Research on Variable Operating Characteristics of Condenser Considering Vacuum Tightness

Youliang Chen¹, Haitao Geng², Pingyang Zi¹, Ming Xu², Rong Fan¹

¹Huadian Electric Power Research Institute Co., Ltd., No. 2 Xiyuan Ninth Road, Hangzhou 310030, China
²Hubei Huadian Wuchang Co-generation Co.Ltd, No. 526, Linjiang Avenue, Wuhan 430061, China
E-mail: cyl_sdu@163.com

Abstract. Considering the effect of vacuum tightness on the performance of condensers, the influence of various operating parameters on condenser pressure and terminal difference was studied by establishing a calculation model of variable operating conditions of condensers. The results show that the change of heat load has a greater impact on the vacuum, and the effect is more pronounced when the initial temperature of the cooling water is higher. Therefore, it is necessary to strictly control the internal leakage of the valve, reasonably adjust the steam parameters of the shaft seal, and minimize the additional heat load on the condenser. The cooling water flow and initial temperature directly affect the condenser vacuum and have a greater impact. The initial temperature of the cooling water is not easy to control. When the initial temperature is high, most power plants use a method of increasing the flow to increase the condenser vacuum. The cleaning coefficient and air leakage have a great impact on the quality of the vacuum. Therefore, regular operation of the rubber ball cleaning system and timely vacuum leak detection are necessary measures to ensure the vacuum of the unit, which can effectively improve the economic efficiency of the unit.

1. Introduction
As the main equipment of the cold end system of the steam turbine in a thermal power plant, the condenser is one of the equipment that has a large impact on the thermal economy of the thermal power plant. It is particularly important [1-5]. There are many factors that affect the heat transfer characteristics of condensers. Among them, the amount of air leaking into the condenser is a very important factor. The change of the amount of air leakage has a great impact on the heat transfer performance of the condenser, and its manifestations are also very complicated. Some domestic power workers have carried out a series of studies in the actual operation of power plants, and analyzed the effects of leaked air on condenser vacuum, condensate subcooling, and circulating water temperature rise [6], and proposed some leaks. The calculation method of air volume [7-8], but because there are many uncertain factors in the field, and it is difficult to control and accurately measure the amount of air leakage, it is difficult to obtain good experimental data. Some foreign scholars have studied the effects of factors such as air leakage and circulating water on condenser performance during non-steady-state operation of the condenser through experiments and numerical calculation methods [9-10].

In summary, it is necessary to establish a variable-temperature thermal calculation model for the condenser, and comprehensively analyze and study the changing law of the condenser performance
with various variable-condition parameters such as heat load, air leakage, and circulating water parameters. The energy saving optimization of the steam turbine provides a theoretical basis.

2. Condenser calculation model
The thermal characteristics of condensers are also called variable operating condition characteristics. The relationship between the pressure in the condenser and the temperature of the saturated steam can be obtained from the following formula:

\[ p_k = 9.8 \times \left( \frac{t_s + 100}{57.66} \right)^{7.46} \]  

(1)

In the formula: \( t_s \) is the condensation temperature of the steam in the condenser, °C; and \( p_k \) is the pressure of the condenser, kPa.

\[ t_s = t_1 + \Delta t + \delta t \]  

(2)

In the formula: \( t_1 \) is the circulating water inlet temperature, °C; \( \Delta t \) is the temperature rise of the circulating cooling water, °C; \( \delta t \) is the heat transfer terminal difference of the condenser, °C.

\[ \delta t = \Delta t / \left( e^{\frac{K \cdot A \cdot C_w \cdot D_w}{T}} - 1 \right) \]  

(3)

In the formula: \( K \) is the overall heat transfer coefficient, kW / (m².°C); \( A \) is the condenser area, m²; \( C_w \) is the specific heat capacity of water, kJ / (kg.°C); \( D_w \) is cooling water flow, kg/s.

