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Theoretical Investigation on the Partial Load Feedwater Heating System with Thermal Vapor Compressor in a Coal-fired Power Unit

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Abstract

When a coal-fired unit operates at a partial load, the decrease at regenerative steam pressure leads to a decrease in boiler feedwater temperature, affecting not only the thermal economical efficiency, but also the selective catalytic reduction (SCR) denitrification effect and the boiler combustion stability. A feedwater system with the thermal vapor compressor has been studied in the present paper. The high pressure regenerative steam is injected by the live steam to heat boiler feedwater to increase its temperature. Mathematical models of the thermal vapor compressor, boiler and turbine regenerative system are established to calculate the performance of a 660MW supercritical air cooling unit at a 60% load. It was found that although the energy-saving effect is small, it is positive to improve the SCR denitrification effect and stabilize the boiler combustion.

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Keywords: regenerative cycle, thermal vapor compressor, thermo-economical analysis

1. Introduction

Energy conversion and application is closely linked to human existence and development. In 2013, 3750 million tons of standard coal of primary energy were consumed in China [1], and half of them were burned up in the thermal power plants. The coal-fired units take up about 78% of the total electricity generation capacity in China, and nearly all of these units undertake not only the basic load but also the peak load. Meanwhile, the rapid development of renewable energy, such as wind energy and solar energy across the world, makes the peak load altering task even escalate, and the coal-fired units have to operate

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at low load conditions frequently [2]. So it is significant to improve the thermal efficiency and reduce the pollution for the coal-fired units operating at a partial load.

When the coal-fired unit operates at the partial load, the live steam flow decreases, and the pressure of regenerative steam drops too, leading to a decrease in feedwater temperature. The feedwater temperature is an important parameter affecting the thermal efficiency of the unit. When the feedwater temperature falls, the average temperature in the heat absorption of thermodynamic cycle drops, the cycle thermal efficiency decreases and the coal consumption rate would rise [3].

The low feedwater temperature may also weaken the NOx elimination and cause instability of the combustion in the coal-fired power unit. In modern coal-fired power units the selective catalytic reduction (SCR) devices are mostly installed between the boiler economizer and air preheater. And the SCR catalyst effective working temperature is about 270-350℃ [4]. When the unit is operated at a partial load, the temperature of the flue gas from the coal economizer will drop below the effective temperature range. In order to tackle this problem, one method is to extract the high- temperature flue gas from the furnace to mix it with the outlet flue gas from the coal economizer to boost the flue gas temperature, thus increasing the investment and complicating the operation [5]. Simultaneously, the low temperature of the flue gas from the economizer may reduce the hot air temperature at the air preheater outlet, thereby leading to dropping the temperature of the boiler furnace, which would affect the combustion stability accordingly.

In order to solve the above problem, a feedwater heating system (FWHS) with a thermal vapor compressor (TVC) was proposed for the coal-fired power unit operating at a partial load. The live steam is used to inject the highest pressure regenerative steam, and the mixed steam is introduced into an additional feedwater heater to improve the feedwater temperature. The TVC was a type of heat pump, which uses higher pressure steam as a motive power and injects the lower pressure steam [6, 7]. Compared with other types of heat pump, the TVC has the advantages of having simple structure, no moving parts, and safe and reliable working process, so it has been widely employed in the field of refrigeration, desalination, and natural gas exploration [8-10]. The thermal economy of the FWHS with TVC was studied in previous literature [11]. It was found that the system can improve the thermal cycle efficiency of a 600 MW unit significantly at a partial load, but the impact on the boiler tail heating surface is not considered.

In the present paper, the performance of the FWHS is carefully studied. Mathematical models of the TVC are constructed, and the turbine regenerative system and the boiler tail heating surface are brought into consideration. A 660MW supercritical direct air cooling unit is chosen to study its performance at 60% of the designed load. This research should be helpful to guiding the application of the FWHS.

