# Analysis of Heating Load Distribution and Operation Optimization for 350MW High Back Pressure Double Extraction Series Units

***Xilin Luan[1],Jianlong Ma[1,2,3] *, Xiaoming Dong[1], Yanchun Yang[1], Shenqiang Nie[1]***

[1] School of Energy and Power Engineering, Inner Mongolia University of Technology, Hohhot 010080, PR China；

[2] Engineering Research Center of Renewable Energy at Universities of Inner Mongolia Autonomous Region, Hohhot 010080, PR China

[3] Key Laboratory of Wind Energy and Solar Energy Technology, Ministry of Education, Hohhot 010080, PR China；

Corresponding author; E-mail: ma_jianlong@yeah.net

*Large-scale highbackpressure cogeneration units can make full use of the waste heat of the spent steam to reducethe unit's cold-end losses, improve the fiel utilization rate, and heating efficiency, the energysaving effect is remarkable. The 2×350MW cogeneration unit of a power plant is modeled as an example. The boundary conditions of the heat network are calculated according to the ambient temperature, and the thermal economy and exergy efficiency of the condensing unit and the high backpressure unit are analyzed during the heating period, to obtain the advantages of the high backpressure unit during the heating period. In turn, the study presents the high backpressure unit extracts steam distribution method is adjusted to optimize the operation strategy during the heating period. The results indicate that: after adopting high back pressure operation during the heating period, the average power generation increased by 24.5MW compared to the condensing unit, The average reduction in coal consumption for power generation is 97.5g·(kW·h)$^{-1}$, exergy efficiency increased by an average of 9.4%, exergy efficiency of the unit's heating network has increased by an average of 19.2%. After the unit adopts optimized allocation of extraction load, the average coal consumption for power generation is reduced by 0.69 g·(kW·h)$^{-1}$ on the basis of high back pressure heating operation. The average efficiency improvement of steam-water exergic is 0.44%, while the efficiency average improvement of heating networks is 0.6%, with a maximum increase of 1.4MW of exergy energy.*

*Key words:cogeneration，high back pressure，exergy analysis，optimize operation*

## 1. Introduction

As a major energy consumer in China, energy conservation and emission reduction are important issues that must be implemented for sustainable social development. Energy saving in thermal power plants has always been the focus of industrial energy saving, so the circular economy development planning of thermal power plants, promoting centralized district heating and advancing energy laddering have attracted widespread attention [1]. Cogeneration (CHP) is one of the forms of centralized heating in northern China. In recent years, China has been accelerating the construction of large-scale cogeneration units with a capacity of 300 megawatts or above [2]. However, in traditional cogeneration units, the exhaust grade of the low-pressure cylinder is low energy quality and the heat loss is large. Therefore, the recovery of exhaust heat from steam turbine units has been widely concerned and is considered an important component of future regional heating systems [3]. Using high back pressure exhaust steam for heating can effectively reduce the exhaust waste heat of generator units, expand the heating capacity of heat sources, and increase heating efficiency [4]. Therefore, promoting the development of high back pressure cogeneration units has significant economic, environmental, and social significance [5].

Compared to traditional cogeneration methods, high back pressure heating systems have significant advantages in terms of power generation operation economy and heating energy efficiency. Lin et al. for the operation of multiple high back pressure units, the heating system is arranged in series to reduce throttling losses and increase the power generation of the units [6]. Shi et al. by studying the changes in heating load and primary network water supply temperature, the energy consumption level of high back pressure heating units during the heating cycle is studied. The range of coal consumption for periodic power supply can reach $4.56g\cdot(kW\cdot h)^{-1}$[7]. Ge et al. analyzing the regional applicability and thermal economy of high back pressure heating technology, it is concluded that high back pressure technology can expand the heating capacity of the unit by 24.8% [8]. Li et al. Established a multi heat source and cascade combined heating system, reducing the equivalent heating energy by 16% and improving the comprehensive energy efficiency of the heating system [9]. Compared to traditional condensing and heating units, high back pressure units have significant advantages in energy conservation and consumption reduction.

In recent years, in addition to the research on direct recovery of high back pressure waste heat for heating, the deep energy-saving optimization of cogeneration units has also been one of the research hotspots. Several scholars have improved the thermodynamic performance of units through aspects such as unit operation, parameter optimization, and optimization algorithms [10,11]. Liang et al. Conduct operational analysis on dual condensing units and high back pressure dual extraction condensing series heating units respectively. Respectively The results show that the optimal operating range and heating capacity of the high back pressure and the operating effect is better [12]. Zhang et al. proposed a new system for combined heating with steam jet pumps, which increased the exhaust heat of high back pressure heating units and designed a new scheme for coupling component systems. The new scheme increased the heating capacity by 31.8MW and reduced the exergy loss by 5.74MW [13]. Wang et al. proposed a new and efficient coupled heating technology solution, which increased the thermal efficiency and thermal index by 19.59% and 2.61% respectively after coupling [14]. Tolga Taner et al. Improved turbine power plant economics through improved thermo-economic analysis performance metrics [15]. Yang et al. obtained the optimal operating back pressure for different heating periods by optimizing multiple parameters of the steam extraction high back pressure heat pump coupled cogeneration system [16]. Ge et al. reduced the additional unit consumption of the low-pressure heater through parameter optimization, redistributed the enthalpy drop at all levels of the low-pressure cylinder, and reduced the exergy loss by 575.5kW [17]. Li et al. built a new type of exhaust steam waste heat utilization heating system for wet cooling units, combining three mature technologies: high back pressure, absorption heat pump, and low-temperature return water in the heating network [18]. Melo et al. Optimized operation of cogeneration units through the use of economic calculations on the demand side of the heat supply[19]. Chen et al. proposed a Grey Wolf algorithm with a coupled penalty function, and after optimization, the average heat consumption of the unit decreased by 117.96GJ/h [20]. For the deep optimization research of high back pressure units, most existing literature focuses on operating optimization by adding steam injectors to change the energy efficiency of exhaust steam heating and optimizing through algorithms and operating parameters, neglect of steam extraction from heating units. Therefore, this paper investigates the extraction steam distribution method for heating units.

Given the above research foundation, this article takes a certain power plant as an example 2×350MW high back pressure cogeneration unit was modeled. Aiming at different ambient temperature changes during the heating period, comparative analysis of the unit double extraction and condensing heat supply and high back-pressure double extraction heat supply operation of the two heating methods, respectively. The impact of environmental temperature changes on the power generation and heating of high back pressure units was studied, and the application scope was determined. On this basis, in-depth research is conducted on the load optimization strategy of high back pressure units, and an optimized operation plan for high back pressure units during the heating period is obtained, providing a theoretical basis for energy conservation and consumption reduction in power plants.

