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Research on Load Flexibility Adjustment of Coal-fired Power Plant Based on Thermal Energy Storage in 50%THA

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ABSTRACT

This paper presents a novel approach to integrating a thermal energy storage (TES) system in coal-fired power plant. Which can improve the load flexibility of coal-fired power plant(CPP) through reheat steam extraction(RSE) for increasing the power output of renewable resources into the grid. The novel system and its operation mode were described. The load flexibility was increased in charging and discharging of CPP. The 50%THA of 600MW coal-fired power plant was select as basic condition. The results show that the operating range of the CPP was widened from 34.78%THA～54.66%THA through integrating TES system and thermal energy release(TER) system. The proposal of this problem can provide some guiding ideology for peak shaving of CPP.

Keywords: coal-fired power plant, reheat steam extraction, thermal energy storage, thermal energy release, load flexibility adjustment

NONMENCLATURE

Abbreviations	
TES	Thermal energy storage
TER	Thermal energy release
CPP	Coal-fired power plant
TCPP	Traditional coal-fired power plant
TV	Steam throttle valve
SMHE	Steam molten salt heat exchanger
PCME	PCM heat exchanger
MWHE	Molten salt water heat exchanger
HT	High temperature molten salt tank
LT	Low temperature molten salt tank
HP	High pressure turbine
IP	Intermediate pressure turbine
LP	Low pressure turbine
H	Regenerative heater
Symbols	
G	mass flow-rate, t/h
m	mass flow-rate, t/h
q	specific enthalpy drop of extraction steam/ low calorific value of coal, kJ/kg
γ	specific enthalpy drop of drain water, kJ/kg
φ	specific enthalpy change of water, kJ/kg
η	efficiency,%
Q	heat power, MW
L	latent heat, MW
C_p	specific heat capacity at constant pressure, kJ/kg·K
T	temperature, K
h	specific enthalpy, kJ/kg

1. INTRODUCTION

In recent years, people's demand for energy is increasing, and the installed capacity of renewable resources represented by wind and solar energy is constantly increasing. However, due to the instability and intermittenency of wind and solar energy, the phenomenon of wind and solar energy abandoning becomes more and more serious. Therefore, how to improve the phenomenon of wind and solar energy abandoning is an urgent problem to be solved.

In order to solve the problem of renewable resources access to the grid, scholars have carried out relevant studies on how to improve the load flexibility operation of coal-fired power plant (CPP). From the coupling

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perspective of renewable resources and CPP, the coupling generation model of solar energy and CPP was established by Dimityr P[1]. The steam extraction system of the turbine regenerative heating system was replaced by the solar energy collection system, so that all the absorbed solar energy could be utilized and the occurrence of solar energy abandon can be reduced. In face the area lack of renewable resources, the coupling transformation model of electric boiler, solar energy, wind energy and cogeneration unit was set up by YU Juan et al.[2] to reduce the power out of cogeneration unit and improve the access of power of renewable resources. Although the model had solved the coupling problem of renewable resources and cogeneration unit, the condensing unit had certain restrictive. The hot water of deaerator stored in the hot pressure water tank during low load was put forward by Marcin Mauritius et al. [3]. The load could continue to cut 21.96 MW by using the tank to store hot water. The lower limit of CPP was 67.5%. The hot water was sent to the boiler feed water system from hot water storage tank to increase the power output of generating unit during the unit high load operation. The load increased by 15 MW. The load flexibility of the unit was improved. But, the related research could not meet the requirements of depth peak shaving of CPP.

Based on the above analysis, the use of reheat steam extraction(RSE) was put forward to promoting the load flexibility of the CPP through thermal energy storage (TES)technologies in this paper. Part of the reheat steam was bypassed during operation to reduce steam intake of intermediate pressure turbine. And the power output would be reduced to 35%THA. Molten salt and PCM was heated by bypassed steam in turn. After condensation, the steam was drained to the deaerator. In the process of thermal energy release(TER), the thermal energy stored in the TES process was released to the primary thermal system to increase the load response capacity of the unit.

