Design and exergy analysis of 1000-MW double-reheat double-turbine regeneration system

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Abstract. The development of ultra-supercritical double-reheat technology is a practical choice to further improve the power generation efficiency, reduce coal consumption, reduce carbon emissions, and save resources. Currently, the outer-steam cooler system in double-reheat units has been typically adopted to solve the problem of prodigious superheat degree of an extraction steam. An increasing number of studies show that the double-turbine regeneration system achieves better economy and practicability in resolving the prodigious superheat degree of an extraction steam for double reheat. Through the thermal equilibrium analysis method and exergy analysis method, the performance of the three units under design conditions and off-design conditions is specifically analyzed, and the exergy loss and exergy efficiency of both the steam turbine and regenerative heater are further analyzed. The results show that the energy-saving performance of the double-turbine regeneration system is better than that of the outer-steam cooler system under the design conditions, and the energy-saving performance of the double-turbine regeneration system gradually decreases as the load decreases. At low loads, the performance of the regenerative turbine is significantly reduced, and the energy-saving effect of the double-turbine regeneration system is not as good as that of an outer-steam cooler system.

1. Introduction

Currently, China's thermal power units are developing in the direction of large capacity and high critical operational parameters. The primary steam pressure and temperature have reached 28 MPa and 620 °C, respectively, reaching the global advanced level [1]. China's thermal power units have undergone a transition from supercritical to ultra-supercritical to ultra-supercritical, resulting in the continuous improvement of power generation efficiency and the continuous decline in coal consumption for power generation. Owing to the limitation of 700 °C high-temperature materials [2], the thermal power unit temporarily cannot reach higher parameters. Before this problem was solved, the development of ultra-supercritical double-reheat technology was significant, which is a practical choice to further increase the power generation efficiency, reduce the coal consumption of power generation, and reduce carbon dioxide emissions. The double-reheat technology was proposed in the 1950s [3] and has been successfully operating in Europe, the United States, and Japan for several years. In the recent years, double-reheat technology has developed rapidly in China and has become a mainstream direction for the development of thermal power units [4-6].

Over the past few years, a detailed study has been conducted on the performance of the steam turbine, the configuration of the regenerative system, and the selection of the regenerative heater type for double-reheat units [7-8]. The system optimization of the double-reheat unit has been continuously improved, and it has been demonstrated that the current double-reheat units often adopt a 10-stage extraction steam
to increase the cycle efficiency of the entire system. However, in the double-reheat unit, a problem exists in that the superheat degree of the extraction steam is too high, and currently, outer-steam coolers are generally used in the project to absorb the energy of the extraction steam and then heat the water, thereby reducing the energy loss and coal consumption of the system [9-10].

To further optimize the system and consider the system performance under off-design conditions, Sven Kjaer[11] proposed the master cycle (i.e., double-turbine regenerative system) in 2010. It uses an independent regenerative turbine and cancels the extraction of the intermediate-pressure cylinder, thus significantly reducing the superheat degree of the regenerative heaters. Many studies show that the double-turbine regenerative system is a feasible and economical technology. Studies on double-turbine regenerative systems with different parameter levels has demonstrated its overall superiority [12-13]. An increasing number of studies show that compared with the outer-steam cooler scheme, the double-turbine regenerative system has a higher cycle efficiency and lower coal consumption, in addition to showing energy-saving effects in off-design conditions [14-15].

In this work, based on the traditional double-reheat units and considering the outer-steam cooler scheme applied in the project, a novel double-reheat double-turbine regenerative system is designed. The Ebsilon software is used to design and simulate a 1000-MW unit in China. The overall performance of the three schemes under design conditions and off-design conditions and the performance of each component are systematically studied through exergy analysis. Finally, this work lays a solid foundation for the practical application of a 1000-MW double-reheat double-turbine regenerative system.

