RESEARCH ON KEY TECHNOLOGY AND APPLICATION OF FLEXIBILITY TRANSFORMATION OF HEATING UNIT TO IMPROVE CLEAN ENERGY CONSUMPTION CAPACITY

by

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The electric regulation capacity of heating units has been constantly improving due to the promotion of the heating units' flexibility transformation. This improvement has effectively alleviated the long remained serious wind and light abandonment phenomena in the heating season in China. In this paper, we discussed the key technologies of the low pressure zero output heating mode and bypass heating mode, both of which are widely used in thermo-electric decoupling. Moreover, the coupling transformation of the two heating modes has been successfully realized in a heating unit. The electric regulation capacity of the unit has been greatly improved, from 18.6% before the transformation to 66.7%, and the minimum technical output has been also reduced to 14.2% THA. After the transformation, the unit now is able to provide several heating modes with its operational flexibility greatly improved. By comparing the economical efficiency of these heating modes, we obtained the operation mode with the lowest heat rate. This transformation mode provides a huge grid space for the consumption of clean energy, so it is of positive reference value and exemplary significance in implementing the flexibility transformation of heating units.

Key words: *deep peak shaving, thermo-electric decoupling, low pressure zero output, high and low bypass heating*

Introduction

China aims to reduce the proportion of non-fossil energy consumption 15% by 2020. Currently, gradually reducing the use of fossil energy and increasing the use of new energy are the two major goals in the energy field. Power industry usually has huge energy consumption, therefore, the development of clean and renewable energy, such as wind power and solar power, has become a significant way to achieve this objective. Over recent years, the installed capacity of new energy sources has been improved. By the end of 2019, the installed capacity of wind power and solar power has exceeded 200 million kWh, ranking first in the world. Both the installed capacity of wind power and solar power have accounted for more than 10%, as shown in fig. 1.

The rising share of wind and solar power in the energy structure has led to the consumption a more serious issue [1]. In particular, the peak-shaving characteristics such as ran-

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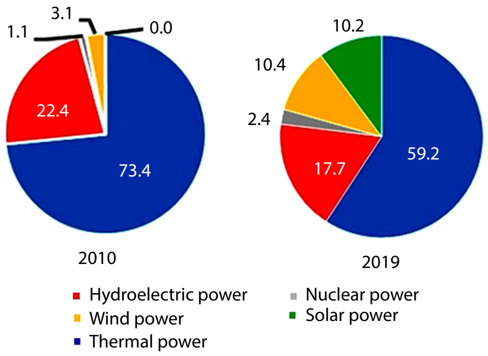

Figure 1. Proportion of installed capacity of various energy sources in China in 2010 and 2019

domness, volatility and uneven distribution of wind power in time and space cause the difficult operation of wind power integration [2], resulting in a serious wind rejection rate [3, 4]. In 2016, the China's wind rejection rate reached 16%, and the wind rejection power reached a record high of 49.7 billion kWh, as shown in fig. 2. Particularly, cogeneration units are the main heat source for winter heating in areas of the northeast, north, and northwest China. Compared with pure condensing units, cogeneration units are subject to the constraint of *heat to* electricity and have limitations in electrical regulation capacity [5] Meanwhile, areas in the northeast, north, and northwest China also face a serious issue called *wind-heat conflicts*. Aforementioned problems led to a wind rejection rate of 43% and wind rejection power of 10.4 billion kWh in China's Gansu Province. In the Xinjiang Uygur Autonomous Region, the wind rejection rate and the wind rejection power were 38% and 13.7 billion kWh, respectively. A huge amount of wind power resources were wasted due to the grid's failure in regulation. The key to consuming new energy is to explore the peak-shaving potential of thermal-electric units, especially the peak-shaving capacity of heating units during the heating season, and to break the operating mode of ordering power by heat [6-8]. Therefore, the flexibility transformation of heating units has become an urgent issue in China's power industry [9].

For this purpose, China plans to implement the flexibility transformation of 220 million-kilowatt coal-fired units during the *13th Five-Year Plan* period, so that the units are capable of deep peak shaving. The pure condensing unit increases the peak shaving capacity by 15-20% of its rated capacity, with the minimum electrical output reaching 30-35% of its rated capacity. Starting from 2017, the newly added peak shaving capacity of thermal power units in China has increased year by year, up to 150 billion kWh in 2019, as shown in fig. 2. Compared with the pure condensing unit, the heating unit needs to be transformed with a thermo-electric decoupling to improve the capacity of electric output regulation under the premise of certain heating load. The situation is more complicated [10, 11].

