Study on the application of comprehensive energy-saving improvement scheme for condenser in a subcritical 600 MW unit

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Abstract. At present, the condenser pressure of the current generation unit is generally not up to the design value during operation, which affects the thermal cycle economy of the power plant. For a subcritical 600 MW unit, for every 1 kPa reduction in condenser pressure, about 2.5g/(kW· h) reduction in power supply coal consumption. There are many problems in the operation of the original condenser of a 600 MW unit, which leads to the reduction of thermal efficiency of the unit. After the improvement of condenser tube bundle arrangement, the improvement of water chamber structure and the improvement of vacuum system, the operation effect became better obviously. The performance test results of condenser after comprehensive energy-saving improvement show that the condenser pressure was reduced by 1.46 kPa under the same boundary condition compared with that before the improvement. According to the vacuum parameter correction curve of the steam turbine of the subcritical 600MW unit, the vacuum is increased by 1.46 kPa, which can reduce the heat consumption rate of the steam turbine by 94.9 kJ/(kW· h) and reduce the power supply coal consumption by 3.65 g/(kW· h).

1. Introduction
The condenser is the important equipment for thermal power generation and nuclear power generation unit, and has great potential for energy-saving [1]. For a subcritical 600 MW unit, for every 1 kPa reduction in condenser pressure, about 2.5g/(kW· h) reduction in power supply coal consumption [2]. At present, the absolute pressure of most condensers in actual operation is generally 1-2 kPa higher than the design value, which leads to the decrease of the circulating thermal efficiency of power plants and the increase of the heat consumption rate of steam turbines. The main reasons are that the tube bundle arrangement of condenser is not reasonable, the rubber-ball cleaning system is not normal operation and the efficiency of cooling water pump is low, the cooling water flow rate does not match and the vacuum system is not satisfactory. As a result of the above reasons, the heat exchange efficiency of condenser is low. Therefore, it is significant to improve the energy-saving of condensers and related systems in large power stations.

The pressure of condenser is not up to the design value, which is common in large thermal power units in China. From the design point of view, the design heat exchange area of condenser is generally sufficient, however, the heat transfer coefficient calculated by the HEI standard widely used at home and abroad [3,4], the effect of tube bundle arrangement of condenser and water chamber structure on heat transfer coefficient was not considered.
The condenser of a large steam turbine unit is connected with low-pressure heaters and steam extraction pipes. Because the condenser of a large steam turbine unit is connected with low-pressure heaters and pipes, the geometric size of the throat is irregular. This property of the condenser results in the following adverse factors during the flow of steam to the cooling tube bundle surface and to the pumping gas area: on the one hand, the steam continues to coagulate, and the steam flow velocity presents irregular changes, the steam is mixed with uncondensable air and its content is gradually increasing; On the other hand, the range of air surrounding the cooling pipe is also increasing. These factors of steam have substantial influence on the heat transfer effect of condenser, and the result is that the heat transfer coefficient of each cooling pipe is different. On the water side of the condenser, cooling water flows into each cooling pipe at an uneven speed, which results in different heat transfer coefficients of each cooling pipe. Therefore, it is almost impossible to accurately calculate the total heat transfer coefficient of the condenser [5]. In engineering application, the calculation method combining theoretical analysis and empirical formula is generally adopted to complete the calculation of the total heat transfer coefficient of the condenser and the design of the condenser [6].

The thermodynamic hypothesis adopted in this study is: The flow process has the characteristics of uniformity, continuity, isotropy and no initial velocity, the flow process of fluid conforms to the application condition of N-S equation. The thermal cycle of the unit is the RANKINE cycle with heat recovery and steam extraction. The initial parameters of the unit including the new steam temperature and the new steam pressure remain unchanged before and after the comprehensive energy-saving improvement of the condenser. The new steam pressure before and after improvement is 16.67 MPa, new steam temperature is 535°C. The performance test method before and after the improvement is the same, and the boundary condition of the performance test is the same.

