Study on Optimization of Reheat Pressure after Retrofit of Coal-fired Power Plants for Heat Supply

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Abstract. After the retrofit of condensing power unit for heat supply, the reheat pressure of the unit deviates from the optimal value. When the heat supply and flow path of the turbine are retrofitted synchronously, or the retrofit of flow path is carried on the units which heat supply retrofit had been done, the reheat pressure should be redetermined during the design phase of the flow path retrofit and the thermal economy of off-rated load should be taken into account to ensure the best operation efficiency of the unit. Taking 660MW supercritical single reheat unit as an example, the reheat pressure optimization analysis was carried out for the heat supply from the cold end piping of reheat system or the connection pipe between IP and LP in the wide load range. The results show that the optimization of the reheat pressure after the retrofit of heat supply can obtain significant gains of heat rate in the wide load range.

1. Introduction
In order to combat global warming, Chinese government has promised that emission of CO2 will peak around 2030[1]. Coal power, as the largest CO2 emission source, becomes the focus of the whole society under the circumstance[2]. Electric Power Research Institute (EPRI) reports that, at present, there are three ways to reduce carbon dioxide emissions in coal-fired power plants: Carbon Capture and Storage (CCS) technology, increasing the initial temperature of steam, and using cogeneration. Among these methods, CCS technology is in a low popularity rate because of the low security, expensive cost, large energy consumption and other factors. Besides that, improving initial temperature of steam is limited by metal material[3]. Therefore, cogeneration central heating is an effective way to save energy and reduce emissions.

However, A large number of cogeneration projects are restricted by the total capacity of power construction and the total capacity of pollutant discharge. In order to solve the problem, the state actively guides and encourages the retrofit of part existing condensing power unit for heat supply, so as to increase the capacity of heat supply by not increasing the scale of electric power[4].

Meanwhile, with the continuous development of science and technology, in China, different advanced flow-path technologies have been used to carry out flow-path retrofit for 300MW and 600MW units. The main purpose is to improve efficiency, increase capacity and heat supply with large flow. In principle, all technical parameters of steam remain unchanged[5].

However, when flow-path retrofit is carried on the units which heat supply retrofit had been done, or the heat supply and flow path of the turbine are retrofitted synchronously, it should be noted that the condition has changed after heat supply retrofit of condensing turbine, original design parameters of steam turbine may have already deviated from the optimal value, combined with the thermoelectric...
decoupling[6], cogeneration units also need to response to the load change, participating peak shaving, resulting in further deviation of design parameters from the optimal value. This puts forward the requirement of parameter optimization for the flow-path retrofit. On this basis, this paper takes reheat pressure as the target parameter and optimizes the parameters of the above-mentioned flow-path retrofit to improve the thermal economy of units.

2. Mechanism of optimal value of reheat pressure

For general condensing units, the existence of optimal value of reheat pressure can be analyzed by the method of work coefficient[7] to analyze the thermal efficiency ($\eta_{rh}$) of ideal reheat cycle

$$\eta_{rh} = \frac{W_{a \ rh}}{q_{rh}} = \frac{W_a + \Delta W_a}{q + \Delta q} = \eta_t \frac{1 + A_{rh}}{1 + A_{rh} \eta_a}$$

(1)

Where $W_{a \ rh}$ denotes work done of reheat cycle; $q_{rh}$ denotes the average heat absorption of reheat cycle; $W_a$ denotes work done of basic cycle; $\bar{q}$ denotes the average heat absorption of basic cycle; $\Delta W_a$ denotes work done of additional reheat cycle; $\Delta q$ denotes the average heat absorption of additional reheat cycle; $\eta = \frac{W_a}{q}$ denotes the heat efficiency of basic cycle; $\eta_a = \frac{\Delta W_a}{\Delta q}$ denotes the heat efficiency of additional reheat cycle; $A_{rh} = \frac{\Delta W_a}{W_a}$ denotes work done factor of additional reheat cycle.