## 2. Introduction and modeling of case units and heating models

### 2.1 Introduction of double pumping steam - back pressure heating tandem unit

In order to improve the thermal energy utilization rate of the unit and reduce exergy losses, based on the energy-saving theory of "temperature matching and cascade utilization" [21], this article studies the high back pressure series heating method. Taking two 350MW condensing units in a certain power plant as an example, the actual calculated and measured operating parameters of the unit are shown in Table 1. High backpressure exhaust tandem heating retrofit for 350MW units, and the heating operation mode is shown in Fig.1. After the renovation, the back pressure of Unit 1 was increased to 36.2MPa, and Unit 2 was increased to 22.4MPa. Both units underwent extraction back pressure heating, and the high back pressure condensers of the two units were connected in series to the heating network and operated in a quality control manner. According to the actual design, the return water of the heating network is first heated to 60.87℃ through the condenser of Unit 2, and then reheated to 71.81℃ through the condenser of Unit 1. After reheating, it enters the heating network heater for peak heating, and the final heating temperature is 95.75℃.

Fig.2 shows the flow chart of the research methodology. The 350MW unit was first modeled and validated for multiple operating conditions of the unit to ensure that the simulation accuracy of the study was within reliable limits. After that, modeling and comparative analysis of economics and exergy efficienc using the first law of thermodynamics and the second law of thermodynamics [22-23] for modeling of extracted steam heating units and modeling of high back pressure heating units, respectively, concluded that modeling of high back pressure heating units is more suitable for heating operation.

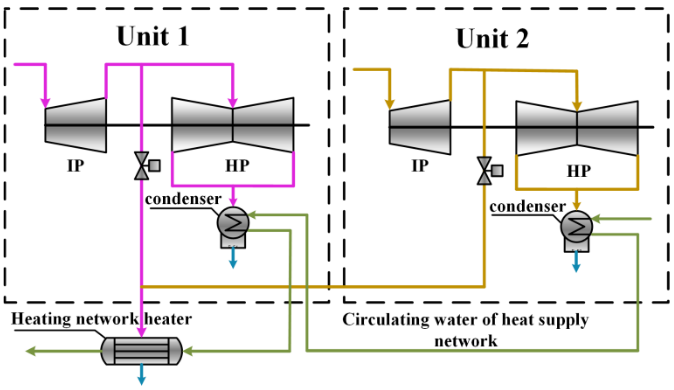



**Fig 1. Two high back pressure series heating**

**Table 1. High back pressure unit and heating network parameters**

| Parameters | Figure | Parameters | Figure |
|---|---|---|---|
| Rated power (MW) | 350 | Heating load of Unit 1 (MW) | 508.7 |
| Main steam pressure (MPa) | 24.4 | Heating load of Unit 2 (MW) | 502.7 |
| Main steam temperature (℃) | 566 | Primary network water supply temperature (℃) | 50 |
| Extraction pressure (MPa) | 0.4 | Primary network return temperature (℃) | 110 |
| Rated extraction flow rate ($t{\cdot}h^{-1}$) | 500 | Secondary network return water temperature (℃) | 45 |
| Unit 1 back pressure (MPa) | 36.2 | Secondary network water supply temperature (℃) | 70 |
| Unit 2 back pressure (MPa) | 22.4 | Heating network water flow rate ($t{\cdot}h^{-1}$) | 11000 |

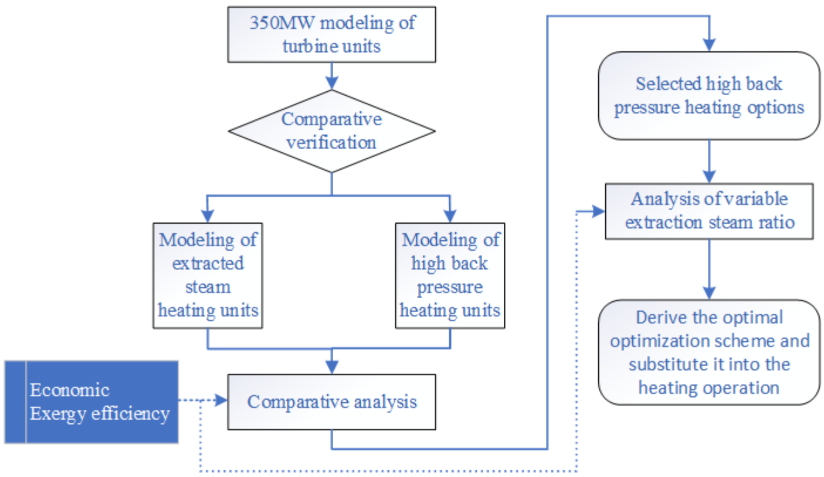



**Fig 2. The flow chart of the research methodology**

## 2.2 Unit calculation model

Table 2 shows the relative error changes when modeling and analyzing the valve fully open state (VWO) and nameplate state (TRL)etc, of the turbine unit and the heating system at variable operating conditions during actual operation using Ebsilon simulation software. The simulation results are compared with the heat balance diagram of the case unit, and the maximum error does not exceed 0.5%, thus ensuring the accuracy of the variable operating condition simulation calculation of the unit.

Fig.3 shows the construction of a high back pressure dual extraction heating system model based on the original two extraction condensing units. The upper side of Fig.3 shows Unit 2, while the lower side shows Unit 1. The turbine is composed of High-Pressure Cylinder (HPC), Medium-Pressure Cylinder (IPC), and Low-Pressure Cylinder (LPC). When heating, the heat network water will be connected to the condenser of Unit 2 and the condenser of Unit 1 in turn for heating and heating, and then the two units will pump steam from the medium-pressure cylinder to the heat exchanger for peak heating. The heat return system of both units in Fig.3 consists of three high-pressure heaters, one deaerator and three low-pressure heaters.

**Table 2. Calculation error analysis for variable operating conditions**

| Working condition | Actual power (MW) | Analog power (MW) | Relative error (%) |
|---|---|---|---|
| VWO | 396.193 | 396.482 | 0.078 |
| TRL | 350.002 | 351.735 | 0.495 |
| 100%THA | 350.002 | 349.473 | 0.156 |
| 75% THA | 262.501 | 262.716 | 0.082 |
| Rated heating extraction steam | 306.287 | 306.572 | 0.093 |

