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To cite this article: Qingbo Hu *et al* 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **227** 042043

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Theoretical investigation on heat-electricity decoupling technology of low-pressure steam turbine renovation for CHPs

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Abstract. The power grid peaking capacity is insufficient due to the increasing installed capacity of renewable power. Moreover, it is also restricted by the operation mode of combined heat and power units (CHPs), the minimum electricity loads of which are determined by the heat load. It is significant to study the heat-electricity decoupling technologies for CHPs. Therefore, the low-pressure steam turbine renovation technology is studied in this paper with a 300MW unit as reference case. Results show that the minimum electric load rate and the coal consumption are decreased, and the heat-electricity ratio is increased significantly for CHP with low-pressure steam turbine renovation. When the heat load is 1200 GJ/h, the minimum electric load rate and coal consumption with low-pressure steam turbine renovation can be reduced by 32.4 and 30.9 % respectively. The heat-electricity ratio can be increased by 68.8 % after renovation of low-pressure steam turbine.

1. Introduction

Renewable power has been increasing rapidly in recent years. The renewable power installed capacity of the world reached 178 GW by the end of 2017, in which photo-voltaic and wind power growth is particularly prominent. According to China's wind power development plan, the maximum capacity of grid-connected capacity wind power will increase by 200 million kilowatts in 2020 [1]. However, renewable power, such as wind power and solar power, has strong randomness, intermittent and anti-peak characteristics. Large-scale grid-connecting of renewable power causes the peaking insufficiency of the power grid. Therefore, coal-fired power units, accounting for more than 70% of total installed power capacity, are responsible for peaking of power grid. Combined heat and power plants (CHPs) have been developed on a large scale due to their high energy efficiency. However, the minimum electricity load of CHPs is determined by heat load which causes the low heat-to-electric ratio and the heat-electric coupling. Therefore, CHPs cannot perform deep peak shaving which leads to the operational inflexibility of CHPs.

Many scholars have conducted researches to develop decoupling technologies. Liu et al.[2] proposed two decoupling technical solutions, namely high-low-pressure bypass combined heating and low-pressure cylinder cut-off operation, and comparative analyses were also studied. Wang [3] et al. studied the thermodynamic characteristics of the heat storage tank and the heating unit, and the operation characteristics of the heating unit equipped with the heat storage tank are also analyzed by

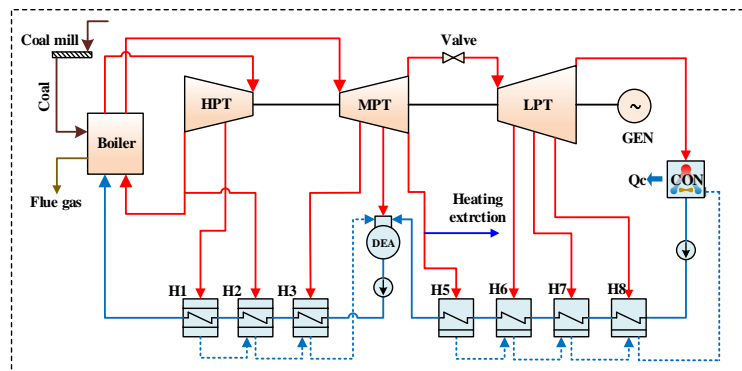


graphical method. Zhang [4] et al. calculated the energy-saving effect of CHPs compared to heat pump heating and boiler heating. Pei [5] et al. analyzed the power consumption characteristics of four common types of decoupling technologies. The economics, energy saving and consumption reduction capacity of electric boilers for heating were also studied [6-8], indicating that it is better to use electric boilers at the beginning and end of heating.

