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Research on operational flexibility and energy consumption characteristics of cogeneration considering primary network heat transfer constraints

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High back pressure cogeneration units demonstrate superior energy utilization efficiency, but their operation is significantly influenced by primary network water temperature and flow rate. The analysis of operational flexibility and energy consumption characteristics must consider the heat transfer performance constraints of the primary thermal network. This study investigates a high back pressure heating unit with steam extraction through off-design performance calculations of its condenser using the efficiency-number of transfer units (ϵ -NTU) method. The research evaluates how air-cooled island flow rate, thermal network return water flow, and temperature parameters affect the heat allocation ratio between steam extraction and high back pressure heating, as well as overall energy consumption characteristics. Key findings reveal that under maximum steam extraction heat load conditions, the coal consumption rate decreases by approximately 0.1 g/(kW·h) with a corresponding 0.43% improvement in energy efficiency. These insights provide operational guidance for optimizing combined high back pressure and steam extraction units through refined control strategies.

KEYWORDS

high back pressure unit, primary network, waste heat recovery, efficiency-number of transfer units method, off-design condition

1 Introduction

Cogeneration can achieve the cascade utilization of thermal energy, improve the efficiency of primary energy and reduce pollutant emissions (Li M. et al., 2016), and has become the main heating method in northern China (Gao et al., 2018; Zhao et al., 2023). In a typical combined heat and power unit with extraction steam heating, the temperature of the extraction steam heating is much higher than the return water temperature of the heating network. During the heat exchange process (Lu et al., 2022), irreversible losses are large, and a large amount of heat from the exhaust steam of the low-pressure turbine is released into the condenser (Cheng et al., 2016; Yang et al., 2008). The cold source loss accounts for more than 30% of the total energy consumption of the power plant

(Ma et al., 2020). By further recovering the loss of cold sources and achieving energy cascade utilization through combined steam extraction for heating, the heating capacity of power plants can be expanded and the energy utilization efficiency of cogeneration can be improved (Wang et al., 2011; Yang et al., 2023; Wang et al., 2021).

The commonly used methods for utilizing cold source loss mainly include heat pump technology (Kang et al., 2015) and high back pressure transformation. The waste heat recovery effect of heat pumps is limited by the performance coefficient of heat pumps (Wang HC. et al., 2023; Chen et al., 2019a). However, high back pressure heating enables direct heat exchange between the heat network and exhaust steam, which can completely eliminate cold source loss under ideal conditions (Ge et al., 2017). It has broad application prospects in coal-fired cogeneration units, especially in the heating renovation of existing power plants. Ge et al. (2018) and Wang et al. (2022) established a model of a high back pressure cogeneration unit under off-design conditions and analyzed the thermodynamic performance and engineering applications of the high back pressure unit. Zhao et al. (2020) conducted a comparative study on the extraction unit and the high back pressure unit. After the high back pressure transformation, the heating capacity and energy-saving effect of the unit were significantly improved. The thermal efficiency and power generation efficiency increased by 17.67% and 33.21% respectively, and the exergy efficiency increased by 7.04 ~ 8.21%. Chen et al. (2019b) conducted a comprehensive analysis of the energy consumption characteristics of a 300 MW high back pressure cogeneration unit. The results showed that after adopting the high back pressure design, the thermal efficiency of the unit increased by 5.97%, the standard coal consumption rate decreased by 23.52 g/(kW·h), the exhaust steam recovery efficiency increased by 57%, and the power generation of the unit increased by 24.58 MW.

With the extensive application of high back pressure units in engineering, the optimal scheduling problem of cogeneration systems integrating high back pressure units has also received extensive attention. Wang and Song (2022) studied the plant-level scheduling problem of cascade heating using high back pressure technology. Considering the constraints of the operation area and load balancing, they predicted the optimal heat load sharing ratio of the high back pressure unit and proposed the optimal scheduling strategy. Ma et al. (Ge et al., 2017) developed a novel ultra-high pressure back pressure series heating system. Compared with the traditional system, the exergy efficiency of the new system was increased by 10.4%, further exploring the energy-saving potential. Zhao et al. (2017) combined the exhaust steam of the high back pressure unit with the heating process of air and condensate water, and proposed an optimized process for deep utilization of exhaust steam. The results showed that under the design conditions, the exhaust steam utilization rate increased by 22.74%, the heating capacity increased by 16.26%, and the net power generation efficiency increased by 5.06%.

Furthermore, cogeneration units face intrinsic operational complexities due to the thermodynamic coupling between power generation and heat supply, particularly under off-design conditions (Liu et al., 2021). Traditional design conditions models fail to address critical constraints including: heat-power interdependence (Wang et al., 2022), heating demand fluctuations (Nuytten et al., 2013; Wang LY. et al., 2023), and dynamic

interactions with district heating networks (Pan et al., 2023; Wang JJ. et al., 2023). This necessitates more appropriate performance calculation methods such as the efficiency-number of transfer units (ϵ -NTU) method (Wang et al., 2017), which enables accurate quantification of condenser behavior under variable boundary conditions while resolving coupled effects in hybrid heating modes (Hou et al., 2022).

During the actual operation of the turbine, the main operating parameters such as the main steam pressure will inevitably deviate from their reference values (Zhou et al., 2011), thereby affecting the energy consumption calculation of the unit (Xiong et al., 2024). Only on the basis of an accurate off-design condition model can a more detailed analysis of the unit operation and energy consumption characteristics be completed (Li et al., 2021). Yan et al. (2006) applied the cyclic function method, the equivalent enthalpy drop method and the theory of off-design conditions analysis of turbine to establish a computational analysis matrix model, achieving the economic analysis of the heating unit - seawater desalination co-production system. Wang et al. (2013) determined the mathematical model of the peak shaving range of the electric load under different extraction steam flow through the calculation of the off-design conditions of turbine, and developed an online monitoring system for determining the electric load based on the thermal load. Li X. E. et al. (2016) established the off-design condition model of turbine and the off-design condition model of air-cooled system, and verified the calculation accuracy. On this basis, they completed the research on the optimal vacuum characteristics of the direct air-cooled system under summer operating conditions.

In conclusion, the energy-saving characteristics of high back pressure units have been widely verified, and the optimization problem of heating systems integrating high back pressure units has also been extensively studied. However, the off-design condition characteristics of high back pressure units need to take into account the heat transfer performance constraints of the primary heat network, and only by clarifying the influencing factors in the off-design condition operation of the units and establishing an accurate off-design condition calculation model can the characteristics of the units be described more accurately. Most existing studies adopt the method of assuming back pressure, which leads to inaccurate description of the unit characteristics. Therefore, taking a certain 620 MW extraction - high back pressure unit as an example, this paper adopts the efficiency-number of transfer units method to analyze the influence of the heat transfer performance of the primary network on the off-design condition operation of the unit, and explores the role of the extraction heating and high back pressure heating sharing ratio in the energy consumption of the unit, providing a theoretical basis for the refined operation of the extraction - high back pressure unit.