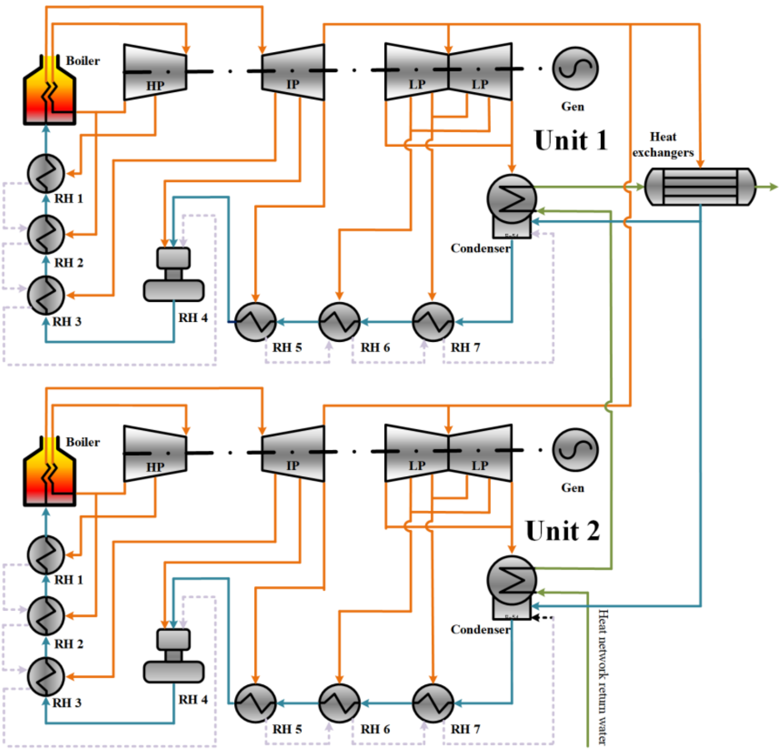



**Fig 3. Model of 2×350MW high back-pressure double pumping steam unit**

## 2.3 Boundary conditions of heating network

Relative heating load ratio as shown in equation (1):

$$\overline{Q} = Q/Q' = t_n - t_w / t_n - t_w' \quad (1)$$

Where $Q$ is the actual heat load; $Q'$ is the design heating load; $t_n$ is the indoor design temperature; $t_w$ is the outside temperature; $t_w'$ is the outdoor calculate temperature.

The secondary network water supply and return temperatures are：

$$t_{\mathrm{g}} = \overline{Q}(t_{\mathrm{g}}' - t_{\mathrm{h}}')[(e^{\overline{Q}^{X}Y} - 1)^{-1} + 1] + t_{\mathrm{n}} \tag{2}$$

$$t_{\mathrm{h}} = \overline{Q}(t_{\mathrm{g}}' - t_{\mathrm{h}}')(e^{\overline{Q}^{X}Y}) - 1)^{-1} + t_{\mathrm{n}} \tag{3}$$

Where $X = 1 - 1/(1+\partial), Y = \ln\left[\left(t_{\mathrm{g}}' - t_{\mathrm{h}}\right)/\left(t_{\mathrm{h}}' - t_{\mathrm{n}}\right)\right]$, (where $\partial$ is the heat sink performance coefficient, $\partial = 0.26$).

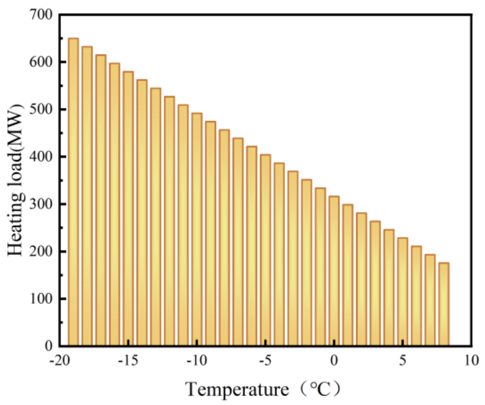
The return water temperature provided by the primary network needs to be adjusted accordingly according to the changes in the return water temperature provided by the secondary network, the temperature of primary network water supply and return is:

$$\tau_{\mathrm{g}} = \frac{([(\tau_{\mathrm{g}}' - \tau_{\mathrm{h}}')\overline{Q} + t_{\mathrm{h}}]e^{D} - t_{\mathrm{g}}}{(e^{D} - 1)} \tag{4}$$

$$\tau_{\mathrm{h}} = \tau_{\mathrm{g}} - (\tau_{\mathrm{g}}' - \tau_{\mathrm{h}}')\overline{Q} \tag{5}$$

Where $D = [(\tau_{\mathrm{g}}' - \tau_{\mathrm{h}}') - (t_{\mathrm{g}}' - t_{\mathrm{h}}')]/\Delta t'$ , Where $\Delta t'$ is the logarithmic average temperature difference during the heat exchange process of the heat exchanger under design conditions $\Delta t' = [(\tau_{\mathrm{g}}' - t_{\mathrm{g}}') - (\tau_{\mathrm{h}}' - t_{\mathrm{h}}')] / \ln[(\tau_{\mathrm{g}}' - t_{\mathrm{g}}') / (\tau_{\mathrm{h}}' - t_{\mathrm{h}}')]$.

Fig.4 and Fig.5 calculate the heating load and the temperature changes of the supply and return water of the heating network based on changes in environmental temperature. It can be found with the increase of environmental temperature, the required heat load on the heating demand side decreases, and the heating load also decreases, the temperature difference between the supply and return water of the heating network gradually decreases.



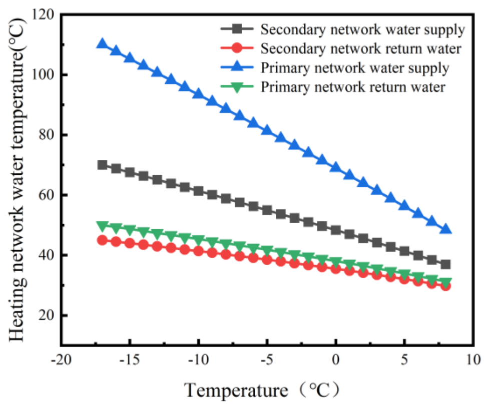




**Fig 4. The relationship between ambient temperature and heating load**

**Fig 5. The relationship between ambient temperature and water temperature of heating network**

## 3.Analysis of the operation of cogeneration units

### 3.1 Unit thermo-electric load range

The relationship between the theoretical power generation and heating capacity of cogeneration can be represented by the thermo-electric characteristic curve, which determines the boundary conditions for unit heating operation. Fig.6 shows the range of thermo-electric load variation for the extraction condensing unit and the high back-pressure unit. ABCD in the figure indicates the theoretical operating intervals of the extraction condensing units, Among them, AB is the maximum main steam flow line, CD is the minimum main steam flow line, BC is the minimum cooling flow line, and AD is the power generation curve without heat supply. When the unit is located at point B, the extraction flow reaches its maximum and the maximum heating load is 439.1MW. The curves EMNOF and EM'N'O'F represent the thermo-electric load range of the heating unit with a back pressure of 22.4KPa and a back pressure of 36.2kpa, respectively. Where EM is the maximum supply line for spent vapor, with a heat load of 250.2MW. As the back pressure rises, the negative back pressure heating boosts to 269.8 MW. The maximum main steam flow line EMN of the unit shifts to the right, and the maximum heat supply load increases from 534.4MW to 549.6MW. The minimum cooling flow line ON and the maximum spent vapor supply line OM are also shifted to the right.