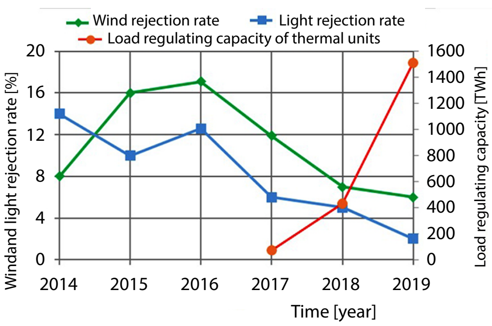

Figure 2. Wind rejection rate, light rejection rate, and load regulating capacity of thermal units

In this paper, methods for thermo-electric decoupling transformation of heating units are compared. The transformation mode of coupling low pressure (LP) zero output and bypass heating is proposed for a 330 MW subcritical unit. The electrical regulation capacity, heating capacity and operating flexibility of the unit during the heating period have been greatly improved after transformation, providing a favorable guarantee for the consumption of new energy.

Comparison of transformation methods of thermo-electric decoupling of heating units

The thermo-electric decoupling transformation of heating units is mainly carried out by four methods: electric boilers installation, heat storage devices installation, bypass heating transformation, and back-pressure heating transformation [12].

The electric boilers are electrode boilers that consume part of the power generated by the steam turbine. They can supplement the unit's heating capacity to realize thermo-electric decoupling and reduce the unit's power on the grid [13]. The biggest advantage of this scheme is that it provides a simple system which is easy to control and is highly automated. However, such *good configuration has met a low utilization rate* due to the transformed heating unit runs counter to the policy of energy conservation and emission reduction. The scheme also requires a large initial cost, so the application rate is low. Therefore, it has relatively few applications.

It is one of the common methods to configure a certain heat storage device such as a heat storage tank for the unit [14]. When the heat demand is low, the steam extraction is used to supply heat to the heating network and heat the water in the heat storage tank. The heat storage tank is an energy storage process. As the power generation load of the turbine is reduced due to peak shaving, the reduction of the steam extraction of the turbine does not meet the heating demand of the heating network, so it is necessary to draw hot water from the heat storage tank to the heating network to supplement the heat supply shortage of the turbine. This way satisfies the heat supply and reduces the load of the turbine, thus realizing the thermo-electric decoupling. This method has less transformation the system and better heating economy. Its deficiency lies in a heat storage device covering a large area, a large investment in transformation, and poor adaptability to long-term continuous peak shaving [2].

The transformation of bypass heating is to add a high pressure bypass from the main steam to the high pressure (HP) cylinder exhaust pipe and a LP bypass from the reheat pipe to the heat network. Bypass heating reduces the work done by HP and intermediate pressure (IP) cylinders while improving the heating capacity of the unit, thus achieving the purpose of thermo-electric decoupling. The peak shaving ability of bypass heating is not restricted by the boiler. The bypass heating with strong peak-shaving ability and flexible operation can realize complete thermo-electric decoupling under extreme conditions, which has become a significant means for the heating unit to improve the electric output regulation capacity [4-6]. However, the heating economy of this method is relatively poor.

The back-pressure heating transformation method includes high back pressure, LP zero output, and optical axis transformation technology, which is the transformation of the thermal power unit itself. The transformation for LP zero output heating has been applied most in recent years. The LP zero output heating breaks the minimum cooling flow limit theory of turbine's LP cylinder. During the heating period, steam admission the LP cylinder is stopped and only a small amount of cooling steam is maintained (about 30 tonne per hour of cooling steam is needed for 300 MW class units), so that the LP cylinder can run at *zero output* under high vacuum conditions, thus improving the heating capacity and peak shaving capacity of the turbine. About 100 units have been retrofitted in China in three years since 2016 because of the low cost, flexible operation, and good thermal economy of the LP zero output transformation. The capacity of the transformed unit is 150-600 MW, with parameters ranging from subcriticality to supercriticality. However, such technology can only improve the heat supply capacity of the unit, with the heating load under the corresponding electrical load limited to a fixed value, making it difficult to realize the complete thermo-electric decoupling operation.