2. Overview and calculation model of the double-reheat double-turbine regenerative system

2.1. Overview of the double-reheat double-turbine regenerative system

The double-reheat double-turbine regenerative system is a novel system. Based on the existing double-reheat system, an independent regenerative turbine is constructed, and the extraction steam of the intermediate-pressure cylinder is eliminated. The steam source of the regenerative turbine is from the exhaust steam of the high-pressure cylinder, and the exhaust steam of the regenerative turbine can be directly fed into the regenerative heater. Hence, the extraction steam can be drawn from an independent regenerative turbine to heat the feed water in the regenerative heater. Because the parameters of the extraction steam of the regenerative turbine are lower, the superheat degree of the extraction steam entering the regenerative heater is reduced, and the heat exchange temperature difference between the feed water and the extraction steam is reduced. Therefore, the exergy loss of the regenerative heater is reduced, and the cycle efficiency of the entire system is improved. After the extraction of the intermediate-pressure cylinder is eliminated, its efficiency was also improved. The energy of the generator connected behind the regenerative turbine can directly drive the feed pump, thereby further improving the energy utilization efficiency, reducing the coal consumption, and achieving the purpose of energy conservation and emission reduction. A large exergy loss of the regenerative heater occurs in the double-reheat unit; therefore, we built a model of the regenerative heater for the exergy analysis. Additionally, we performed a concrete analysis of the turbine, in which the double-turbine regenerative system and other schemes are compared from the specific equipment. Ultimately, a complete understanding of the double-turbine regenerative system will be realized.

2.2. Mathematical model of double-turbine regenerative system

2.2.1. Exergy analysis Exergy analytical methods generally use exergy loss, exergy efficiency as evaluation indicators.

In any irreversible process, exergy transformation along with the increase in the system entropy is inevitable, thus causing exergy loss. Exergy loss is the difference between the exergy cost and the exergy profit in this process. The formula is as follows:

$$E_{x,l} = E_{x, pay} - E_{x, gain}$$

(1)
In the equation (1), $E_{x,pay}$ is the exergy cost of the system; $E_{x,gain}$ is the exergy profit of the system; $E_{x,l}$ is the exergy loss of the system.

The exergy efficiency is the ratio of the exergy gain to the exergy cost in the material and energy transformation process of the system. The formula is as follows:

$$\eta_{ex} = \frac{E_{x,gain}}{E_{x,pay}}$$

In the equation (2), $\eta_{ex}$ is the exergy efficiency of the system.

2.2.2. Mathematical models of turbine and regenerative heater

Table 1. Mathematical models of turbine and regenerative heater

| Device          | Icon | Exergy loss | Exergy efficiency |
|-----------------|------|-------------|-------------------|
| Turbine         | ![Turbine Icon] | $E_{x,l} = E_1 - E_2 - E_3 - W$ | $\eta_{ex} = \frac{W}{E_1 - E_2 - E_3}$ |
| Surface heater  | ![Surface Heater Icon] | $E_{x,l} = E_1 + E_2 + E_4 - E_5$ | $\eta_{ex} = \frac{E_1 - E_2}{E_1 + E_4 - E_5}$ |
| Mixing heater   | ![Mixing Heater Icon] | $E_{x,l} = E_1 + E_2 + E_4 - E_5$ | $\eta_{ex} = \frac{D_1(e_3 - e_2)}{D_1(e_1 - e_2) + D_4(e_4 - e_5)}$ |