2. Mathematical model

The thermal system of a 660MW supercritical direct air cooling coal-fired power unit with the FWHS is shown in Fig.1. Seven regenerative extraction steam devices including one deaerator (No.4), three low-pressure heaters (No.1-3) and three high-pressure heaters (No.5-7) respectively. A TVC and an additional heater No.8 are introduced to increase the feedwater temperature at a partial load. The extraction steam of high-pressure heater No.7 is injected by the live steam in the TVC, and the outlet steam of the TVC enters into additional heater No.8 to heat the boiler feedwater. The drainage from additional heater No.8 flows into high-pressure heater No.7.

In Fig.1, the extracted steam from high-pressure heater No.7 is injected by the TVC to heat the boiler feedwater, so the cycle thermal efficiency increases. However, as the feedwater temperature increases, the heat transfer process in the economizer and air preheater in the boiler is affected. To study the performance of the entire system, mathematical models for the TVC, boiler economizer and air preheater need to be comprehensively established in the heat balance calculation of the unit.

The performance of the TVC could be described by the injection ratio and the the compressed ratio. The former ss defined as the ratio of the mass flow of low-pressure steam to the mass flow of high-pressure steam, and the latter ss defined as the ratio of the mixed steam pressure to the injected steam pressure. The mathematical model of the TVC in literature [6,7] has been used in the present work.

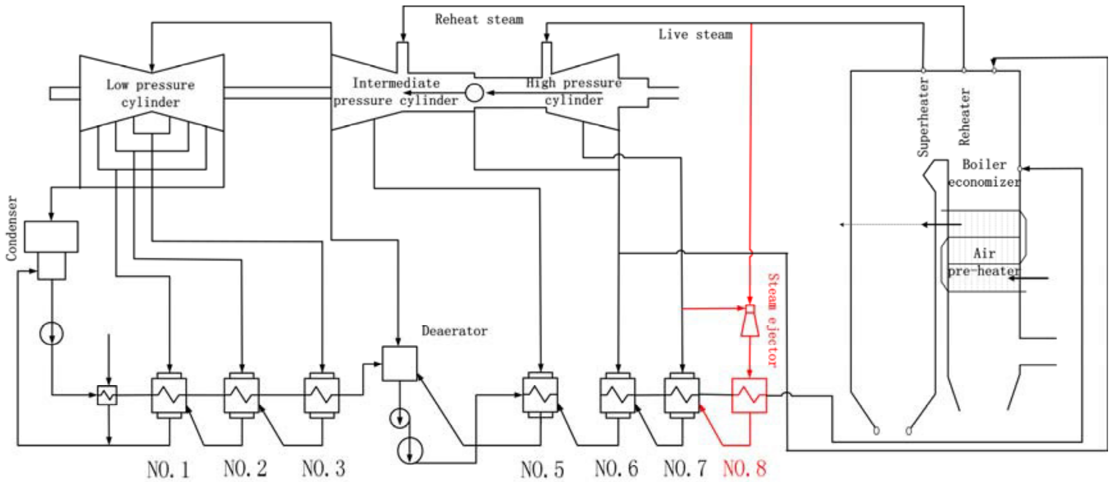


Fig. 1 the system diagram of the FWHS

Neglected the minor heat loss in the TVC, the enthalpy of the mixed steam discharged from the TVC and entered into No.8 heater could be calculated by the energy balance equation as follows:

$$h_8 = \frac{G_{80}h_0 + G_{87}h_7}{G_8} \quad (1)$$

The additional heater No.8 in FWHS can be treated as a single regenerative heater. The temperature of the feedwater and the drainage out of No.8 can be determined by its upper and drainage temperature differences. Here it is assumed that the temperature differences were as same as the high-pressure heater No.7. Then the heat balance can be achieved for the regenerative system as demonstrated in Fig.1[3].

When the feedwater temperature changes, the thermal efficiency of the boiler will change as well. To simplify the analysis, it is assumed that only the boiler exhaust gas heat loss caused by the feedwater temperature changes and the other losses are considered to contribute to the change in the boiler efficiency. Based on the boiler anti-balance calculation, the change in the boiler efficiency can be expressed as:

$$\Delta\eta_b = -\Delta q_2 \quad (2)$$

As the boiler exhaust gas lose q_2 is linked to its temperature, the heat transfer mathematical model of the economizer and air preheater can be established when the feedwater temperature changes. [12].

