

Operation Flexibility Analysis of Combined Heat and Power Plant Using High and Low Bypass

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Abstract—China's energy structure is currently in the transition stage, in order to absorb large-scale new energy into the network, it is necessary to improve the flexibility of cogeneration units, high and low bypass heating technology is an excellent flexibility transformation technology, can effectively improve the peak load capacity and heating capacity of heating units. Based on a 2×350 MW supercritical unit in North China, this paper uses EBSILON modeling and simulation software to build thermodynamic models of the unit's pure condensate condition, IP cylinder exhaust steam extraction heating mode and high and low bypass heating mode. The reliability of the models is demonstrated by comparing with the designed values. According to the boundary conditions of variable operating conditions of the unit, the calculation results of the whole operating range of the model show that the thermo-electric decoupling ability of the unit is improved by the high-low pressure bypass heating mode. Compared with the IP exhaust steam extraction heating mode, the maximum heat load is increased by 41.6%, and the minimum electric load after heating is reduced by 13.2%. The heat economy of the high and low bypass heating system is relatively poor, and the heat consumption of power generation is increased by 14%–47% compared with that of the IP exhaust steam extraction heating system. The unit with high and low bypass heating operation has a larger thermoelectric load operation range, and under the same heating load, the high and low bypass heating unit has a larger electric load peak loading range, so that the unit has a better flexible operation capacity, which has a positive reference value for the implementation of the flexibility transformation of the heating unit.

Keywords—thermo-electric decoupling, high and low bypass heating, depth peak regulation, flexible transformation

I. INTRODUCTION

With the proposed goal of China's dual-carbon strategy, China's energy structure needs to be transformed and reformed. Renewable energy based on wind power and photovoltaic power has been developing rapidly, but due to the characteristics of volatility and instability of renewable energy, its rapid development has brought great challenges to the stability of power system operation. China's existing energy base

determines that thermal power units will be the main pillar of the power system for a long time, so it is necessary to implement flexible transformation of thermal power units under the premise of not affecting the safe and stable operation of existing power plants, in response to the national policy requirements on renewable energy consumption and improving the flexibility of unit operation. Improve the peak load capacity of the unit under the premise of ensuring the constant external heating capacity, so as to achieve better new energy consumption.

According to the statistics of relevant departments, in the past 10 years, the grid-connected capacity of wind power and photovoltaic power has accounted for an increasing proportion in the structure of China's power system. From 2010 to 2022, the total grid-connected capacity of wind power and photovoltaic power has increased from 54.7 million kilowatts to 758.1 million kilowatts, and the proportion of installed capacity has increased from 4.5% to 29.6% [1.2]. Renewable energy represented by wind power and photovoltaic power is developing rapidly. At present, the power system mainly realizes the collaboration between new energy and thermal power by adjusting the load of coal-fired power plants, and realizes the absorption of wind power photovoltaic renewable energy. At the same time, due to the consideration of improving energy efficiency and meeting the heating demand of various aspects of the city, most thermal power plants now adopt the operation mode of cogeneration, and most of them adopt the mode of "fixing electricity by heat" [3]. This operation mode makes it impossible for cogeneration units to carry out deep peaking during the heating period and causes the phenomenon of wind power and photovoltaic power abandonment during the heating period in areas of the northeast, north, and northwest China [4.5].

The traditional heating unit often adopts the heat supply technology of IP exhaust steam extraction. When the unit needs to be modified flexibly, high and low bypass heating as a depth peak heating technology has been widely concerned. Huang et al. proposed a strategy to adjust the high and low voltage bypass flow, evaluated the thermoelectric decoupling scheme, and

proposed to take the maximum heating capacity and minimum electric load of the unit as the quantitative evaluation index [6]. Liu et al. proposed the basic control principle that the high and low bypass steam flow should be properly matched according to the system characteristics of the high and low bypass heating transformation and the safe operation requirements of the unit, designed the control strategy of the high and low bypass, turbine medium pressure regulating valve and bypass water spray temperature reduction system, and added the compensation loop for unit coordinated control [7]. Gao et al. put forward a calculation method of the safety zone including two-stage bypass heating unit, and made use of the design parameters of the unit and bypass system for calculation and comparison verification, and found that the introduction of two-stage bypass compensation heating can greatly improve the thermo-electric decoupling and deep peaking capacity of the heating unit [8].