When the reheat pressure is low, as shown at the point $P_{rh}$ in figure 1, the average endothermic temperature of the additional reheat cycle is smaller than that of the basic cycle ($T_{rh} < T_0$). That is, the thermal efficiency of the reheat cycle is less than that of the basic cycle ($\eta_{rh} < \eta_t$). Then adding the reheating cycle will impair the economy of the whole cycle. With the increasing of reheat pressure, $T_{rh}$ is also increasing. To the point $P_{rh}$, $T_{rh} = T_0$, additional cyclic thermal efficiency equals that of base cycle ($\eta_a = \eta_t$). Putting it in the formula (1), $\eta_{rh} = \eta_t$. At this point, the economic income of reheat cycle is zero. Reheat pressure continues to rise to the point $P_{\infty}$, the average endothermic temperature of the additional reheat cycle is smaller than that of the basic cycle ($T_{rh} > T_0$). Reheating cycle starts to gain. When the point of reheat coincide with that of initial steam ($T_{rh} = T_0$). And the work done factor of additional reheat cycle is zero ($A_{rh} = 0$). Putting it in the formula (1), $\eta_{rh} = \eta_t$. Therefore, between the two points, there must be extreme value, that is, the optimal value. The optimum reheat pressure is the corresponding reheat pressure at the extreme point.
3. Optimization of reheat pressure after retrofit

The core of reheat pressure optimization is to ensure the economic optimum of the retrofitted unit in a wide load range after the heat supply and flow path of the turbine are retrofitted synchronously. It is necessary to calculate the deviation between the actual value and the optimal value of reheat pressure and its influence caused by the deviation on thermal economy under each load after retrofit.

3.1 Methods and models of calculation

The selection of reheat pressure adopts the method with enumeration, the design of regenerative system follows the principle of equal enthalpy rise distribution. Variable load range of calculation is 50%THA~100%THA. Based on the design scheme of THA working conditions, the degree to which the actual value of reheat pressure deviates from the optimal value under this condition and the influence of thermal economy caused by this deviation are calculated quantitatively by establishing mathematical model. And calculating the thermal economic gains of adopting the scheme of reheat pressure optimization during the design phase of flow path retrofit under wide load, when compared with the scheme of constant parameters of traditional flow path retrofit.

The degree to which the reheat pressure deviates from the optimal value can be observed by the offset ($\Delta P_{rh}^o$) and relative offset ($\Delta P_{rh}^{rel}$) of the reheat pressure. Their expression is:

$$\Delta P_{rh} = P_{rh}^o - P_{rh}^{op}$$

$$\Delta P_{rh}^{rel} = \frac{P_{rh}^o - P_{rh}^{op}}{P_{rh}^o}$$

Where $P_{rh}^o$ denotes reheat pressure after the traditional retrofit of constant parameters under each load; $P_{rh}^{op}$ denotes the optimum reheat pressure after retrofit under each load.

The thermal economic loss caused by the deviation from the optimum reheat pressure is the increment of heat rate ($\Delta H_R^0$). Its expression is:

$$\Delta H_R^0 = H_R^0 - H_R^{op}$$

Where $H_R^0$ denotes heat rate after the traditional retrofit with parameters constant under each load; $H_R^{op}$ denotes the heat rate corresponding to optimum reheat pressure after retrofit under each load.

Whether the unit reheat pressure is optimal or not is judged by the comprehensive heat rate income ($\delta H_R$):

$$\delta H_R = \frac{1}{N} \int_{R_i}^{R_{max}} n_i \cdot \Delta H_{R_i} \cdot dR_i$$

Where $R_i$ denotes argument—load; $N$ denotes the total operation time of unit; $n_i$ denotes...
operation time under \( R_i \) load; \( \Delta H_{H_i} = H_{H_i} - H_{H_0} \) denotes the difference value between the heat rate after the change of reheat pressure \( H_{H_i} \) and the heat rate after traditional retrofit with parameters constant \( H_{H_0} \).