2. SYSTEM DESCRIPTION

2.1 TES system of RSE and operation mode

As shown in Fig.1, the diagram of RSE and TES system includes two parts: traditional coal-fired power plant (TCPP)[4-5] and TES system. The TES system mainly includes: steam throttle valve(TV), steam molten salt heat exchanger (SMHE), low temperature molten salt tank (LT), high temperature molten salt tank (HT) and PCM heat exchanger (PCME). TCPP retains the original operation mode in the process of TES. The reheat steam is bypass to TES system through the tee of the pipe (Point B). The steam is throttled and depressurized by a TV before entering the SMHE. The molten salt is heated by the steam sensible heat, the molten salt in LT is heated to high temperature and stored in HT. Latent heat and drain water heat are released during heating PCM in PCME. The drain water is gone back to the deaerator and conveyed by the main feed pump to the high pressure heater.

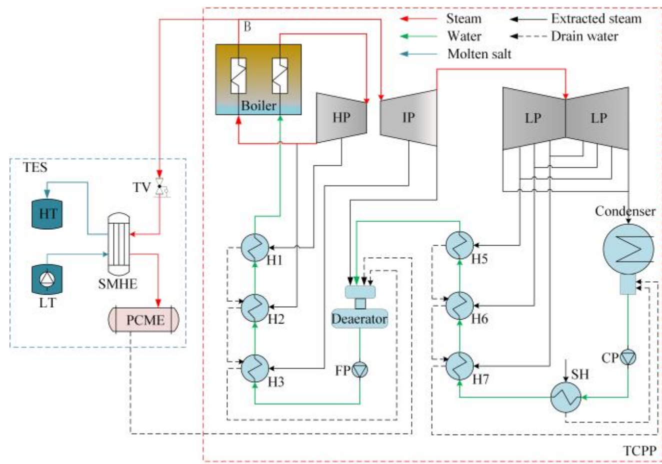

Fig 1 Diagram of TES system of CPP

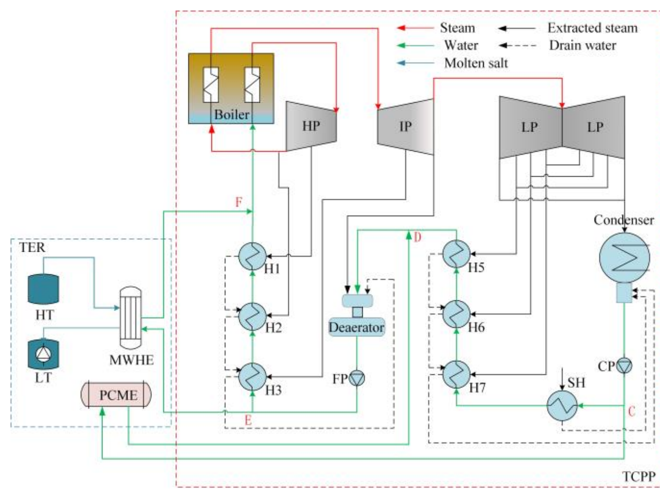

Fig 2 Diagram of TER system of CPP

2.2 TER system and operation mode

As shown in Fig.2, the diagram of TER system of CPP includes two parts: TCPP and TER system. The TER system mainly includes: PCME, molten salt water heat exchanger (MWHE), LT and HT. According to two different temperatures of thermal energy storage medium, TES of molten salt and TES of PCM can be used to heat the feed-water and condensate water, respectively. The operation mode of the system is as follows. The condensate water enters the PCME from the condensate pump outlet through the bypass system (Point C). The condensate water is heated to the same parameters as the outlet of 5th regenerative heater in the PCME, and enters the deaerator (Point D). The feed-water enters the MWHE through the bypass at the outlet of the feed-water pump (Point E). The feed-water is heated in MWHE to the same parameters as the outlet of 1st regenerative heater, and enters the boiler economizer (Point F). TCPP retains the original operation mode in the process of TER.