The above research mainly expounds the layout design of the heat-supply unit bypass system, the operation strategy of the high and low bypass transformation system of the heat-supply unit, and the use of the high and low bypass heating to improve the depth of the cogeneration unit peak regulation. In this paper, the EBSILON simulation software is used to establish the thermodynamic model of two heating modes for a 350MW supercritical cogeneration unit in North China. The thermo-electric decoupling capacity, generation heat consumption and operating range of thermoelectric load of the two heating modes are analyzed according to the simulation operation results. It provides a reference for the flexible transformation of cogeneration units.

II. UNIT OVERVIEW AND MODEL BUILDING

A. Case Unit Overview and Modeling

The unit used in this paper is a 2×350MW cogeneration unit of a power plant in North China. The supporting boiler model is B&WB-1242/25.4-M; The supporting turbine model is CJK350/279-24.2/0.45/566/566, with features of supercritical single reheating, double cylinder and extraction type indirect air-cooling. The main parameters of the unit are shown in Table I.

TABLE I. MAIN PARAMETERS OF THE UNIT

Item	Unit	Content
Rated power	MW	350
Maximum power	MW	394.4
Main steam pressure	MPa	24.2
Main steam temperature	°C	566
Main steam flow	t/h	1078.9
Reheat steam temperature	°C	566
Exhaust pressure	kPa	10
Feed temperature	°C	288.4
Heat rate	kJ/kW. h	7943

The unit initially uses the conventional IP cylinder exhaust steam extraction heating method, uses 5-stages of extraction steam as the heating steam source, and the steam drain into the condenser after heating. The rated heating pressure is 0.45MPa,

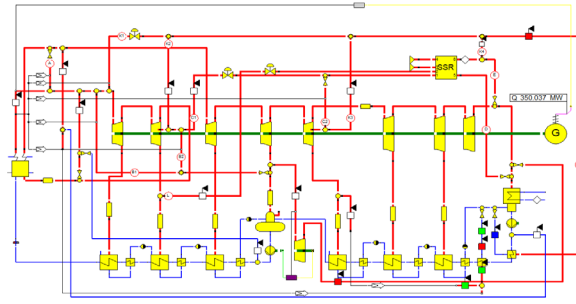


Fig. 1. Integrated heating model of the unit.

the rated extraction steam volume and the maximum extraction steam volume are 550 t/h and 570 t/h respectively.

Based on the thermodynamic design drawing of the unit and the actual thermodynamic system parameters, the thermodynamic system is modeled by EBSILON. The boiler, steam turbine, condenser, water pump, deaerator, heater and other components in EBSILON are used for modular modeling of the unit system, and the unit model is built as shown in Figure 1.

In order to verify the reliability of the built model [9], 100%THA working conditions and 75%THA working conditions of the unit were selected as the baseline comparison working conditions of the model according to the steam flow process of the thermal system of the whole plant, and the calculation data of the model under the two working conditions were compared with the design parameters to verify the accuracy of the simulation results under variable operating conditions. The design parameters of the unit are obtained from the thermal balance diagram of the turbine under varying working conditions. The comparison results are shown in Table II.

TABLE II. COMPARISON OF SIMULATION PARAMETERS AND DESIGN PARAMETERS IN PURE COAGULATION CONDITION

Item	100%THA			75%THA		
	Design value	Simulation value	error	Design value	Simulation value	error
#1 Extraction pressure	7.29	7.27	0.26%	5.375	5.327	0.89%
#1 Extraction temperature	385.6	385.58	0.01%	375.8	369.8	1.59%
#2 Extraction pressure	5.247	5.234	0.25%	3.893	3.862	0.79%
#2 Extraction temperature	340.2	340.18	0.01%	332.3	326.8	1.66%
#3 Extraction pressure	2.265	2.26	0.22%	1.694	1.676	1.06%
#3 Extraction temperature	455.8	455.8	0.00%	457.8	457.7	0.02%

#4 Extraction pressure	0.913	0.911	0.22%	0.7	0.692	1.14%
#4 Extraction temperature	330	330.0	0.00%	335.4	335.22	0.05%
#5 Extraction pressure	0.452	0.45	0.22%	0.348	0.344	1.15%
#5 Extraction temperature	244.7	244.69	0.00%	250.2	249.82	0.15%
#6 Extraction pressure	0.14	0.14	0.00%	0.108	0.107	0.926%
#6 Extraction temperature	133.5	133.52	-0.02%	137.7	138.18	-0.35%
#7 Extraction pressure	0.069	0.069	0.00%	0.054	0.054	0.00%
#7 Extraction temperature	89.5	89.55	-0.06%	83.1	83.03	0.08%
Exhaust enthalpy	2381.9	2382.2	0.01%	2424.9	2425.2	0.01%
Feed temperature	288.1	286.83	-0.44%	268.2	269.4	0.45%

As can be seen from Table 2, compared with the design value, the relative errors of the parameters calculated by the model established in this paper are all less than 3%. The parameters of the simulation model established are highly consistent with the design parameters of the reference unit, which meets the accuracy requirements of the actual project, and can be used for the analysis of the unit's variable working condition characteristics.