2 Model development

2.1 Model development of the direct air-cooled unit

The direct air-cooled unit operates in a high back pressure heating mode, and the turbine exhaust steam flow rate is D_C . A portion of the exhaust steam flow D_{HC} is used as the heat

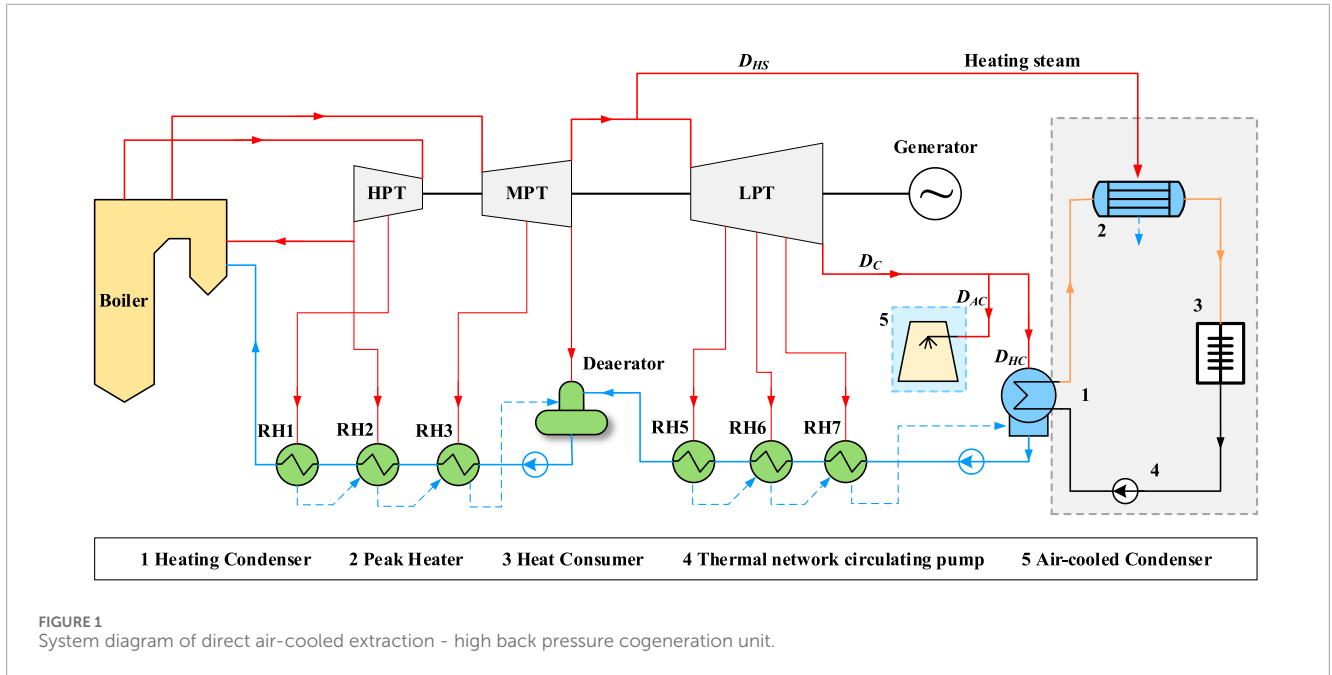


FIGURE 1 System diagram of direct air-cooled extraction - high back pressure cogeneration unit.

source for the heating condenser, which can fully utilize the waste heat. The remaining D_{AC} is cooled by the air-cooled island. As shown in Figure 1, after the D_{HC} heats the return water of the heat network, the heat supply extraction steam is used for secondary heating to meet the water supply temperature requirements of the heat network.

This article takes a certain 620 MW direct air-cooled cogeneration unit as an example, and the main parameters are shown in Table 1. After the high back pressure transformation, the rated back pressure is 35 kPa. The parameters of the heating condenser are shown in Table 2. The temperature of the circulating water in the heat network is 40 °C, and the rated flow rate is 16,000 t/h. The unit retains the heating extraction steam and combines high back pressure heating to achieve energy stepwise utilization, with a maximum extraction steam flow rate of approximately 250 t/h.

The purpose of the unit's off-design condition calculation is to determine the steam parameters at each extraction port and exhaust end of the steam turbine, as well as the corresponding parameters of the regenerative system. The calculation method for off-design conditions of steam turbine thermal system can be described as follows:

First, conduct a heat balance calculation for the unit under rated or base conditions. The efficiency $\eta_{i(r)}$ of each stage group r of the steam turbine is calculated using Equation 1. The main steam flow rate and stage group efficiency vary under different operating conditions and have a specific functional relationship. After fitting the main steam flow rates and stage group efficiencies, the efficiency of each stage group under off-design conditions is determined (Zhang et al., 2021).

$$\eta_{i(r)} = \frac{h_{1(r)} - h_{2(r)}}{H_{s(r)}} \quad (1)$$

where $h_1(r)$ is the inlet steam enthalpy of stage group r , kJ/kg; $h_2(r)$ is the outlet steam enthalpy of stage group r , kJ/kg; $H_s(r)$ is the

TABLE 1 Main technical parameters of the unit.

Parameters	Units	Values
Rated power	MW	620
Maximum power	MW	677.2
Rated main steam flow rate	t/h	1879.5
Maximum main steam flow rate	t/h	2090
Rated main steam pressure	MPa	24.2
Rated main steam temperature	°C	566
Reheat steam pressure	MPa	4.088
Reheated steam temperature	°C	566
Rated back pressure	kPa	16

isentropic expansion enthalpy drop of steam in stage group r within the steam turbine, kJ/kg.

During the off-design condition calculation, the new main steam flow rate is an unknown quantity and needs to be obtained through iterative calculation after assuming an initial value. To improve the efficiency of iterative calculation, the assumed value can be roughly determined based on the ratio to the electrical load, i.e., the ratio of main steam flow rate to electrical load under off-design conditions is equal to that under base conditions (Equation 2):

$$D = \frac{N_d}{Nd_0} D_0 \quad (2)$$

where D is the main steam flow rate under off-design conditions/kg·h⁻¹; D_0 is the main steam flow rate under base

TABLE 2 Main technical parameters of the heating condenser.

Parameters	Units	Values
Design back pressure	kPa	35
Design flow rate	t/h	16,000
Heat exchange area	m ²	18,000
Design temperature on the drain side	°C	68

conditions/kg·h⁻¹; N_n is the unit electrical load under off-design conditions/kW; N_{n0} is the unit electrical load under base conditions/kW.