Due to the complicated internal heat exchange process of the condenser, the overall heat transfer coefficient is related to the steam parameters, circulating water parameters, air concentration, and the arrangement of the condenser tubes, and the calculation is more complicated. The heat transfer coefficient \( K \) in this paper is expressed by the formula formulated by the HEI standard "Surface Steam Condenser":

\[ K = K_0 \beta_c \beta_t \beta_m \beta_a \]  

(4)

In the formula: \( K_0 \) is the basic heat transfer coefficient, which is determined by the outer diameter of the pipe and the cooling water flow rate, kW / (m².K); \( \beta_c \) is the correction factor considering the cleanliness of the inner wall of the condensation pipe; \( \beta_t \) is the correction coefficient for cooling water inlet temperature; \( \beta_m \) is the correction coefficient for pipe and wall thickness; \( \beta_a \) is the correction factor for air leakage.

3. Results and discussion
In this paper, the condenser of a 9E gas-steam combined cycle unit is selected as the research object, and the condenser performance calculation model established above is used to analyze various operating conditions of various influencing factors. The design parameters of the condenser of this power plant are as follows: the cooling area is 6200m²; the number of cooling pipes is 11124; the cooling pipe size is Φ22×0.7mm; the cooling pipe material is TP316L; the steam flow is 223.75t/h; the cooling water flow is 13000t/h; cooling water inlet temperature is 20°C; steam side working pressure is 5.4kPa.

3.1 Condenser heat load
As shown in Figure 1, when the cooling water volume and cooling water temperature are constant, as the condenser heat load increases, the condenser pressure and terminal difference will increase. However, the increasing trends of the two are not the same. As the heat load increases, the increasing trend of condenser pressure gradually accelerates, and the terminal difference of the condenser basically changes linearly. For example, at 50% of the design cooling water volume, when the condenser heat load is increased from 50% to 60%, the condenser pressure is increased from 4.73kPa to 5.38kPa, an increase of 0.65kPa, and the condenser terminal difference is increased from 2.53°C. When the heat load of the condenser is increased from 100% to 110%, the pressure of the condenser increases from 8.78kPa to 9.84kPa, an increase of 1.06kPa, and the terminal difference of the condenser increases from 4.95°C to 5.42°C, an increase of 0.47°C.

In addition to the normal unit load adjustment, there are many factors that cause the condenser heat load to change. For example, the main steam pipe of the unit is automatically drained in front of the
main valve and the steam in front of the adjusted valve is drained. The shaft seal steam overflows and the main steam bypass. Internal leaks, etc., will enter the condenser, increase the additional heat load on the condenser, and affect the unit's vacuum. Therefore, it is necessary to strictly control the internal leakage of the valve, reasonably adjust the steam parameters of the shaft seal, and minimize the additional heat load on the condenser.

![Condenser Pressure](image1)

![Condenser Terminal Difference](image2)

Figure 1. Effect of Condenser Heat load on Condenser Pressure and Terminal difference

3.2 Cooling water flow

As shown in Figure 2, when the condenser heat load and cooling water temperature are constant, as the cooling water flow increases, the condenser pressure and terminal difference will decrease. However, the decreasing trends of the two are not the same. As the cooling water volume increases, the decreasing trend of the condenser pressure gradually slows down, while the condenser terminal difference basically changes linearly. For example, at the initial temperature of 20℃ cooling water, when the cooling water flow rate increases from 60% to 70%, the condenser pressure is reduced from 7.52kPa to 6.69kPa, which is reduced by 0.83kPa, and the condenser terminal difference is reduced from 4.98℃ to 4.94℃, a decrease of 0.04℃; when the cooling water flow rate is increased from 90% to 100%, the condenser pressure decreases from 5.67kPa to 5.33kPa, which decreases by 0.34kPa, and the condenser terminal difference decreases from 4.79℃ to 4.71℃.

