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STUDY ON THE DYNAMIC PERFORMANCE OF A NOVEL STEAM TURBINE SYSTEM WITH AN ADDITIONAL REGENERATIVE TURBINE

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ABSTRACT

The integration of an additional regenerative turbine is an effective method to decrease the irreversibility of regenerative heaters for ultra-supercritical coal-fired power plants. However, the regenerative turbine belongs to the backpressure turbine and its steam pressure is influenced greatly by the steam mass flow. The purpose of this study is to investigate the dynamic characteristics of regenerative turbine system. Dynamic models were developed and the turbine power and heat consumption rate were calculated during processes of loading down and regenerative heater shutting down. The results indicated that the heat storage in the metal and working medium leads to the delay of the load and the delay increases more at the load-down rate 4%TMCR min^{-1} compared to 2%TMCR min^{-1}. The load increases greatly in the moment that the regenerative heater shuts down .The respond speed of the high-pressure heater shutting down decreases obviously compared to that of the low-pressure heater shutting down. Moreover, the energy efficiency reduces ultimately with the regenerative heater shutting down.

Keywords: ultra-supercritical unit, regenerative turbine, heat storage, dynamic characteristics

NONMENCLATURE

Abbreviations	
RT	Regenerative Turbine
TP	Turbine Power
HCR	Heat Consumption Rate
LPH	Low-pressure Heater
HPH	High-pressure Heater

1. INTRODUCTION

With the development of the economy and industry, China has become the largest energy consumer in the world [1]. Aiming at saving energy and decreasing the pollution, the proportion of renewable energy sources increases rapidly around the world [2]. However, thermal power generation still accounts for a large proportion in China. Improving the efficiency of thermal power units can not only reduce the emission of flue gas pollutants and carbon dioxide, but also reduce the coal consumption of power generation. It is essential to develop the ultra-supercritical units with high parameters and large capacity to reach the goal of cleanness and high efficiency. Nevertheless, it increases the temperature difference between the superheated steam and feed water. Integrating the regenerative turbine (RT) is an effective method to solve the problem and improve the thermal efficiency of units.

Several researches have studied the RT system in the ultra-supercritical coal-fired power plants, the results indicated that integrating the RT could improve the generation efficiency of the unit and decrease the steam superheat [3-6]. Kan et al. [7] simulated the RT system with EBSILION software and concluded that the RT could decrease the coal consumption under different loads. Guo et al. [8] studied the scheme of employing the RT and steam cooler in the double reheat supercritical unit. It was found that the RT cycle is much superior in both thermal economy and technical economy. Qiao et al. [9] studied the thermodynamic

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characteristics of the RT system with the method of the exergy analysis and concluded that the RT could decrease the superheat degree of the steam and exergy loss of the unit. Cui et al. [10] used the model of the externally arranged steam cooler and RT system as evidence that the turbine efficiency of the unit could be increased equipped with the RT.

However, the studies mainly focus on the numerical calculation of the steady state condition or variable condition. There is less attention to the dynamic simulation on the RT system. Because the thermal power plants are undertaking the task of peak shaving at present, dynamic characteristics are significant for the operational flexibility of the unit. The purpose of this study is to establish the model of the RT system and investigate the dynamic characteristics during processes of the loading down and the regenerative heater shutting down.

2. SYSTEM DESCRIPTION

Fig. 1 shows the schematic layout diagram of the RT system. One partial steam through the super high-pressure cylinder enters into the RT instead of entering the boiler. Moreover, the steam of some HPHs is from the RT rather than the high-pressure cylinder, which declines the superheat of the steam in the high-pressure heater (HPH) and increases the thermal economy of the unit.

3. MATHEMATICAL MODELS

This study mainly introduces the transient models of the turbine, the pump and the heat exchangers. After the steam works in the turbine, the temperature and pressure of the steam decline and the exhausted steam is condensed to condensate water. Through the pump, the pressure of the condensate water increases in case that the temperature in the heat exchanger is higher than the saturation temperature and it could improve the plant thermal efficiency.

3.1 Modeling of the turbine

For the high speed of the steam in turbine, the steady state models were used without the decrease of accuracy to some degree [11].

