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THERMODYNAMIC AND MECHANISM ANALYSES OF COMBINED HEAT AND POWER PLANT WITH HIGH BACK-PRESSURE TURBINE INTEGRATED WITH THE STEAM JET PUMP

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ABSTRACT

To recover the excess exhaust steam heat of the combined heat and power plant with high back-pressure turbine (CHP-HBP), a novel system integrated with the steam jet pump (SJP) was proposed in this study. Compared with the conventional system, the novel system remains the same power output and all the exhaust steam can be used for district heating (DH), leading to an improvement of the maximum heat capacity by 36.78MW. Meanwhile, the total exergy loss and standard coal consumption rate of the novel system are reduced by 3MW and 7.32 g/kWh, respectively. And the novel system also has better adaptability to the change of supply/return water temperatures.

Keywords: CHP-HBP; heating system; thermodynamic analysis; waste heat utilization;

1. INTRODUCTION

Combined heat and power system (CHP) simultaneously provides electricity and heat efficiently and environmentally friendly, which is a major approach of energy cascade utilization and pollutant concentration control for fossil-fueled power plants in the world. The overall energy utilization efficiency of the CHP system can reach 80% and more theoretically. The global installed capacity of CHP power plants has reached 755.2GW by 2016, of which Asia-Pacific region, Europe and other regions account for 46%, 39% and 15% respectively. In China, the CHP power plants installed capacity has reached 430GW by 2018, contributing 37% to the total thermal power plants installed capacity. And China has the ambitious goal of making the installed capacity reach 630GW during the 13th Five-Year Plan period (2016-2020). Therefore, due to the depletion of fossil fuel resources, further energy conservation in CHP power plants is critical to energy security for China's energy industry.

The waste heat recovery of exhaust steam in the CHP plants is an effective way to solve the problem of insufficient heat sources in urban cities in northern China. Such research mainly concentrated on the following respects:

(1) CHP with the absorption heat pumps (CHP-AHP). This technology can use extraction steam to recover the waste heat of the exhaust steam in the heating process. Yan Li et al [1] established the calculation model and analysed the CHP-AHP heating system in full operating conditions. The performance analysis showed that the comprehensive equivalent electricity of the CHP-AHP heating system is 16% lower than the original heating system, and the energy efficiency is improved;

(2) CHP with the high back-pressure turbine (CHP-HBP) technology. In this technology, the exhaust steam of the CHP units can heat the supply water directly by raising the back-pressure of the steam turbine. Ge [2] and Sun [3] established the models of CHP-HBP units under off-design operating conditions and analyzed the heating efficiency. The results indicated that the average coal consumption rate during the heating season is much lower than that of the traditional heating mode, meanwhile, the significant energy-saving and CO_2 emission reduction are obtained;

(3) CHP with the absorption heat exchanger (AHE) technology. AHE could decrease the return water

temperature of the primary pipe, so the exhaust steam of the CHP units can heat the supply water directly, and increase the heating capacity of current heating pipes significantly [4];

(4) CHP with the low-pressure cylinder cut off technology. The steam inlet pipe of the low-pressure cylinder is cut off and only remains a small amount of steam to cool down the cylinder, by which the CHP units can extract more heating steam from the intermediate-pressure cylinder.

However, among all the process of technology applications, the boundary conditions such as the pressure level of extraction steam for heating, the back-pressure of CHP units and the supply/return water temperature of the primary heating networks, have a great influence on techno-economic performances. Therefore, reducing the limitations of the above boundary conditions to improve the performances of practical applications is essential for the promotion and application of these technologies.

In this study, a novel CHP-HBP system integrated with the SJP was proposed. In the novel system, the waste heat recovery rate of exhaust steam is improved to increase the heating capacity of CHP-HBP and increase insensitivity to the supply/return water temperature changes. The goals of this paper are the followings: (1) to reveal the theory of the novel CHP-HBP heating system; (2) to evaluate the thermal performance and to reveal the energy-saving mechanism of the novel system; (3) to demonstrate the better tolerance to the supply/return water temperature changes of the novel system.