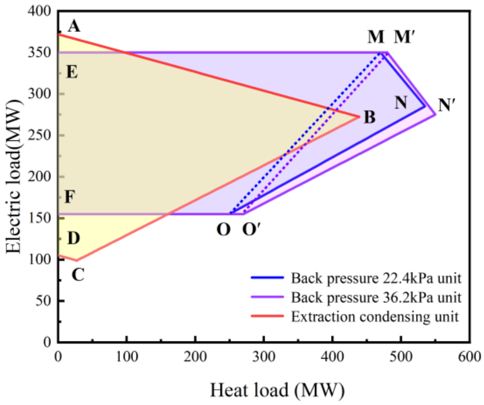



**Fig 6. Thermo-electric characteristic curves of condensing units and high back pressure units**

### 3.2 Thermal load distribution of the unit at ambient temperature

The total heating load of the high back pressure cascade heating unit is:

$$Q = Q_c + Q_e = \left[ \dot{m}_w C_{pw} \left( \tau_g - \tau_h \right) \right] / 3600 \tag{6}$$

The heating network water is heated by the condensers of Unit 2 and Unit 1, so the heat absorbed by the heating network water in the heating condenser is:

$$Q_1 = Q_{c1} + Q_{c2} = [\dot{m}_c (h_c - h_c')] / 3600 \tag{7}$$

$$Q_{c1} = [m_{c1} (h_{c1} - h_{c1}')] / 3600 \tag{8}$$

$$Q_{c2} = [m_{c2} (h_{c2} - h_{c2}')] / 3600 \tag{9}$$

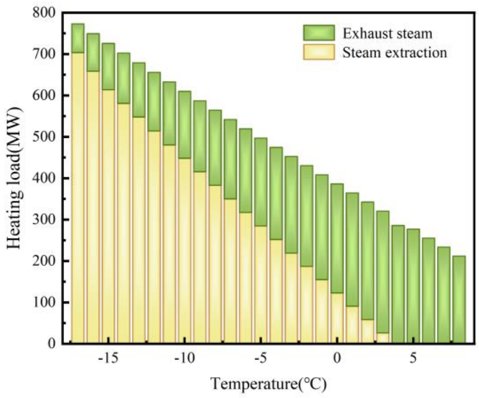
The heat load for steam extraction in the heating network is jointly borne by Units 1 and 2, so the steam extraction heat load of the units is divided into two parts:

$$Q_1 = Q_{e1} + Q_{e2} = [\dot{m}_e (h_e - h_e')] / 3600 \tag{10}$$

$$Q_{e1} = [\dot{m}_{e1}(h_{e1} - h_{e1}^{'})]/3600 \tag{11}$$

$$Q_{e2} = [\dot{m}_{e2}(h_{e2} - h_{e2}^{'})]/3600 \tag{12}$$

Fig.7 and Fig.8 show the distribution of extraction and exhaust steam heat loads for the heating operation of series units with changes in environmental temperature. As the environmental temperature increases, the demand for heating load gradually decreases, and the temperature of the circulating water in the heating network decreases accordingly. Under the design working conditions, the temperature difference at the heat exchange end of the condenser of the unit is taken as 2℃. The temperature of the circulating water in the heating network can be increased to 71.81℃ by heating the condenser of the series unit, corresponding to a heating load of 311.5MW. When the ambient temperature is higher than 3.8℃, the series unit stops extracting steam for heating and only operates with spent steam for heating. The water temperature of the heating network is 59.3℃. When the ambient temperature is below 3.8℃, relying solely on exhaust steam heating cannot meet the heating demand, and steam extraction heating needs to be added. As the temperature decreases, the proportion of steam extraction heating in the heating load gradually increases, reaching 784.2MW at -17℃.



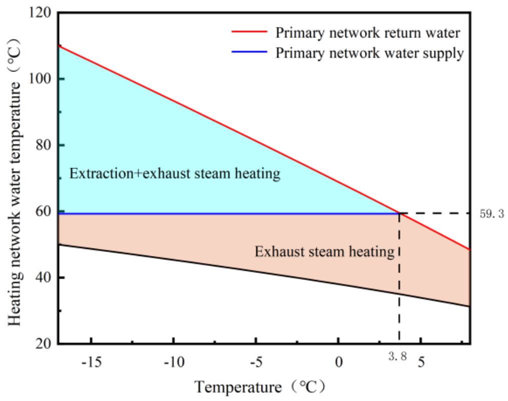




**Fig 7. Changes in exhaust steam and extraction steam with temperature load**
**Fig 8. Heat load distribution of exhaust steam heating and extraction steam heating**

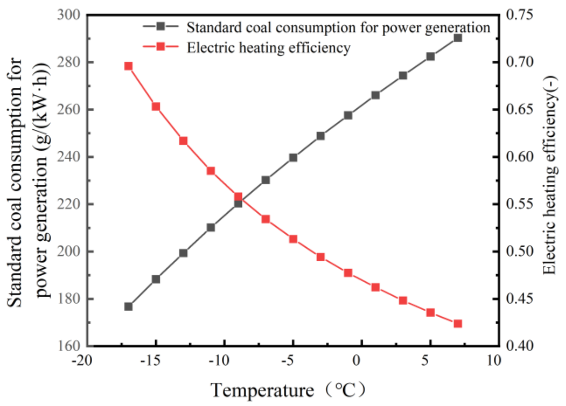
### 3.3 Economic analysis of unit operation

This article uses the heat distribution method to analyze the economic performance of the unit during the heating period. The thermal efficiency of power generation and coal consumption of power generation are used as indicators to evaluate the economy, is:

$$\eta_{tp(e)} = 3.6P / Q_{tp(e)} \tag{13}$$

$$b_{tp(e)} = 123 / \eta_{tp(e)} \tag{14}$$

The thermal efficiency and coal consumption changes of the extraction condensing unit and the high back pressure series unit are shown in Fig.9 and Fig.10. It can be concluded from the figure that with the increase of ambient temperature, the thermo-electric ratio of the extraction condensing unit decreases, the extraction steam flow gradually decreases, the thermal efficiency of power generation decreases, and the coal consumption of power generation increases, and the change trend gradually slows down with the increase of temperature. On the contrary, the thermal efficiency of the high back pressure series unit increases with the increase of the ambient temperature, and the coal consumption of the power generation decreases. When the ambient temperature is higher than 3.8°C, the trend of increasing the thermal efficiency of the power generation unit by relying only on steam heating increases, and the coal consumption of power generation decreases more. In the heating zone, high back-pressure units always extract less steam flow when supplying heat than condensing units, generating higher power and lower coal consumption, and their economy is always better than that of condensing units. With the increase of temperature, this advantage is gradually increased, and the average coal consumption in the heating zone is reduced by 97.5g·$(kW·h)^{-1}$。