The four methods have their advantages and disadvantages, so the suitable thermo-electric decoupling scheme will be found according to the characteristics of the unit, heating scale, and policies related to peak load regulation of the power grid. Generally speaking, the transformations of LP zero output and bypass heating are the two mostly used technologies in thermo-electric decoupling transformation. Non-etheless, the two technologies have their shortcomings. The ideal situation is applying the two technologies in one unit, bringing their advantages together, so as to realize the goal of a safe and economical operation of the heating unit.

Introduction the unit and its necessity of transformation

The unit of a power plant is extraction heating unit, with features of subcritical, single-shaft and double cylinder. The inlet flow rate of the turbine under TMCR operating conditions is 1046 tonne per hour, and the rated electrical power under pure condensing operating conditions is 330 MW. The main parameters of the turbine and thermodynamic system are given in tab. 1.

Table 1. Main parameters of the unit

Item	Unit	Content
Rated power	MW	330
Rated speed	rpm	3000
Main steam pressure	MPa	16.7
Main steam temperature	°C	538.0
Reheat steam temperature	°C	538.0
Main steam flow (TMCR conditions)	tonne per hour	1046
Exhaust pressure	kPa	4.90
Number of heaters	3 high heaters + 1 deaerator + 4 low heaters	
Feed temperature	°C	272.4
Heat consumption	kJ/kWh	7859.1
Length of last-stage moving blade	mm	900.0

Before the transformation, the unit controls the opening of the LV valve for the communicating pipe of the IP and LP cylinders and extracts steam from the 5-stage extraction pipe for external heating. The system is presented in fig. 3. Under this heating mode, the operating condition of the steam extraction and heating of the unit [7] is shown in fig. 4. The heating condition, heat rate and heating capacity of the unit is calculated by EBSILON. Point A represents the load point of the minimum flow (313.8 tonne per hour) of steady combustion of the boiler as the unit is in a pure condensed state. Point B represents the heating operating point to ensure that the minimum inlet flow of the LP cylinder reaches 140 tonne per hour at the minimum flow of steady combustion of the boiler. Point C represents the maximum heating point of the unit as the minimum inlet flow of the LP cylinder represents 140 tonne per hour at the maximum evaporation capacity of the boiler (1046 tonne per hour). Point D represents the maximum electrical load point in the pure condensing condition. This unit is required to meet the heating area of 9 million m^2 in the heating season. According to the heat supply index of 46.2 W/m^2, the heat extraction flow rate is 450 tonne per hour. On the premise of the heating load, the operation adjustment range of the unit is the CEF region, as shown in fig. 4. The range of electric output regulation capacity is 206-268 MW, the minimum electric output is 62.4% THA, and the regulation range is 18.8% of the rated load. The unit is extremely limited in the electric output regulation capacity at the heating season.

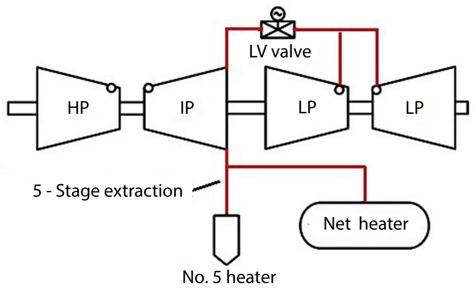

Figure 3. Heating system of the unit before transformation

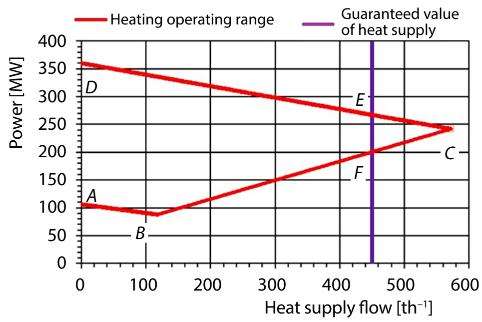

Figure 4. Load adjustment range of the unit under heating conditions

To consume new energy, it is necessary to perform an in-depth peak-shaving operation of heating units. The national grid subsidizes the electricity price for in-depth peak-shaving of heating units in the region by a stepped subsidy mechanism. During the heating period, the electricity price is CNY 1 when the electric load is less than 30% THA, and CNY 0.3 when the electric load is more than 50%THA. At present, the lower limit of the unit's electric output does not reach the compensation lower limit of 50% THA. Therefore, the unit is in urgent need of flexible transformation achieve deep peak shaving operation.