3. Design and exergy analysis of 1000-MW double-reheat double-turbine regeneration system

3.1. Thermal economic analysis of 1000-MW double-reheat double-turbine regeneration system

In this study, a 1000-MW unit is used as an example. Figure 1 is a schematic diagram of the original scheme of a 1000-MW double-reheat unit. The system is equipped with a 10-stage extraction steam, including four high-pressure regenerative heaters, one deaerator, and five low-pressure regenerative heaters. Figure 2 is a schematic diagram of the outer-steam cooler scheme of a 1000-MW double-reheat unit. In front of the no. 1 high-pressure regenerative heater, two parallel steam coolers, OSC1 and OSC2 are provided to cool the second and fourth stage extraction steam, respectively and this will lead to an increase in the temperature of the feed water. Figure 3 is a schematic diagram of the double-turbine regeneration scheme of a 1000-MW double-reheat unit, from which we can observe that the double-turbine regeneration scheme has an independent turbine named R-Turbine, compared to the original scheme. The extraction and exhaust steam of the double-turbine regeneration scheme are respectively introduced into the RH2 to RH7 heaters and the extraction steam is eliminated in the intermediate-pressure cylinder. In addition, the generator is connected behind the R-Turbine, and its work can drive the feed water pump.

The following assumptions are established to implement the simulation and performance assessment of the thermal systems.

1. The operation of the power plant is considered to be in a steady state.
2. For the different stages of the high-pressure, intermediate-pressure, and low-pressure turbines, the mean isentropic efficiencies are 0.90, 0.93, and 0.89, respectively.
3. The terminal temperature difference of the outer-steam cooler is 10 °C.
4. The isentropic efficiency of the regenerative turbine is 0.865.
Figure 1. The Original scheme of a 1000-MW double-reheat unit

Figure 2. The Outer-steam cooler scheme of a 1000-MW double-reheat unit

Figure 3. Double-turbine regeneration scheme of a 1000-MW double-reheat unit
Table 2 is a comparison of the thermodynamic parameters of the three schemes. As shown, the power generation efficiency of the outer-steam cooler unit is 0.17% higher than that of the original unit, and the power generation efficiency of the double-turbine regeneration system is 0.18% higher than that of the outer-steam cooler unit. The coal consumption for double-turbine regeneration system is only 256.57 g/kW·h, which is 1.89 g/kW·h and 0.97 g/kW·h lower than that of the original unit and the outer-steam cooler unit, respectively.

**Table 2. Comparison of thermodynamic parameters of unit**

| Items                          | Original scheme | Outer-steam cooler scheme | Double-turbine regeneration scheme |
|-------------------------------|-----------------|---------------------------|-----------------------------------|
| Live steam pressure (MPa)     | 29.895          | 29.895                    | 29.895                            |
| Live steam temperature (℃)   | 600             | 600                       | 600                               |
| Live steam flow rate (kg s⁻¹) | 682.22          | 698.82                    | 730.50                            |
| First reheat steam pressure (MPa) | 10.19         | 10.19                     | 10.19                             |
| First reheat steam temperature (℃) | 620           | 620                       | 620                               |
| Second reheat steam pressure (MPa) | 3.091          | 3.091                     | 3.091                             |
| Second reheat steam temperature (℃) | 620           | 620                       | 620                               |
| Power generation output (MW)  | 1000            | 1000                      | 1000                              |
| Power generation efficiency (%) | 47.59          | 47.76                     | 47.94                             |
| Heat consumption rate (kJ kW⁻¹ h⁻¹) | 7119.21       | 7093.29                   | 7065.43                           |
| Coal consumption (g kW⁻¹·h⁻¹)  | 258.46          | 257.54                    | 256.57                            |

From Figure 4, we can conclude that the regenerative heaters of the original unit have high superheat degrees, especially the RH2, RH4, and RH5 (deaerator) heaters, because their extraction steam originates from the live steam that has been reheated in the boiler. The outer-steam cooler system primarily reduces the superheat degree of two regenerative heaters, RH2 and RH4, and the double-turbine regeneration system further significantly reduces the superheat degree of each regenerative heater. The superheat degree of RH2, RH4, and RH5 in the double-turbine regeneration system is reduced by 182.1 °C, 309.3 °C, and 273 °C, respectively, compared to the original unit and this effectively reduces the energy loss caused by the heat exchange between the extraction steam and the feed water.