The off-design conditions of the unit and thermal system are mainly reflected in the change of the steam inlet flow rate of the turbine or the steam flow rate passing through the turbine. The change in steam flow rate inside the turbine will cause changes in the pressure before and after the stage group, and their relationship is determined by the Flügel formula (Equation 3) (Wang et al., 2019):

$$\frac{D_1}{D_{10}} = \sqrt{\frac{(P_1^2 - P_2^2)}{(P_{10}^2 - P_{20}^2)}} \sqrt{\frac{T_{10}}{T_1}} \quad (3)$$

The work done per unit of new steam (H_0) can be obtained from the extraction share of each stage group, and then the new steam flow rate is determined by the Equation 4:

$$D_{01} = \frac{3600N_d}{\eta_m \eta_g H_0} \quad (4)$$

where P_r is the extraction pressure at the current extraction port under off-design conditions/MPa; P_{r+1} is the extraction pressure at the next extraction port under off-design conditions/MPa; D_r is the extraction flow rate under off-design conditions/kg·h⁻¹; D_{r0} is the extraction flow rate under rated conditions/kg·h⁻¹; P_{r0} is the extraction pressure at the current extraction port under rated conditions/MPa; $P_{(r+1)0}$ is the Extraction pressure at the next extraction port under rated conditions/MPa.

2.2 Heat transfer characteristics of direct air-cooled systems

This study focuses on a direct air-cooled (dry cooling) system, distinct from conventional evaporative cooling towers (which need a latent heat term for water evaporation). This dry cooling system only uses sensible heat exchange (affected by dry-bulb temperature and frontal wind speed).

The direct air-cooled unit relies on air-cooled fan to cool the exhaust steam of the turbine. Heat exchange occurs between the steam and the air through the outer surface of the heat exchanger tube bundle. The efficiency - number of heat transfer units method is often used to analyze the off-design condition characteristics of the air-cooled system (Zhou and Li, 2011).

Heat release from the condensation of the steam D_{AC} entering the air-cooled island is calculated using Equation 5:

$$Q_{AC} = D_{AC}(h_C - h_{AC}) \quad (5)$$

The heat absorbed by the air outside the heat exchanger tubes is equal to the heat released by the condensation of the D_{AC} :

$$Q_{AC} = G_a C_a (t_{a2} - t_{a1}) = F_F v_{NF} \rho C_a (t_{a2} - t_{a1}) \quad (6)$$

where $G_a = F_F v_{NF} \rho$ is the air flow rate, kg/s; v_{NF} is the frontal wind speed of the air-cooled heat exchanger, m/s; ρ is the local air density, kg/m³; C_a is the specific heat of air, J/(kg·°C).

In the heat exchanger, condensation on the steam side releases heat, and the efficiency ε of the heat exchanger is Equation 7:

$$\varepsilon = 1 - e^{-NTU} = \frac{t_{a2} - t_{a1}}{t_C - t_{a1}} \quad (7)$$

where the number of heat transfer units (NTU) is Equation 8:

$$NTU = \frac{K_a A_a}{F_F v_{NF} \rho C_a} \quad (8)$$

The saturation temperature t_C of the turbine exhaust steam is:

$$t_C = \frac{D_{AC}(h_C - h_{AC})}{F_F v_{NF} \rho C_a} \cdot \frac{1}{1 - e^{-NTU}} + t_{a1} \quad (9)$$

where D_{AC} is the turbine exhaust steam flow rate entering the air-cooled island, kg/s; h_C is the specific enthalpy of exhaust steam, kJ/kg; h_{AC} is the specific enthalpy of condensate water in the air-cooled island, kJ/kg; F_F is the windward area of the air-cooled heat exchanger, m²; K_a is the heat transfer coefficient of the air-cooled island, W/(m²·°C); A_a is the heat dissipation area of the air-cooled island heat exchange tube bundle, m²; t_{a1} and t_{a2} are respectively the temperatures of the air before and after entering the air-cooled condenser, °C.

This heat balance Equation 6 is specific to the direct air-cooled system studied herein. Unlike conventional evaporative cooling towers (which require an additional latent heat term for water evaporation), the direct air-cooled system only involves sensible heat exchange—hence (Equation 6) excludes latent heat-related parameters. Notably, Equation 9 is also applicable solely to the direct air-cooled system, as it is derived based on Equation 9 and dry cooling-specific heat transfer mechanisms.

For a well-designed direct air-cooled system, the total heat dissipation area A_a and the total windward area F_F have been determined. While the local air physical parameters ρ and C_a are affected by the ambient temperature t_{a1} , and the heat transfer coefficient is affected by the frontal wind speed v_{NF} and the ambient temperature t_{a1} . Thus, the influencing factors of the turbine exhaust steam pressure P_C are obtained (Equation 10):

$$P_C = f(t_C) = f(D_{AC}, v_{NF}, t_{a1}) \quad (10)$$

2.3 Heat transfer characteristics of heating condenser

The turbine exhaust steam and the return water of the heat network undergo heat exchange in the heating condenser to recover the waste heat of the exhaust steam and improve the overall thermal economy of the unit. The heat transfer analysis was carried out by using the efficiency - number of heat transfer units method. The

efficiency ε represents the ratio of the actual heat transfer effect of the heat exchanger to the maximum possible heat transfer effect, and the number of heat transfer units characterizes the comparative relationship between the heat transfer performance and thermal convection performance of the heat exchanger.

In the heating condenser, the cold and hot fluids exchange heat in counter-flow, and the steam undergoes phase change heat transfer. The efficiency formula is Equation 11 (Bejan, 1988):

$$\varepsilon = 1 - e^{-NTU} = \frac{t_{w2} - t_{w1}}{t_C - t_{w1}} \quad (11)$$

where t_{w1} and t_{w2} are respectively the inlet and outlet temperatures of the return water in the heat network, °C; t_C is the saturation temperature of the turbine exhaust steam, °C.

NTU represents the number of heat transfer units, and its calculation formula is Equation 12:

$$NTU = \frac{K_w A_w}{C_w G_w} \quad (12)$$

where K_w is the heat transfer coefficient of the heating condenser, W/(m²·°C); A_w is the heat exchange area of the heating condenser, m²; C_w is the specific heat of the return water in the heat network, J/(kg·°C); G_w is the circulating water flow rate of the heat network through the condenser, in kg/s.

The saturation temperature t_C of the turbine exhaust steam is also the saturation temperature corresponding to the pressure of the heat supply condenser. According to the above formula, it can be obtained (Equation 13) (Zhou and Li, 2011):

$$t_C = t_{w1} + \frac{D_{HC}(h_C - h_{HC})}{C_w G_w \left[1 - \exp\left(-\frac{K_w A_w}{C_w G_w}\right) \right]} \quad (13)$$

where D_{HC} is the turbine exhaust steam flow rate entering the condenser, kg/s; h_C is the specific enthalpy of exhaust steam, kJ/kg; h_{HC} is the specific enthalpy of condensate water in the heating condenser, kJ/kg.

