Quantitative Analysis of Operating Economical Performance by Valve Leakage in Bypass System

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Abstract. In this paper, the influence of steam leakage of the control valve in bypass system on unit operating economy is analysed. Through quantitative analysis, the formulas for calculating the influence of the steam leakage of control valves in high-pressure, medium-pressure and low-pressure bypass systems on the parameters of unit work and heat absorption are obtained. In the end, combined with the design data, the thermal economy of 1000MW double reheat unit is analyzed in view of the internal leakage of control valve in high-pressure, medium-pressure and low-pressure bypass system.

1. Introduction
In recent years, with the development of units toward high capacity and high parameter technology, more and more 1000MW double reheat units are put into commercial operation. Three-stage series bypass system is installed in the thermal system of double reheat unit to coordinate the unbalance between boiler steam flow and intake flow rate of steam turbine during unit start-up process [1]. In the process of unit start-up, bypass system is used to preheat boiler superheater, primary reheater and secondary reheater system, so as to realize rapid start-up of unit. During the actual operation of the unit, the tightness of the valve is affected by the manufacturing level, installation level and operation mode of the unit [2,3], steam leakage of the control valve may occur in the high-pressure, medium-pressure and low-pressure bypass systems of the unit, this will have a certain impact on the economical operating performance of unit.

2. Quantitative analysis of operating economical performance by valve leakage in bypass system
Steam leakage in the control valve of bypass system will have an impact on the safety of economical operation performance, as well as on unit work and heat absorption. When the steam leakage occurs in the control valve of low-pressure bypass system, the steam in the secondary reheat cooling section leaks into the condenser through the low-pressure bypass system, which will increase the heat load of the condenser, affect the vacuum of the unit and the economic operation of the unit [2].

This paper will be based on the thermal system of 1000MW double reheat unit of Jiangsu Huadian Jurong Power Generation Co., LTD. Under the condition that the main steam flow rate is the corresponding flow rate under the rated design condition, when the bypass system control valve leaks (assuming the flow rate is a fixed value) and the cooling water is not put into operation, the influence of the leakage of the control valves of high-pressure, medium-pressure and low-pressure bypass system on the performance and heat absorption of the unit is analyzed.
2.1 Introduction of bypass system of double reheat unit
The 1000MW double reheat unit of Jiangsu Huadian Jurong Power Generation Co., LTD. adopts three-stage series bypass system to realize the combined start-up of steam turbine. The bypass system is shown in Figure 1.

High-pressure bypass system: The main steam pipe and the exhaust pipe of the VHP are connected by connecting pipes, and the connecting pipes are equipped with high-pressure bypass control valves. Through the throttling effect of the control valve of the high-pressure bypass system, the main steam pressure is reduced to the level of the exhaust pressure of the ultra-high pressure cylinder [4].

Medium-pressure bypass system: The hot section of the primary reheater and the exhaust pipe of high-pressure cylinder are connected with connecting pipe, and medium-pressure bypass control valve are installed in the connecting pipe. Through the throttling effect of the control valve of the medium-pressure bypass system, the steam pressure in the hot section of the primary reheater is reduced to the level of the exhaust pressure of the high-pressure cylinder [4].

Low-pressure bypass system: The steam pipe in the hot section of the secondary reheater and condenser are connected by the low-pressure bypass system. When the low-pressure bypass control valve is opened, the steam in the hot section of the secondary reheater passes through the control valve and is decompressed before entering the condenser [4].

2.2 Quantitative analysis of economical operation performance by valve leakage in bypass system
According to the definition of equivalent enthalpy drop in literature [5,6], the leakage flow rate of the bypass control valve of the double reheat unit is 0 kg/s, the net equivalent enthalpy of 1.0 kg new steam decreases to (Eq. 1):

\[ H = h_0 + \sigma_1 + \sigma_2 - h_c - \sum_{r=1}^{z} \tau_r \eta_r^0 - \sum \pi \]  

The circulating heat per unit working fluid is (Eq. 2):

\[ Q = (h_0 - h_{fw}) + \alpha_{rh1} \sigma_1 + \alpha_{rh2} \sigma_2 \]  