3. MODELING METHODOLOGY

3.1 Regenerative heating system of steam turbine

The heat balance equation of the steam turbine system is calculated by the feed-water regenerative matrix [5]:

$$\begin{bmatrix} q_1 & & & & & & \\ \gamma_2 & q_2 & & & & & \\ \gamma_3 & \gamma_3 & q_3 & & & & \\ \gamma_4 & \gamma_4 & \gamma_4 & q_4 & & & \\ 0 & 0 & 0 & 0 & q_5 & & \\ 0 & 0 & 0 & 0 & \gamma_6 & q_6 & \\ 0 & 0 & 0 & 0 & \gamma_7 & \gamma_7 & q_7 \end{bmatrix} \begin{bmatrix} G_1 \\ G_2 \\ G_3 \\ G_4 \\ G_5 \\ G_6 \\ G_7 \end{bmatrix} = \begin{bmatrix} G_{feed}\varphi_1 \\ G_{feed}\varphi_2 \\ G_{feed}\varphi_3 \\ G_{feed}\varphi_4 \\ G_{cond}\varphi_5 \\ G_{cond}\varphi_6 \\ G_{cond}\varphi_7 \end{bmatrix} \quad (1)$$

where, G_i is mass flow-rate of extraction steam in the ith stage, G_{feed} is mass flow-rate of main feed-water from deaerator, G_{cond} is mass flow-rate of condensation water from condenser, φ_i is the specific enthalpy change of water in the ith heater, q_i is specific enthalpy drop of extraction steam in the ith heater, γ_i is specific enthalpy drop of drain water in the ith heater[5].

q,*γ* and *φ* can be calculated as follows [5]：

$$q_i = h_i - h_{di} \quad (2)$$

$$\varphi_i = h_{wi} - h_{wi+1} \quad (3)$$

$$\gamma_i = h_{di-1} - h_{di} \quad (4)$$

Where, h_i is the specific enthalpy of extraction steam for the ith heater, h_{wi} is the specific enthalpy of feed-water at outlet for the ith heater; h_{di} is the specific enthalpy of drain water in the ith heater[5].

3.2 Thermal energy balance of boiler system

After the thermal energy balance of the turbine is given. The thermal energy absorption of the working medium in the boiler could be obtained. The thermal energy balance of the boiler needs to be calculated. The equivalent relationship between the thermal energy absorption balance and the combustion balance can be calculated by:

$$\mathrm{m}_{coal} q_{dw} \eta_b = G_{feed}(h_s - h_{w1}) + G_r(h_r - h_{gp}) \quad (5)$$

Where, G_r is mass flow-rate of reheat steam, h_s is the specific enthalpy of main steam, h_{w1} is the specific enthalpy of feed-water at outlet of the H1, h_r is the specific enthalpy of reheat steam, h_{gp} is the specific enthalpy of high pressure turbine exhaust steam, m_{coal} is mass flow-rate of coal, q_{dw} is low calorific value of coal,17981 kJ/kg, η_b is efficiency of bolier.

3.3 Thermal energy balance of TES system

In the process of TES, the relationship between the mass flow-rate of RSE, the reheat steam mass flow-rate and the steam intake of intermediate pressure turbine is as follows:

$$G_{st} = G_r - G_t \quad (6)$$

Where, G_{st} is mass flow-rate of reheat steam, G_t is mass flow-rate of the steam intake of the intermediate pressure turbine.

Thus, molten salt and PCM heated by sensible heat and latent heat of steam can be calculated as follows:

$$Q_{x,st} = G_{st}(h_s - h_{s,sat}) = m_{salt} C_{p,salt}(T_H - T_L) \quad (7)$$

$$Q_{q,st} = G_{st}(h_{s,sat} - h_{ss}) = L_{PCM} \quad (8)$$

Where, $Q_{x,st}$ is the sensible heat power of TES, $h_{s,sat}$ is the specific enthalpy of corresponding extraction steam storage pressure under the dry saturated steam, m_{salt} is mass flow-rate of molten salt, $C_{p,salt}$ is specific heat capacity of molten salt at constant pressure,T_H and T_L are high and low temperature of molten salt, $Q_{q,st}$ is the latent heat power of TES, h_{ss} is the specific enthalpy of drain water, L_{salt} is latent heat of PCM.

The total TES power ($Q_{z,st}$)of the reheat steam during steam extraction is obtained from Equations(7) and(8):

$$Q_{z,st} = Q_{x,st} + Q_{q,st} \quad (9)$$

3.4 Thermal energy balance of TER system

In the process of TER, the sensible heat release power and the latent heat release power can be calculated as follows:

$$\begin{aligned} Q_{x,re} &= G_{feed,by}(h_{w1} - h_{w3in}) \\ &= m_{salt} C_{p,salt}(T_H - T_L) \end{aligned} \quad 10)$$

$$Q_{q,re} = G_{cond,by}(h_{w5out} - h_{w7in}) = L_{PCM} \quad (11)$$

Where, $Q_{x,re}$ is the sensible heat release power of TER, $Q_{q,re}$is the latent heat release power of TER, $G_{feed,by}$ is bypass mass flow-rate of feed-water, $G_{cond,by}$ is bypass mass flow-rate of condensed water, h_{w3in} is the specific enthalpy of the inlet of H3, h_{w5out} is the specific enthalpy of the outlet of H5, h_{w7in} is the specific enthalpy of the inlet of H7.

