Experimental Study on Low-load Sliding Pressure Operation of Supercritical Unit

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Abstract. This work reports the variation of the heat rate (HRT) and the efficiency of the high-pressure cylinder by the test of the operation mode of different control valves of the first home-made supercritical 660MW unit. The heat consumption rate and high pressure cylinder efficiency of sequential valve operation are better than that of single valve operation, especially heat consumption rate and high pressure cylinder efficiency are quite different under low-load condition of 400MW and 500MW. Above 600MW, the economic indexes of sequential valve operation and single-valve operation with three-valve are similar, of which the heat rate and the efficiency of high-pressure cylinder are better than that of single-valve operation with four-valve. When the unit adopts the sliding pressure operation mode at the load ranging from 360MW to 550 MW, the optimal sliding pressure operating curve is different from the designed curve. According to the analysis of the experimental sliding pressure operating curve and the sliding pressure operation characteristics of the unit, the higher main steam pressure can be used to increase the throttling of the governing valve when the operating conditions close to the sliding pressure curve, which can quickly increase the load and enhance the variable load response ability and peak regulation capacity of the unit.

1. Introduction
The steam turbine load regulation of large-capacity units above 600MW is divided into nozzle governing (PA), throttle governing (FA) and by-pass governing in terms of the steam distribution mode; from the view of running mode, it can be divided into constant-pressure operation and sliding-pressure operation. The general unit adopts constant-sliding-constant mode operation with nozzle admission: constant pressure nozzle regulation is adopted with THA load being more than 80% and less than 30%, and sliding pressure operation is adopted with THA load ranging from 30% to 80% [1].

At present, along with the increase of the gap between peak load and valley load in power system, the low-load operation problem of the unit is prominent. In order to meet that requirement of the peak regulation of the electric network, the economy of low-load operation of the unit is improved to save energy and reduce consumption. The present supercritical and ultra-supercritical unit adopts the compound sliding pressure operation mode: high load with the rated steam pressure, low load minimum allowable steam pressure and the intermediate load with compound sliding pressure operation [2, 3]. This compound sliding pressure operation mode has the best cycle thermal efficiency and flexible load
regulation ability making the unit maintain rated pressure during the highest load operation. The composite sliding pressure operation mode can keep the unit under the rated pressure at the maximum load operation, and has the best cycle thermal efficiency and flexible load regulation function. In the middle load, the volume flow rate of the turbine through-flow part with the basic constant of the composite sliding pressure operation is basically unchanged with the higher internal efficiency ensured, and the steam temperature of the stable steam turbine high-pressure cylinder provides a small thermal stress and a flexible rapid load-changing capacity. The optimal comprehensive performance of constant pressure operation at low load can prevent the flow instability problem by preventing the pressure from being too low. In a word, the unit with combined sliding pressure operation have the ability of shutdown at night, fast start-up, frequent start-up and variable load, keeping the unit high efficiency at high load and low load, so as to meet the requirements of intermediate load and peak shaving.

2. Test of different regulating Valve configuration Mode of 660mw Supercritical Unit

Operation mode and regulation mode of the unit are realized by sequential valve or single-valve operation in terms of valve characteristics. A 660MW Supercritical Unit adopts compound sliding pressure operation with nozzle admission. In order to master the influence of the operating characteristics of the governing valve on the economy of the unit under the condition of low load, the sliding pressure tests under different combination of governing valve and variable load were carried out. The economic index of the unit was calculated with the field feed water flow rate as the calculation benchmark, and the test conditions and the economic index of the unit were shown in Table 1.

| Test Condition | Main pressure (MPa) | Main temp (ºC) | Modified power (kW) | Test Heat rate (kJ/kW-h) | Modified Heat rate (kJ/kW-h) | HP cylinder efficiency (%) | HP exhaust temp (ºC) |
|----------------|--------------------|----------------|---------------------|------------------------|-----------------------------|---------------------------|----------------------|
| Sequential valve operation | 400 | 18.80 | 558.17 | 412836.4 | 8266.32 | 8079.99 | 81.18 | 299.30 |
| | 500 | 21.00 | 558.72 | 517652.4 | 8162.34 | 7911.86 | 81.32 | 309.53 |
| | 600 | 21.96 | 557.49 | 649799.4 | 8100.67 | 7750.62 | 83.75 | 324.79 |
| | 660 | 23.99 | 556.72 | 696629 | 8081.52 | 7719.94 | 83.97 | 319.84 |
| | 680 | 24.10 | 557.31 | 720764.2 | 8093.29 | 7705.00 | 84.08 | 323.20 |
| Single-valve Operation with four valves | 400 | 18.82 | 557.47 | 407974.8 | 8428.71 | 8244.25 | 72.05 | 321.70 |
| | 500 | 21.05 | 555.62 | 517122.4 | 8257.49 | 8005.60 | 75.75 | 320.04 |
| | 600 | 22.05 | 557.00 | 651422.7 | 8086.27 | 7758.42 | 82.18 | 326.84 |
| | 660 | 24.00 | 555.54 | 692515.6 | 8145.32 | 7740.97 | 82.17 | 321.55 |
| Single-valve Operation with three valves | 400 | 18.80 | 557.47 | 415942.6 | 8316.05 | 8152.34 | 75.75 | 313.53 |
| | 500 | 21.00 | 558.88 | 518940.4 | 8175.39 | 7969.24 | 79.46 | 314.45 |
| | 600 | 22.09 | 556.95 | 626237.1 | 8092.83 | 7772.64 | 84.41 | 317.52 |
| | 660 | 24.24 | 556.16 | 688847.3 | 8083.98 | 7714.44 | 84.43 | 314.77 |