After the heat rate of the turbine-generator set and the thermal efficiency of the boiler are obtained, the coal consumption rate of the unit can be calculated by the following formula:

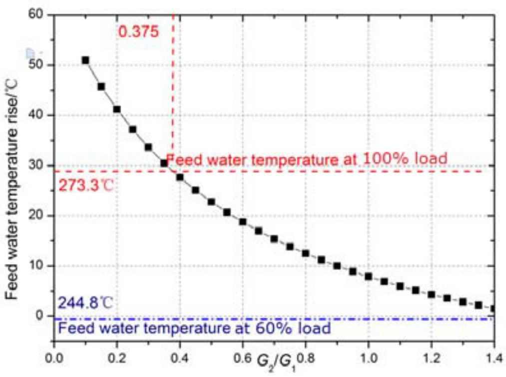
$$b_0 = \frac{123}{\eta_b \eta_p} \times \frac{HR}{3600} \tag{3}$$

3. Results and discussion

According to the statistics collected by the China Electricity Council, from 2008 to 2013, Chinese annual average utilization hours of thermal power units were 4885, 4865, 5031, 5294, 4780 and 5012 hours respectively[1], and the average load rate was about 70%. The 660MW unit studied in the present paper operates under 60% load for a long period of time. So the partial load of the unit is chosen as 60% load in the present paper.

The temperature rise, namely the feedwater temperature rise, caused by the additional heater, is calculated with different injection ratios, with the results being shown in Fig.2. It is demonstrated that the feedwater temperature rise decreases with the injection ratio decline, but the decline rate decreases gradually with the rise of the injection ratio. When the injection ratio is 0.375, the outlet water temperature of the additional heater approximates the corresponding temperature parameter of 100% load. When the injection ratio is less than 0.5, the injection ratio is caused by rapid temperature rise. When the injection ratio is more than 1, there is a gentile increasing trend of the temperature rise. The heat transferred by the additional heater is expressed as the temperature rise. The more the heat is transferred, the higher the temperature rise will be. The temperature rise in the high-pressure heater of the typical large thermal power units is about 20-40℃, so the injection ratio should be chosen around 0.3-0.65 to make sure that the temperature rise in the additional heater be in this range.

The FWHS is designed to raise the boiler feedwater temperature, so this will reduce the heat transfer temperature difference in the economizer and increase the temperature of the flue gas from the economizer. From Fig.3 it can be seen that, when the injection ratio increases, the temperature rise of the flue gas at the economizer outlet decreases too. When the original unit is operating under 60% load, the temperature of the flue gas from the economizer is too low to keep the SCR denitrification efficiency. However when the injection ratio is 0.5, such a flue gas temperature increases about 10℃, resulting in improving the SCR denitrification efficiency.



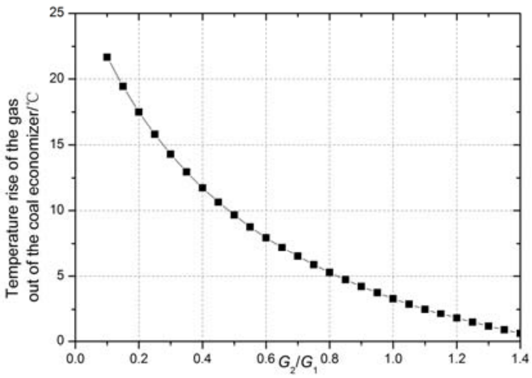


Fig.2 the feedwater temperature rise Fig.3 the temperature rise of the economizer outlet flue gas

As the temperature of the economizer outlet flue gas changes, the heat transfer process in the air preheater will be influenced and the outlet hot air temperature has a positive trend varying with the flue gas temperature. The temperature rise of the air preheater outlet hot air with different injection ratios is shown in Fig.4. The feedwater temperature has a negative trend to the injection ratio, causing the flue gas temperature from the economizer and the hot air temperature at the outlet of the air preheater both to decrease with the injection ratio rise. When the original unit is at a 60% load, such hot air temperature drops to 288℃. However, when the injection ratio is chosen as 0.5, it can be increased about 10℃, thus boosting the boiler combustion stability.