B. Introduction and Model Building of Extraction Steam Heating Technology

The thermal system of medium-pressure cylinder exhaust steam extraction heating technology is shown in Figure 2. The IP exhaust steam extraction heating technology is a traditional external heating method used in thermal power plants. The heating method perforates the connecting pipe of the medium-pressure cylinder and the low-pressure cylinder to extract steam to the heating network heater for heating. This part of steam is originally to enter the low-pressure cylinder to do work, so the power generation of the heating extraction unit will decrease, and the heat utilization rate of the unit will decrease. The model of IP exhaust steam extraction heating unit is built by modifying the model of pure condensing condition of the unit. The minimum load condition of 500t/h for IP exhaust steam extraction heating was selected to verify the model, and the simulation parameters were compared with the design parameters of the heat balance diagram to verify the correctness of the model. The comparison results are shown in Table III.

The thermal system of high-low bypass combined heating technology is shown in Figure 3. The main principle of this heating technology is to extract steam from the main steam through the high-pressure bypass pipe, reduce the temperature and reduce the pressure through the high-side desuperheater, and

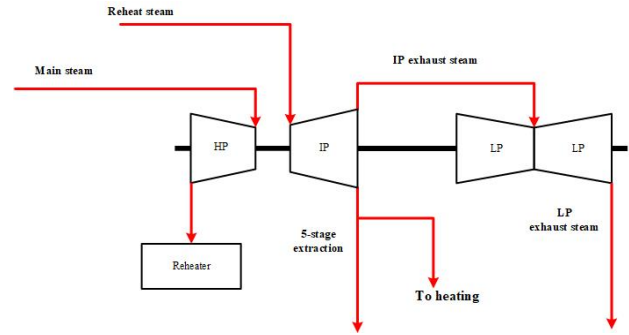


Fig. 2. Unit IP exhaust steam extraction heating system.

then transport it to the exhaust steam end of the high-pressure cylinder, and then enter the steam turbine reheat steam pipe through the boiler reheater. Then, the steam extracted from the reheated steam pipeline is used as the steam source for heating extraction after the temperature and pressure reduction of the low-side desuperheater [10.11]. Under the heating extraction method, the amount of steam entering the high-pressure cylinder is reduced, and the work of the high-pressure cylinder is reduced, which will also cause the power generation to decrease, and the heat consumption rate of the unit will also decrease. The high-low bypass steam extraction heating model was built through the transformation of the unit's pure condensate working condition model, and 30%THA bypass heating condition was selected for model verification. The simulation parameters were compared with the design parameters of the heat balance diagram to verify the correctness of the model, and the comparison results were shown in Table III.

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As can be seen from Table III, compared with the design value, the relative errors of the parameters calculated by the model established in this paper are all less than 3%. The parameters of the simulation model established are highly consistent with the design parameters of the reference unit, which meets the accuracy requirements of the actual project, and can be used for the calculation and simulation of the heating extraction process of the heating unit.

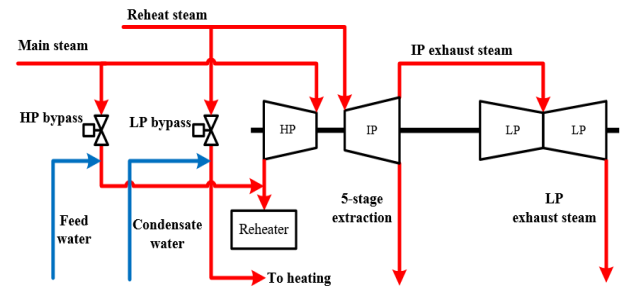


Fig. 3. High and low bypass combined heating system.