3.2 Optimal object and main design parameters

Taking the synchronous retrofit of the heat supply and flow path of the turbine as an example, the reheat pressure optimization design of 660 MW supercritical single reheat unit is carried out. The main design parameters before retrofit are as follows:

**Form of the unit:** supercritical, single shafting, three cylinders and four outlets of turbine, single reheat, with adjustments in turbine

**Run mode:** sliding pressure operation under the load of 50%~75%, fixed pressure operation under the load of 75%~100%

**Power rating:** \( P_e = 660 \text{ MW} \)

**Parameters of primary and reheat steam:** 24.2 MPa/566℃/566℃

**Reheat pressure:** 5.8 MPa (This is the optimal value selected for rated working conditions.)

**Pressure of exhaust steam:** \( P_{e_h} = 5.10 \text{ kPa} \)

**Rated temperature of feedwater:** \( t_{f_w} = 273.5℃ \)

In addition to the reheat pressure, the other main parameters of steam remain unchanged during the retrofit of flow path. The efficiency of cylinder under each load after retrofit is shown in Table 1.

| Table 1. Design value of cylinder efficiency under different load after retrofit. | HP efficiency | IP efficiency | LP efficiency |
|---|---|---|---|
| 100%THA | 89.30% | 92.03% | 86.82% |
| 85%THA | 88.10% | 92.06% | 87.31% |
| 75%THA | 86.94% | 92.04% | 87.45% |
| 50%THA | 86.86% | 92.01% | 87.65% |

This paper mainly discusses two forms of heat supply retrofit: 120t/h of steam extracted from cold end pipe of reheat system and from the connection pipe between IP and LP is used for heat supply. Based on these two retrofit methods as a case, the optimal value of the reheat pressure of the retrofitted unit is calculated and analyzed. In order to simplify the analysis, it is assumed that the parameters of steam extraction can meet the heating demand in the range of electric load.

3.3 Results of calculations

The steam parameters still follow the original design according to the traditional principle of flow path retrofit. It is calculated that the optimum value of reheat pressure under rated condition without heat supply remains around 5.8 MPa. The main results under each load are shown in Table 2.

| Table 2. Calculation results of each load of the unit after the traditional flow path retrofit. | 100%THA | 85%THA | 75%THA | 50%THA |
|---|---|---|---|---|
| Reheat pressure (MPa) | 5.80 | 4.85 | 4.25 | 2.84 |
| Heat rate (kJ/kw·h) | 7617.67 | 7660.96 | 7720.26 | 7996.94 |

If the heat supply was added, Taking the heat supply from the cold end piping of reheat system as an example, the heat rate under each load are shown in Table 3.

| Table 3. The heat rate under each load after the traditional retrofit of the heat supply and flow path of the turbine. | 100%THA | 85%THA | 75%THA | 50%THA |
|---|---|---|---|---|
| Heat rate(kJ/kw·h) | 7355.42 | 7372.58 | 7400.82 | 7535.03 |
In order to determine whether the reheat pressure under each load is optimal in this case, it is necessary to observe whether the corresponding heat rate under each load is the lowest by changing the reheat design pressure under rated working conditions in the design phase of the flow path retrofit.

Figure 2 shows the relationship curve between reheat design pressure and the heat rate under 100%THA load condition.

Thus, under THA conditions, the optimal reheat design pressure of the unit is at 4.2 MPa, and the corresponding heat consumption of the unit is 7343.60 kJ/kw⋅h. Compared with the reheat design pressure (5.8 MP) of the original unit, the offset is 1.6 MPa. An increase of 11.82 kJ/kw⋅h in heat rate due to the deviation of the reheat pressure from the optimum.

Table 4 shows the calculation results of relevant parameters under 50%THA–100%THA

| THA          | 85%THA | 75%THA | 50%THA |
|--------------|--------|--------|--------|
| Optimal reheating pressure under each load (MPa) | 4.20   | 3.28   | 2.69   | ——    |
| Minimum heat rate under each load (kJ/kw⋅h)   | 7343.60| 7354.25| 7370.06| ——    |
| Offset of reheat pressure (MPa)                | 1.60   | 1.57   | 1.56   | ——    |
| Relative offset                                 | 27.59% | 32.37% | 36.71% | ——    |
| Incremental heat rate (kJ/kw⋅h)                | 11.82  | 18.33  | 30.76  | ——    |