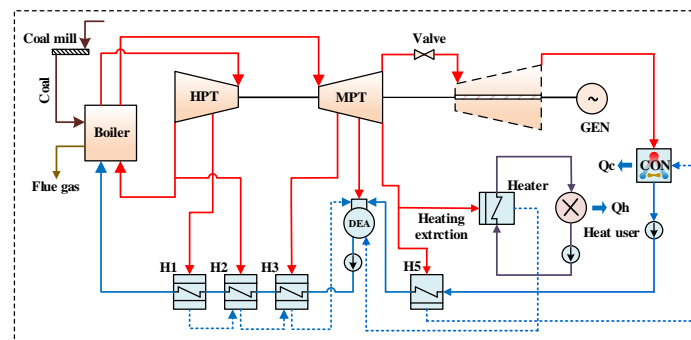
As discussed above, many decoupling technologies, such as electric boilers, compression heat pumps and heat storage tanks, have been proposed to solve the heat-electricity decoupling problem of CHPs. However, the energy consumption characteristics and decoupling performances of the low-pressure steam turbine renovation technology are not previously studied. It is significant to study this new heat-electricity decoupling technologies. Therefore, the low-pressure steam turbine renovation technology is studied with a 350MW CHP as a reference case in this paper. The aim of this paper is to provide a guide for the safe and flexible operation of CHPs with low-pressure steam turbine renovation.

2. Thermo-electricity decoupling technology with low-pressure steam turbine renovation

The system of CHP is shown in Figure 1 (a). The feed water absorbs heat in the boiler and becomes live steam, which is sent into turbine to convert its enthalpy to work. Steam exhaust of low pressure turbine releases heat in the condenser; its temperature increases through low-pressure heaters, the deaerator, high-pressure heaters; then the heat water is sent back to boiler to complete the cycle. The heating extraction is part of the exhausts of medium-pressure cylinder and condensates in heat network heater and then is sent to deaerator.



(a) Heat and power cogeneration unit



(a) Low-pressure steam turbine renovation

Figure 1. System diagram.

The system of CHP with low-pressure steam turbine renovation is shown in Figure 1 (b). The proposed system is proposed to decrease the electricity load with the same heat load compared with conventional CHPs. The main steam directly enters the high and medium pressure cylinders to expand and convert its enthalpy to work. Except for a small amount of cooling steam, the medium pressure cylinder exhaust all enters the heat network heater for heating. The low pressure rotor is replaced with an optical axis with no blades in order to connect the rotor of high-medium pressure cylinders and generator and to transmit torque. The condenser should be renovated accordingly whereas the other parts of the system are similar to conventional CHPs. The rotor of low-pressure is only replaced by optical axis in the heating period, which will increase the operating costs. Because the live steam flow rate must be lower than the maximum index flow rate of turbine, the maximum power output of CHP with low-pressure steam turbine renovation will also be decreased.

2.1. Theoretical models

The off-design operation conditions of power plants, regardless of causes, ultimately lead to the change of the live steam flow rate. Parameters of the power plants change as a result. The calculation of the off-design condition of the unit is based on the benchmark condition. The basis for the calculation of off-design condition of thermal system is the Flugel formula, which is as follows[9]:

$$\frac{D_1}{D_{10}} = \sqrt{\frac{P_1^2 - P_2^2}{P_{10}^2 - P_{20}^2}} \cdot \sqrt{\frac{T_{10}}{T_1}} \quad (1)$$

where D represents the steam flow of the group, t/h; P is the pressure of steam at inlet and outlet of group, MPa; T is inlet temperature of steam of the group, K; subscripts with 0 and without 0 are the design and off-design conditions, respectively; subscripts 1 and 2 represent the inlet and the outlet of the group, respectively.

The heat-electric ratio is defined as the ratio of heat supply to power supply and it can be expressed as

$$\chi = \frac{Q_h}{P_e} \quad (2)$$

The electric load rate is the ratio of the power generation of the power plant at the off-design and the reference condition, and it can be calculated with

$$f_d = \frac{P_e}{P_{e0}} \quad (3)$$

where Q_h is head load of unit, MW; and P_e is electric load of the unit, MW.