TABLE III. COMPARISON OF SIMULATION PARAMETERS AND DESIGN PARAMETERS OF TWO HEATING CONDITIONS

Item	IP exhaust steam extraction 500t/h minimum load condition			30%THA bypass heating condition		
	Design value	Simulation value	error	Design value	Simulation value	error
Generating capacity	258.48	258.48	0.00%	105	105	0.00%
Main steam flow	1065.5	1055.5	0.94%	792	807.56	-1.97%
Reheat steam flow	853.99	846.49	0.88%	310.57	314.36	-1.22%
Exhaust enthalpy	2427.7	2381.7	1.89%	2403.3	2382.6	0.86%
Feed water temperature	288.5	286.99	0.52%	221.4	222.8	-0.63%
High-side extraction steam flow				352.8	353.12	-0.09%
Low-side extraction steam flow				418.2	417.34	0.21%

III. COMPARATIVE ANALYSIS OF THE PERFORMANCE OF TWO HEATING METHODS

To determine the boundary conditions of the model, the main steam flow rate of the unit is 1242t/h when the valve is fully open (VVO condition), and the main steam flow rate is 365.4t/h when the minimum steady combustion operation condition is 365.4t/h. Therefore, the variation range of the main steam flow in the simulation calculation in this paper is 365.4-1242 t/h. The unit should ensure the limit of the low-pressure cylinder inlet steam flow, the minimum inlet steam flow of the low-pressure cylinder is 136.4t/h, so the minimum inlet steam of the low-pressure cylinder cannot be less than 136.4t/h.

A. Maximum Heating Load

When the main steam flow is constant, limited by the minimum inlet steam flow of the low-pressure cylinder, the steam extraction capacity of the unit has a maximum value, and the heating capacity is the maximum heating load of the unit under the main steam condition, and its calculation formula is as follows:

$$Q_{gr} = \frac{M_{cq}(h_{cq} - h_{sh})}{3600} \quad (1)$$

In the above formula, Q_{gr} is the maximum heat supply, MW; M_{cq} is the maximum heat extraction volume of the unit, t/h; h_{cq} is the enthalpy of heat extraction, kJ/kg; h_{sh} is the hydrophobic enthalpy after heating, kJ/kg.

When only the heat load of the heat supply network is considered, the main steam flow of the model is set, and other parameters are simulated with the principle of maximum heat load under the condition that the boundary conditions are not

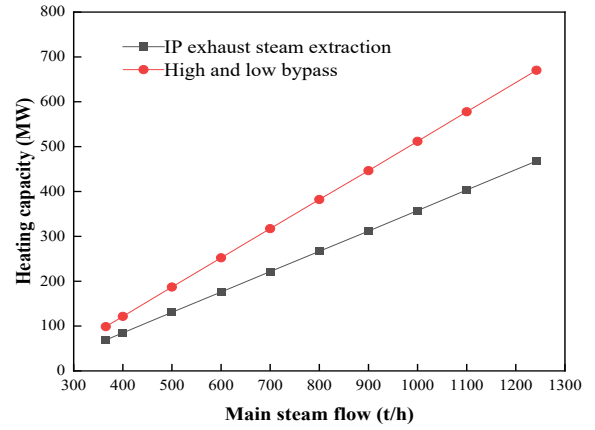


Fig. 4. Relationship between maximum heating capacity and main steam flow.

exceeded. In order to compare the maximum heating capacity of the two heating methods, the steam extraction simulation of the unit was carried out under the same main steam flow rate. The maximum heat supply of the unit varies with the main steam flow, as shown in Figure 4. It can be concluded from the figure that under the condition of a certain main steam flow, the heating capacity of the high and low bypass heating unit is greatly improved compared with that of the IP exhaust steam extraction heating.

B. Minimum Electrical Load

Under the condition that the heat supply demand of the unit is certain, the electric load has the minimum value, that is, the minimum electric load. The lower the minimum electric load, the stronger the peaking capacity. Under the condition of providing the same amount of heat supply, the heat supply simulation of different heating methods is carried out to analyze the peak load capacity of different heating methods on the unit.

In the operation range of the main steam flow, the same heat supply is taken as the setting condition, and two extraction steam heating methods are respectively run to simulate the unit, so as to compare and analyze the peak load capacity of different heating methods. According to the calculation results obtained from the simulation, the relationship between the minimum electric load of the unit and the main steam flow under the same heating demand is shown in Figure 5.