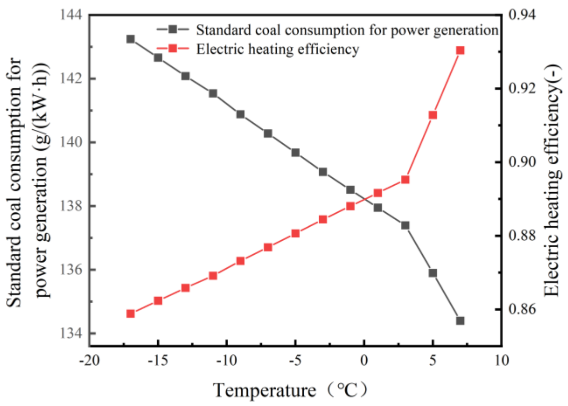




**Fig 9. Changes in thermal efficiency and coal consumption of extraction condensing unit power generation**

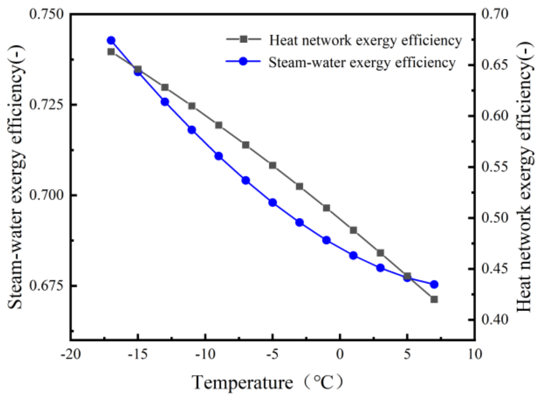
**Fig 10. Changes of thermal efficiency and coal consumption of high back pressure series units**

### 3.4 Exergy analysis of unit operation

Heat distribution method is an evaluation index based on the first law of thermodynamics, but it ignores the level of energy quality. In order to analyze the thermodynamic performance of heating units, exergic efficiency of extraction condensing units and high back pressure units was analyzed according to the second law of thermodynamics. Exergic efficiency is:

$$\eta_{ex} = P + E_{gr} / E_{fw} + E_{rh} \tag{15}$$

The exergy efficiency of the extraction condensing unit and the high back pressure tandem unit are shown in Fig.11 and Fig.12. As for the extraction condensing unit, exergy efficiency of steam-water exergic and exergy efficiency of thermal network exergic decreased gradually as the ambient temperature rose. Exergy efficiency of steam-water exergy efficiency decreased when the ambient temperature rose to a higher value, and the decrease trend would gradually slow down. Compared with units with high back pressure, exergy efficiency of exergy went up steadily under extraction and exhaust steam heating mode, while exergy efficiency of exergy decreased first and then rose as temperature rose. This is because when the ambient temperature was lower, exergy heating accounted for a larger proportion, and exergy efficiency decreased with the increase of temperature. When the ambient temperature rose, the proportion of exhaust steam heating gradually exceeded that of exhaust steam heating, and the exergy efficiency increased with the increase of temperature. When the temperature exceeds 3.8℃, the extraction steam heating exits, and relying solely on exhaust steam heating leads to a sharp increase in efficiency. Compare extraction condensing units，In the heating period of high back pressure units, the exergy efficiency of exergic heating is higher than that of extraction condensing unit, while exergy efficiency of steam-water exergic goes up by 9.4% on average and exergy efficiency of exergic heating network goes up by 19.2% on average.



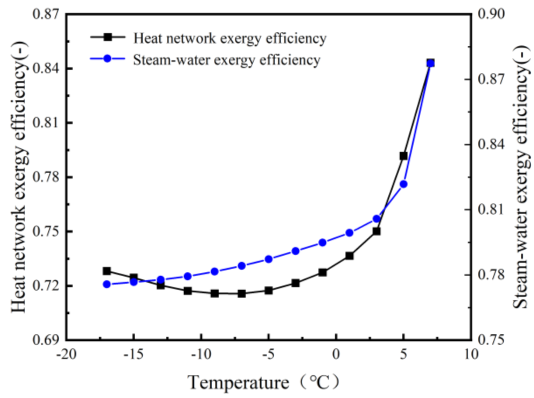




**Fig 11. Exergic efficiency of extraction condensing unit heating**

**Fig 12. Exergic efficiency of high back pressure unit heating**

### 3.5 Analysis of the results of the heating operation

According to the analysis of coal consumption and energy efficiency of the unit during the heating period, the economy and energy efficiency of the high backpressure tandem unit in the heating interval are always better than that of the extraction condensing unit, so it is beneficial for the plant to keep the unit in the operation mode of high back pressure tandem heating during the heating period.

## 4.Optimization of the operation of cogeneration units

Under the condition of constant heat load, the total extraction steam required for heating is basically unchanged, but because of the different operation conditions of the two units, when the respective extraction steam volume changes, the economy of the unit will inevitably change. At present, there is no clear extraction steam distribution principle, and power plant operators are generally allocated according to experience, so it is necessary to optimize the extraction steam distribution mode. For the convenience of analysis, the extraction ratio $\beta_1$ and $\beta_2$ of the two units are defined as the ratio of the extraction volume of Unit 1 and Unit 2 to the total extraction volume required for heating, namely, i.e:

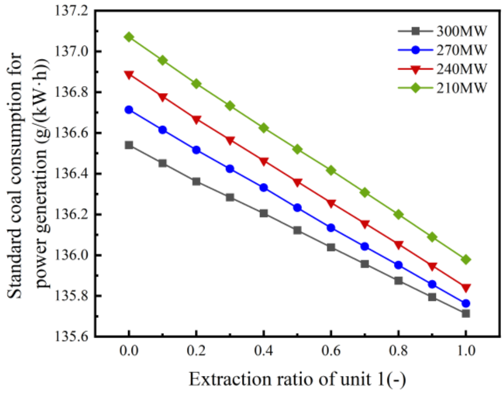
$$\beta_1 = m_{e1}/m_e \tag{13}$$

$$\beta_2 = m_{e2}/m_e = 1 - \beta_1 \tag{14}$$

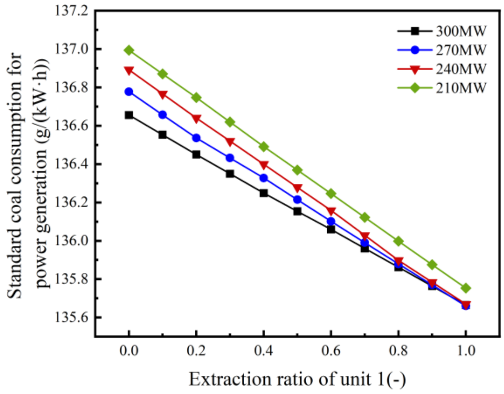
Heat method and exergy analysis were used to analyze the economic and thermodynamic performance of a high back pressure heating unit, and an optimal operation plan for the unit during the heating period was obtained.