4. RESULTS AND DISCUSSION

4.1 Selection of CPP and TES parameters

In this paper, the 600MW subcritical CPP was selected as the research object. The CPP includes three stage high pressure regenerative heater (H1～H3), a deaerator (H4) and a three stage low pressure regenerative heater (H5～H7).

The pressure and temperature of the main steam and reheat steam are 16.67/538 and 3.414/538 (MPa/℃), respectively, in 100%THA. The main steam mass flow-rate is 1848.755 t/h. The extraction parameters of the regenerative heater are shown in Tab.1.

Tab 1 Steam extraction parameters of regenerative heater

	Pressure(MPa)	Temperature(℃)
H1	6.081	385.3
H2	3.793	322.5
H3	2.045	461.5
H4	1.016	361.0
H5	0.615	302.5
H6	0.2404	196.3
H7	0.08064	93.73

The main content of this paper was the analysis of TES performance under low load, and 50%THA condition was selected as the basic condition. 35%THA output of CPP can be reached through TES system. The stored thermal energy was released to the primary thermal system, which makes the CPP load rise from 50%THA condition to a certain in the TER process.

In the above two processes, the main steam parameters maintained 50% of THA operating parameters. In the process of system integration and analysis, TES and TER were based on the first law of thermodynamics, and the depreciation of energy and heat dissipation loss were ignored. At the same time, the TES temperature and the TER temperature meet the temperature requirements of each node, and the operating pressure and the steam drain temperature of the extraction steam were stipulated as constant values, which were 0.65 MPa and 153.32 ℃, respectively.

4.2 Influence of RSE mass flow-rate on TES and CPP load

Fig.3 shows that in the process TES under the condition of 50%THA, sensible heat storage power($Q_{x,st}$), latent heat storage power($Q_{q,st}$) and total heat storage power ($Q_{z,st}$) gradually increased with the increase of the mass flow-rate of RSE. When the extraction mass flow-rate was 60 t/h, 120 t/h, 180 t/h, 240 t/h and 300 t/h, the total heat storage power was 48.47 MW, 96.94 MW, 145.41 MW, 193.88 MW and 242.34 MW, respectively. With the increase mass flow-rate of RSE, the load of CPP gradually decreased. The reason is that the increase mass flow-rate of RSE leaded to a gradual decrease in the mass flow-rate of steam entering the intermediate pressure turbine, the output power of the turbine was correspondingly reduced. When the mass flow-rate of RSE was 300 t/h, namely the total heat storage power was 242.34 MW, the power output was 208.65 MW, which was the 34.78%THA of CPP. It was less than 35%THA of CPP. It shows that the use of TES can further reduce the load of CPP.

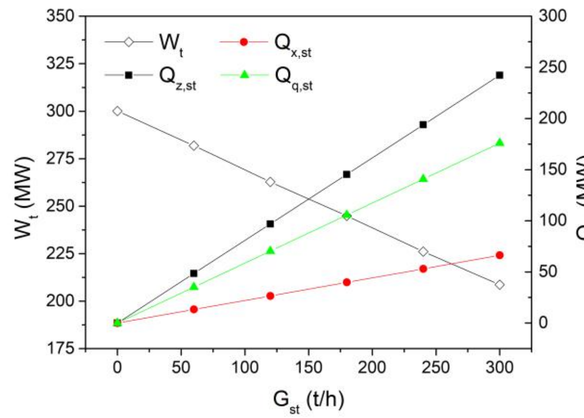

Fig 3 Influence of RSE mass flow on TES and CCP load

4.3 Influence of feed-water bypass mass flow-rate on heat release power

Since both the extraction enthalpy and the drain water enthalpy was constant, the cut-off point of sensible heat and latent heat was the dry saturated steam temperature at 0.65MPa. According to 4.2, the ratio of sensible heat storage power and latent heat storage power can be calculated as 0.3763. When the TES process, the release time of sensible heat storage and latent heat storage must be the same, that is, the ratio of sensible heat release power and latent heat release power was also 0.3763. The relationship between the feed-water bypass flow($G_{feed,by}$) and the TER power($Q_{z,re}$) and the condensate water bypass flow($G_{cond,by}$) was shown in Fig.4.