According to the influence of the FWHS on the turbine and boiler regenerative system, the energy saving efficiency with different injection ratios is studied. The decline of coal consumption rate is calculated, as shown in Fig.11. When the injection ratio increases, the decline of coal consumption rate increases first, and then decreases gradually. When the injection ratio is 0.75, the decline reached the maximal value, 0.78g/kWh. It is larger than the decline of the turbine heat consumption rate, because the boiler efficiency increases with the injection ratio. When the injection ratio changes in the range of 0.45-1.2, the decline of coal consumption rate varies slowly with the value above 0.6g/kWh. In the design of the FWHS, the energy-saving efficiency, system investment, and requirements of the SCR denitration device should be considered comprehensively in the choice of injection ratio for the best results of energy saving and emission reduction.

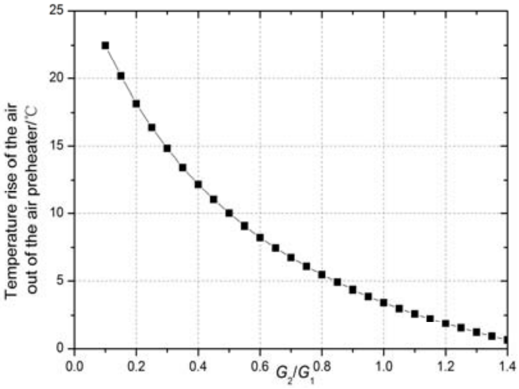


Fig.4 the temperature rise of the hot air

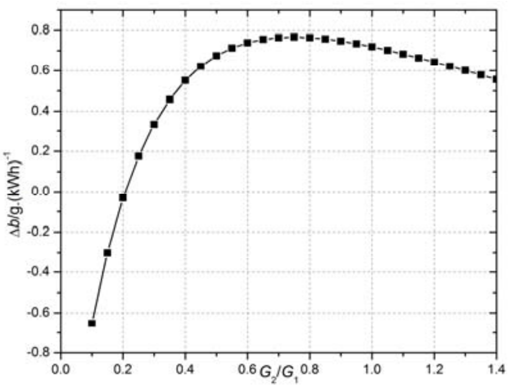


Fig.5 the energy-saving effect

4. Conclusion

The feedwater temperature decreases when the thermal power unit is operated at a partial load. To address the problem, a feedwater heating system (FWHS) with a thermal vapor compressor (TVC) for partial load is proposed and the mathematical models are established. The system is used in a 600MW supercritical air cooling unit to study the effects of injection ratio on the performance. Conclusions are reached as follows:

(1) The thermal vapor compressor is applied in the regenerative system. The live steam is used to inject the regenerative extracted steam, and the mixed steam flows into the additional heater to heat the feedwater. When the feedwater temperature rises, the thermal economical efficiency of the unit under partial load is improved. The denitrification effect of the SCR denitration device is ensured, and the boiler combustion stability at the partial load is improved.

(2) For the 660MW supercritical air cooling unit at a 60% load, when the injection ratio is 0.5, the feedwater temperature will rise 20℃. The economizer outlet flue gas temperature and the air preheater outlet hot air temperature increase about 10℃ and 5 ℃ respectively. The denitrification effect and combustion stability are improved.

(3) With the FWHS, the turbine heat consumption rate decreases and the boiler thermal efficiency increases as well. For a 660MW supercritical air cooling unit at a 60% load, when the injection ratio is

0.75, the energy saving effect reaches its best value and the decline of coal consumption rate is 0.78g/kWh. When the injection ratio varies in the range of 0.45-1.2, the decline of the coal consumption rate is above 0.6g/kWh. Energy-saving efficiency, system investment, the requirements of SCR denitration device should be considered comprehensively in the choice of the injection ratio for achieving the best results of energy saving and emission reduction.

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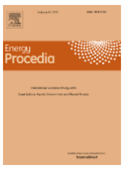

Biography

Dr. Liu Jiping is a professor at the School of Energy and Power Engineering, Xi’an Jiaotong University. He received his Ph.D. from Xi’an Jiaotong University in 1996. His research interests include CFD, enhanced heat transfer, emulation and optimization of thermal systems, steam-water two phase flow, and phase-change heat transfer.