In formula, \( h_0 \) is the new vapor enthalpy, kJ/kg; \( \sigma_1 \) is 1.0 kg steam heat absorption of primary reheater, kJ/kg; \( \sigma_2 \) is 1.0kg steam heat absorption of secondary reheater, kJ/kg; \( h_c \) is the exhaust enthalpy of steam turbine, kJ/kg; \( \tau_r \) is the feedwater enthalpy of the r-stage heater, kJ/kg; \( \eta_r^0 \) is the extraction efficiency of the turbine r-stage, \%; \( z \) is regenerative extraction series; \( \sum \pi \) is the work loss of the additional component, kJ/kg; \( h_{fw} \) is the enthalpy of feedwater, kJ/kg; \( \alpha_{rh1} \) is the share of primary reheated steam; \( \alpha_{rh2} \) is the share of secondary reheated steam.
2.2.1 Quantitative analysis of operating economy by valve leakage in high-pressure bypass system
As shown in Figure 1, under the condition of slight leakage of control valve in high-pressure bypass system and no input of cooling water, the feedwater flow and condensate water flow of the unit remain unchanged, and the extraction steam flow of each section remains unchanged. Steam leaked from the high-pressure bypass control valve passes through the valve throttle and directly enters the primary re heater cooling section, then enters the boiler reheater for heating. When the main feedwater flow and condensate flow remain unchanged, regardless of the leakage flow rate of the high-pressure bypass control valve, it will not change the steam flow rate in the hot section of the primary reheater. The leakage flow of the high-pressure bypass control valve is \( \alpha L \) kg, and the work done by the super high pressure cylinder of the steam turbine will be reduced by \( \Delta H_1 \) (Eq. 3):

\[
\Delta H_1 = \alpha L (h_0 - h_{rhc1})
\] (3)

In formula, \( h_0 \) is the enthalpy of steam entering the super high-pressure cylinder, kJ/kg; \( h_{rhc1} \) is the enthalpy of steam in the primary reheat cold section, kJ/kg.

When the steam leakage occurs in the control valve of the high-pressure bypass system, the heat absorbed by the boiler superheater remains unchanged, the heat absorbed by the primary reheater decreases, and the heat absorbed by the secondary reheater remains unchanged. The process of steam throttling through regulating valve is steam throttling process, so the steam enthalpy after throttling is still \( h_0 \). When the flow rate of steam leaked from the control valve of the high-pressure bypass system is \( \alpha L \) kg, the heat absorption of primary reheater is reduced to \( \Delta Q_1 \) (Eq. 4).

\[
\Delta Q_1 = \alpha L (h_0 - h_{rhc1})
\] (4)

During the thermal cycle of the double reheat unit, the heat absorption of 1.0 kg steam changes as follows (Eq. 5):

\[
Q' = Q - \Delta Q_1
\] (5)

2.2.2 Quantitative analysis of operating economy by valve leakage in medium -pressure bypass system
As shown in Figure 1, under the condition that the steam leakage occurs in the control valve of the medium-pressure bypass system and the cooling water flow is zero, the feedwater flow and condensate water flow of the unit remain unchanged, and the steam extraction share of each section of the turbine remains unchanged. After throttling, the steam leaked from the control valve of the medium-pressure bypass system enters the cold section of the secondary reheater, and the flow rate of the secondary reheat steam hot section remains unchanged. The leakage flow of the medium-pressure bypass control valve is \( \alpha L \) kg, and the work done by the high pressure cylinder of the steam turbine will be reduced by \( \Delta H_2 \) (Eq. 6):

\[
\Delta H_2 = \alpha L (h_{rhh1} - h_{rhc2})
\] (6)

In formula, \( h_{rhh1} \) is the enthalpy of steam in hot section of primary reheater, kJ/kg; \( h_{rhc2} \) is the enthalpy of steam in cold section of secondary reheater, kJ/kg.

At this time, the heat absorbed by the superheater of the boiler unchanged, the heat absorbed by the primary reheater unchanged, and the heat absorbed by the secondary reheater decreases. The throttling process of steam passing through the control valve of the medium-pressure bypass system is an equal enthalpy process, and the enthalpy of steam after throttling is \( h_{rhh1} \).

