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Combined heating operation optimization of the novel cogeneration system with multi turbine units

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ABSTRACT

At present, large extraction condensing turbine units are generally adopted for combined heating in the cogeneration plants of northern China. A large amount of condensed waste heat of the exhaust steam releasing to the environment leads to a great heat loss of the cold end system. The novel cogeneration system significantly improves energy efficiency of the plant by efficiently recovering the condensed waste heat of multi turbine units. For the turbine units with complete recovery of the condensed waste heat, the corresponding cooling towers are closed during the freezing period. With the reduction of the heat load, the surplus condensed waste heat should be discharged by the cooling towers. However, the outdoor wet-bulb temperature is very low during the severe cold period, which results in a surplus of the cooling capacity of the cooling towers. When releasing a small amount of the condensed waste heat, the cooling towers may confront with the frozen risk. A new type of connecting and switching method for the cold end system of the multi turbine units is proposed to avoid the frozen risk. On this basis, with the method of equivalent electricity of heating, an optimized combined heating operation strategy is proposed for the multi turbine units under full operating conditions. The case study takes 4 × 300 MW turbine units as an example, the heat load regulation process is simulated according to the optimized strategy and the discussions are made on the seven regulation stages. Furthermore, the heating performance of the absorption heat pumps and the variation and distribution regularities of the energy consumptions during the heating period are analyzed in detail. Case study results show that, the heating coefficient of performance of the absorption heat pumps is obviously improved after the steam-water heat exchanger withdraws from heating. Compared with the traditional cogeneration heating system, the novel cogeneration system reduces heating energy consumption by 47.7% under the premise of avoiding the frozen risk of the cooling towers during the winter.

1. Introduction

Cogeneration is one of the major forms of central heating in northern China. In recent years, China is in full swing to launch constructions of large extraction condensing turbine units with 300 MW and above grade [1,2]. Currently, the condensed waste heat produced by the cogeneration turbine units in the three northern regions of China reaches about 0.8 trillion kWh/year. Recovering the condensed waste heat is significant for the cogeneration heating system. On the one hand, the heating capacity of the cogeneration plant can be greatly improved. The coal-fired boilers with low energy efficiency can be closed to reduce the emission of the air pollutants. On the other hand, the heat loss of the cold end system can be evidently reduced or even eliminated. The condensed waste heat used for heating has lower energy consumptions compared with the heat supplied by the extraction steam, which results in a great improvement of energy efficiency of the cogeneration plant [3–5]. Two technical paths are commonly adopted for recovering the condensed waste heat. One is to improve the backpressure of the turbine unit, and the other is to use heat pumps. The former technical path realizes direct heat exchange between the return water of the primary heating network and the exhaust steam of the turbine unit. However, the safety threshold of the backpressure is closely related to the volume flow of the low-pressure cylinder, the corresponding axial Mach number of the exhaust steam should not be lower than 0.23 [6,7]. If the backpressure is further promoted, the structure of the low-pressure cylinder needs to be reconstructed. For instance, replacing the low-pressure cylinder rotor with fewer and shorter blades [8,9], or even removing all the blades of the low-pressure cylinder rotor [10], which have been applied in dozens of projects so far. Because the power load and the heat load interact and restrict

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Nomenclature

A	heat exchange area, m^2
AHE	absorption heat exchanger
AHP	absorption heat pump
BC	bypass cooling water, t/h
BH	bypass heating water, t/h
COP	coefficient of performance of absorption heat pump
D	steam flow, t/h
el	electricity power, kW
G	water flow of the heating network, t/h
h	specific enthalpy, kJ/kg
N	days of heating period
P	pressure, kPa
Q	heat output, GJ
q	heat power, MW or kW
R	ratio
S	heating area, m^2
SWE	steam-water heat exchanger
T	temperature, °C
V	valve
WWE	water-water heat exchanger
w	equivalent electric power of heating, MW/MW or kW/kW
$\overline{w}$	comprehensive equivalent electric power of heating, MW/MW or kW/kW
E	electricity output, kWh
$\overline{W}$	comprehensive equivalent electricity of heating in the heating period, kWh/GJ