### 4.1 Economic analysis of variable extraction steam ratio

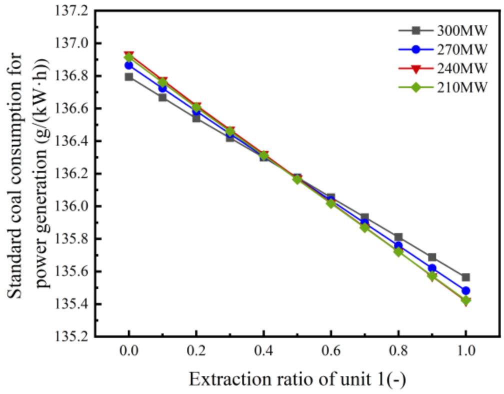
Because the extraction steam ratio $\beta_1$ and $\beta_2$ are linearly related, only the relationship between the average coal consumption and extraction steam ratio $\beta_1$ can be analyzed only. Select the average temperature of -7℃ during the heating period in the area where the power plant is located, analyze and optimize the operation plan. At this temperature, the supply and return water temperature of the heating network is 86.1/41.8℃, and the heating load is 541.8MW.



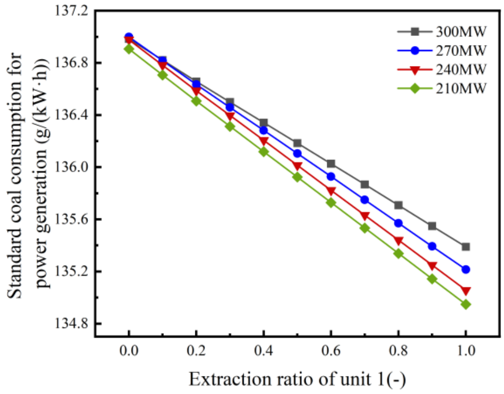

**a) $P_1$=300MW**




**b) $P_1$=270MW**




**c) $P_1$=240MW**



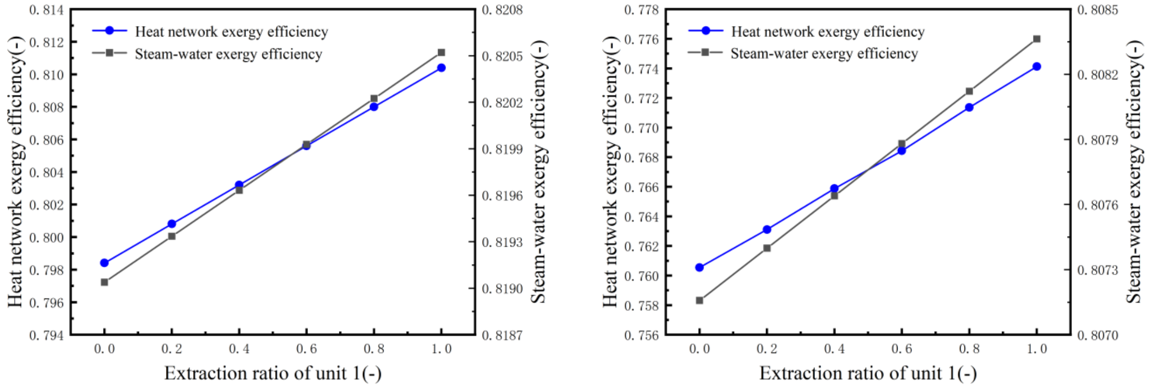

**d) $P_1$=210MW**

**Fig 13. Under different power generation, the change of extraction steam ratio causes the change of coal consumption**

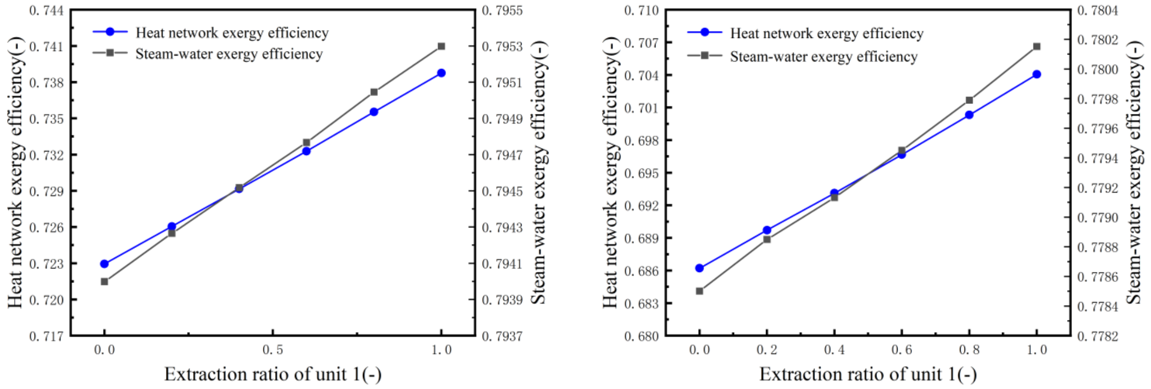
Fig.13 shows the change of coal consumption after changing the extraction steam ratio $\beta_1$ of the two units under different power generation within the safe operation range of the cogeneration unit. In Fig.a), when P2 is 300MW, the overall average coal consumption for power generation is the lowest, And as the proportion of extraction steam $\beta_1$ in Unit 1 increases, the coal consumption for power generation decreases from 136.5g·(kW·h)$^{-1}$ to 135.7g·(kW·h)$^{-1}$, and the coal consumption decreases by 0.8g·(kW·h)$^{-1}$. When P2 is 210MW, the maximum change in coal consumption occurs, with $\beta_1$ from 0 to 1, resulting in a decrease of 1.2g·(kW·h)$^{-1}$ in coal consumption . In Fig.b), $\beta_1$ is in the range of 0 to 0.8, and when P2 is 300MW, the unit's coal consumption is the lowest. When $\beta_1$ is between 0.8 and 1, and P2 is 270MW, the unit's coal consumption is the lowest, and the coal consumption decreases by 1.1g·(kW·h)$^{-1}$. In Fig.c), in the range of $\beta_1$ from 0 to 0.5, the coal consumption of the unit is the lowest when P2 is 300MW, and the highest when P2 is 240MW. On the contrary, in the range $\beta_1$ of 0.5 to 1, when P2 is 240MW, the unit's coal consumption is the lowest, and when P2 is 300MW, the unit's coal consumption is the highest. In Fig.d), if P2 is 210MW, the coal consumption of the unit remains the lowest as $\beta_1$ changes, with a coal consumption variation of 2g·(kW·h)$^{-1}$. From this when Unit 1 is fully responsible for steam extraction and the power generation P2=P1, the unit has the lowest coal consumption for power generation.

### 4.2 Exergy analysis of variable extraction steam ratio

Based on the results obtained from the heat distribution method, in order to further explain the optimization energy-saving mechanism, the second law of thermodynamics analysis method is used to select Unit 1 and Unit 2, with the same generation power, to change the heating and steam extraction ratio of Unit 1, and analyze the changes in the heat network exergy efficiency and steam-water exergy efficiency of high back pressure series units.