When the leakage steam flow rate of the control valve of the medium-pressure bypass system of the unit is \( \alpha L \) kg, the heat absorption reduction value of the secondary reheater is \( \Delta Q_2 \) (Eq. 7).

\[
\Delta Q_2 = \alpha L (h_{rhh1} - h_{rhc2})
\] (7)

During the thermal cycle of the double reheat unit, the heat absorption of 1.0 kg steam changes as follows (Eq. 8):

\[
Q'' = Q - \Delta Q_2
\] (8)

2.2.3 Quantitative analysis of operating economy by valve leakage in low-pressure bypass system
As shown in Figure 1, under the condition that the steam leakage occurs in the control valve of the low-pressure bypass system and the cooling water flow is 0, the feedwater flow and condensate water flow of the unit remain unchanged, and the steam extraction share of each section of the turbine
remains unchanged. Because of the leakage of the control valve in the low-pressure bypass system, part of the steam from the secondary reheater does not work in the medium-pressure cylinder and low-pressure cylinder, but directly enters the condenser. Without considering the influence of steam leakage from control valve of low-pressure bypass system on vacuum value of unit, leakage of \(\alpha_L\) kg steam from control valve of low-pressure bypass system will reduce the work of medium pressure cylinder and low pressure cylinder of steam turbine.

\[
\Delta H_3 = \alpha_L(h_{rhh2} - h_c)
\]  

In formula, \(h_c\) is the exhaust enthalpy of low-pressure cylinder, kJ/kg.

The feedwater flow and condensate water flow of the unit have not changed, the steam extraction share of each section has not changed, so the heat absorption of boiler superheater, primary reheater and secondary reheater remains unchanged, but the work done by the medium-pressure cylinder and the low-pressure cylinder is reduced, the output power of the steam turbine is reduced, and the heat consumption rate of the unit is increased.

In fact, the high-temperature steam leaked from the control valve of low-pressure bypass system directly enters the condenser in the process of unit operation, the heat load of the condenser increases and the vacuum of the unit decreases, which ultimately affects the operating economy of the unit. The influence of vacuum variation on unit output and heat consumption can be calculated by the corrected curves of condenser pressure-heat consumption and condenser pressure-output provided by steam turbine manufacturers.

3. Example calculation of influence of bypass system leakage of double reheat unit

Based on the above formulas, assuming that steam leakage occurs in the control valve of bypass system with steam flow rate of 3.0kg/s and no leakage occurs in the control valve of other bypass systems, the work changes of the cylinders of the 1000MW double reheat unit are calculated. Combining with the calculation results, the change of output and heat consumption rate of the whole unit is analyzed when the control valve of bypass system leaks and the leakage flow rate is constant.

Design parameters of 1000MW double reheat unit of Jiangsu Huadian Jurong Power Generation Co., LTD. are shown in Table 1.

| Name                                      | Symbol | Unit     | Design parameters |
|-------------------------------------------|--------|----------|-------------------|
| Feedwater flow                           | \(F_{gs}\) | kg/s     | 712.196           |
| Enthalpy value of feedwater               | \(h_{gs}\) | kJ/kg   | 1454.9            |
| Enthalpy value of main steam              | \(h_0\)   | kJ/kg   | 3447.9            |
| Enthalpy value of exhaust steam from super high-pressure cylinder | \(h_{VHP}\) | kJ/kg | 3164.4 |
| Steam flow of primary reheated            | \(F_{rhh1}\) | kg/s   | 634.52            |
| Enthalpy of primary reheated steam        | \(h_{rhh1}\) | kJ/kg | 3674.9 |
| Enthalpy value of exhaust steam from high-pressure cylinder | \(h_{HP}\) | kJ/kg | 3327.7 |
| Secondary reheated steam flow rate        | \(F_{rhh2}\) | kg/s   | 546.568           |
| Enthalpy of secondary reheated steam      | \(h_{rhh2}\) | kJ/kg | 3728.0 |
| Exhaust Enthalpy Value of low-pressure cylinder | \(h_c\) | kJ/kg | 2407.7 |
| Unit output                              | \(P_e\)   | MW      | 1000.0            |
| Heat rate                                | HR       | kJ/(kW·h) | 7063.6 |

The main steam flow rate of unit is 712.196kg/s, when the steam leakage occurs in the control valve of bypass system, the leakage steam flow rate is 3.0kg/s, and the leakage flow rate of the control
valve of other bypass systems is zero, the changes of work done by each cylinder of the steam turbine are shown in Figure 2.