2. Introduction to the condenser of a subcritical 600 MW unit
A subcritical 600 MW steam turbine unit was designed and produced by dongfang electric and Hitachi co., LTD, the steam turbine is subcritical, single shaft, three cylinder, intermediate reheat unit, and it put into operation in 1997. The auxiliary condenser of the unit is N-36000 type, double shell, double flow, double pressure and surface condenser manufactured by dong-fang steam turbine factory, the condenser adopts circulating water cooling method. The cooling water system is equipped with three cooling water pumps and one auxiliary cooling water pump (model 1600HTCX4). It can meet the cooling water requirement of the unit in different seasons and conditions. The pumping air system is equipped with two water ring vacuum pumps. When the unit is running normally, one is running and the other is standby. The technical specifications of condensers are shown in table 1.

| Table 1. The technical specifications of the condenser. |
|---------------------------------------------------------|
| model | N-36000 | cooling area | 18000/18000m² |
| cooling water flow | 67700t/h | the temperature of the cooling water | 20°C |
| water velocity in the cooling pipe | 2m/s | outside diameter of cooling pipe | 25 mm |
| effective length of cooling pipe | 10230mm | total number of cooling pipes | 44880 |
| bundle specification | HSn70-1B, Φ25×1mm, 38136 | | |
| | BFe30-1-1, Φ25×1mm, 2712 | | |
| | 1Cr18Ni9, Φ25×1mm, 4032 | | |
| design condenser pressure | 4.9kPa (4.4/5.4 kPa) | | |

3. The operating status of condenser and related systems of the unit

3.1. The operating status of condenser
In order to accurately evaluate the current operation of the cold-end system of the unit, the condenser performance test was conducted by the test institution. The test process was completed in accordance with DL/T 1055-2008. The test result is: the condenser pressure is 6.23 kPa, which is revised to the design of cooling water flow rate (67700.0 t/h) and the cooling water temperature (20°C). The test result is 1.33 kPa higher than the performance guarantee value (≤4.9 kPa). The heat transfer end-difference of the condenser is 4.27°C, which is 2.47°C higher than design value. The cooling water flow of the unit under rated conditions is about 63749.9 t/h, which is over 4000 t/h lower than the design value of 67700 t/h.

3.2. The operation of the vacuum system
The unit is equipped with three water ring vacuum pumps, two for normal operation, three for summer operation. The original water ring vacuum pump is equipped with 160 KW motor, and the operating current of a single water ring vacuum pump is 270 A. After long-term operation, the vacuum pump mainly has the following problems: (1) the designed capacity of the vacuum pump is weak, when the unit is in high load, especially the high temperature in summer season, a vacuum pump work not ideal, it need two or three vacuum pump work can meet the demand of vacuum at the same time; (2) In summer the temperature is higher, for a long time remain above 35°C, the water temperature of the vacuum pump is high, so it is easy to vaporize. This is easy to lead to the vacuum pump impeller cavitation damage, the suction effect is not ideal, the output of the vacuum pump will be reduced, it affects the vacuum of the unit and makes the power supply coal consumption increase. (3) during the operation of the unit, there is a problem of large vibration of the vacuum pump, especially in the summer under high load, and the unit will be not safe.

4. The reasons why the heat transfer performance of the condenser is poor
The main reasons for the substandard heat transfer performance of condenser are: first, the cooling area of condenser is small; second, the cleaning coefficient of condenser is low. Third, the unit has been in operation for a long time, and the copper pipe of condenser has been corroded in many places. The wall of the pipe was seriously thinned, and there were frequent leakage of copper pipes, which was forced to be blocked. The total number of blocked pipes reached several hundred. As a result, the heat exchange area of the condenser decreases and the heat exchange effect becomes worse and worse. Fourth, the cooling pipe structure of the condenser is not properly arranged and relatively backward, so it cannot form a clear inlet and exhaust steam channel. As a result, there is eddy current in the local pipe bundle, which reduces the total heat transfer coefficient. Fifth, the efficiency of the glue ball cleaning system is not high, resulting in low cleaning coefficient of the condenser, serious scaling, and low heat transfer capacity of the condenser. The unit has been in service for more than 20 years since it was put into operation in 1997. The expansion joint of throat of the condenser gradually cracked and rapidly expanded into a large crack, resulting in the reduction of vacuum tightness of the unit and affecting the safe operation of the unit, as shown in figure 1.