Key technologies of the zero-power heating and bypass heating

Introduction the transformation system

Considering characteristics of this heating unit and the demand for heating, the coupling method of LP zero output and bypass heating is proposed. The system of the transformation scheme is shown in fig. 5.

In the LP zero output transformation, the LV valve of the original communicating pipe is replaced by a fully sealed hydraulic butterfly valve to completely cut off the steam admission the LP cylinder. A thinner LP cylinder cooling steam pipe is added with a regulating valve to adjust the steam flow into the LP cylinder. As the LP zero output mode runs, the butterfly valve of the communicating pipe is fully closed. The regulating valve on the newly added communicating pipe is used to control the inlet steam flow into the LP cylinder to take away the blast loss of the LP cylinder. In this case, the output of the LP cylinder can be basically tested as *zero*.

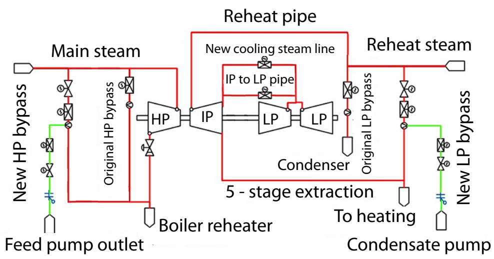

Figure 5. Diagram of the coupling transformation for LP zero output and bypass heating

In the bypass heating transformation, a pipe from the original main steam pipe is drawn to the HP cylinder exhaust stream pipe and is installed with temperature reduction and pressure reduction devices. The desuperheating water comes from the outlet of the feed pump. A pipe leading from the reheat pipe is connected to the heater pipe, with temperature reduction and pressure reduction devices installed. The desuperheating water comes from condensed water. The designed flow rate of steam supplied externally by bypass is 366 tonne per hour, which takes up 35% of the rated main steam flow.

Key technologies for transformation and operation

Key technologies for transformation and operation of LP zero output

In the LP zero output mode, the flow state in the stage composed of the last two-stage blades of the LP cylinder changes greatly with the decrease of the internal volume flow of the stage. It is mainly manifested the negative angle of attack of the incoming steam is generated, the flow separation is formed on the pressure surface of the blade, and the flow separation at the blade root forms a shedding vortex. Such a flow will mainly generate three kinds of potential hazards: small flow blade flutter, blade strength caused by blast frictional heating, and blade water erosion [15]. Measures need to be taken to deal with the three problems to reduce the harm in the transformation and operation period.

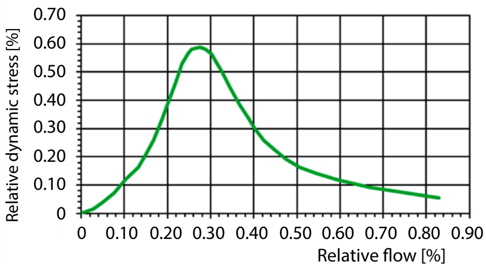

Figure 6. Dynamic stress characteristics of blades

The relationship between the dynamic stress of the last stage blade and the volume flow can be seen in fig. 6 [16]. The dynamic stress peaks at a certain small volume flow. Blade flutter caused by the increase of dynamic stress is the biggest threat to the safety of the LP last stage blade. In the LP zero output mode, the required cooling steam flow is about 10~30 tonne per hour, which is less than 0.1 of its rated volume capacity. In switching to the LP cylinder operation mode, the butterfly valve on the communicating pipe can be controlled to quickly pass through the dangerous working area with the maximum dynamic stress on the blade, that is, the area with the relative volume flow in the range of 0.2-0.4, fig. 6. As such, the damage caused by the steam flow to the blade can be avoided. From the on-site operating experience, the LP zero output heating mode can be switched within 10 minutes. It should be noted that different types of blades have different dynamic stress sensitive areas, and the shorter the blade is, the narrower the dangerous working area will be.

The heat brought by the blast friction is mainly carried away by the cooling steam in the LP cylinder. In addition, water spraying in the rear cylinder and back pressure control during operation are also adopted to ensure that the temperatures of the last stage and the secondary last stage are not overheated. Due to the lack of temperature measurement points for the secondary last stage blades of the LP cylinder, it is necessary to add temperature measurement points at the outlets of the moving blades of the last stage and the secondary last stages, so as to monitor the temperature at both places during operation.