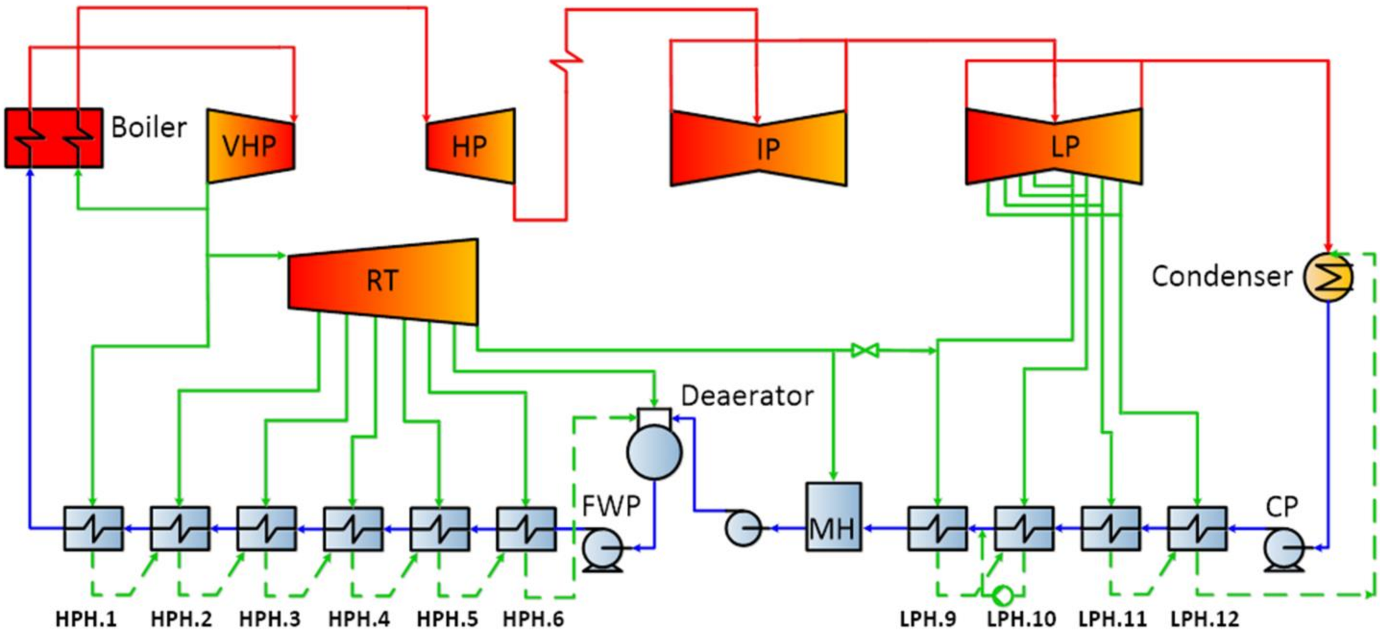
$$W_{\mathrm{turbine}} = \sum G_{\mathrm{i-turbine}} \eta_{i-\mathrm{turbine}} \Delta h_{\mathrm{isn}} \tag{1}$$

where $G_{\mathrm{i-turbine}}$ is the steam flow in the stage of the turbine, kg s^{-1}; $\eta_{\mathrm{i-turbine}}$ is the efficiency in the stage of the turbine; Δh_{isn} is the decrease of the enthalpy, J kg^{-1}.

The pressure in the stage of the turbine is obtained by Flugel correlation with the parameters of the steam flow, temperature and initial pressure.

$$\frac{G_{\mathrm{i-tb}}}{G_{\mathrm{i-tb}}^{0}} = \sqrt{\frac{T_{\mathrm{i0}}}{T_{\mathrm{i}}} \frac{P_{\mathrm{i-tb}}^{2} - x P_{\mathrm{i-1-tb}}^{2}}{P_{\mathrm{0i-tb}}^{2} - x P_{\mathrm{0i-1-tb}}^{2}}} \tag{2}$$

where $G_{\mathrm{i-tb}}^{0}$ is the initial steam flow in the stage of the turbine, kg s^{-1}; T_{i0} is the initial temperature of the steam, K; T_{i} is the temperature of the steam; $P_{\mathrm{i-tb}}$ is



VHP-super high-pressure cylinder; HP-high-pressure cylinder; IP-intermediate-pressure cylinder; LP-low-pressure cylinder; HPH-high-pressure heater; LPH-low-pressure heater; MH-mixing heater; RT-regenerative turbine; FWP-feed water pump; CP-condensate pump

Fig. 1 Schematic layout diagram of the RT system

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the pressure in the i stage of the turbine, MPa; $P_{\mathrm{i-1-tb}}$ is the pressure in the i-1 stage of the turbine, MPa; the subscript 0 is the initial parameter; x is the coefficient which equals to 0 if the velocity of the steam is the supersonic speed, while it equals to 1 if the velocity of the steam is the subsonic speed.

3.2 Modeling of the regenerative heater

This study employs the model which has the condensing section, superheated steam section and cooling water section as shown in Fig. 2.