Note: the test results in the table did not take into account the correction of main steam pressure and reheat pressure loss.

Under the same load, the main steam pressure was close to eliminate the influence of the main steam pressure on the economic index of the unit. From Table 1, under low load, the unit adopted compound sliding pressure operation mode with different operation mode of governing valve and different throttling loss of governing valve, which led to the difference of economic index of the unit. The heat consumption rate and high pressure cylinder efficiency under the operation mode of sequential valve were better than those of single-valve operation. Under a certain load, when the single valve operation mode was used, the opening of the three valve was larger than that of the four valve with small throttling loss, high efficiency of the high pressure cylinder and high cycle thermal efficiency, so the heat
consumption rate of the three valve operation was lower than that of the four valve operation, especially under the low load condition of 400MW or 500MW. The heat consumption rate of sequential valve mode was 162kJ/kW·h less than that of single valve mode, and the efficiency of high pressure cylinder was 9.125% higher than that of single valve mode. When the single-valve mode was used, the heat consumption rate of the three-valve was 91.91kJ/kW·h lower than that of the four-valve, and the high-pressure cylinder of the three valve mode had a high-pressure cylinder efficiency of 3.7%. Under the condition of 500MW, the heat consumption rate of the sequence valve was 93.89 kJ/kW·h lower than that of the four valves, and the efficiency of the high pressure cylinder of the sequence valve was 5.578% higher than that of the four valves. The heat consumption rate of the three valves was 36.37 kJ/kW·h lower than that of the four valves, and the efficiency of the high pressure cylinder of the three valves was 3.715% higher than that of the four valves. Above 600MW, unit in single-valve operation with three valves can basically carry full load of 660MW. Due to the small throttling loss of the third and fourth governing valves, there is little difference between the economic index of the sequence valve and that of the single-valve operation with three valves. However, the heat consumption rate and high pressure cylinder efficiency of sequential valve and single-valve operation with three valves are better than those of single-valve operation with four valves. The heat consumption rate of the unit operated by sequential valve was low when the test load was in the range from 400MW to 680 MW. At present, the average load rate of the unit is 500MW to 550 MW during the day and 350 MW to 400MW at night, in which the economic index of the single valve and the sequence valve was distinctly different. The energy saving effect was significantly improved after changed from single valve operation to sequential valve operation.

3. Unit sliding pressure running test under low-load

With the sliding pressure operation of the unit, the initial steam pressure decreases with the decrease of the main steam flux. The variable speed feed pump can reduce the outlet pressure of the feed pump by reducing the speed, which can save the power consumption of the feed pump. In this way, the new steam pressure and the speed of feed pump is lower at low load, and the power consumption of pump is reduced. The power consumed by steam turbine feed pump in sliding pressure operation is much smaller than that in constant pressure operation, and the reduction is inversely proportional to the new steam flux. Therefore, the economy of sliding pressure operation mode under different pressures depends mainly on the decrease of cycle efficiency and the reduction of power consumption of feed pump.

The sequential valve sliding pressure operation mode in the normal operation of the unit was adopted according to the sliding pressure curve given by the manufacturer at low load. In Table 1, the steam inlet pressure of the steam turbine corresponding to 600MW was 22 MPa, the main steam pressure corresponding to the 500MW and the 400MW was lower. In order to know the relationship between the unit economic index and the main steam pressure under low load, the main steam pressure test at low load was carried out to obtain the optimal sliding pressure operation curve which was different with the sliding pressure operation curve of the manufacturing plant. As shown in Table 1, there was no obvious difference in heat consumption rate between several working conditions under 600MW, so the operating condition of 550 MW, 500 MW, 450 MW, 400 MW and 350MW were set in the test of low load sliding pressure operation condition from 550MW to 350 MW. The field feed water flow rate was used as the calculation benchmark to calculate the economic index of the unit, and the test results were compared with the test results of 500MW, 600MW and 660MW constant pressure operation after overhaul. The main steam pressure of the test was determined by the designed constant slip pressure operation curve and the opening of governing valve in the actual operation of the unit. The test conditions and results of sliding pressure operation mode of sequential valve under different low loads were contained in table 2.
Table 2. Test results of low load sliding pressure Operation of Supercritical 660MW Unit.