The turbine exhaust steam pressure P_C corresponding to t_C can be obtained through the steam parameter table. For the designed heating condenser, the heat exchange area A_w has been determined. The heat exchange coefficient is affected by the circulating water flow rate G_w of the heat network and the inlet temperature t_{w1} of the return water of the heat network. During the heat exchange process of the return water of the heat network, the specific heat C_w does not change much and is mainly affected by the inlet temperature t_{w1} . Thus, the influencing factors of the turbine exhaust steam pressure P_C are obtained (Equation 14):

$$P_C = f(t_C) = f(D_{HC}, G_w, t_{w1}) \quad (14)$$

2.4 Efficiency analysis of heating condensers

The saturation temperature corresponding to the condenser pressure can also be calculated from the inlet and outlet temperatures of the return water in the heat network and the heat transfer end difference, that is Equations 15–17:

$$t_C = t_{w1} + \Delta t_w + \delta t \quad (15)$$

$$\Delta t_w = t_{w2} - t_{w1} = \frac{D_{HC}(h_C - h_{HC})}{C_w G_w} \quad (16)$$

$$\delta t = t_C - t_{w2} = \frac{\Delta t_w}{e^{\frac{K_w A_w}{C_w G_w}} - 1} \quad (17)$$

Where Δt_w is the temperature rise of the return water of the heat network in the heating condenser, °C; δt is the heat transfer end difference, °C.

Combined with the efficiency calculation formula, the relationship between efficiency and the return water temperature rise Δt_w of the heat network, as well as the heat transfer end difference δt , can be derived (Equation 18):

$$\varepsilon = \frac{1}{\frac{\delta t}{\Delta t_w} + 1} \quad (18)$$

The number of heat transfer units NTU reflects the combined influence of the heat transfer coefficient K_w , the circulating water flow rate G_w of the heat network, and the inlet temperature t_{w1} of the return water of the heat network. The influencing factors of the turbine exhaust steam pressure P_C are simplified as being characterized by the more measurable return water temperature rise Δt_w of the heat network and the heat transfer end difference δt (Equation 19):

$$P_C = f(D_{HC}, NTU) = f(D_{HC}, \delta t, \Delta t_w) \quad (19)$$

2.5 Calculation method for condenser off-design conditions

The common calculation methods for off-design conditions of condensers include the fixed back pressure method, the logarithmic mean temperature difference method, and the efficiency - number of heat transfer units method. In the actual operation of the unit, it is difficult to maintain a stable back pressure, so the fixed back pressure method does not conform to the actual situation. The logarithmic mean temperature difference method is based on the fixed end difference and is also difficult to truly reflect the actual operation of the heating condenser. The number of heat transfer units can comprehensively reflect the influence of the condenser heat transfer coefficient and cold end parameters on the heat transfer effect, and the efficiency changes little in actual operation.

As shown in Figure 2, it is the back pressure, end difference and efficiency change trend of the extraction - high back pressure unit on a certain day. The average value and standard deviation of the data within a day are calculated respectively, as shown in Table 3. The standard deviation of the efficiency is the smallest, and the change range is very small. It can basically be regarded as remaining unchanged. Therefore, the fixed efficiency method can be adopted to conduct off-design condition analysis on the heating condenser.

2.6 Performance indicators

The energy utilization rate is defined as Equation 20:

$$\eta_{tp} = \frac{3.6P_e + Q_h}{Q_{tp}} \quad (20)$$

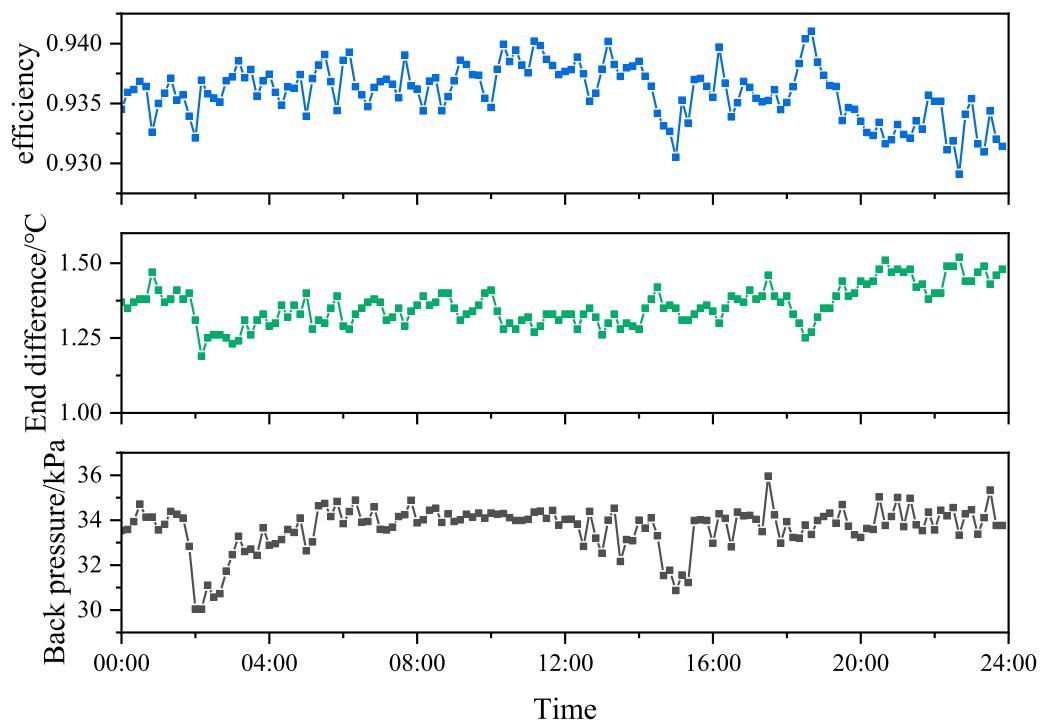


FIGURE 2 The changes in the back pressure, end difference and efficiency of the unit within a certain day.

TABLE 3 The average value and standard deviation of the changes in the back pressure, end difference and efficiency of the unit within a certain day.

Parameters	Average	Standard deviation
Back pressure/kPa	33.67	0.9856
End difference/°C	1.36	0.0649
Efficiency	0.9359	0.0023

where P_e is the power generation output in MW; Q_h is the total heat load of the plant, GJ/h; Q_{tp} is the total heat consumption of the plant, GJ/h.

The coal consumption rate coal consumption rate is calculated by Equation 21:

$$b_e = \frac{Q_{tp}}{P_e Q_{LHV}} \cdot 10^{-6} \quad (21)$$

where Q_{LHV} is the low heat value of coal, kJ/kg.

2.7 Model validation

When establishing the thermodynamic model of the direct air-cooled unit, the design parameters of the unit under the Boiler Maximum Continuous Rating (BMCR) condition, Turbine Heat Acceptance (THA) condition, and 30% of the rated main steam flow

rate condition, provided by the combined heat and power (CHP) plant, were adopted. Off-design condition simulation calculations were conducted for the above three operating conditions, and the results were compared with the parameters from the heat balance diagram provided by the steam turbine manufacturer. As shown in Table 4, the simulation calculation errors of the main steam flow rate and heat rate under the three operating conditions are all less than 1%. This indicates that the established model has high accuracy and can be used for the thermal system simulation of the unit under off-design conditions.

3 Results and discussion

3.1 The influence of exhaust steam flow from air-cooled islands

The back pressure of the direct air-cooled unit decreases with the increase of the head-on wind speed and increases with the increase of the ambient temperature (Zhao et al., 2014). This study focuses on discussing the operation characteristics of the air-cooled extraction-high back pressure unit. The head-on wind speed and ambient temperature can be regarded as remaining constant, and the exhaust steam flow rate entering the air-cooled island affects the heating situation of the unit.