The total coal consumption of CHPs is divided into two parts including the coal consumption for heating and the coal consumption for generating power, as

$$B_{tp} = \frac{Q_{tp} \times 10^6}{q_L} = B_{tp}(e) + B_{tp}(h) \quad (4)$$

where B_{tp} is the total coal consumption rate, t/h; Q_{tp} is the total heat consumption rate, kJ/h; q_L is the lower heating value of the coal; $B_{tp}(e)$ and $B_{tp}(h)$ are coal consumption rates for generating power and heating, t/h, respectively.

2.2. Reference unit

To quantitatively calculate the energy saving and decoupling potentials of low-pressure steam turbine renovation decoupling technology, a 300MW power plant is taken as the reference case and the calculation is carried out. The unit is a subcritical power plant with single reheat and the main parameters of the unit's reference condition are shown in Table 1 (100%THA condition is selected as

the benchmark condition in this study) , and the parameters of the regenerative system are shown in Table 2. The lower heating value of the feeding coal of reference case is 23840 kJ/kg.

Table.1 Main parameters of the benchmark condition of the unit.

Parameters	Basic data
Type	Subcritical, double cylinders, condensing turbine
The live steam flow rate/t/h	915.09
The maximum live steam flow rate t/h	1025.001
Power/MW	300
Pressure of live steam/MPa	16.70
Temperature of live steam/°C	538
Pressure of reheat steam/MPa	3.18
Temperature of reheat steam/°C	538
Exhaust pressure/kPa	5.20
Temperature of feed water/°C	274.6

Table 2. Parameters of reheating system.

Number	RH8	RH7	RH6	RH5	RH4	RH3	RH2	RH1
Extraction pressure/MPa	5.946	3.534	1.678	0.880	0.553	0.131	0.0697	0.0226
Extraction temperature/°C	386.1	319.2	440.9	349.6	290.7	144.2	89.9	62.7

3. Results and discussions

3.1. Decoupling performance

In this study, the heating steam extraction pressure is 0.5 MPa. The heating water return enthalpy is the saturated water enthalpy under the heating extraction pressure, and the heating return water temperature is the saturated water temperature under the heating extraction pressure. It is assumed that the minimum condensate flow is 20 % of the live steam flow of the reference condition of CHP without low pressure steam turbine renovation. Two assumptions were made to simplify the calculation for the CHP with low pressure steam turbine renovation: the cooling steam flow rate of the low pressure cylinder is set as 10t/h; and station service power consumption rate is 4%; and the exhaust pressure of medium pressure cylinder is unchanged at off-design conditions with low-pressure steam turbine renovation.

The minimum electric load rate exists for CHPs due to the limitation of the minimum condensing volume of the low-pressure turbine. The minimum electric load rate is an important indicator for evaluating performances of thermo-electricity decoupling technologies. Therefore, the variation of the minimum electric load rate along with the heat supply rate of CHP with and without low-pressure steam turbine renovation are calculated, and results are shown in Figure 2. Figure 2 shows that the minimum electric load rate increases with the heat load. The electric load ratio is decreased greatly by low-pressure steam turbine renovation. The relative reduction is 32.4 percentages with low-pressure steam turbine renovation when the heat load is 1200 GJ/h.

The heat-electric ratio is the technical and economic index of the cogeneration unit and it reflects the operation level and management benefits of CHP. Therefore, the maximum heat-electric ratios of cogeneration unit and low-pressure steam turbine renovation technology are shown in Figure 3. Figure 3 indicates that the heat-electric ratio is increased greatly after low-pressure steam turbine renovation when the electricity is kept constant. The heat-electric ratio CHP with low-pressure steam turbine renovation increase with the electricity output. When the electricity load is 200 MW, the heat-electric ratio is increased by 0.97 after renovating.