| Test Condition | Main pressure | Main Temp | Modified power | Test heat rate | Modified heat rate | HP cylinder efficiency | HP exhaust temp | Inlet flow of BFPT |
|---------------|--------------|-----------|---------------|---------------|-------------------|-----------------------|----------------|-----------------|
| 660 MW        | 24.149 MPa   | 560.377℃ | 628468 kJ/kW·h| 8248.038 kJ/kW·h| 7964.472℃ | 80.407% | 316.265℃ | 17.0794 t/h |
| 550 MW        | 23.981 MPa   | 560.704℃ | 562711.5 kJ/kW·h| 8076.09 kJ/kW·h| 8029.83 % | 82.579 % | 302.493 ℃ | 18.0797 t/h |
| 450 MW        | 23.083 MPa   | 560.218℃ | 557853.8 kJ/kW·h| 8067.26 kJ/kW·h| 8030.80 % | 82.754 % | 306.485 ℃ | 20.0895 t/h |
| 350 MW        | 22.0935 MPa  | 561.762℃ | 552546.3 kJ/kW·h| 8066.36 kJ/kW·h| 8033.56 % | 83.366 % | 311.351 ℃ | 21.0912 t/h |

Note: The test results in the table did not take into the correction of the main steam pressure and the reheater pressure loss account.

3.1. Economic Analysis of low load sliding pressure Operation

By comparing the test results shown in Table 2, the economic indexes of the unit operation at different low load are analyzed, and the relationship between the main steam pressure and the heat consumption rate and the efficiency of the high-pressure cylinder under different test loads is obtained. Under each load, with the decrease of the main steam pressure of the unit, the opening of the governing valve and the efficiency of the high pressure cylinder increased and the power consumption of the steam feed pump decreased, all of which are reflected in the decrease of the inlet steam flow of BFPT. However, there is an optimal operating main steam pressure under each load, which is in line with the constant-sliding-constant operation mode of the manufacturer, but not necessarily consistent with the constant pressure operation curve or the sliding pressure operation curve designed by the manufacturer.

As shown in Table 2, it was found that under certain load conditions, with the decrease of main pressure, the cycle thermal efficiency was reduced by sliding pressure, but the cycle thermal efficiency was increased because of the decrease of throttling loss and the of the increase of high pressure cylinder efficiency. Meanwhile, under the same load, the inlet steam flow of BFPT was obviously reduced, and the increased exhaust temperature of high pressure cylinder and the decrease of steam consumption of BFPT have different positive effects on cycle thermal efficiency and the negative effects of the decrease of main steam pressure on cycle thermal efficiency vary with load, so there is an optimal main steam pressure. Constant pressure operation is adopted when the unit load is above 600MW. In the range of 360-550MW load, the optimal operating main steam pressure obtained from the test is 24MPa, 21MPa, 21MPa, 20MPa and 17MPa corresponding to 550MW, 500MW, 450MW, 400MW and 360MW. However, the optimal operating main steam...
pressure is 24.2MPa, 24.2MPa, 22.5MPa, 20MPa, and 18.5MPa according to the constant-sliding pressure curve designed by the manufacturer. The difference between the test constant-sliding pressure operation curve and the designed constant-sliding pressure operation curve is shown in fig 1.

When the combustion state of the boiler is stabilized, the main steam temperature is easier to rise with the main steam pressure reducing, which can increase the water volume of the desuperheater with the main steam temperature reaching the design value, but the desuperheating water of the unit is led out from the high-pressure heater having no influence on the unit economic indicators. Therefore, it was not considered in the experiment. On the other hand, reducing the pressure of the main steam and maintaining the temperature of it, the exhaust temperature of the high-pressure cylinder increases corresponding the increase of main steam enthalpy and reheat temperature increases along with reheat steam absorbing less heat, which is helpful to solve the problem that the reheat steam temperature is lower than the design value under the low-load working condition of the unit, so that the circulating heat efficiency is improved. As we can see from the data of the sliding pressure test of the unit in Table 2 that when the main steam temperature is close to the design value, the reheating temperature still does not reach the design value, so it is necessary to continue to strengthen the combustion adjustment during the sliding pressure operation of low load.