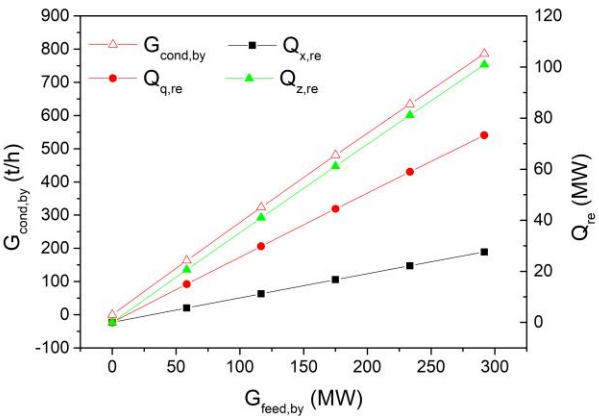

Fig 4 Influence of the feed-water bypass mass flow on the TER power and the condensate water bypass mass flow

As can be seen from Fig.4, with the increase of the feed-water bypass mass flow-rate, the condensate water mass flow-rate increased correspondingly, the sensible heat release power and latent heat release power also increased. When the feed-water bypass mass flow-rate was 58.35 t/h, 116.70 t/h, 175.05 t/h, 233.40 t/h, 291.75 t/h, the corresponding condensate water bypass mass flow-rate was 163.50 t/h, 323.50 t/h, 481.00 t/h, 634.50 t/h, 786.00 t/h, and the total heat release power was 20.61 MW, 41.00 MW, 61.18 MW, 81.15 MW, 100.92 MW. According to the calculation of 50%THA condition of the CPP, when the feed-water bypass mass flow-rate was 291.75 t/h, the corresponding condensate water bypass mass flow-rate was 786.00 t/h. The extraction mass flow-rate of H5～H7 was 0, all the steam kinetic energy in the low-pressure turbine was converted into work. The maximum heat release power of the unit was 100.92 MW.

4.4 Influence of total heat release power on CPP load

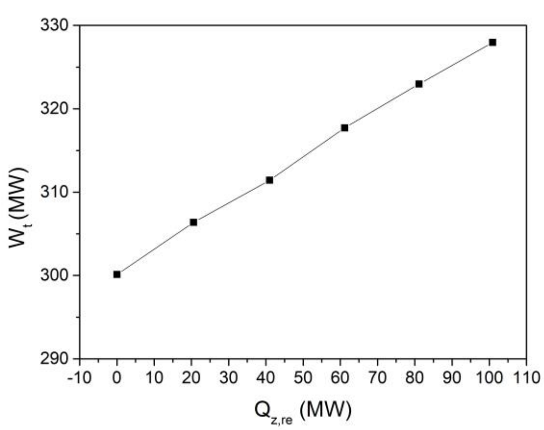

Fig 5 Relationship between total heat release power and CPP load

As shown in Fig.5, as the feed-water bypass mass flow-rate and the condensate water bypass mass flow-rate gradually increased, the total heat release power ($Q_{z,re}$) was gradually rised. The mass flow-rate of steam extracted from the feed-water heater corresponding to the steam turbine system was reduced accordingly, leaded to the gradual increase of steam flow in the steam turbine. When the total heat release power reached 100.92 MW, the maximum output power of CPP was 327.96 MW, which was 54.66%THA of CPP.

5. CONCLUSIONS

In this paper, the TES system and TER system were integrated with 50%THA condition of 600MW CPP as the benchmark condition to achieve the purpose of peaking load regulation of CPP.

The flexible operation of CPP can be realized by means of RSE system and TES system. When the TES power and the TER power were 242.34 MW and 100.92 MW, the power output of the CPP were 208.65 MW and 327.96 MW, respectively. The power output range of the CPP was 34.78%THA ~ 54.66%THA.

ACKNOWLEDGEMENT

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