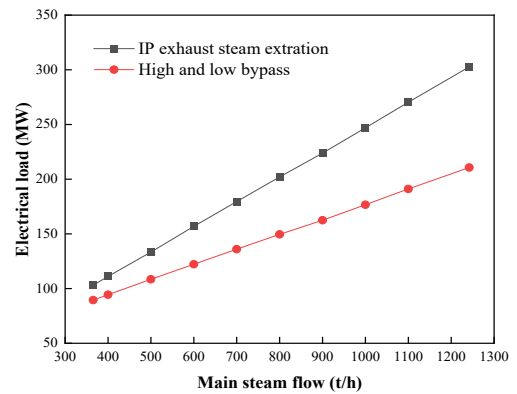


Fig. 5. Relationship between minimum electric load after heating and main steam flow.

As can be seen from Figure 5, under the same heat load condition, the electric load of high and low bypass heating mode is lower than that of IP exhaust extraction steam heating mode under different main steam conditions, and the minimum electric load is 13.2% lower. With the increase of main steam flow, the difference of electric load between high and low bypass heating and IP exhaust extraction steam heating is also increasing, the maximum is 92MW. When the unit adopts the high and low bypass heating mode, the unit has a larger electric load operating range.

C. Heat Consumption of Electricity Generation after Heating

After steam extraction for external heating, the power generation heat consumption of the unit will change because part of the total heat of the boiler is used for external heating. For the heating unit, the power generation heat consumption is the ratio of the net power generation heat of the unit to the power generation, the calculation formula is as follows:

$$q_r = \frac{Q_{gl} - Q_{gr}}{P} \times 3600 \quad (2)$$

In the above formula, q_r is the electric heating consumption after heating the unit, kJ/(kW·h); Q_{gl} is the total heat absorption of boiler, MW; Q_{gr} is the external heating capacity of the unit, MW; P is the generator power, MW.

In order to study the influence of two heating methods on the power generation heat consumption of the unit, by determining the same heating amount, the heating simulation of the unit with two heating methods is carried out to compare the change of the electric heating consumption of the unit with two heating methods after heating. The variation of electric heating consumption after unit heating with main steam flow is shown in Figure 6.

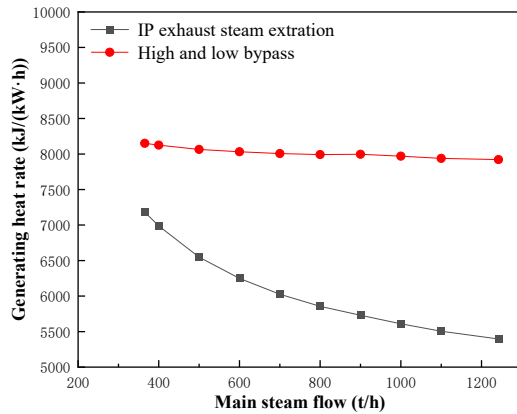


Fig. 6. Relationship between generation heat rate after heating and main steam flow.

As can be seen from Figure 6, when the heating load is the same, the electric heating consumption after heating of the high and low bypass heating unit is generally higher than that of the IP exhaust extraction steam heating unit. Compared with the medium-exhaust extraction steam heating unit, the high-quality steam heat loss of the high and low bypass heating unit is greater, the heat economy is worse, and the power generation heat consumption is higher, which is 17.6%~53% higher than that of

the IP exhaust extraction steam heating mode. The power generation heat consumption of the high and low bypass heating unit changes little with the change of the main steam. After the IP exhaust steam extraction heating unit, the power generation heat consumption increases with the increase of the main steam, and with the increase of the main steam flow of the unit, the steam extracted from the heating unit is limited, so that more steam can be used for power generation, the energy utilization rate is higher, and the power generation heat consumption is smaller.

D. Minimum Electrical Load for Different Heating Quantities

When the unit is heating, the heat load will change according to the actual heat demand, and the heating capacity of the unit will increase with the increase of the electric load. Because the low-pressure cylinder has the minimum intake flow limit, the unit has the minimum electric load after heating when the heating volume is set. The minimum electrical load of the two heating modes is calculated by changing the heating capacity of the unit. The minimum electrical load of the unit under different heating modes varies with the heating capacity, as shown in Figure 7.

As can be seen from Figure 7, under the condition of the same heating quantity, the minimum electrical load of the unit with high and low bypass heating is always smaller than that with IP exhaust steam extraction heating. Moreover, with the increasing heating quantity, the difference of minimum electrical load between high and low bypass heating and IP exhaust steam extraction heating becomes larger and larger, reaching a maximum of 182.8MW. The flexibility of the unit can be improved by using the high and low bypass heating method, and the unit has a larger heat load operating range.