![Condenser Pressure](image3)

![Condenser Terminal Difference](image4)

Figure 2. Effect of cooling water flow on condenser pressure and terminal difference

It can be seen that the cooling water flow is an important factor affecting the condenser pressure, and it is particularly prominent in the summer high temperature period. To prevent the vacuum from
decreasing, you must first ensure that there is sufficient cooling water. Increasing the cooling water flow will increase the vacuum, but this is also limited by some conditions. The appropriate cooling water flow should be determined according to the water supply method, the initial temperature of the cooling water and the performance of the circulating pump.

3.3 Cooling water inlet temperature

As shown in Figure 3, when the condenser heat load and cooling water flow rate are constant, as the cooling water inlet temperature increases, the condenser pressure increases, and the increasing trend gradually increases; the terminal difference decreases, but the decreasing trend is gradually slowing down. For example, at a 100% design cooling water flow rate, when the cooling water inlet temperature is increased from 5°C to 10°C, the condenser pressure is increased from 2.60kPa to 3.28kPa, an increase of 0.68kPa, and the condenser terminal difference is reduced from 7.19°C. When the cooling water inlet temperature is increased from 30°C to 35°C, the condenser pressure is increased from 8.70kPa to 11.05kPa, which increases by 2.35kPa, and the condenser terminal difference is reduced from 3.95°C to 3.71°C, a decrease of 0.24°C.

![Figure 3. Effect of cooling water inlet temperature on condenser pressure and terminal difference](image)

It can be seen that the influence of cooling water temperature on condenser pressure and terminal difference is large. In winter, the water temperature is low, the condenser pressure is low, and the terminal difference is large; in summer, the water temperature is high, the condenser pressure is high, and the terminal difference is small. At this time, the increase in water temperature has a greater impact on the unit vacuum than in winter. Therefore, it is more necessary to keep the cooling water temperature at a lower level in summer, which requires the cooling tower equipment to maintain a higher cooling capacity.
3.4 Condenser cooling area

As shown in Figure 4, when the condenser heat load and other conditions are constant, as the effective cooling area decreases, the condenser pressure and terminal difference will increase, and the increasing trend will gradually accelerate.

For example, under 100% condenser heat load, when the effective cooling area is reduced from 100% to 72%, the condenser pressure increases from 5.33kPa to 5.77kPa, an increase of 0.44kPa, and the condenser terminal difference increases from 4.71°C to 6.15°C, an increase of 1.44°C.

It can be seen that the reduction of the effective cooling area will have a large adverse effect on the condenser pressure and the terminal difference. During the regular inspection of the condenser, if it is found that the cooling pipe blocking rate is too high, you should clean up the debris and replace the cooling pipe in time to ensure that the condenser runs at its best.

3.5 Vacuum tightness

As shown in Figure 5, when other conditions such as the heat load of the condenser are constant, as the vacuum falling speed increases, the pressure and terminal difference of the condenser will increase, and the increasing trend will gradually accelerate; The lower the heat load of the condenser, the greater an effect of the amount of air leakage have on the condenser pressure and the terminal difference. For example, under 100% condenser heat load, when the vacuum drop speed is reduced from 0 to 700Pa/min, the condenser pressure increases from 5.33kPa to 5.97kPa, an increase of 0.64kPa, and the terminal difference of the condenser is 4.71°C. Increased to 6.78°C, increased 2.07°C; Under 50% condenser heat load, when the vacuum drop speed was reduced from 0 to 700Pa / min, the condenser pressure increased from 3.59kPa to 6.95kPa, 3.36kPa, condensate Steam turbine terminal difference increased from 2.39°C to 14.25°C, an increase of 11.86°C.
Excessive air leakage will not only reduce the vacuum, and affect the economics of the unit, but also affect the safety of the unit equipment. When the amount of leaked air exceeds the output of the extraction equipment, the subcooling of the condensate increases, and the supercooled condensate increases the unit's heat consumption. In addition, the increase in the oxygen content of the condensate will exacerbate pipeline corrosion. Therefore, in the operation of the unit, the leakage of the condenser should be grasped at any time, which is of great significance to the safety and economic operation of the unit. The tightness of the vacuum system of the unit is poor. The common reasons are the tight connection between the low pressure cylinder and the condenser and cracks in the corrugated throat.