**Figure 4. Comparison of superheater of regenerative heaters for different schemes**

3.2. Exergy analysis of turbine

We divide the steam turbine into five sub-units for analysis: the high-pressure cylinder (HP), the no.1 intermediate-pressure cylinder (IP1), the no.2 intermediate-pressure cylinder (IP2), the low-pressure cylinder (LP), the small turbine (ST) or the regenerative turbine (RT).
Table 3 shows the results of the exergy analysis of each cylinder among the three units. It can be concluded that in the original unit, the exergy efficiency of the IP1 cylinder and the IP2 cylinder is the highest, followed by the HP cylinder, and the exergy efficiency of the LP cylinder is lowest. Compared with the original system, owing to the increase in the extraction steam flow of the second and fourth sections in the outer-steam cooler system, the exergy losses of the HP cylinder and the IP1 cylinder are slightly higher, and the exergy loss of the small steam turbine is slightly higher. When we apply the double-turbine regeneration system, the exergy loss of the HP cylinder increases owing to the increase in the live steam rates, but the exergy efficiency of the HP cylinder has almost no change. After the extraction steam was eliminated in the IP cylinder, the energy loss caused by part of the extraction steam was reduced. Compared with the original scheme, the exergy losses of the IP1 and IP2 cylinders were reduced by 2956.19 kW and 3431.19 kW, respectively, and the exergy efficiencies were increased by 0.61% and 0.78%, respectively. The exergy loss of the LP cylinders of the double-turbine regeneration system is reduced by 3714.51 kW compared with the original unit, and the exergy efficiency is increased by 1.56%. The mean isentropic efficiencies of the regenerative turbine and the LP cylinder are relatively close, and their exergy efficiencies are slightly higher than that of the LP cylinder. Compared with the small turbine in the original system and the outer-steam cooler system, the exergy loss of the regenerative turbine is also relatively low. In addition, the exergy loss of the LP cylinder in the double-turbine regeneration system is significantly lower than that of the original system and the outer-steam cooler system.

Table 3. Exergy analysis of turbine for different schemes under THA condition

| THA | HP         | IP1        | IP2         | LP          | ST/RT       |
|-----|------------|------------|-------------|-------------|-------------|
| Original scheme | Exergy loss (kW) | 9776.92    | 8576.50     | 12780.94    | 32180.72    | 5683.53    |
|      | Exergy efficiency (%) | 95.07      | 96.08       | 96.16       | 90.05       | 84.67      |
| Outer-steam cooler scheme | Exergy loss (kW) | 10013.48   | 8719.84     | 12748.64    | 31945.49    | 5894.45    |
|       | Exergy efficiency (%) | 95.07      | 96.07       | 96.16       | 90.05       | 84.67      |
| Double-turbine regeneration scheme | Exergy loss (kW) | 10490.24   | 5620.31     | 9349.75     | 28466.21    | 6442.50    |
|       | Exergy efficiency (%) | 95.07      | 96.69       | 96.94       | 91.61       | 91.99      |

3.3. Exergy analysis of regenerative heaters

The table listed above shows the superheat degree of the regenerative heaters. According to the exergy analysis model of the regenerative heater proposed in section 2, we analyzed R1–RH10. From Table 4, we can conclude that the outer-steam cooler system significantly reduced the exergy loss on RH2 and RH4. Compared to the original scheme, the exergy losses of RH2 and RH4 are reduced by 2519.67 kW and 1351.43 kW, respectively, and the exergy efficiencies are increased by 4.54% and 5.87%, respectively. RH5 also has a certain degree of reduction in exergy loss. Compared to the outer-steam cooler system, the exergy losses of the different stages of the regenerative heater in the double-turbine regeneration system have been significantly reduced except that RH4 has a slightly higher exergy loss than the others. The exergy losses of RH2 and RH5 are reduced by 300.41 kW and 48.82 kW, respectively, and the exergy efficiencies of RH2, RH4, and RH5 are increased by 0.13%, 0.56%, and 3.59%, respectively. In summary, the regenerative heaters of the double-turbine regeneration system perform better.
Table 4. Exergy analysis of regenerative heaters for different schemes under THA condition