When the power load N_d and the heating steam D_{HS} remain constant, the influence of the change in the exhaust steam D_{AC} entering the air-cooled island on the operating parameters of the unit is shown in Figures 3, 4, and the influence on the energy consumption characteristics of the unit is shown in Figure 5.

TABLE 4 Model validation of the.

Condition	Main steam flow rate (t/h)			Heat consumption rate (kJ/kWh)		
	Calculation results	Designed value	Error	Calculation results	Designed value	Error
BMCR	1179.06	1172	0.60%	17239.56	17,387.33	0.85%
THA	1103.61	1112	0.75%	17438.59	17,588.62	0.85%
30%THA	358.19	360	0.50%	52613.08	52,906.27	0.55%

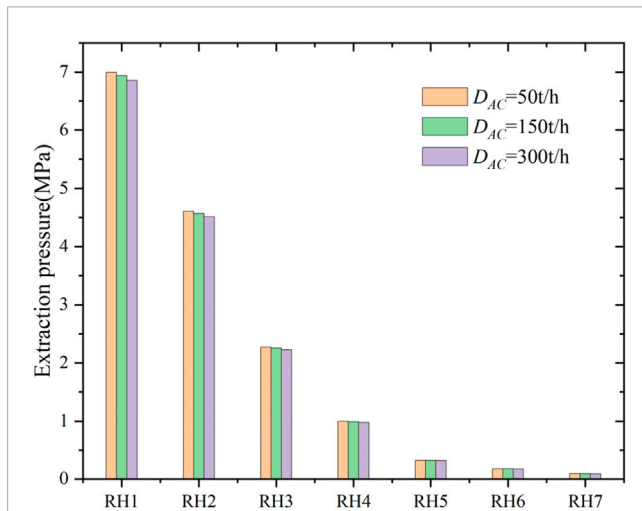


FIGURE 3 The influence of the exhaust steam entering the air-cooled island on the extraction pressure at each stage of the unit.

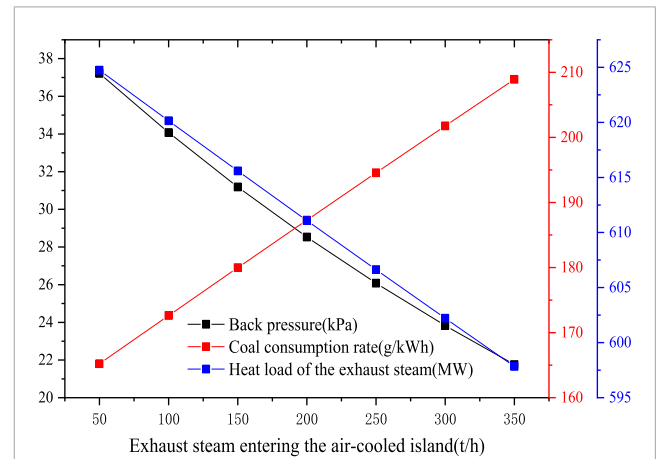


FIGURE 5 The influence of the exhaust steam entering the air-cooled island on the energy consumption of the unit.

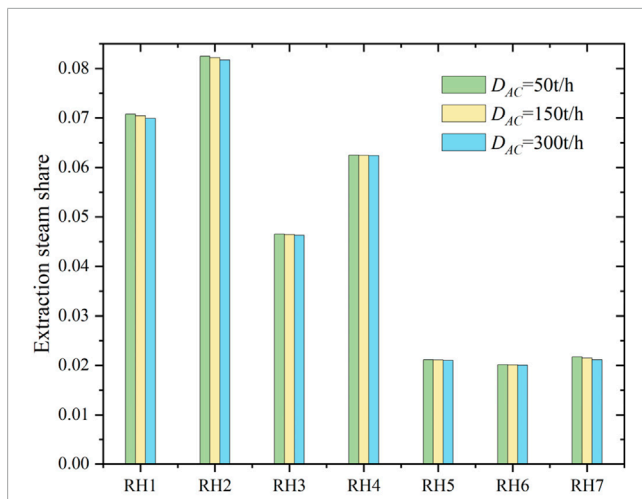


FIGURE 4 The influence of the exhaust steam entering the air-cooled island on the extraction steam share at each stage of the unit.

