\max}$ increases from 311kW to 341kW. Thus, the influence of the condensate recovery ratio e on the optimum collector temperature T_M is negligible.

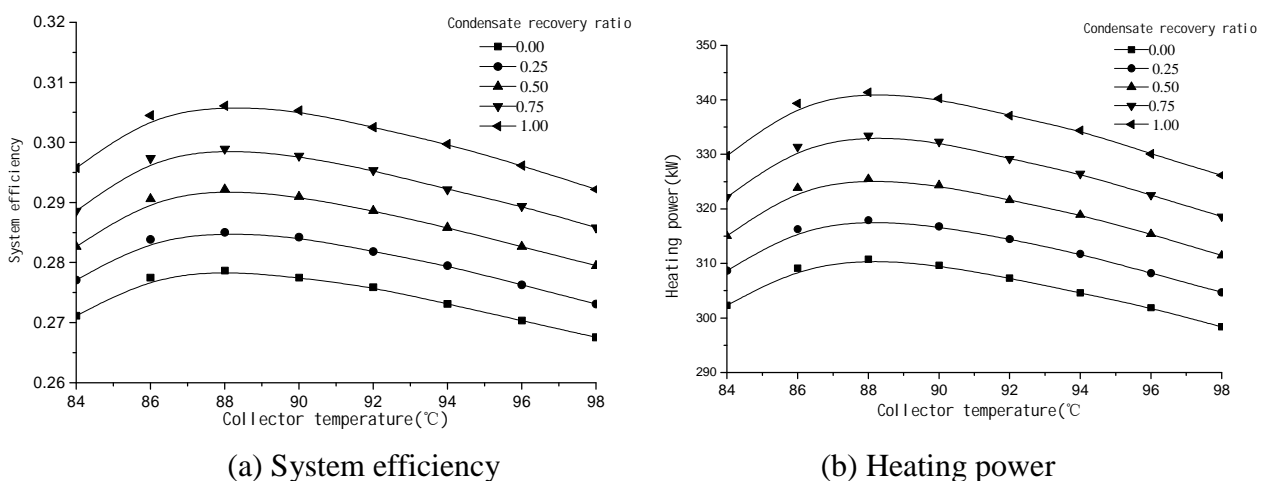(a) System efficiency   (b) Heating power

Fig.7 The rule between property and collecting temperature under different recycle ratio of condensate water

Figure 8 reflects the ambient temperature T_a at different values, the system thermal efficiency h and heating power Q_o with the collector temperature changing. In the process of T_a changing from 15°C to 35°C, T_M increases from 80°C to 92°C, the corresponding $h_{\max}$ increases from 26.7% to 29.2%, $Q_{o\max}$ increases from 300kW to 324kW. It can be seen that within the given range,

with the increase of T_a, the corresponding optimal collector temperature T_M is increasing, and the maximum value of h and Q_o rises accordingly.

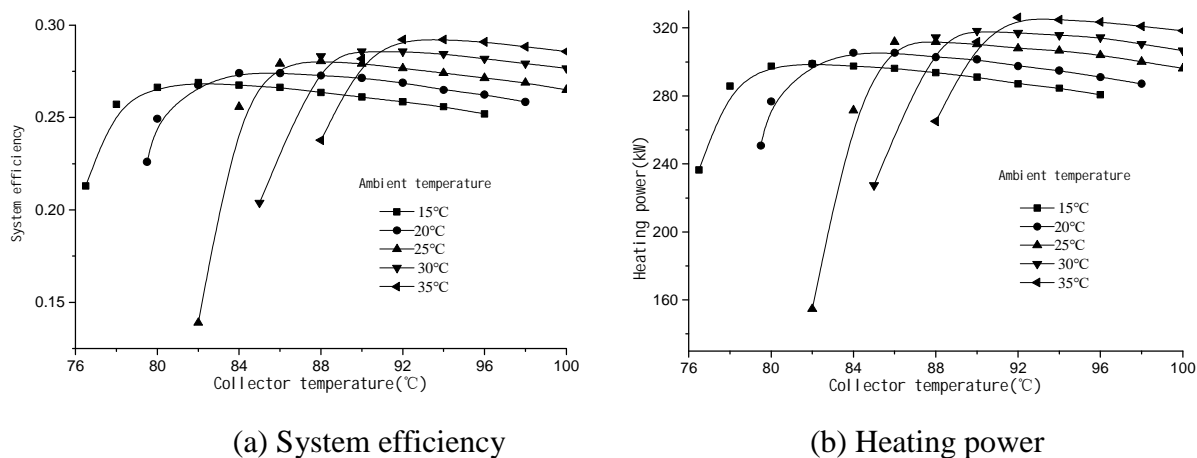(a) System efficiency   (b) Heating power

Fig.8 The rule between property and collecting temperature under different ambient temperature

Conclusion

In this paper, a thermodynamic model of the steam system for the solar heat change was established, the performance of the system under the design conditions and off-design conditions was analyzed. By studying the influence of solar radiation intensity, environmental temperature, condensate recovery ratio and collector temperature on system efficiency and heating power, the following conclusions are obtained.

(1) Increasing the solar radiation intensity has a significant improvement on the system performance. Under the design condition, when the radiation intensity increases from $0.2kW/m^2$ to $1.0kW/m^2$, the efficiency of the system increases by 20%, and the heating power increases by 11.8 times.

(2) The recovery of condensate has little effect on the efficiency, but the improvement of heating power is more obvious. Under the design condition, the system efficiency is increased by 2%, and the heating power is raised by 30kW when the condensate recovery ratio changes from 0 to 1. In the condition of condensate water being recycled for heating occasions, increasing the pipeline equipment investment can get a good heating capacity upgrade.

(3) In a certain temperature range, the increase of ambient temperature is beneficial to improve system efficiency and heating power. When the ambient temperature exceeds a certain value (design conditions for 30°C), performance of heat exchanger, system efficiency and heating power are drastically reduced. At this point, the performance of the system can be improved by changing the heat source water flow to adjust the working temperature of the heat change device.

(4) With the increase of collector temperature, the system efficiency and heating power increase rapidly to the maximum and then decline gradually. The optimum collector temperature is independent of the condensate recovery ratio, which increases with the increase of radiation intensity and ambient temperature. When operating under different conditions, the collector temperature should be optimized as much as possible so that the system efficiency and heating capacity can be optimized.

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