**e) $P_1$= $P_2$=300MW** **f) $P_1$= $P_2$=270MW**




**g) $P_1$= $P_2$=240MW** **h) $P_1$= $P_2$=210MW**

**Fig 14. Exergy efficiency variation of variable extraction steam ratio under the same power generation**

Fig.14 shows the exergy efficiency of heating for a unit under variable extraction steam. As the generating power of the unit decreased, the exergy efficiency of the unit decreased accordingly. Taking Fig.g) in Fig.14 as an example, as $\beta_1$ improved the exergy efficiency of thermal network exergy increased from 72.294% to 73.875%, up 1.6%, and steam-water exergy efficiency increased from 79.4% to 79.53%, up 0.13%. In Fig.h), exergy efficiency of thermal network and exergy efficiency of steam-water increased by 1.78% and 0.17%, respectively.

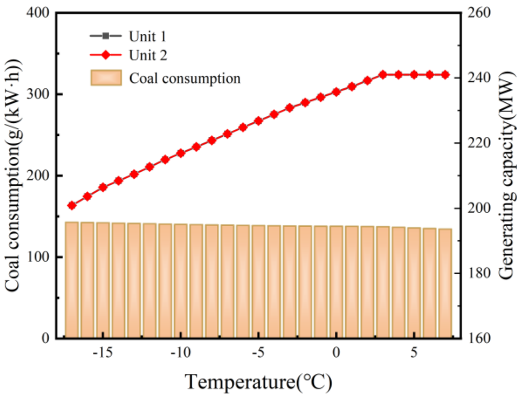
### 4.3 Analysis of variable extraction steam ratio results

From the analysis, it was concluded that with the increase of $\beta_1$, the exergy efficiency of heating network and exergic efficiency of steam-water rose to different degrees, and with the decrease of generation power, the exergy efficiency increased more. This is because as the back pressure increases, the ideal enthalpy drop of the unit's exhaust steam decreases, exergy efficiency of exhaust steam heating of unit 1 is lower than that of unit 2, so unit 1 bears more exhaust steam heating load and increases exhaust steam flow rate to reduce exhaust steam heating flow. At the same time, the exhaust heating load of Unit 2 was increased, and the overall heating exergy efficiency of high back pressure unit was increased.

By analyzing the energy consumption of variable extraction steam ratio and exergy efficiency of the heat supply, the results shows when P2=P1, $\beta_1$=1, that is, when both units have the same power generation capacity, and Unit 1 operates at the maximum extraction steam load, the insufficient extraction heat supply is supplemented by Unit 2. And under the condition of high back pressure heating for both machines simultaneously, the coal consumption is the lowest, exergy efficiency for heating is the highest, the operation energy efficiency is optima.

### 4.4 Optimization analysis of unit operation

The power generation efficiency and standard coal consumption of high back pressure units before and after optimization are shown in Fig.16. Compared with the original operation plan, the optimized electric heating efficiency has significantly improved, and the coal consumption for power generation has decreased. Both trends increase first and then decrease as the temperature increases, the maximum increase in power generation efficiency is 0.66%, and the maximum difference in standard coal consumption for power generation is 1.07g·(kW·h)$^{-1}$. When the ambient temperature is below 3.8℃, the average efficiency of electricity generation increases by 0.42%, and the average standard coal consumption for power generation decreases by 0.69g·(kW·h)$^{-1}$. When the ambient temperature is higher than 3.8℃, the heating of the unit is entirely borne by the exhaust steam heating, and the efficiency of electricity generation and coal consumption will no longer change.



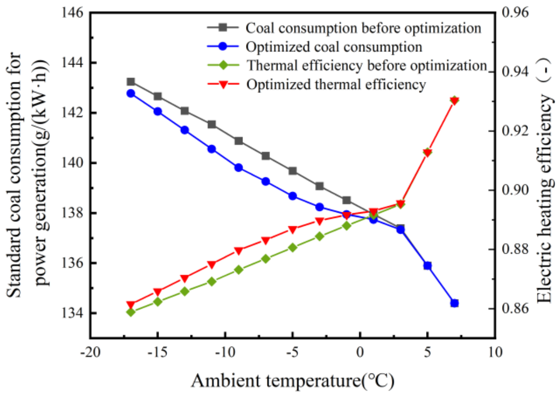




**Fig 15. Optimized Unit Power Generation**

**Fig 16. Power generation coal consumption and standard coal consumption of units before and after optimization**

Exergy efficiency of heat-supply before and after optimization of a high back pressure unit is shown in Fig.17. When the ambient temperature was lower than 3.8℃, exergy efficiency of thermal network and exergy efficiency of steam-water exergic increased to different degrees. As shown in the figure, while exergic efficiency of steam-water exergic is relatively stable, exergy efficiency of thermal exergic goes up first and then goes down. In the heating period, exergy efficiency of steam and water increased by an average of 0.44% with a maximum increment of 0.5%, while exergy efficiency of thermal network increased by an average of 0.6% with a maximum increment of 0.96, Exergy loss of cold source can decrease to a maximum of 1.4MW. When the ambient temperature was higher than 3.8 ℃, the exergic heating efficiency no longer increased.

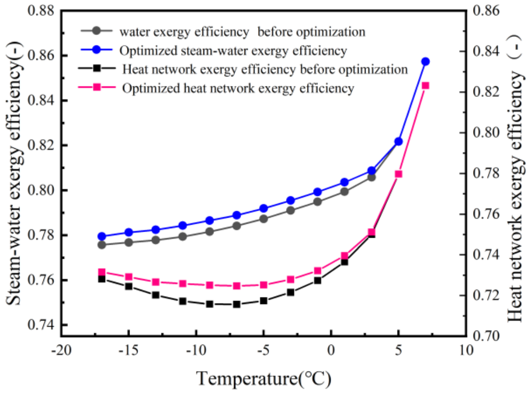



**Fig.17. Exergy efficiency change of unit heating before and after optimization**

## 5.Conclusion

In this paper, the 2×350MW unit of a power plant is taken example，variable operating condition models were constructed for a double extraction condensing heating unit and a high back pressure tandem heating unit. Calculation of heat network boundary conditions using ambient temperatures.By comparing the thermal economy and exergy efficiency of the two heating modes, it is concluded that the high back-pressure heating mode is more suitable for operation during the heating period. It also optimized the unit's operation during the heating period by adjusting the unit's extraction steam distribution on the basis of high back-pressure operation. The following conclusions were obtained:

1）During the heating period, the high back-pressure unit has an advantage over the extraction steam unit in terms of generation load, coal consumption and exergy efficiency.At ambient temperatures above 3.8°C, the heating economy advantage gradually expands as the ambient temperature increases. The average increase in power generation of high backpressure units during the heating period is 24.5 MW., and the average coal consumption for power generation decreased by 97.5g·$(kW·h)^{-1}$. efficiency of steam-water exergy increased by 9.4% on average, while exergy efficiency of the heat network increased by 19.2% on average.

2）According to the variable extraction ratio analysis, when the two electrical loads are the same, the high back pressure heating unit is operated by Unit 1 at the maximum extraction load, and the remaining extraction steam heating is supplemented by Unit 2.The best energy savings are achieved under this mode of operation, and the exergy efficiency of heating network and steam and water exergy efficiency can increase by 1.78% and 0.17%.