3.2. The influence of low-load sliding pressure operation on unit economic index
Due to the positive influence of the improvement of high pressure cylinder efficiency and reheat temperature on the economic index of the unit during sliding pressure operation, there is little difference in the economic index of the unit under different main steam pressures during low load operation, although there is an optimal operation main steam pressure. As the main steam pressure increasing from 22MPa to 24MPa at 550MW, from 19MPa to 20 MPa at 500MW, from 18MPa to 19MPa at 450MW and from 17MPa to 19MPa at 400MW, the reduction of heat consumption rate is about 4 kJ/kW·h, 4 kJ/kW·h, 10 kJ/kW·h and 10 kJ/kW·h, respectively.

![Figure 1. Design and experiment of constant-sliding pressure operation curve](image-url)
Due to this sliding pressure characteristic, the unit can deviate slightly from the optimal sliding pressure operation curve to maintain a high main steam pressure and increase the throttling of the governing valve under low-load working conditions. When the load is changed slowly, the load is increased by increasing the main steam pressure without change of governing valve opening.

3.3. Influence of low-load sliding pressure Operation Mode on Unit Safety

Due to the change of temperature, the uneven temperature distribution in each part of steam turbine or the deformation constraint of it will produce thermal stress in each part of steam turbine. The magnitude of thermal stress is proportional to the value of temperature change. That is, the greater the range of temperature change, the greater the thermal stress, so the value of temperature change can be used to characterize the magnitude of thermal stress. With the decrease of unit load, the temperature decreases sharply after the regulating stage of constant pressure operation mode, which results in large thermal stress of rotor harmful to the safety of the unit. Therefore, the rate of load change is limited in the operation process of the unit in order to avoid large thermal stress and thermal deformation caused by excessive load change. As shown in table 2, the decrease of main steam pressure and the relative increase of exhaust steam temperature of high pressure cylinder make the thermal stress of high pressure cylinder flow components decrease along the direction of steam flow running in low-load sliding pressure operation mode. Under the working condition of 500MW, the exhaust temperature of high pressure cylinder under the maximum operating pressure 23MPa is 22.82 °C lower than that of high pressure cylinder under the lowest operating pressure 19MPa. The exhaust steam temperature of high pressure cylinder increases from 295.24 °C to 308.773 °C with the unit running according to the optimal sliding pressure curve from 360MW to 550MW, in which the range of temperature and the thermal stress of rotor is small, so the rate of variable load can be larger, which greatly improves the ability of the unit to participate in the primary frequency modulation of power grid. Therefore, low-load sliding pressure operation mode is beneficial to the safety of peak shaving operation.

4. Conclusion

The operation mode of different control valves of the first domestic supercritical 660MW unit is carried out to obtain the operation of single-valve operation (including the three-valve and four-valve) and the operation of the sequential valve and the efficiency of the high-pressure cylinder for each test load of the unit. The heat consumption rate and high pressure cylinder efficiency of sequential valve operation mode are better than that of single-valve operation. Because the opening of the three valves is greater than that of the four valves operating in single valve mode, the heat consumption rate of the three valves is lower than that of the four valves with the smaller throttling loss, higher high pressure cylinder efficiency and higher cycle thermal efficiency, especially in the low-load conditions of 400MW and 500MW. Above 600MW, the heat consumption rate and high pressure cylinder efficiency of sequential valve operation are similar to those of single-valve operation with three valves, except that the efficiency of high pressure cylinder operated by sequential valve is low. However, the heat consumption rate and high pressure cylinder efficiency of sequential valve operation and single-valve operation with three valves are better than those of single valve operation with four valves.

When the unit adopts the sliding pressure operation mode at the load of 360MW to 550 MW, the opening of the regulating valve and the efficiency of the high-pressure cylinder is increased along with the main steam pressure of the unit, the power consumption of the steam feed pump and the steam inlet flow of BFPT is reduced. The optimum main steam pressure of 550MW, 500MW, 450MW, 400MW and 360MW is 24MPa, 21MPa, 21MPa, 20MPa and 17MPa, and the optimal sliding pressure operating curve is different from the designed curve. According to the analysis of the experimental sliding pressure operating curve and the sliding pressure operation characteristics of the unit, the higher main steam pressure can be used to increase the throttling of the governing valve when the operating conditions close to the sliding pressure curve, which can quickly increase the load and enhance the variable load response ability and peak regulation capacity of the unit. Meanwhile, the sliding pressure operation of the unit has a large variable load rate, which greatly improves the ability of the unit to participate in the
primary frequency modulation of the power grid in view of the advantages of small temperature fluctuation of the high pressure cylinder and small thermal stress of the rotor.

References

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