2. SYSTEM DESCRIPTION

2.1 The conventional CHP-HBP heating system

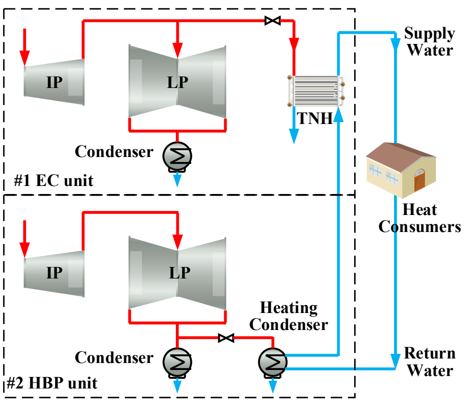

Fig. 1. The schematic of the conventional CHP-HBP system

The conventional CHP-HBP heating system is composed of two units, which are an extraction condensing (EC) unit and an HBP unit, as illustrated in Fig. 1. The return water is heat by the heating condenser of the HBP unit and the thermal network heater (TNH) driven by the EC unit sequentially, which form a two-stage cascade heating process. In this study, a 2×350MW subcritical power plant is chosen as the reference system and its main parameters under the rated heating condition are given in Table 1. The back-pressure of HBP unit is 54 kPa with the corresponding saturated temperature of 83 ℃. Considering the terminal temperature difference of the heating condenser is 2℃, the return water can be heated up to 81℃. Since the design temperature of the supply/return water is 110/50℃, the preheating water is further heated to the demanded temperature (110 ℃) in the TNH driven by the extraction steam of the EC unit.

Table 1. Main parameters under the rated heating condition

Items	unit	#1 EC unit	#2 HBP unit
Main steam flow	t/h	1124.47	1124.47
Main steam pressure	MPa	24.2	24.2
Main steam temperature	℃	566	566
Electric power	MW	292.59	334.26
Heat-supply capacity	MW	361.22	392.90
Extraction steam flow for heating	t/h	500	——
Exhaust steam flow for heating	t/h	——	623.34
Exhaust steam pressure	kPa	8	54

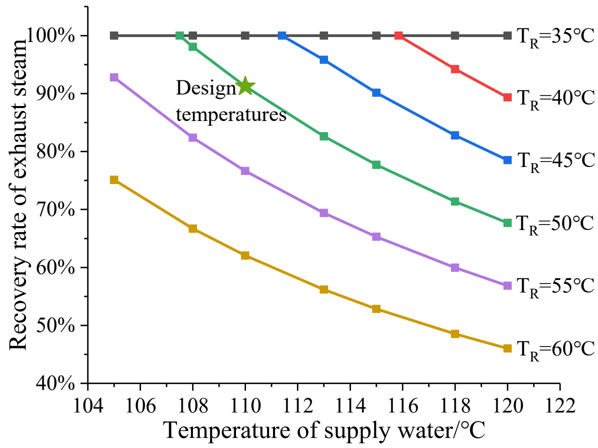

Fig. 2. Influences of the supply/return temperatures on the recovery rate of exhaust steam

The energy cascade utilization is more efficient in the CHP-HBP heating process when recovering more waste heat. However, owing to the mismatch of heating capacity of this two units, the diverse heat-supply demand and the different temperature range of the return/supply water, a considerable part of the exhaust steam is wasted instead of heating the supply water. Fig. 2 shows the recovery rate of exhaust steam in the case of the supply/return water temperature changes with the same main steam flow. At the design temperature (110/50℃) point, the recovery rate of the exhaust steam is 91.23%. The recovery rate of the exhaust steam can reach 100% when the supply water temperature is 107.4℃, but it is reduced to 67.68% when the supply water temperature is 120℃. It can be seen that the higher the supply water temperature demand is, the lower the recovery rate of exhaust steam will be, leading to the larger cold source loss and greater energy-saving potential. Meanwhile, the extraction steam for heating of EC unit should be increased to meet the demand of heating the water to the required temperature which partially against the basic rule of energy cascade utilization of the CHP-HBP heating system.

2.2 Proposal of the novel CHP-HBP heating system

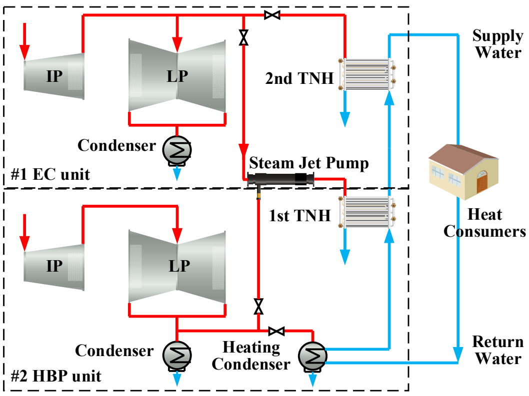

Fig. 3. The schematic of the novel CHP-HBP system

To recover the excess exhaust steam of the HBP unit, a steam jet pump is integrated into the novel system, as shown in Fig. 3. In the novel system, the SJP is driven by the high-pressure steam of the EC unit and extract the exhaust steam of the HBP unit, which can produce medium-pressure steam for the 1st TNH. Compared with the reference system, the cascade heating process in the novel is 3-stage composed by the heating condenser, 1st TNH and 2nd TNH, and has a lower temperature difference. And due to the addition of the SJP, the exhaust steam utilization rate and the heating capacity of the novel system can be higher. The SJP also can be self-designed according to the specific requirements, such as the safety, reliability as well as the economic performance.