3）After optimizing the operation of the unit during the heating period, the maximum thermal efficiency increases by 0.66%, with an average increase of 0.42%. Maximum reduction of power generation standard consumption by 1.07g·$(kW·h)^{-1}$, Average reduction of 0.69g·$(kW·h)^{-1}$. During the heating period, exergy efficiency of steam-water exergic increased by an average of 0.44%, Maximum increment of 0.5%，exergy efficiency of thermal network increased by 0.6% on average, and the maximum increment of exergy efficiency was 0.96%. Exergy efficiency of thermal network heating can increase by up to 1.4MW.

**Acknowledgements**

This study is financially supported by Inner Mongolia Autonomous Region Major Science and Technology Special Project (2021ZD0036), Inner Mongolia Autonomous Region Science and technology project (2023YFHH0070), Inner Mongolia Autonomous Region ‘Open bidding for selecting the best candidates’ project (2023JBGS0012), Many thanks for the help with these programs!

**Nomenclature**

| | | | |
|---|---|---|---|
| $C_{pw}$ | specific heat of water at constant pressure, $kJ\cdot(kg\cdot ℃)^{-1}$ | $P$ | power generation,MW |
| $b$ | coal consumption,$g\cdot(kW\cdot h)^{-1}$ | $\overline{Q}$ | heat load ratio |
| $E$ | water exergy variation | $Q$ | heat load,MW |
| $h$ | exhaust enthalpy, $kJ\cdot kg^{-1}$ | $t$ | temperature,℃ |
| $m$ | flow rate, $t\cdot h^{-1}$ | | |

**Greek symbols**

| | | | |
|---|---|---|---|
| $\partial$ | heat sink performance coefficient, 0.26 | $\tau$ | primary heating network water temperature,℃ |
| $\beta$ | extracted Steam Ratio | $\eta$ | efficiency,% |

**Subscripts**

| | | | |
|---|---|---|---|
| c | exhaust steam | 2 | Unit 2 |
| e | extraction of steam | ' | design condition |
| g | heat network water supply | ex | exergy efficiency |
| h | heat network return water | gr | primary heat network |
| n | indoors | fw | stove |
| w | outdoors | rh | reheat steam |
| 1 | Unit 1 | th(e) | generating station |

**References**

[1] Huang C., *et al.*, The Upgrading of Coal-fired Power Generation Industry Supports China 's National Strategy of Energy Conservation, Emission Reduction and Carbon Neutrality, *Thermal Power Generation,50*(2021), 4, pp.1-6.

[2] Gu Y., *et al.*, Overall Review of Peak Shaving for Coal-fired Power Units in China, *Renewable and Sustainable Energy Reviews, 54*(2016), pp.723-731.

[3] Lia W., *et al.*, Combined Heating Operation Optimization of the Novel Cogeneration System with

Multi Turbine Units, *Energy Conversion and Management,171*(2018), pp.518-527.

[4] Li P., *et al*., Analysis and Calculation on Energy Consumption of 300MW CHP Heating Systems, *Journal of Chinese Electrical Engineering, 32*(2012), 23, pp.15-20.

[5] Li P., *et al*., Energy Conservation Analysis and Improvement on Combined Heat and Power Heating System, *Journal of Engineering Thermophysics*, *34*(2013), 8, pp.1411-1415.

[6] Lin Z., *et al*., Applied Research on the Serial Distribution Mode of Heating System, *Proceedings of the CSEE, 35*(2010), 30, pp.13-17.

[7] Shi B., *et al*., Impacts of Water Supply Temperature on Energy Consumption of High Back Pressure Cogeneration System, *Chemical Industry and Engineering Progress, 37*(2018), 1, pp.96-104.

[8] Ge Z., *et al*., Applicability Analysis of High Back-pressure Heating Retrofit for Large-scale Steam Turbine Unit, *Proceedings of the Chinese Society of Electrical Engineering*, *37*(2017), 11, pp.3216-3222.

[9] Li Y., *et al*., Full Operating Conditions Optimization Study of New Co-generation Heating System Based on Waste Heat Utilization of Exhausted Steam, *Energy Conversion and Management, 155*(2018).

[10] Wang C, Song J. Optimal Dispatch of the Cascade Heating CHP Plants Integrating with the High Back-pressure Technology, *Case Studies in Thermal Engineering, 38*(2022), 102330.

[11] Silva, H.C.N.et al., Combined Financial and Environmental Optimization of a Trigeneration System, Thermal Science,27(2023), pp.321-334

[12] Ge Z., *et al*., Energy Analysis of Cascade Heating with High Back-pressure Large-scale Steam Turbine, *Energies*, *11*(2018), 119, pp.1-15.

[13] Zhang Y., *et al*., A Novel Cascade Heating Systemfor Waste Heat Recovery in the Combined Heat and Power Plant Integrating with the Steam Jet Pump, *Applied Energy, 278*(2020), 115690.

[14] Wang Z., *et al*., Study on New High-efficiency Coupling Heating Technology of Cogeneration Unit, *Thermal Power Generation, 51*(2022), 1, pp.130-138.

[15] Taner T., *et al*., A Techno-economic & Cost Analysis of a Turbine Power Plant: A Case Study for Sugar Plan, *Renewable and Sustainable Energy Reviews*, *78*(2017), pp.722-730.

[16] Yang K., *et al*., Operation Optimization of Heat and Power Cogeneration System Coupled With Extraction Unit, High Back Pressure Unit and Heat Pump, *Journal of Engineering Thermophysics, 44*(2023),6, pp.1459-1464.

[17] Ge Z., *et al*., Optimization of Low-pressure Flow Part of High Back-pressure Heating Steam Turbine, *Chemical Industry and Engineering Progress, 38*(2019), 12, pp.5264-5270.

[18] Li Y., *et al*., Integrated Optimization of a New Co-generation System Based onWaste Heat Recovery of Water-cooled Unit, *Proceedings of the CSEE*, *19*(2017), 37, pp.5688-5695.

[19] Melo F.M., *et al*., Optimization and Sensitivity Analyses of a Combined Cooling, Heat and Power System for a Residential Building, *Thermal Science, 25*(2023), pp.3969-3986.

[20] Chen R., *et al*., Research on Load Optimization of High Backpressure Extraction CHP Units based on PC-GWO. Journal of Engineering for Thermal Energy and Power, 2023, 38(2)pp.18-25.

[21] Ma L., *et al*., A Novel Super High Back Pressure Cascade Heating Scheme with Multiple Large-scale Turbine Units, *Energy, 201*(2020),117469.

[22] Taner T., *et al*., Energy–exergy Analysis and Optimisation of a Model Sugar Factory in Turkey, *Energy,93*(2015), pp.641.654.

[23] Taner T., *et al.*, Optimisation Processes of Energy Efficiency for a Drying Plant: A case of Study for Turkey, *Applied Thermal Engineering*, *80*(2015), pp.247-260.

Received: 11-12-2023

Revised: 18-02-2024

Accepted: 20-02-2024