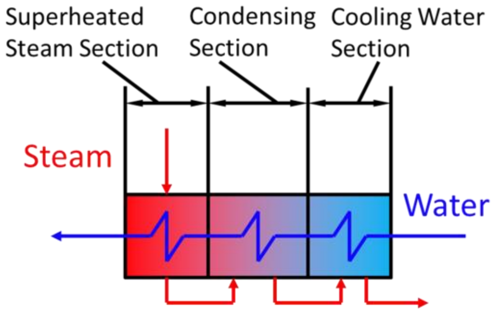

Fig. 2 The schematic of the heater

The heat transfer of the steam in the condensing section is as follows:

$$Q_{\mathrm{s,COND}} = \alpha_{\mathrm{s,COND}} A_{\mathrm{COND}} \left(T_{\mathrm{s,COND}} - T_{\mathrm{m,COND}}\right) \quad (3)$$

where $\alpha_{\mathrm{s,COND}}$ is the heat transfer coefficient of the steam, W (m^2 K)$^{-1}$; A_{COND} is the heat exchange area, m^2; $T_{\mathrm{s,COND}}$ is the average temperature of the steam, K; $T_{\mathrm{m,COND}}$ is the wall temperature, K.

The heat transfer of the water in the condensing section is as follows:

$$Q_{\mathrm{w,COND}} = \alpha_{\mathrm{w,COND}} A_{\mathrm{COND}} \left(T_{\mathrm{m,COND}} - T_{\mathrm{w,COND}}\right) \quad (4)$$

where $\alpha_{\mathrm{w,COND}}$ is the heat transfer coefficient of the water, W (m^2 K)$^{-1}$; $T_{\mathrm{w,COND}}$ is the average temperature of the water, K.

The wall temperature of this iteration time is influenced by the wall temperature of the last iteration time in the transient model. The calculation of the wall temperature is as follows:

$$T^{n+1}_{\mathrm{m,COND}} = T^{n}_{\mathrm{m,COND}} + \frac{Q^{n}_{\mathrm{s,COND}} - Q^{n}_{\mathrm{w,COND}}}{M_{\mathrm{m,COND}} c_{\mathrm{p}}} dt \quad (5)$$

where $M_{\mathrm{m,COND}}$ is the mass of the wall, kg; c_{p} is the specific heat of the wall, J (kg K)$^{-1}$; dt is the time step, s; the subscript n indicates to the parameters in the last time, the subscript n+1 indicates to the parameters in this time.

The calculation formulas of the superheated steam section and cooling water section are similar with that of the condensing section.

3.3 Modeling of the pump

The pump pressurizes the water at the isentropic process ideally, while the entropy of the water increases in practice. The simplified calculation model of the pump power is as follows:

$$\tau_{\mathrm{tb}} = \tau_{\mathrm{isn}} / \eta \quad (6)$$

where τ_{isn} is the pump power at the isentropic process, J kg^{-1}; η is the isentropic efficiency of the pump.

4. RESULTS AND DISCUSSION

With the increasing proportion of the renewable energy sources, it is significant to research the dynamic characteristics to improve peak shaving capacity of the unit. The condition of the loading down and regenerative heater shutting down is studied with the dynamic modeling.

4.1 The unit dynamic characteristics during loading down condition

The turbine power (TP) and heat consumption rate (HCR) are calculated at the initial condition, namely 100%TMCR and the end condition, namely 80%TMCR. The rates of loading down are set as 4%TMCR min^{-1} and 2%TMCR min^{-1} to study the dynamic characteristics of the RT system. The load reduces with the mass flow of the main feed water declining lineally and the mass flow of the water stops reducing at 300s and 600s.

Fig. 3 shows the dynamic responses of TP. The TP declines lineally and then it decreases slightly to the steady state value. Because of the thermal storage in the metal and working medium, the TP continues to decline even though the mass flow of main feed water keeps invariant. It makes the practical TP later than the command TP. Moreover, the TP at the rate of 4%TMCR min^{-1} delays much more than that at the rate of 2%TMCR min^{-1}.

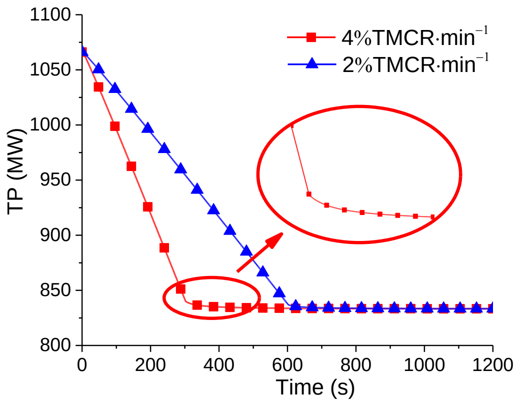

Fig. 3 Dynamic responses of TP

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The dynamic responses of HCR are shown in Fig. 4. The HCR declines to the minimum value at the first stage. Then it begins to increase until the main feed water maintains constant. Because the parameter variation of the temperature is later than that of the pressure, the HCR continues to rise up to the steady state value which is higher than the initial one. At the same time, the minimum value of the HCR decreases with the increase of load-down rate.