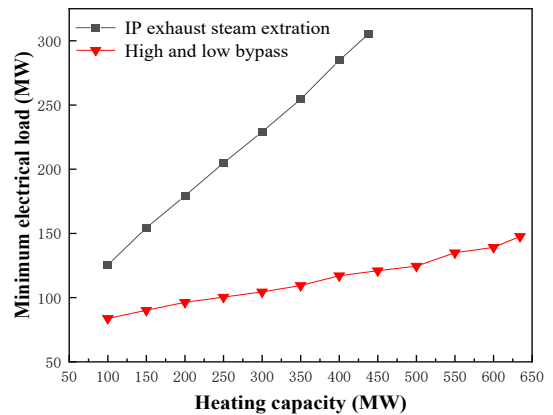


Fig. 7. Minimum electrical load variation for different heating quantities.

E. The Thermal and Electrical Load Operating Range of the unit Heating

When the unit provides external heat supply, it can also play the role of peak regulation. When the unit provides heat supply through the IP exhaust steam extraction method, it realizes the peak regulation function of the unit by adjusting the steam intake volume of the low-pressure cylinder. When the unit is heating by high and low bypass extraction, the peak regulation of the unit is carried out by adjusting the flow of steam into the main

turbine and the flow of steam into the low-pressure cylinder. Due to the limitation of the main steam flow and the minimum steam flow of the low-pressure cylinder, the thermal and electrical load of the unit has an operating range, so the peak load range and thermoelectric characteristics of the unit can be reflected by delimiting the thermal and electrical load operating range of the unit for safe operation. The thermal and electrical load operation range of the unit in the two heating modes is shown in Figure 8.

As shown in Figure 8, the ABCD area is the operating range of the unit under the IP exhaust steam extraction heating mode, while the BCDEF area is the extended operating range of the unit under the high and low bypass heating mode compared with the IP exhaust steam extraction heating mode. Assuming that the heat load of a certain heating demand is H' , PP_1 is the peak load range of the IP exhaust steam extraction heating unit, PP_2 is the peak load range of the high and low bypass heating unit, and P_1P_2 is the increased peak load capacity of the high and low bypass heating mode compared with the IP exhaust steam extraction heating mode. As can be seen from the figure, the peaking capacity of the unit under the operation of high and low bypass heating mode has great advantages compared with the IP exhaust steam extraction heating mode. As the heating load increases, the peaking range of the high and low bypass heating mode also has a larger heat load operating range.

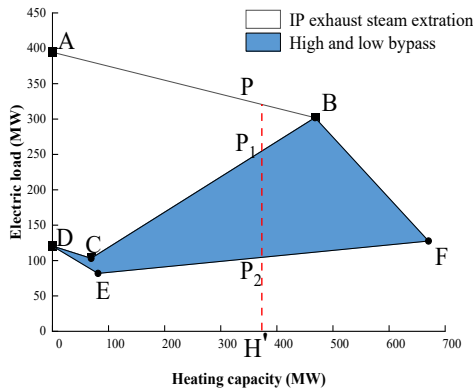


Fig. 8. Operating range of thermo and electric load for heating operation.

IV. CONCLUSION

In this paper, the thermal system model of the heating unit of the power plant is established by using EBSILON simulation software. Based on the built model, the heating simulation of different heating modes is carried out, and the thermoelectric characteristics of the heating capacity, power generation capacity and peak load regulation capacity of the heating unit are analyzed. The following conclusions are drawn:

1) The high and low bypass heating mode has stronger thermo-electric decoupling capacity than the IP exhaust steam extraction heating mode. The high and low bypass heating mode

not only increases the maximum heat supply of the unit, but also reduces the electrical load of the unit. The maximum heat load of the high and low bypass heating mode is increased by 41.6% compared with the IP exhaust steam extraction heating mode, and the minimum electric load is reduced by 13.2% compared with the IP exhaust steam extraction heating mode.

2) When the unit is heated by the high and low bypass heating method, the high quality steam heat loss is greater and the power generation heat consumption is higher than that of the IP exhaust steam extraction heating method, which increases by 14%-47%, and the thermal economy is worse. From the perspective of thermal economy, the high and low bypass heating method is worse.

3) The high and low bypass heating mode has better peak load regulation capacity than the IP exhaust steam extraction heating mode. Under the same heating load, the high and low bypass heating mode always has a larger electric load operating range. Based on the unit operation limit, the high and low bypass heating mode has a larger thermoelectric load operation range, that is, the unit has greater flexibility.

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