It can be seen from the Table 4 that if the steam parameters of the original design are used and the heat supply from the cold end piping is used, the reheating pressure deviates from the optimum condition under each load. And the lower the load, the more serious the optimal value of the reheat pressure shift, and the increase of the heat rate caused by the reheat pressure shift increases sharply. The heat rate increment has reached 30.76 kJ/kw⋅h under 75% THA. By 50% THA load conditions, the curve shown in Figure 3 is hard to find the extreme point. It represents that the optimal value of reheat pressure is far away from the original 2.84 MPa. That is, for that load, the lower the reheat pressure is, the better the thermal economy within the permissible range.
Figure 3. Relationship between reheat pressure and the heat rate under 50% THA.

The calculation result trend of the retrofit of heat supply of the connection pipe between IP and LP is similar to that of the cold end piping of reheat system. The results are shown in Table 5

| THA | 85%THA | 75%THA | 50%THA |
|------|--------|--------|--------|
| Reheat pressure under each load after traditional retrofit (MPa) | 5.80   | 4.85   | 4.25   | 2.84   |
| Heat rate under each load after traditional retrofit (/kJ/kw⋅h) | 7227.55 | 7230.40 | 7241.28 | 7273.40 |
| Optimal reheating pressure under each load (MPa) | 4.30   | 3.39   | 2.78   | ——     |
| Minimum heat rate under each load (kJ/kw⋅h) | 7217.40 | 7213.48 | 7212.50 | ——     |
| Offset of reheating pressure (MPa) | 1.50   | 1.46   | 1.47   | ——     |
| Relative offset | 25.86% | 30.02% | 34.63% | ——     |
| Incremental heat rate (kJ/kw⋅h) | 10.15  | 16.92  | 28.78  | ——     |

It can be seen that for the heat supply of the connection pipe between IP and LP, if the steam parameters of the original design are used, the reheat pressure also deviates from the optimum condition under each load. And the lower the load, the more serious the optimal value of the reheat pressure shift. By 50% THA load conditions, the curve of relationship between reheat pressure and the heat rate are also hard to find the extreme point. But the offset degree of reheat pressure under the same load is smaller than that of the heat supply from the cold end piping, and the increment of heat rate is relatively smaller.

However, the optimum reheat pressure under each load cannot be guaranteed regardless of the value of the reheat design pressure. Therefore, the reheat design pressure can only be adjusted properly in the design phase of flow path retrofit. The comprehensive heat rate income in formula (5) can be evaluated and the final optimal reheat design pressure can be determined.

Under the assumption that the operating hours of each load are equal throughout the year, the relationship between the comprehensive heat rate income and the value of the reheat design pressure of the two retrofit modes of heat supply can be obtained by optimizing the reheat pressure within the load range of 50%THA~100%THA. As shown in Figure 4.
Figure 4. The relationship between the heat rate and the reheat design pressure for the two types of heat supply.

Ignoring factors such as axial thrust balance of turbine, to meet the minimum heat rate in the load range, the reheat design pressure value of the heat supply of the connection pipe between IP and LP is 3.6 MPa, the comprehensive heat rate income ($\delta H_\delta$) is 26.96 kJ/kWh. And the reheat design pressure value of heat supply from the cold end piping is 3.4 MPa, the comprehensive heat rate income ($\delta H_\delta$) is 32.16 kJ/kWh.

3.4 Interpretation of result
First, the calculation results of the deviation of the optimal reheat pressure after the heat supply from the cold end piping is analyzed. Taking example of THA working conditions, the optimum reheat pressure runs from 5.8 MPa to 4.2 MPa after 120t/h of steam have been extracted from cold end pipe of reheat system. In order to analyze the reason that the reheat pressure deviates from the optimum after increasing heat supply, the work done by steam turbine can be separated by virtual, the virtual separation is shown in Figure 5.

After the retrofit of heat supply, the work of steam used for heat supply in steam turbine and the work of extraction steam increment of regenerative system which was used to heat the water supply that caused by heat supply can be separated from the total work done by the steam turbine, and can be seen as work done by two separate back pressure turbines.