Figure 1. The crack of expansion joint of low pressure cylinder.
5. The introduction of the comprehensive energy-saving renovation scheme of condenser

In order to improve the performance of condensers and related systems of the unit and reduce the energy consumption of the unit, the power plant has carried out the following comprehensive energy-saving transformation scheme:

5.1. The introduction of tube bundle arrangement of the condenser before improved

The original condenser of the 600MW unit adopts the modular tube bundle arrangement technology of German B-D company, or TEPEE tube bundle arrangement, which is one of the most commonly used tube bundle arrangement technologies in China. The numerical simulation results are shown in figure 2 and table 2. The simulation results show that the condenser pipe is not very reasonable. The advantages of this tube bundle are small steam resistance, good heat transfer effect and small supercooling degree. However, there is uneven distribution of pressure gradient field and velocity of steam flow, especially there is a certain steam leakage. The performance of the condenser can not meet HEI standards when its tightness is not good.

![Figure 2. Numerical simulation of TEPEE tube bundle.](image)

![Table 2. Numerical simulation results of the tube bundles before improved (TEPEE bundle arrangement).](table)

| NO | medium air tightness | non-condensing resistance | clean coefficient | instructions |
|----|----------------------|---------------------------|-------------------|--------------|
| 1  | 0.052%               | 120Pa                     | 1.0               | The heat transfer performance cannot meet the design conditions. Problem: air leakage + uneven vapor resistance + low speed zone. |
| 2  | 0.074%               | 173Pa                     | 0.9               | The heat transfer coefficient is calculated to be more than 20% lower than HEI. |

5.2. Improved measures: adopt bionic double connected tree-shaped tube arrangement technology

As mentioned above, the current general tube bundle design of condenser has certain subjectivity and arbitrariness. In particular, in the process of transformation, due to the limitation of capacity expansion
and existing structure, it is likely that the design is not reasonable. It is mainly reflected in whether the location and structure of air cooling zone are reasonable, whether the gas resistance of pipe bundle is even, whether the design of steam baffle plate and water baffle plate is reasonable. The analysis shows that the unreasonable design may reduce the heat transfer capacity by 10% to 30%, especially for the limited space of the condenser.

On the basis of the existing structure frame of condenser, the arrangement method of original mountain pipe bundle is improved by using numerical simulation technology. The numerical simulation results are shown in table 3 and figure 3. The results show that the heat transfer performance of the bionic double-connected tree pipe scheme can be improved by more than 20% compared with that of the ordinary mountain pipe scheme. This method can not only meet the requirements of HEI, but also the heat transfer coefficient is 15% higher than the HEI calculation value. The energy-saving effect is obvious.

| NO | non-condensing rate | resistance | clean coefficient | instructions |
|----|---------------------|------------|-------------------|--------------|
| 1  | 0.011%              | 121        | 0.9               | It meets the HEI requirement, which is more than 15% higher than the HEI calculation value. |
| 2  | 0.014%              | 135        | 0.85              |              |
| 3  | 0.018%              | 151        | 0.8               |              |
| 4  | 0.023%              | 215        | 0.75              |              |

Figure 3. The numerical analysis of heat transfer performance of bionic double-connected tree tube bundles.

Meanwhile, on the basis of keeping the size of the condenser shell constant, the heat exchange area of the condenser is increased. The number of tube bundles increased from 44,880 to 47,752, and the cooling area of condenser increased from 36,000 m² to 384,80 m². The original Ø 25 × 1 mm copper tube all replacement for Ø 25 × 0.5/0.7 mm TP316L stainless steel pipe, the effective length remains the same as 10230 mm, which can solve the problem of corrosion of copper pipes, and improve the ability of anti-erosion and anti-corrosion of pollutants.

5.3. The improvement of water chamber of the condenser
The structure of the water chamber of the condenser was improved, and the numerical simulation analysis of the water side (including the inlet and outlet pipelines) was carried out. The flow field, pressure drop and velocity distribution in each part of the water side of the condenser are obtained. By
improving the structure of water chamber. The flow rate of water in the heat exchanger tube becomes more uniform, which can improve the heat transfer performance and reduce the possibility of the pipe being blocked. After improvement, the resistance of inlet and outlet of water chamber can be reduced by about 10%, so as to reduce the power consumption of cooling water pump and achieve the effect of energy saving. Figures 4 and 5 are 3D numerical simulation of flow field of original water chamber and improved water chamber. It can be seen that the complex eddy dead zone (red area in the figure) exists before and after the ordinary water chamber, and the improved water chamber basically eliminates the eddy dead zone. Because the improved scheme basically eliminates the eddy dead zone, it is very beneficial to the operation of the rubber ball cleaning device.