| Scheme                           | Exergy loss (kW) | Exergy efficiency (%) |
|----------------------------------|------------------|-----------------------|
| Original scheme                  | THA 4691.64      | RH2 2469.66           | RH4 1654.11          |
| Exergy efficiency (%)            | 91.36            | 89.14                 | 91.73                |
| Outer-steam cooler scheme        | Exergy loss (kW) | 2171.97               | 1118.23              | 1392.75              |
| Exergy efficiency (%)            | 95.90            | 95.01                 | 93.03                |
| Double-turbine regeneration scheme | Exergy loss (kW) | 1871.56               | 1720.50              | 911.93               |
| Exergy efficiency (%)            | 96.03            | 95.57                 | 96.62                |

4. Analysis under partial load conditions

Considering the frequent peaking requirements of the unit in China, we need to further analyze the performance of the three schemes under partial load conditions. The live steam temperature of the units remains unchanged, and the live steam pressure and flow rate are based on the Flugel formula. The boiler efficiency and turbine efficiency also remained the same. Here, we study from 75% THA, 50% THA, and 40% THA.

Figure 5 and Figure 6 compare the power generation efficiency and coal consumption of the three units under different operating conditions, respectively. As the load decreases, the difference between the power generation efficiency of the outer-steam cooler system and the original system is slightly reduced. However, the power generation efficiency of the double-turbine regeneration system is significantly reduced at low loads. At the THA operating condition, the power efficiency of the double-turbine regeneration system is 0.18% higher than that of the outer-steam cooler system. The double-turbine regeneration system is only 0.06% higher at the 75% THA operating condition. At the 50% THA operating condition, the power generation efficiency of the double-turbine regeneration system is comparable to that of the original system, which is 0.13% lower than that of the outer-steam cooler system. However, the power generation efficiency of the double-turbine regeneration system is only 0.4391 at the 40% THA operating condition, which is lower than that of the original system and the outer-steam cooler system. At this condition, the coal consumption of the double-turbine regeneration system is 280.12 g/kW·h and the coal consumption of the original system and the outer-steam cooler system is 279.35 g/kW·h and 278.53 g/kW·h, respectively, which is respectively 0.77 g/kW·h and 1.59 g/kW·h lower than the double-turbine regeneration system.

Table 5 shows the exergy loss of the steam turbine at the 75% THA operating condition for the three units. Owing to the reduction in the unit parameters, the absolute difference of the exergy losses between IP1 and IP2 in the double-turbine regeneration system and the other two systems is reduced and the exergy loss of the regenerative turbine is slightly higher. Compared with the outer-steam cooler system, the exergy losses of the IP1 and IP2 cylinders of the double-turbine regeneration system are reduced by...
2061.42 kW and 2201.07 kW, respectively, and the exergy efficiency does not change much when compared with the design conditions.

Table 5. Exergy analysis of turbine for different schemes under 75% THA condition

| Scheme                         | Exergy loss (kW) HP | Exergy loss (kW) IP1 | Exergy loss (kW) IP2 | Exergy loss (kW) LP | Exergy loss (kW) ST/RT |
|-------------------------------|---------------------|----------------------|----------------------|---------------------|------------------------|
| Original scheme               | 7964.42             | 6517.85              | 9580.44              | 23524.15            | 3228.27                |
| Outer-steam cooler scheme     | 8143.94             | 6495.68              | 9318.92              | 22759.25            | 3309.59                |
| Double-turbine regeneration scheme | 8286.74         | 4434.26              | 7117.85              | 24593.16            | 6016.27                |