Greek symbols

Δ	difference
ε	recovery rate of condensed waste heat
θ	heat load proportion of the absorption substations

Superscripts

'	the value after improving backpressure
ahp	absorption heat pump
as	absorption substation
av	average temperature in the heating period
b	backpressure
bc	bypass cooling water
bh	bypass heating water
c	recovered condensed waste heat
cd	condensation
cl	inlet and outlet of cooling tower
clw	cooling water
cn	condenser
cs	condensed water of exhaust steam
cw	circulation water
e	extraction steam
es	drain water of extraction steam
ev	evaporation
h	heating
hs	heat source
i	instantaneous value of a working condition
o	outlet temperature
od	outdoor temperature
r	recovered condensed waste heat of absorption heat pump
rp	return water of primary heating network
rs	return water of secondary heating network
sp	supply water of primary heating network
sta	regulation stage of the heat load
ss	supply water of secondary heating network
swe	steam-water heat exchanger
t	total condensed waste heat
th	total heating area of the heat source
1–4	serial numbers of the steam turbine unit

mutually, usually no more than half of the turbine units can be reformed, although there is no heat loss of the cold end system in this way. While for the heat pump technologies, the applications of the extraction steam driven compression heat pump [11] and the AHP [12–14] are more extensive. The extraction steam driven compression heat pump is mainly used when the extraction steam pressure is above 0.8 MPa. While the optimal range of extraction steam pressure for the AHP is about 0.3–0.7 MPa. By the restrictions of the heating temperature (about 90 °C) and the heating coefficient of performance ($COP_h \approx 1.7$–1.8), the recovery rate of the condensed waste heat of the AHP reaches only about 50% [15].

It has been proved by the theories and practice that the extraction steam, the exhaust steam and the circulation water of the heating network could not appropriately match with each other in quality and quantity by adopting the single technical path mentioned above. Consequently, it is difficult to realize complete recovery of the condensed waste heat of the multi turbine units simultaneously [16]. With the fast increment of power generation capacity of the cogeneration plant, combined heating by four or even six turbine units is very common at present, which produces a huge amount of condensed waste heat with low energy level. If the condensed waste heat is not recovered thoroughly, the increase of the heating energy consumption will be enlarged. Additionally, the wet-bulb temperature is very low in the severe cold period, owing to the surplus cooling capacity of the cooling towers, more turbine units may confront with the frozen risk that threatens the safety operation.

Drastically reducing the return water temperature of the primary heating network provides an effective way for complete recovery of the condensed waste heat. Based on the concept and method of "absorption heat exchange" [17–19], the AHEs are proposed to be installed in the substations [20–21], which are driven by high temperature water of the primary heating network. The return water temperature can be decreased to about 25 °C by the unit. Meanwhile, on the side of the heat source, combining with improving backpressure and using AHP, the cascaded heating process is established and the recovery rate of the condensed waste heat is greatly promoted. Based on the work of the predecessors, our research group further studies the optimal integration of the novel cogeneration heating system. By connecting the condensers, AHPs and SWE in series and adding a bypass water pipeline on the heating network, the backpressures of the turbine units are further decreased, which effectively reduces the negative effect on electricity generation of the system. According to the novel cogeneration heating system, the factors affecting the heating energy consumptions are analyzed, such as the flow of the bypass heating water, the extraction-condensation ratio of the turbine units, the return water temperature and so on [22]. Moreover, according to the 2 × 300 MW air-cooling turbine units, the heating energy consumptions of the stable backpressure operation mode and the variable backpressure operation mode are compared between the series-cascaded heating system and the parallel-cascaded heating system [23].

However, for the waste heat recovery system consists of multi turbine units, the operation safety requirements are high, and the cold end system is confronted with more challenges of anti-freezing problems. Besides, the system is much more complex thus combined heating with multi turbine units has great difficulties in operation and regulation. Consequently, based on the previous studies, a novel type of connecting and switching method of the cold end system is provided to avoid the frozen risk. On this basis, the method of equivalent electricity of heating