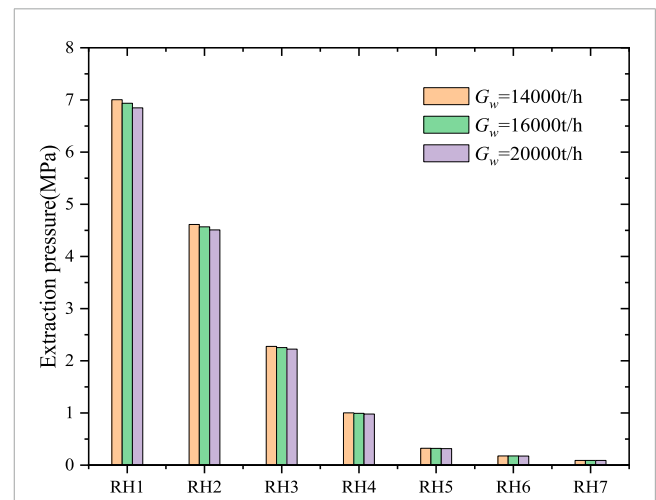
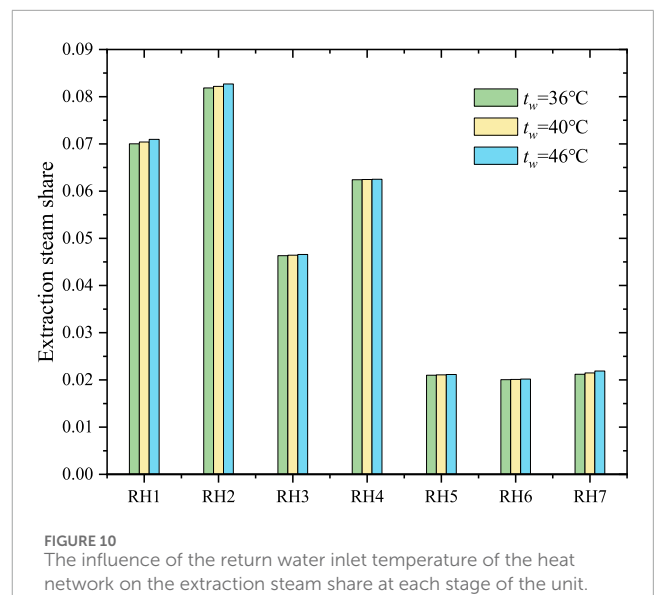
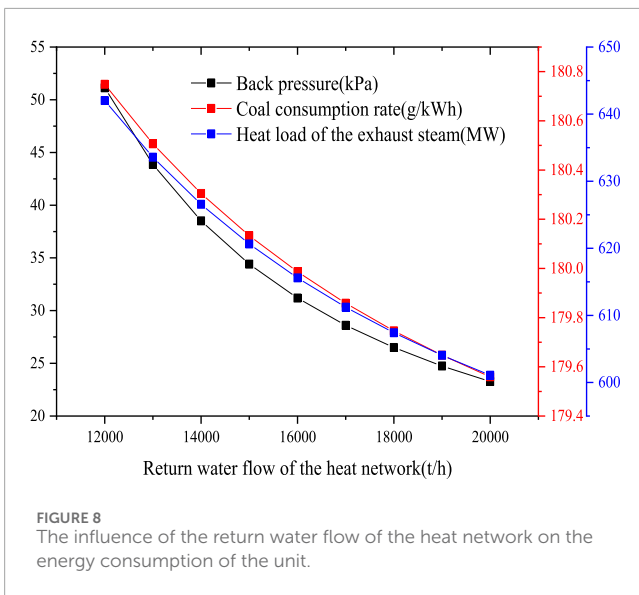
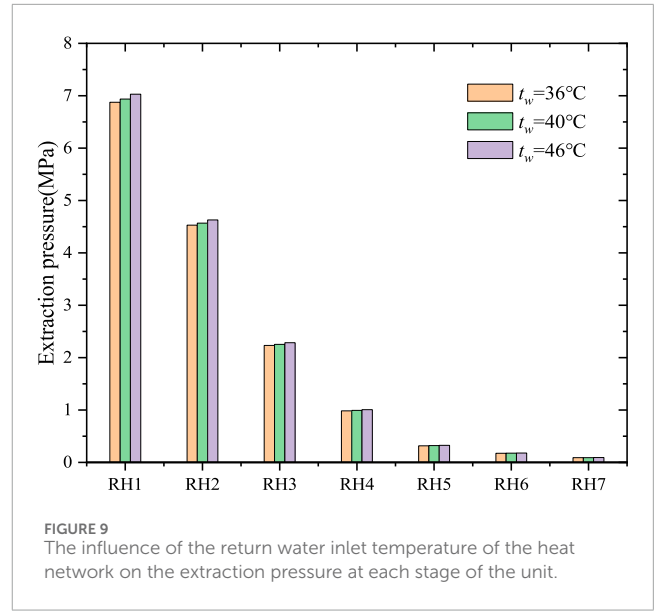
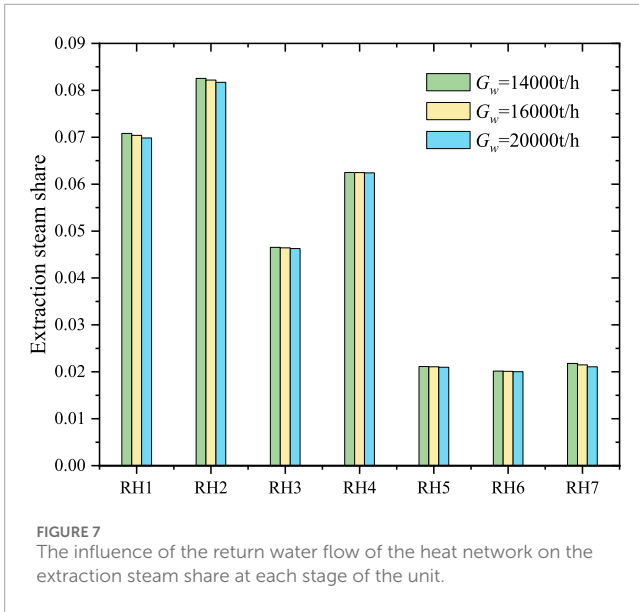


FIGURE 6 The influence of the return water flow of the heat network on the extraction pressure at each stage of the unit.

With the increase of the exhaust steam flow entering the air-cooled island, the main steam pressure and the extraction steam pressure at each stage of the regenerative system decrease uniformly, and the extraction steam share also decreases uniformly, resulting in a reduction in the main steam flow. The exhaust steam used for heating

is more affected by the exhaust steam entering the air-cooled island, with a significant reduction in flow rate. Correspondingly, the heat load of the exhaust steam decreases, the back pressure also drops, and the energy consumption for heating decreases. Moreover, the exhaust steam entering the air-cooled island, as a cold source loss, keeps increasing, thus the coal consumption rate rises.



3.2 The influence of heat network return water flow

The high back pressure unit relies on the heating condenser to provide the heat load. The heat load of exhaust steam is affected by the heat exchange capacity of heating condenser, the exhaust steam parameters, and the return water parameters of the heat network.

When the power load N_d and the heating steam D_{HS} remain constant, and the exhaust steam flow D_{AC} entering the air-cooled island is kept at 150 t/h, the influence of the return water flow of the heat network on the operating parameters of the unit is shown in Figures 6, 7. With the increase of the heat network return water flow, the main steam pressure of the unit and the extraction steam pressure at each stage of the regenerative system decrease. The greater the heat network return water flow, the smaller the decrease,

and the extraction steam share also decreases accordingly, resulting in a reduction in the main steam flow.

The impact on the energy consumption characteristics of the unit is shown in Figure 8. As the heat network return water flow increases, the proportion of heating exhaust steam decreases, and the heat absorption capacity of the return water increases. Since the efficiency of the heating condenser remains unchanged, the saturation temperature of the heating condenser decreases, the back pressure drops, and the heat load of the exhaust steam also decreases accordingly. If the D_{AC} remains unchanged, the cold source loss remains basically the same, the heat absorption capacity of the return water increases, the coal consumption of the unit decreases as the main steam flow decreases, the overall energy consumption drops, and the coal consumption rate decreases.

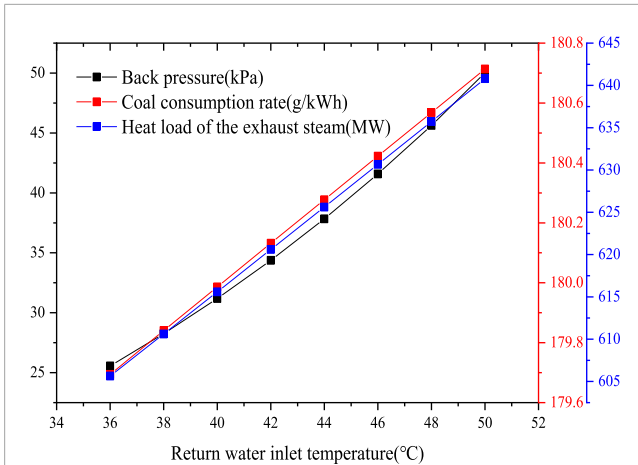


FIGURE 11
The influence of the return water inlet temperature of the heat network on the energy consumption of the unit.