Table 6 and Table 7 show the exergy loss of the steam turbines under the 50% THA and 40% THA conditions, respectively, for the three units. The exergy losses of the IP1 and IP2 cylinders of the double-turbine regeneration system are relatively low. However, as the load decreases, the efficiency of the regenerative turbine gradually decreases. Compared with the 75% THA operating conditions, the exergy efficiency of regenerative turbines at 50% THA and 40% THA conditions is reduced by 1.17% and 2.26%, respectively. The exergy efficiency of the small turbines of the original system and that of the outer-steam cooler system remain unchanged. Under the low load conditions, the feedwater flow rate and the feedwater temperature of the regenerative system are significantly reduced; therefore, the extraction steam flow rate in the regenerative turbine is also reduced accordingly and the effect of using the extraction steam to reduce the superheat degree is very small. Therefore, the energy-saving effect of the double-turbine regeneration system is reduced, and the outer-steam cooler system can increase the feed water temperature of the regenerative system. To a certain extent, it reduces the exergy loss of the system, therefore it still shows a particular energy-saving effect.

Table 6. Exergy analysis of turbine for different schemes under 50% THA condition

| Scheme                          | Exergy loss (kW) IP1 | Exergy loss (kW) IP2 | Exergy loss (kW) ST/RT |
|--------------------------------|---------------------|----------------------|------------------------|
| Original scheme                 | 4348.46             | 6372.85              | 1631.55                |
| Outer-steam cooler scheme       | 4365.82             | 6350.91              | 1688.07                |
| Double-turbine regeneration scheme | 3148.81          | 4869.73              | 3938.27                |

Table 7. Exergy analysis of turbine for different schemes under 40% THA condition

| Scheme                          | Exergy loss (kW) IP1 | Exergy loss (kW) IP2 | Exergy loss (kW) ST/RT |
|--------------------------------|---------------------|----------------------|------------------------|
| Original scheme                 | 3555.73             | 5190.36              | 1201.49                |
| Outer-steam cooler scheme       | 3533.36             | 5135.24              | 1236.74                |
| Double-turbine regeneration scheme | 2623.10          | 3994.51              | 3152.19                |

Figure 7 shows the exergy analysis of the regenerative heaters under different operating conditions for the three schemes. We focus on RH2, RH4, and RH5. As the load decreases, the exergy efficiencies...
of RH2, RH4, and RH5 of the original system gradually decrease, while the exergy efficiency of RH5 of the outer-steam cooler system decreases more significantly, and the exergy efficiency of the RH2 is slightly reduced but the exergy efficiency of the RH4 is continuously increasing. The exergy efficiency of RH2 of the double-turbine regeneration system is continuously decreasing, and the exergy efficiencies of RH4 and RH5 are significantly reduced at the 40% THA condition. Overall, the energy-saving effect of each heater in the double-turbine regeneration system is significantly reduced with the decrease in the load, indicating that the double-turbine regeneration system has a poor energy-saving effect at low loads.

Figure 7. Exergy analysis of regenerative heater for different schemes under various conditions

**5. Conclusions**

(1) Both the double-turbine regeneration system and the outer-steam cooler system can improve the problem of large superheat degree of extraction steam in the double-reheat system under the design conditions, and the double-turbine regeneration system performs better.

(2) As the load decreases, the power generation efficiency of the outer-steam cooler system gradually increases and the coal consumption for power generation gradually decreases compared with the original system under off-design conditions.

(3) The power generation efficiency of the double-turbine regeneration system is higher than that of the outer-steam cooler system and the original system at the 75% THA condition. When the load is reduced to 50% THA, the power generation efficiency of the double-turbine regeneration system is lower than that of the outer-steam cooler system, which is equivalent to the original system. When the load is further reduced to 40% THA, the power generation efficiency of the double-turbine regeneration system is significantly lower than that of the outer-steam cooler system and the original system. It is resulted from the reduction of the live steam flow rate and the extraction steam flow rate of the regenerative turbine at low loads. Furtherly, the reduction of the feedwater flow rate and temperature rise also results in a significant reduction in the energy utilization effect of its superheat degree.

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