The LP cylinder spraying water reduces the temperature of the blade. However, in the LP zero output operation mode, the vortex sucks the water droplets sprayed by the rear cylinder into the working face of blade due to the negative reaction at the root of the blade, and the water droplets will corrode the back profile of the blade's trailing edge. A more feasible treatment is to spray stellite alloys on the blade to prevent water erosion.

Key technologies for transformation and operation of bypass heating

The main safety hazards brought by the bypass heating transformation include the over-limit of axial thrust, the increase of stress in the last stage of the high pressure cylinder blade, the overspeed of steam in the pipe, and the vibration of the IP CV – intermediate pressure control valve.

For high and medium pressure combined cylinder units, the flow into the HP and IP cylinder has certain matching characteristics. Bypass heating breaks the original matching characteristics, leading to changes in the axial thrust of the turbine. In bypass heating, a control strategy of *low bypass steam flow = high bypass steam flow + high bypass desuperheating water flow* can be adopted, that is, the steam flow equivalent to the external supply is all passed through the new high bypass pipe and the axial thrust of the turbine will not be affected during heating. In operation, the over-limit of the axial thrust is determined by such parameters as axial displacement, thrust tile temperature, and differential expansion.

The external heat supplied by the bypass inevitably decreases the high discharge pressure, which will increase the stress of the last stage blade of the high pressure cylinder. As the high discharge pressure decreases, the specific volume of steam increases, and the steam from HP cylinder exhaust pipe to the reheater tends to overspeed. The two problems can be solved by the involvement of an IP CV to ensure that the high discharge pressure is similar to pure condensing conditions. However, the IP CV often has problems of low vibration and poor regulating characteristics when participating in the regulating process, so improvements to the valve need to be made in the bypass transformation achieve stable operation and flow regulation capacity under small opening.

Key technologies for transformation and operation of coupling LP zero output and bypass heating

The transformation for LP zero output and bypass heating can be completed independently. It should be noted that part of the heating network hydrophobic should be returned to the condenser during the coupling transformation. This will avoid the situation where the low bypass desuperheating water cannot be satisfied in the operation of LP zero output and bypass coupling heating. During the operation of the heating unit, both heating modes can be successively put into operation or one heating mode can be operated according to the demand of heating load and electric load. There is no conflict between their order of use and operational control.

Effect of the transformation on the deep peak shaving operation of the unit

The LP zero output mode on the deep peak shaving operation

The operating condition of the unit after LP zero output transformation is shown in fig. 7. The heating operating condition before the transformation is in the range of ABCD. It changes to a straight line B_1C_1 after the LP zero output heating transformation. Under the condition of the 450 tonne per hour (EF line) heating extraction steam flow, the minimum electrical load of the unit can be reduced to 143.5 MW (43.5% THA), and the regulating range of the electrical load can reach 37.7%, which is 18.9% higher than that (18.8%) before the transformation. This greatly improves the unit's electrical load regulation ability during the heating peri-

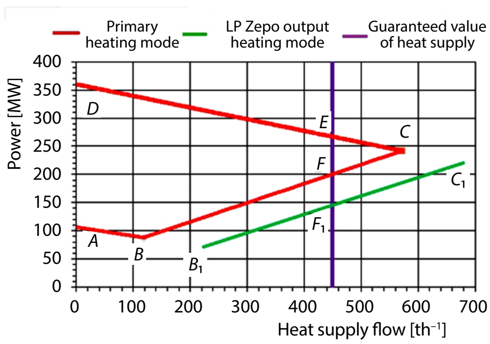

Figure 7. Operating conditions of LP zero output mode

od. However, the heating load under the corresponding electric load is a constant value in the zero-output mode. When the heating load needs to be increased, the electric load also needs to be increased accordingly, which to some extent limits the application of this mode.