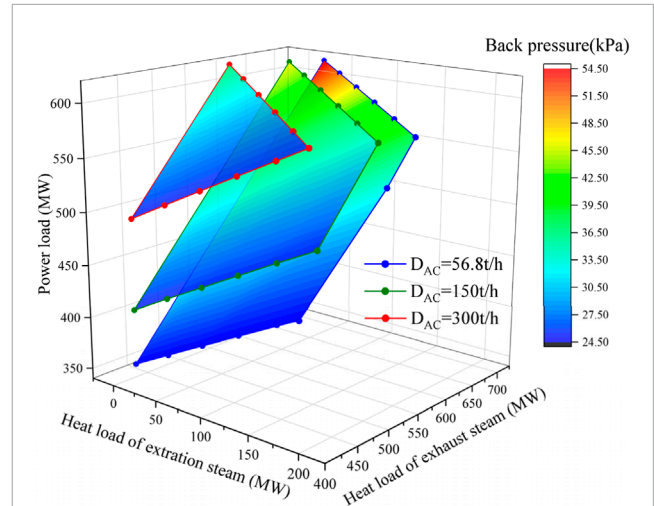


FIGURE 13
The variation of back pressure within the operating domain under different air-cooled island flow rates.

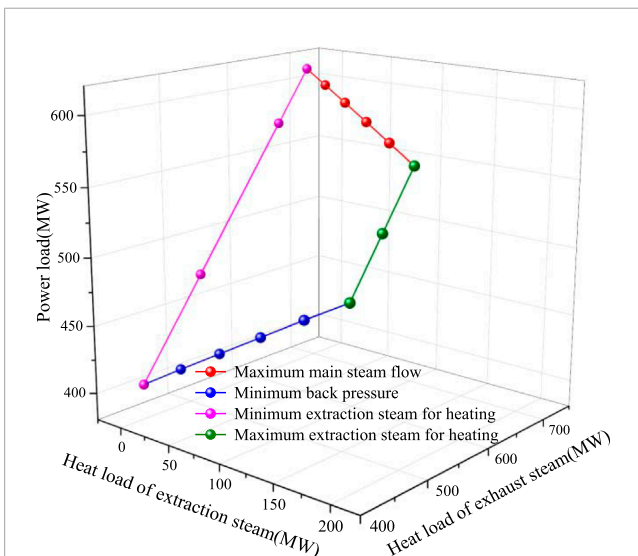


FIGURE 12
The operation domain of the unit (the exhaust steam entering the air-cooled island is 150 t/h).

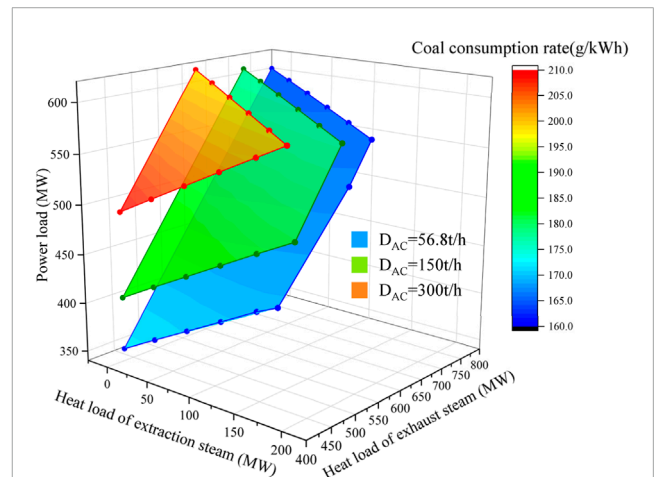


FIGURE 14
The variation of coal consumption rate within the operating domain under different air-cooled island flow rates.

3.3 The influence of heat network return water inlet temperature

When the power load N_d and the heating steam D_{HS} remain constant, and the exhaust steam flow D_{AC} entering the air-cooled island is kept at 150 t/h, the influence of the return water inlet temperature of the heat network on the operating parameters of the unit is shown in Figures 9, 10. As the return water inlet temperature increases, the main steam pressure of the unit and the extraction steam pressure at each stage of the regenerative system rise uniformly, and the extraction steam share also rises uniformly, resulting in an increase in the main steam flow rate.

The impact on the energy consumption characteristics of the unit is shown in Figure 11. As the return water inlet temperature

increases, the proportion of heating exhaust steam increases, the saturation temperature of the heating condenser and back pressure rise, the heat load of the exhaust steam increases, and the coal consumption of the unit increases with the increase of the main steam flow. The overall energy consumption rises, and the coal consumption rate increases.

3.4 The operation domain of the unit

After the unit is modified to have a high back pressure, the rated back pressure is 35kPa, and it is not less than 25 kPa in actual operation. After adding extraction steam for heating, up to 250 t/h of extraction steam can be provided for heating, with a maximum heating capacity of approximately 195 MW. The operation of the unit is restricted by the maximum main steam flow rate, the

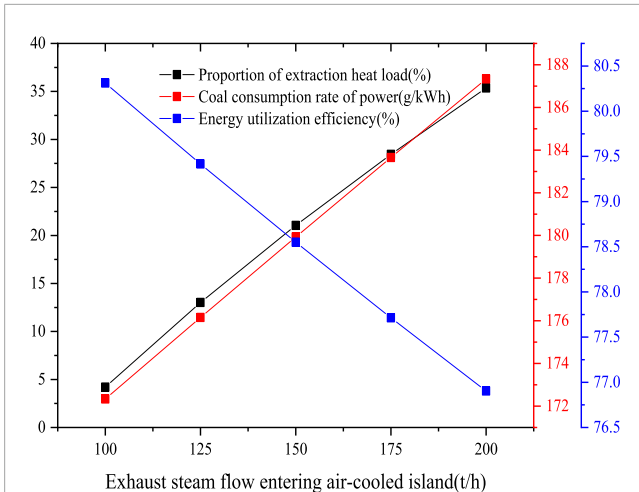


FIGURE 15
The influence of the exhaust steam entering air-cooled island on the sharing ratio of heat load of extraction steam and exhaust steam of the unit and energy consumption.

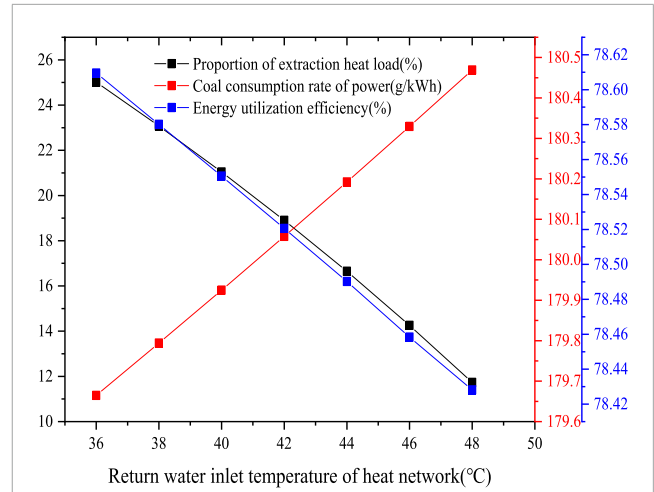


FIGURE 17
The influence of the return water inlet temperature of heat network on the sharing ratio of heat load of extraction steam and exhaust steam of the unit and energy consumption.