Figure 4. 3D numerical simulation results of original water chamber.

Figure 5. 3D numerical simulation results of improved water chamber.

5.4. The improvement of vacuum system
Two sets of high efficiency vacuum pump system are added to the unit, they include roots pumps, tubular heat exchangers and small capacity water ring vacuum pumps. Non-condensing gases from high and low pressure condensers are extracted respectively. Each set of high efficiency vacuum pumps consists of a roots vacuum pump, a tube condenser and a small capacity water ring vacuum pump, which is defined as the roots vacuum pump group. A roots vacuum pump is connected to the
pump master pipe of the high pressure condenser, and a tubular heat exchanger and a small capacity water ring vacuum pump are connected in series. The other roots vacuum pump is connected with the suction master pipe of the low pressure condenser and connected with a tubular heat exchanger and a small capacity water ring vacuum pump. The high efficiency vacuum pump is connected to the original vacuum master tube. A manual valve and a pneumatic valve are mounted on the inlet pipe of the roots vacuum pump. After the gas mixture is pumped into the roots vacuum pump and pressurized, it is cooled by a tubular heat exchanger and then enters the low-capacity water ring vacuum pump. Non-condensable gas is discharged directly from the atmosphere through the exhaust pipe. The original water ring vacuum pump is still in reserve to ensure the system is safe and reliable.

6. Effect analysis of condenser after comprehensive energy saving improvement

The unit was put into operation on March 25, 2017 after the comprehensive energy-saving improvement of the condenser and related systems. So far, the operation is stable and reliable. The performance test of the condenser was conducted in April 2017, and the test results showed that: the condenser pressure is 4.77 kPa under 600 MW load and is modified to design condition. It is 0.13 kPa lower than the design value (4.9 kPa), 1.46 kPa lower than before the modification (6.23 kPa), and the vacuum of the condenser is significantly increased. The main test results are shown in table 4.

| Performance indicators                                      | data      |
|--------------------------------------------------------------|-----------|
| designed condenser pressure (kPa)                           | 4.9       |
| condenser pressure before improvement (kPa)                 | 6.23      |
| pressure of condenser before improvement is higher than design value (kPa) | +1.33     |
| condenser pressure after improvement (kPa)                  | 4.77      |
| pressure of condenser after improvement is lower than design value (kPa) | -0.13     |
| improvement effect (kPa)                                   | -1.46     |

After the comprehensive energy-saving improvement of condenser of the 600 MW unit, the final parameters (exhaust pressure) of the steam turbine decreased significantly. Performance test results show that the condenser pressure is reduced by 1.46 kPa under the same boundary condition. According to the parameter correction curve of the steam turbine of the subcritical 600 MW unit, the heat consumption rate of the steam turbine can be reduced by 65 kJ/(kW·h) when the vacuum is increased by 1 kPa. Therefore, the heat consumption rate of the steam turbine can be reduced by 94.9 kJ/(kW·h) after the comprehensive energy-saving improvement of condenser. This is equivalent to a 3.45g/(kW·h) reduction in power supply coal consumption.

7. Conclusions

At present, the absolute pressure of most condensers in actual operation is generally 1-2 kpa higher than the design value, as a result, the circulating thermal efficiency of power plant is low and the heat consumption rate of steam turbine is increased. In this paper, a subcritical 600 MW unit in China is taken as an example, after analyzing the problems of the condenser, a comprehensive energy-saving improvement scheme was proposed, which included improving the arrangement of pipe bundles, optimizing the structure of the water chamber and improving the vacuum system. After the above comprehensive energy-saving improvement scheme, the performance test results show that: under the same boundary condition, the condenser pressure is 1.46 kPa lower than before the improvement, which can reduce the heat consumption rate of the turbine by 94.9 kJ/(kW·h). This is equivalent to a 3.45g/(kW·h) reduction in power supply coal consumption. The application shows that the comprehensive energy saving improvement scheme of condenser is effective. This energy-saving measure can improve thermal cycle efficiency of thermal power units, improve economic index of power units and reduce fuel cost for power enterprises. It has certain engineering application value.
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