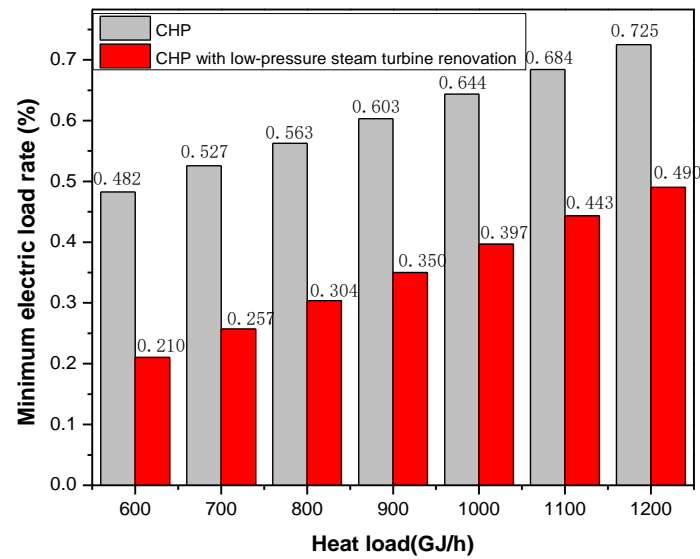


Figure 2. Comparison for minimum electric loads.

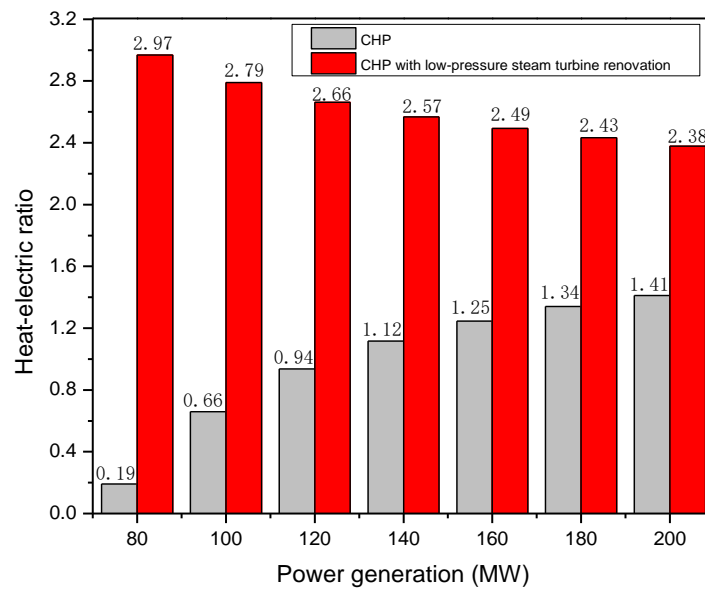


Figure 3. Comparison for heat-electric ratio.

3.2. Comparison of energy consumption

Table 3. The calculation results.

Parameters	Heat and power cogeneration	Low-pressure steam turbine renovation
The live steam flow rate(t/h)	793.119	997.504
The maximum heat capacity of unit(MW)	257.91	476.95
Electric load(MW)	200	200
Heat-to-electric ratio	1.29	2.38
Power supply(MW)	192	192
Total coal consumption(t/h)	96.97	117.05
The total efficiency of plant(%)	31.16	25.81

To analyze the energy consumption characteristics deeply and quantitatively, the electric load of 200 MW is selected as the calculation working condition in this study, and the maximum heating capacities with and without renovation in this working condition are calculated. Besides, the energy consumption of the heat and power cogeneration unit and the low-pressure steam turbine renovation are compared and calculated. The results are shown in Table 3.

It can be obtained that the steam do not convert its enthalpy to work in low-pressure steam turbine and the deduction of electricity of low-pressure steam turbine is compensated by high and medium steam turbine by increasing the steam into the turbine when the electric load is constant. Therefore, the coal consumption rate with renovation is higher than without renovation when the electric load is constant. When the power load is 192MW, the coal consumption rates of CHP without and with renovation for low-pressure steam turbine are 96.97 and 117.05 t/h, respectively. However, the heat load of optical axis is far greater than heat and power cogeneration unit, increase of 219.04 MW. The heating benefits is significantly increased with the renovation of low-pressure steam turbine.