![Figure 2. Work distribution of steam turbine](image)

The calculation results in Figure 2 show that:

- The work done by medium pressure cylinders accounts for the highest proportion of the total power of steam turbines, while the work done by super high-pressure cylinders and high pressure cylinders accounts for a relatively low proportion.

- When steam leakage occurs in control valves of different bypass systems, the change of work of each cylinder is different when the steam flow rate is constant. When the steam of the high-pressure bypass control valve leaks, the work of the ultra-high pressure cylinder decreases by 0.85MW; When the steam of the medium-pressure bypass control valve leaks, the work of the high-pressure cylinder decreases by 1.04MW; When the steam of the low-pressure bypass control valve leaks, the work of the medium-pressure cylinder and the low-pressure cylinder decreases by 3.97MW.

After deducting factors such as turbine mechanical loss and generator efficiency, when steam leakage occurs in the control valve of bypass system (steam flow rate is 3.0kg/s), the variation of unit output and heat consumption rate is shown in Table 2.

| Name                                      | $P_e$, MW | $Q_{boiler}$, MJ/s | HR, kJ/(kW·h) |
|-------------------------------------------|-----------|--------------------|---------------|
| Turbine heat -acceptance (THA)            | 1000.0    | 1962.12            | 7063.6        |
| Steam leakage of control valve in high-pressure bypass, $F_{HPB}=3.0$kg/s | 999.16    | 1961.27            | 7066.5        |
| Steam leakage of control valve in medium-pressure bypass, $F_{HPB}=3.0$kg/s | 998.97    | 1960.75            | 7066.0        |
| Steam leakage of control valve in low-pressure bypass, $F_{LPB}=3.0$kg/s | 996.08    | 1962.12            | 7091.4        |

As can be seen from Table 2.

- The main steam flow rate is 712.196kg/s, the steam leakage occurs in the control valves of different bypass systems, which results in different changes in the heat absorption of boiler. The steam leakage occurred in the control valve of the high-pressure bypass system with steam flow rate of 3.0kg/s, the heat absorption of the boiler is 1961.27MJ/s, which is 0.85MJ/s lower than that of turbine
heat-acceptance; The steam leakage occurred in the control valve of the medium-pressure bypass system with a flow rate of 3.0kg/s, the heat absorption of the boiler is 1960.75MJ/s, which is 1.37MJ/s lower than that of turbine heat-acceptance; The steam leakage of the control valve of the low-pressure bypass system will not change the heat absorption of the boiler, which is still 1962.12MJ/s.

- The steam leakage of bypass system control valve will change the output of unit and the heat absorption of boiler, resulting in the change of heat consumption rate of steam turbine. Steam leakage occurs in control valves of high-pressure and medium-pressure bypass systems, and the change of heat consumption rate of steam turbines is relatively small, and the impact on unit operating economy can be neglected; The steam leakage occurred in the control valve of the low-pressure bypass system with a flow rate of 3.0kg/s, the heat consumption rate of steam turbine is 7091.4kJ/(kW·h), which is 27.8 kJ/(kW·h) higher than the design value 7063.6kJ/(kW·h) under THA condition, which has a great influence on the unit operating economy.

Through comparison and analysis, it can be seen that the steam leakage of the control valve of the low-pressure bypass system has a greater impact on the unit output and heat consumption rate.

4. Conclusion

- The work done by medium-pressure and low-pressure cylinders accounts for a large proportion of the work done by the whole steam turbine, so it has great influence on the work of medium-pressure and low-pressure cylinders of steam turbines when the steam leakage occurs in the control valve of the low-pressure bypass system.

The steam leakage of the control valve in the low-pressure bypass system will not change the heat absorption of the boiler, but it will reduce the work done by the middle-pressure and low-pressure cylinders of steam turbines and eventually increase the heat consumption rate of the units.

Quantitative analysis of steam leakage in bypass control valve of 1000MW double reheat unit shows that the steam leakage of low-pressure bypass control valve has great influence on unit operating economy. In the process of operation, it is necessary to pay attention to the temperature of the measuring points after the control valves of each bypass system, and to timely repair or replace the valves which are confirmed to be leaking [2,3].

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