4. Conclusion
(1) The effect of heat load change on vacuum is greater, and the effect is more obvious when the initial temperature of cooling water is high. In addition to the normal unit load adjustment, various steam drains, overflows, and internal leaks will all enter the condenser, increasing the additional heat load on the condenser, and affecting the unit's vacuum. Therefore, it is necessary to strictly control the internal leakage of the valve, reasonably adjust the steam parameters of the shaft seal, and minimize the additional heat load on the condenser.

(2) The cooling water flow and initial temperature directly affect the condenser vacuum, and the impact is greater. The initial temperature of the cooling water is not easy to control. When the initial temperature is high, most power plants use a method of increasing the flow to increase the condenser vacuum. The appropriate cooling water flow should be determined according to the specific conditions during operation.

(3) The cleaning coefficient and air leakage have a great impact on the quality of the vacuum. The dirty water side of the cooling pipe will affect the heat transfer effect of the water pipe. If the water pipe and its tube sheet are blocked by dirt, it will also cause insufficient cooling water for the condenser. Excessive air leakage not only seriously affects the vacuum, but also exacerbates pipeline corrosion and affects the safety of the unit equipment. Therefore, regular operation of the rubber ball cleaning system and timely vacuum leak detection are necessary measures to ensure the vacuum of the unit, which can effectively improve the economic efficiency of the unit.

Acknowledgment
The authors would like to acknowledge the financial support received from the China Huadian Corporation Ltd. The funding was provided through a science and technology project to Huadian Electric Power Research Institute Co., Ltd.
References
[1] Wang Peihong, Zhu Yuna, Jia Junying et al. Application of fuzzy pattern recognition[J]. Proceedings of the CSEE, 1999, 19(10): 46-49.
[2] Ma Liangyu, Wang Bingshu, Tong Zhensheng et al. Fuzzy pattern recognition and artificial neural network used for fault diagnosis of the double-channel condenser[J]. Proceedings of the CSEE, 2001, 21(8): 68-73.
[3] Li Xiuyun, Yan Junjie, Lin Wanchao. Study on thermo-economics diagnosis method and index evaluation system for the cold-end system in steam power unit[J]. Proceedings of the CSEE, 2001, 21(9): 94-98.
[4] Li Yong, Dong Yuliang, Yang Shanrang. Research on the correcting method to the results of vacuum system tightness test of steam turbine[J]. Proceedings of the CSEE, 2002, 22(1): 70-73.
[5] Zhang Jianhua, Hou Guolian, Zhang Wei et al. A research on fuzzy rules and genetic algorithm based method for a condenser fault diagnosis[J]. Proceedings of the CSEE, 2004, 24(4): 205-209.
[6] Zhang Maoyi. Research on the influence of air in-leakage on the condenser operation performance[J]. East China Electric Power, 2001, (8): 22-25.
[7] Gan Changqi, Tian Henian. Experimental research and calculation of air in-leakage into the condenser[J]. Power Station Auxiliary Equipment, 2000, 3(9): 46-50.
[8] Li Yong, Zhang Ruiqing, Cao Lihua. The measure of air leakage into vacuum system of steam turbine with soft-sensing technique[J]. Journal of System Simulation, 2003, 15(3): 444-446.
[9] Alcock J L, Webb D R, Botsch T W et al. An experimental investigation of the dynamic behaviour of a shell-and-tube condenser[J]. International Journal of Heat Mass Transfer, 1997, 40(17): 4129-4135.
[10] Botsch T W, Stephan K, Alcock J L et al. Modeling and simulation of the dynamic behaviour of a shell-and-tube condenser[J]. International Journal of Heat Mass Transfer, 1997, 40(17): 4137-4149.