3. SYSTEM SIMULATION AND ANALYSIS

3.1 System simulation and analysis

To analysis the thermal performance of the CHP-HBP heating system, EBSILON software was applied to model the thermal system based on the mass and energy balance, which uses a matrix solving method for the simulation and optimization of different types of power plants. In this article, the “heat quantity based method” was adopted to evaluate the thermal performance of the CHP heating system, which considers the heat consumption for heating and the heat consumption for power generation separately. For the CHP units, the electricity generation efficiency can be expressed as:

$$\eta_{CHP}^{e}=\frac{P_e}{m_c q_c - Q_h/\eta_b \eta_p} \tag{1}$$

where Q_h denotes the heating supply output; P_e is the net electricity output; m_c and q_c are the mass flow and the lower heating value of the coal; η_b and η_p are the boiler efficiency and steam pipe thermal efficiency.

The standard coal consumption rate for generating is given as:

$$b_{CHP}^{e}=\frac{123}{\eta_{CHP}^{e}} \tag{2}$$

3.2 System simulation and analysis

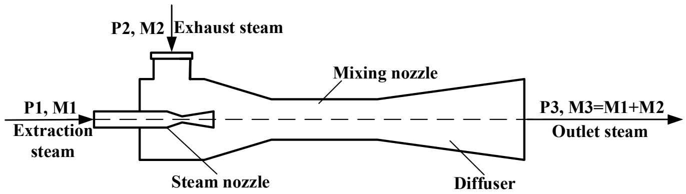

Fig. 4 Structural diagram of the steam jet pump

Fig. 4 shows the basic structural and principle of the SJP. The SJP consists of three sections: steam nozzle, mixing nozzle and diffuser. The extraction steam passes through the steam nozzle and creates a supersonic steam jet. After the steam nozzle, the supersonic steam blows into the exhaust steam in the mixing nozzle. Flowing through the diffuser, the velocity of the mixed steam is reduced and its kinetic energy is converted into pressure potential energy. Then the mixed steam will be discharged because of the high pressure in the diffuser. The mixing nozzle area of the SJP is sized based on the speed of sound for the resulting flow of the extraction steam. The flow in the mixing nozzle is always at the speed of sound so that this value determines the flow through the mixing nozzle as a function of the motive pressure P1 also under off-design conditions. The nominal effective mixing nozzle area can be calculated using correlations published by GEA [5].

Table 2. The main design parameters of the steam jet pump

Items	Unit	Extraction steam	Exhaust steam	Outlet steam
Pressure	MPa	0.40	0.054	0.10
Enthalpy	kJ/kg	2957.00	2617.77	2819.07
Saturated temperature	℃	143.61	83.26	99.61
Mass flow	t/h	87.00	59.66	146.66
Design parameters		μ=0.6875	β=7.4074	σ=1.8519
Nominal effective mixing nozzle area = 0.0439 m^2				

In the design calculation of the SJP, the relationship between the ejector coefficient μ=M2/M1, the expansion ratio β=P1/P2 and the compression ratio σ=P3/P2 are mainly determined. The parameters of the extraction steam and the exhaust steam are determined, so β is known. The higher the ejector coefficient μ, the lower the extraction consumption, but the calculation results show that the increase of μ is of no obvious improvement for the recovery rate of the exhaust rate. In addition, the saturated temperature rise of the exhaust steam before and after compression is a vital performance index for the steam heating system, mainly depending on the compression ratio σ. Considering the above factors, the main design parameters of the SJP is presented in Table 2.

3.3 Thermodynamic analysis

The T-Q analysis on the heat exchange process according to the first and the second law of thermodynamics is illustrated in Fig. 5 to reveal the energy-saving mechanism of the CHP-HBP heating system. The novel CHP-HBP heating system includes three heat exchange sections and the temperature difference between the steam and the supply water is smaller than that of the conventional system, leading to that the average temperature of heat release is declined from 112.91℃ to 108.16℃, which manifests that the energy transfer of the novel system is more rational. The total exergy loss during the heating process reduced by 3MW. In the meantime, the recovery rate of the exhaust steam is increased by 8.77% owing to the SJP compared with the conventional system, and the maximum heat-supply capacity is 36.78MW higher, as presented in Table 3. The standard coal consumption rate of the novel system is 7.32g/kWh less than the conventional system, which manifests the SJP improves the overall performance of the CHP-HBP heating system by recovering the exhaust steam with more sufficient energy cascade utilization.