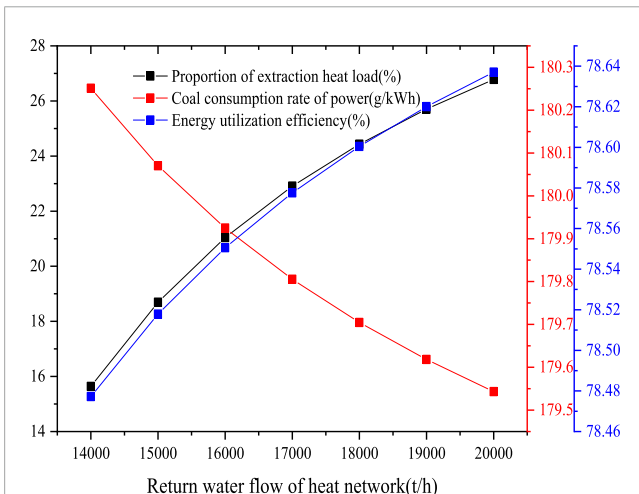


FIGURE 16
The influence of the return water flow of heat network on the sharing ratio of heat load of extraction steam and exhaust steam of the unit and energy consumption.

minimum back pressure, the minimum extraction steam flow rate for heating (without extraction steam), and the maximum extraction steam flow rate for heating. When the exhaust steam flow rate D_{AC} entering the air-cooled island is 150 t/h, the operation domain is shown in Figure 12.

When the exhaust steam flow of the air-cooled island changes, the unit operation domain also changes. When the exhaust steam flow (D_{AC}) of the air-cooled island is 56.8 t/h, 150 t/h, and 300 t/h respectively, the unit operation domains are shown in Figures 13, 14. As D_{AC} increases, the area of the electric-heat load operation domain gradually decreases, and the flexibility of the unit decreases.

When the D_{AC} is 56.8 t/h, the back pressure operation range of the unit is 24.5–54.5 kPa. However, when the D_{AC} increases to 300 t/h, the back pressure operation range of the unit is reduced to 24.5–38 kPa, a reduction of 55%. At the same time, the larger the

exhaust steam flow of the air-cooled island, the more stable the unit's back pressure. However, when the D_{AC} increases from 56.8 t/h to 300 t/h, the coal consumption rate of the unit increases by 50 g/kWh.

3.5 The influence of the sharing ratio of extraction heat load and exhaust heat load

The heat load of the extraction - high back pressure unit is composed of the extraction heat load and the exhaust heat load together. When the external heating load and the supply water temperature remain unchanged, changing the cold end parameters will affect the proportional relationship between the heat load of the extraction and the heat load of the exhaust, and thereby affect the overall energy consumption of the cogeneration unit. As shown in Figures 15–17, they respectively represent the influence of the changes in the exhaust steam flow rate entering air-cooled island, the heat network return water flow rate and the return water inlet temperature on the sharing ratio of heat load of extraction steam and exhaust steam of the unit and energy consumption.

With the increase of the exhaust steam flow rate entering air-cooled island, the heat load of exhaust steam decreases, the proportion of the heat load of extraction steam increases, the cold source loss of the unit increases, the coal consumption rate rises, and the energy utilization efficiency decreases. When the exhaust steam flow rate entering air-cooled island remains unchanged, with the increase of the return water flow rate, the heat exchange capacity of the heating condenser is enhanced, the back pressure is reduced, the proportion of the heat load of the extraction steam increases, but the waste heat of the exhaust steam is fully utilized, the coal consumption rate decreases, and the energy utilization efficiency improves. As the return water temperature rises, the heat exchange capacity of the heating condenser weakens, the back pressure increases, the proportion of the heat load of the extraction steam decreases, the coal consumption rate increases, and the energy utilization efficiency drops, which is not conducive to the effective utilization of waste heat.

TABLE 5 The adjustment result of the heat load of the extraction steam.

Conditions	Extraction heating steam flow (t/h)	Proportion of extraction heat load (%)	Coal consumption rate (g/(kWh))	Energy utilization efficiency (%)
No extraction steam heat load	0	0	179.57	78.22
Air-cooled island regulation	250	27.88	183.35	77.78
Return water flow regulation	250	27.88	179.47	78.65
Return water temperature adjustment	250	27.88	179.47	78.65

The maximum extraction heating capacity can reach 250 t/h, with a heating capacity of approximately 195 MW. When the total heat load is 700 MW, the proportion of the extraction heat load is approximately 27.9% at its maximum. By adjusting the exhaust steam flow rate entering air-cooling island, the return water flow rate and temperature of the heat network, the proportion of the heat load of the extraction steam can be changed to maximize the heat extraction steam supply. The adjustment results are shown in Table 5. Compared with no extraction steam heat load, the adjustment of the air-cooled island will increase the coal consumption rate by approximately 3.78 g/(kW·h) and reduce the energy utilization efficiency by 0.44%. The regulation effect of the return water flow and temperature of the heat network is consistent, which can reduce the coal consumption rate by approximately 0.1 g/(kW·h) and increase the energy utilization efficiency by 0.43%.

4 Conclusion

This paper comparatively analyzes the calculation methods of off-design conditions of the heating condenser. The off-design condition analysis is carried out by using the efficiency-number of heat transfer unit method. The operation and energy consumption characteristics of the cogeneration unit under the constraints of the exhaust steam flow rate entering air-cooled island, the return water flow rate of the heat network, and the return water temperature of the heat network are discussed. The following conclusions are obtained.

1. The exhaust steam flow rate entering air-cooled island, the return water flow rate of the heat network, and the return water temperature of the heat network not only affect the heat transfer performance of the primary network but also influence the extraction pressure and extraction ratio of the regenerative system of the cogeneration unit.
2. The operation of the unit is restricted by the maximum main steam flow, the minimum back pressure, and the minimum and maximum heating extraction steam flow. As the exhaust steam flow rate entering air-cooled island increases, the operation domain gradually decreases, the flexibility of the unit declines, the variation range of the back pressure shrinks, and the coal consumption rate increases.
3. The exhaust steam flow rate entering air-cooled island, the return water flow and temperature of the heat network can regulate the heating extraction steam and thereby affect the energy consumption of the unit. The decrease of back pressure

and the increase of the proportion of extraction steam heat load caused by the exhaust steam flow rate entering air-cooled island will increase the energy consumption of the unit, while the decrease of back pressure and the increase of the proportion of extraction steam heat load caused by the return water flow rate and temperature of the heat network can reduce the energy consumption of the unit. Compared with no extraction steam heat load, under the maximum extraction heat load condition, the coal consumption rate decreases by approximately 0.1 g/(kW·h), and the energy utilization efficiency increases by 0.43%.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

CS: Conceptualization, Methodology, Writing – original draft. TW: Conceptualization, Supervision, Writing – review and editing. CF: Methodology, Visualization, Writing – original draft. WH: Methodology, Validation, Writing – original draft. XY: Investigation, Resources, Writing – review and editing. BZ: Formal Analysis, Investigation, Writing – review and editing.

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Conflict of interest

Authors CS, TW, WH, XY, and BZ were employed by Chn Energy Zhejiang Beilun Power Generation Co., Ltd. Author CF was employed by Guoneng Nanjing Electric Power Test and Research Limited.

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