After virtual separation, for condensing steam turbines that remove the work done by two virtual back presses turbine, the optimal value of reheat pressure before and after heat supply is basically unchanged under the same electric load. But for back presses turbine of heat supply, because of the exhaust steam all being sent to heat without cold source loss, the lower the reheat pressure, the greater the enthalpy drop of the steam used to supply heat per mass flow in the steam turbine, so the more work done by the steam which was used for heat supply, the higher the overall cycle efficiency of the
unit. No consideration is given to the backpresses turbine of the increment of regenerative system. After heat supply is added, the optimum value of reheat pressure is bound to be lower than the original design value. But it's not the lower the better. In fact, in the process of reducing the reheat pressure, on the one hand, the decrease of the average endothermic temperature leads to the decrease of the cycle efficiency; on the other hand, the increase of the work share of the backpresses turbine of heat supply leads to the improvement of the cycle efficiency. There is a game relationship between the two. To the equilibrium point (4.2 MPa), the unit will obtain the maximum benefit under THA load conditions.

Similarly, for the heat supply of the connection pipe between IP and LP, the reheat pressure is reduced, the inlet pressure and the exhaust pressure of the IP cylinder is also reduced, the work share of the backpresses turbine of heat supply is also increased. When reheat pressure is 4.3 MPa, the unit obtains the maximum income under the THA condition.

Figure 6. The trend of the work share of heat-supplying steam with the load changing.

The lower the load, the more serious the optimal value of the reheat pressure shift, and by 50% THA load conditions, the curve is hard to find the extreme point. The main reasons can also be analyzed by the above method of virtual separation of steam turbines. The steam intake of turbine is gradually reduced during the load reduction process of 100% THA~50% THA, but the extraction of steam for heat supply is not reduced. That is, the amount of steam used for heat supply has gradually increased in share of total steam intake and the amount of work done has gradually increased. Figure 6 shows the variation trend of the share of total work done by the steam for heat supply under a certain heat pressure. It can be seen that the variation trend of the proportion of work done by the steam for heat supply is consistent with the trend of the degree of deviation from the optimal value of the reheat pressure, whether it is the heat supply from the cold end piping of reheat system or heat supply of the connection pipe between IP and LP.

Therefore, in the process of reducing the load, the proportion of work done by backpresses turbine is increasing, so the income generated has more and more influence on the overall efficiency of the unit. By 50% THA, the increase of cycle efficiency caused by the increase of the proportion of work done by heat supply steam after reducing the reheat pressure has completely covered the negative caused by the decrease of average endothermic temperature, and then the lower the reheat pressure, the lower the heat rate.

It should be noted that after the reduction of reheat pressure, the effect of the relative pressure dropping of the reheat system on the heat rate has not been considered in the above study. Therefore, this factor should be considered in the actual optimization design.

4. Conclusion
Taking 660MW supercritical unit as an example, by analyzing and comparing the problem that the reheat pressure deviates from the optimal value which exist in the heat supply from the cold end
piping of reheat system and the heat supply of the connection pipe between IP and LP, and the reasonable selection of the reheat pressure in the design phase of flow path retrofit. The following conclusions were drawn:

(1) When flow-path retrofit is carried on the units which heat supply retrofit had been done, or the heat supply and flow path of the turbine are retrofitted synchronously, the reheat pressure under each load deviates from the optimal value after the traditional retrofit of flow path with parameters constant. The reheat design pressure should be adjusted properly at the design phase of the flow path retrofit.

(2) The lower the load, the more serious the reheat pressure deviation from the optimal value. By 50% THA, the curve is hard to find the extreme point, it represents that the lower the reheat pressure, the better the economy of the unit. The optimization of reheat pressure needs to take the thermal economy of non-design conditions into account. Optimized overall heat rate gains are considerable.

(3) A case study of 660 MW supercritical units was carried out, and conclusions (1) and (2) are universal. It is also applicable to other different types of units with retrofit of heat supply. However, the specific degree of reheat pressure deviating from the optimum of other units still needs to be studied.

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