The exhaust of medium-pressure steam turbine are all discharged into the heater of heat network, it needs less steam flow rates with renovation when the heat load is same. Therefore, the live steam flow rate and the coal consumption rate with renovation will be decreased with the same heat load. The minimum electricity output can be also decreased significantly with low-pressure steam turbine renovation when the heat load is constant. The reduction of the electricity can be compensated by wind power or others renewable power, which will be otherwise abandoned. Therefore, the coal consumption CHP with and without low pressure turbine renovation are calculated when the heat load and electric load are constant. The steam flow rate of low-pressure steam turbine of CHP is the minimum condensate flow rate in this calculation. The results are shown in Figure 4. It can be known that they have similar variation discipline that the coal consumption increases with the heat load increases, and the coal consumption after renovation is significantly less that the coal consumed by CHP without renovation. When the heat load is 1200 GJ/h, the coal consumptions consumed by CHP with and without low-pressure steam turbine renovation are 79.82 and 115.51 t/h, respectively.

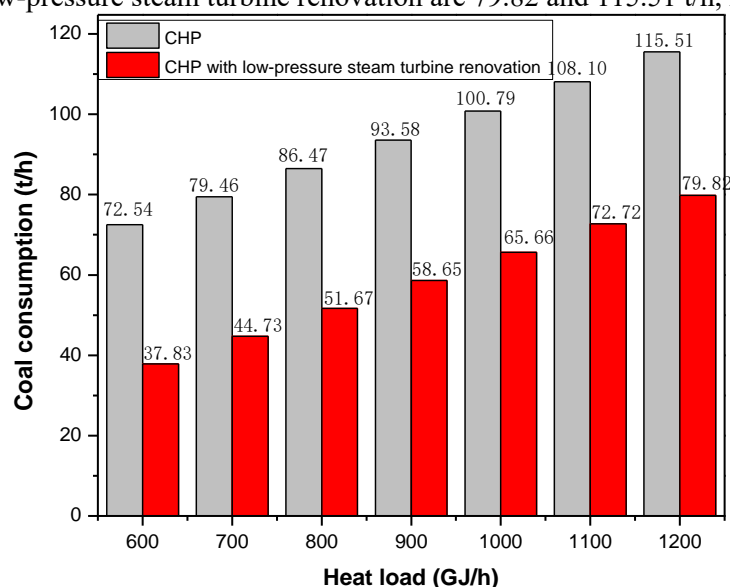


Figure 4. Comparison for coal consumption rates.

4. Conclusions

The heat-electricity decoupling technology of low pressure steam turbine renovation for CHPs is theoretically investigated in this study. A 300MW unit is used as the reference case.

The minimum electricity load is decreased significantly through the renovation for low-pressure steam turbine, and the relative reduction is 32.4 % with low-pressure steam turbine renovation when

the heat load is 1200 GJ/h. The heat-electric ratio is increased significantly for CHP with the renovation of low-pressure steam turbine, and when the electricity is the value of 200MW, the heat-electric ratio is increased by 0.97 after renovating. Therefore, the renovation for low-pressure steam turbine can realize heat-electric decoupling effectively for CHPs.

The coal consumption consumed by CHP is higher than the coal consumed by CHP with low pressure steam turbine renovation. When the heat load is 1200 GJ/h, the coal consumed by CHP with and without low-pressure steam turbine renovation are 79.82 and 115.51 t/h, respectively.

Acknowledgments

This work was supported by “Science and Technology Project of State Grid Tianjin Electric Power Company (KJ18-1-10 Study and Application of Flexibility Improvement and Control Strategy of Cogeneration Units under the New Normal Condition)”.

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