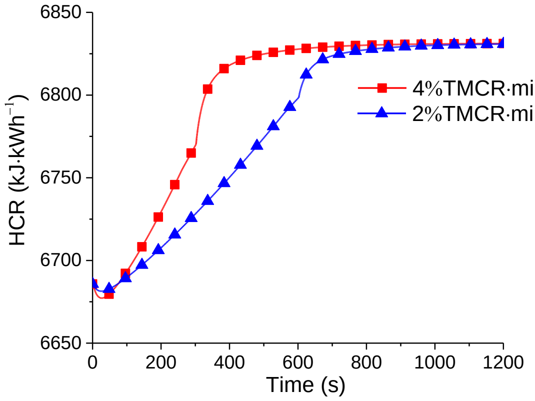

Fig. 4 Dynamic responses of HCR

4.2 *The unit dynamic characteristics during the condition of the LPH shutting down*

As shown in Fig. 5, the TP increases greatly when the low-pressure heater (LPH) shuts down. Then TP decreases gradually to the steady state value which is less than the initial one. The reason why the trend of HCR is opposite to that of TP is that HCR is the ratio of the heat and power. Because the heat almost remains stable, the HCR has an inverse proportion with the power.

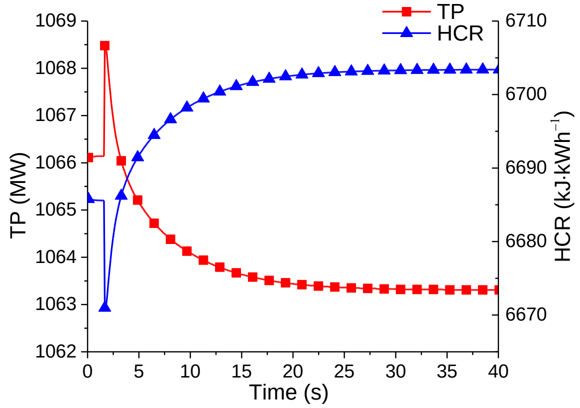

Fig. 5 Dynamic responses of the TP and HCR

4.3 *The unit dynamic characteristics during the condition of the HPH shutting down*

In Fig. 6, it is shown that the TP increases with the HPH shutting down and then it declines rapidly to the minimum value. Finally, it increases gradually to the steady state value. The trend of the HCR is also contrary to that of the power. However, the RT pressure is influenced greatly by the steam mass flow because the RT belongs to the pressure back turbine. If the HPH shuts down, the steam mass flow in the RT increases, which makes the RT pressure change obviously. Therefore it decreases the unit respond speed and makes the unit dynamic characteristics more complicated.

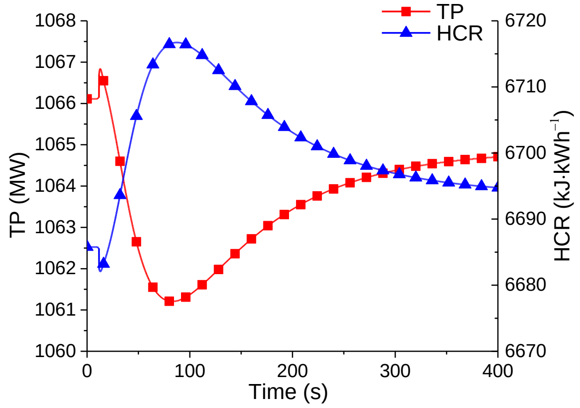

Fig. 6 Dynamic responses of the TP and HCR

5. CONCLUSION

The numerical models were carried out to research the unit dynamic characteristics. The main conclusions could be drawn from the numerical results.

(1) The dynamic characteristics of the TP could be influenced by the heat storage in the metal and working medium during the load-down process. Moreover, the delay of the TP increases with the load-down rate increasing.

(2) The HCR declines first and then rises to the steady state value that is higher than initial one during the load-down condition. The minimum value of the HCR decreases when the load-down rate increases.

(3) The TP increases greatly in the moment that the heater shuts down and the steady state of the TP is less than the initial value. The respond speed of the HPH shutting down decreases obviously compared to that of the LPH shutting down. Besides, the heater shutting down reduces the thermal economy of the unit ultimately.

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