Bypass heating mode on the deep peak shaving operation

The operating condition of the unit after bypass heating transformation is shown in fig. 8. The heating range of the unit is AB_1GC_1CD after bypass heating transformation. The B_1 represents the operating point when the external heating supplied by bypass reaches the maximum at the minimum flow of steady combustion of the boiler. The G represents the corresponding minimum electrical load point when the bypass heating reaches the maximum designed heating flow of 366 tonne per hour. The C_1 represents the maximum operating point with the external heating capacity of 5-stage extraction and bypass at the maximum evaporation capacity of the boiler. Under the condition of 450 tonne per hour heating extraction flow, the minimum electric load of the unit can be reduced to 95.4 MW (28.9% THA), and the regulating range of electric load can reach 52.3%, which is 33.5% higher than that (18.8%) before the transformation. The improvement of the unit's electric regulation capacity exceeds the figure collected after the LP zero output transformation. In addition, in extreme cases, the bypass can also be used to achieve the *operation with furnaces running while turbine shutdown*. It means that the steam generated from the boiler is sent to the heat-grid heater by-passing the added HP bypass, where the temperature and pressure are reduced. At this point, the power generated by the turbine is reduced to zero, truly realizing the complete thermo-electric decoupling operation. So far, a number of power plants have been trying this operation mode.

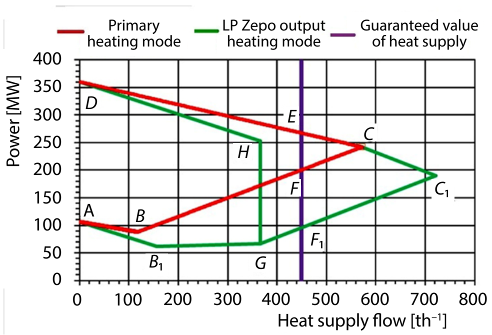

Figure 8. Operating conditions of bypass heating mode

Coupling mode of LP zero output and bypass heating on the deep peak shaving operation

The operation conditions of coupling of LP zero output and bypass heating are presented in fig. 9. The heating condition of the unit is in the range of AB_1GHC_1D. In the newly added heating range, the unit can operate in the LP zero output mode, bypass heating mode, and mode of LP zero output and bypass coupling. In the fig. 9, C_1 represents the maximum value (846 tonne per hpur) of the unit's external heat supply at the boiler's maximum evaporation capacity in the mode of LP zero output and bypass heating. The H represents the minimum output point of the electrical load in the LP zero output mode when the bypass heating load reaches a maximum of 366 tonne per hour. The G represents the operating point of the external heating from both the LP zero output and bypass

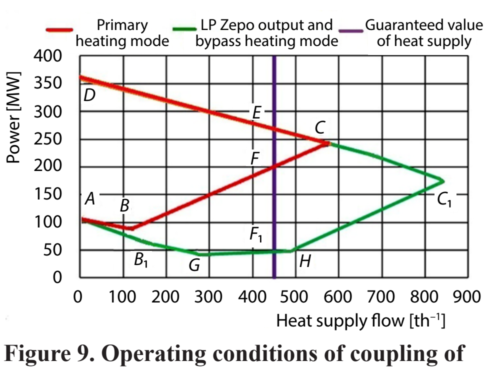

Figure 9. Operating conditions of coupling of LP zero output and bypass heating

when the boiler is burning stably at a minimum flow rate. The B_1 represents the operating point when the external heating supplied by the bypass reaches the maximum at the minimum flow of steady combustion of the boiler. It can be seen that the LP zero output and bypass heating greatly increase the unit's heating capacity and in-depth peak-shaving capacity. Under the condition of 450 tonne per hour heat extraction flow, the minimum electrical load of the unit can be reduced to 47.0 MV (14.2% THA), and the adjustment range of electric load can reach 67.0%, which is 48.2% higher than that (18.8%) before the transformation.

Operating mode and economy of the unit

Distribution area of multiple heating modes

After the transformation, the unit's heating mode can be divided into the following five modes: 5-stage extraction, LP zero output, bypass, bypass, and 5-stage extraction, bypass and LP zero output. The distribution regions of various heating modes are shown in fig. 10. It can be seen that multiple heating modes exist in the same region, so it is necessary to study which heating mode is the most favorable for the unit.

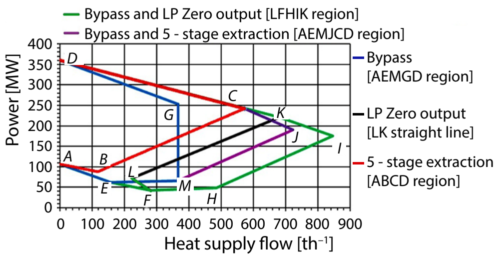

Figure 10. Distribution regions of various heating modes

Economy of different heating modes

Adopting the most economical operation mode is the key to increasing the profit of a power plant. The income of a power plant includes three parts: the income from power generation, the income from heat supply, and the income brought by in-depth peak-shaving. The final benefit of a plant is those income minus the cost of generation, operation and maintenance.