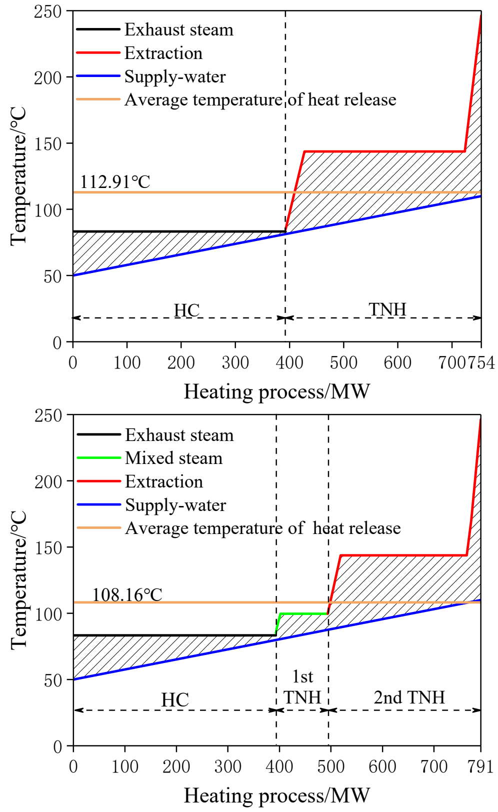

Fig. 5. T-Q diagram of the conventional and novel CHP-HBP heating system

3.4 Further analysis

To further demonstrate the better adaptability to the change of supply/return water temperature of the novel system, thermodynamic analysis of the two systems was conducted, assuming the temperature difference of the supply/return water is 60℃. It can be seen in Fig. 6, at the design temperature of supply/return water (110/50℃) point, the recovery rate of the exhaust steam of the reference system is 91.23%, which of the novel system is increased to 100%. In the temperature of supply/return water (120/60℃) condition, the recovery rates of the exhaust steam of the novel and reference systems are 58.00% and 46.03%, the electricity generation efficiencies are 66.44% and 63.74%, and the coal consumption rates are 233.68 g/kWh and 234.47 g/kWh. In general, the recovery rate of the exhaust steam of the novel system is 10~20% higher than that of the conventional system, moreover, the coal consumption rate is lower and the electricity generation efficiency is higher under the water temperature change conditions.

Table 3. Overall performances of the conventional and novel CHP-HBP heating system

Items	Unit	The conventional system	The novel system
Main steam flow	t/h	2248.95	2248.95
Maximum extraction steam flow	t/h	500	500
Electric power	MW	626.85	626.85
Exhaust steam flow	t/h	683.23	683.23
Recovery rate of the exhaust steam	%	91.23	100
Maximum heat-supply capacity	MW	754.12	790.90
Standard coal consumption rate	g/kWh	194.30	186.98
Electricity generation efficiency	%	63.50	67.00

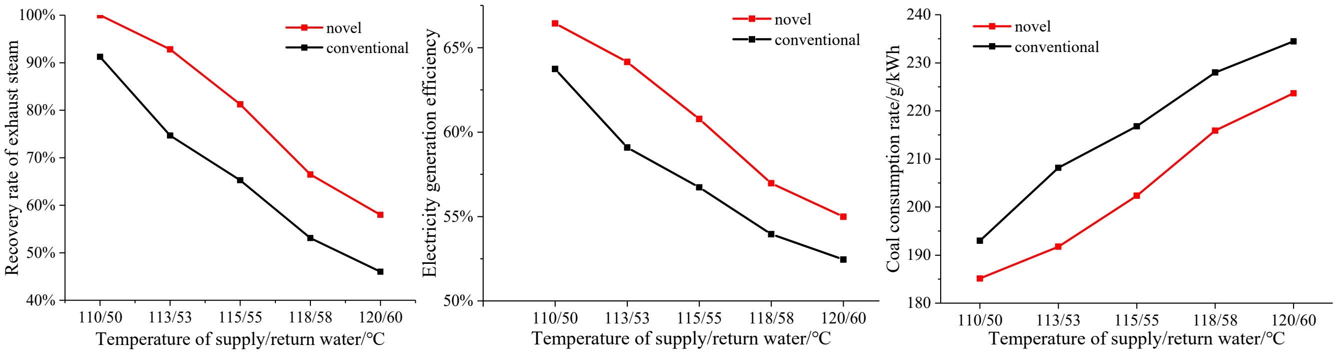

Fig. 6. Influences of the supply/return temperatures on the performances of the conventional and novel CHP-HBP heating system

4. CONCLUSION

This paper performed a study of the further cascade utilization of CHP-HBP heating system integrated with the SJP and thermodynamic performance of the novel system was analyzed to show the advantages. Compared with the conventional system, the novel system remains the same power output and all the exhaust steam can be used for district heating, leading to an improvement of the maximum heat capacity by 36.78MW. Meanwhile, the total exergy loss and standard coal consumption rate of the novel system are reduced by 2.91MW and 7.32 g/kWh, respectively. The better adaptability to the change of supply/return water temperature of the novel system was demonstrated, the recovery rate of the exhaust steam of the novel system is 10~20% higher than the conventional system. The coal consumption rate and the electricity generation efficiency are both perform better under the water temperature change conditions.

ACKNOWLEDGEMENT

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