The earnings of heating and peak-shaving are related to local policies and heating settlement methods, so it is difficult to make comparison among the most economical heating modes of different power plants. In fact, an important parameter often concerned by thermal power plants is the heat rate of power generation (the cost of power generation) when certain heating load is met. The heat rates of different heating modes are calculated by EBSILON. Figures 11 and 12 show the heat rate of power generation under loads of 99 MW (30% THA) and 175 MW (53% THA), which can be seen

Before the transformation, the unit supplied heat externally from 5-stage extraction, and the heat rate of power generation-linear decreases significantly with the increase of heat load.

Bypass heating method has the highest heat rate among the heating methods mentioned in this paper, because the high grade steam supplies heat after temperature and pressure reduction. The heat rate of power generation decreases less with the increase of heat load.

The LP zero output heating can greatly reduce the heat rate, so it has the lowest heat rate among the heating modes mentioned in this paper. This characteristic is also an important reason for the vigorous promotion of this transformation in China in recent years. However, its heat load under a certain electrical load is also fixed, which has limited its further application.

Bypass heating can be used as a supplementary heating method for 5-stage extraction heating and LP zero output heating. It can make up for the shortage of heat load under the two heating methods.

The heating mode with the lowest heat rate is shown in fig. 13. The 5-stage extraction heating mode is used when the heating load is small. As the heating load increases, the coupling of 5-stage extraction and bypass heating mode can be adopted. As the heating load increases further, the coupling of LP zero output and bypass heating mode is preferred.

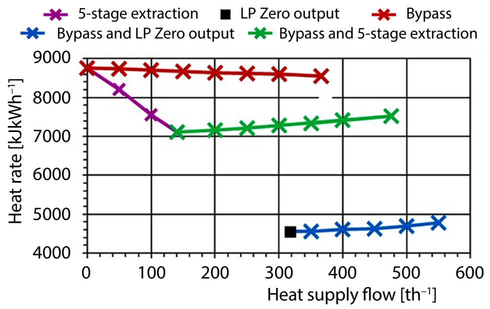

Figure 11. Heat rate of 99 MW power generation with different heating modes

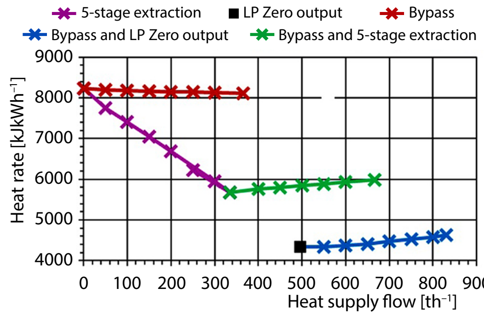

Figure 12. Heat rate of 175 MW power generation with different heating modes

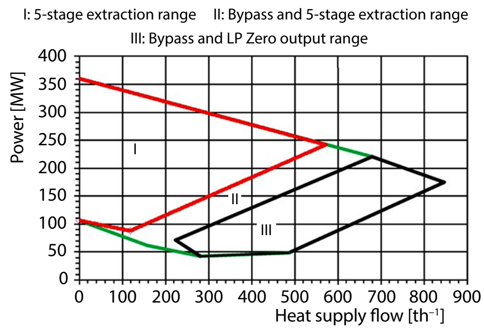

Figure 13. Operating mode of heat supply with the lowest heat rate

Conclusion

- The coupling transformation of LP zero output and bypass heating has realized on a 330 MW subcritical unit. The five heating modes of the units all run in a stable condition and show flexible operation in various heating modes after the transformation.
- The coupling transformation of LP zero output and bypass heating greatly improves the in-depth peak-shaving of the heating unit and creates a huge space for the consumption of new energy. The electrical regulation capacity of the unit can be increased to 67.0% from 18.8% before transformation, and the minimum electric load of the unit can be reduced to 14.2% THA. The successful transformation of the unit has a positive reference value and exemplary significance for the implementation of flexibility transformation of heating units.

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