Dynamic Operational Characteristics for Condenser and Correlative Equipment

Wu Hao¹, Hou Yingzhe¹ and Qian Feng¹
¹Wuhan Secondary Ship Design and Research Institute, Wuhan, Hubei, 430205, China

Abstract. Effective control of condenser backpressure and outlet supercooling plays important role in thermal deaeration process. The back pressure model of condenser is established to analyze the influence of condenser pressure and temperature on circulating water flow, circulating water temperature and suction capacity of air ejector. The dynamic control characteristics and ability of the above factors to backpressure are analyzed.

1. Introduction
The condenser is an important heat transfer equipment in the steam turbine thermodynamic system, which plays an important role in cooling the source, reducing steam exhaust temperature and improving the cycle thermal efficiency [1]. The condenser system is composed of condenser, condensate pump, circulating pump and air ejector [2]. Figure 1 is a schematic of condenser system.

2. Principles of systems and establishment of model
2.1. Principles of systems
Circulating pump provides a certain pressure of circulating cooling water, which flows through the cooling water pipe in condenser to take away some of the steam turbine exhaust steam heat [2]. Steam exhaust of turbine condenses to form condensate, so that the volume decreases sharply, thus maintaining a certain vacuum in the condenser. Reducing steam exhaust pressure of turbine can improve the thermal efficiency of circulation. The condensate water is collected in the hot well of the condenser. The function of the condensate pump is to pump out the condensate and raise the pressure, and then deliver it to the steam turbine water supply system. In the course of shipping, the circulating water required by the condenser changes constantly with the change of the propelling power of the ship.
As the condenser works under high vacuum conditions, the air trapped in the steam exhaust of turbine and the air leaking into the system from where the seal is not tight in system will leak into the condenser continuously. The leaking air will destroy the vacuum of the condenser as the air is non-condensable. The role of the air ejector is to continually pump air out while the condenser is working to maintain and establish the vacuum of the condenser.

The temperature change of circulating water (i.e. seawater) is obvious during ocean voyage, and the temperature change of circulating water will have a certain influence on the vacuum control of condenser. The condensation process of Steam exhaust of turbine in the condenser is basically an isobaric process, and the absolute pressure value depends on the saturation temperature during steam condensation, which in turn depends on the temperature of cooling water and the temperature difference of heat transfer between cooling water and steam [3-5].

2.2. Establishment of model

In order to ensure the normal operation of the steam turbine, the system should meet the following criteria,

1) The condenser back pressure remains constant;

2) The supercooling degree of condenser condensate is maintained at about 3℃.

This paper studies the partial pressure model of air and steam in the condenser to establish the back pressure model of the condenser. Considering that the load of ship steam power plant changes frequently and greatly when it is running, and it often works under variable working conditions, in order to analyze the characteristics of the unit under a wide range of operating conditions, the nonlinear model of each equipment will be established, and the simulation model of the system will be established on this basis. During the modeling process, the model will not be linearized.

According to the steam parameters under various working conditions, the thermal load \( W_{tot} \) of the condenser back pressure can be calculated. Since heat \( W_{tot} \) needs to be taken away by the absorption of heat from the circulating water. If the circulating water flow \( D \) is set as the iteration value, according to the following formula,

\[
W_{tot} = DC_p (t_{ou} - t_{in}) \tag{1}
\]

The outlet temperature \( t_{ou} \) of the circulating water can be calculated from an iterative value of the circulating water flow \( D \).

Since the heat \( W_{tot} \) is also equal to the heat transferred to the circulating water by the steam through the heat transfer tube, according to the heat transfer formula,

\[
W_{tot} = KA \frac{t_{ou} - t_{in}}{\ln \frac{t_s - t_{in}}{t_s - t_{ou}}} \tag{2}
\]

By using the outlet temperature \( t_{ou} \) of circulating water calculated by formula (2), the thermal load \( W_{tot} \) can be obtained by the iterative value of circulating water flow \( D \). The thermal load \( W_{tot} \) can be equalized through repeated iteration by dichotomy. The demand for circulating water can be solved under the condition of back pressure.

The calculation formula of heat transfer coefficient is

\[
K = 1095.5 \sqrt{v} \cdot \frac{1}{\sqrt{T}} + 17.8 \cdot 0.9 \cdot 0.03 \cdot \left(0.7 + 0.3 \frac{R'}{R}\right) \tag{3}
\]

Based on the above principle, The circulating water flow \( D \) is iterated by Matlab programming, and the circulating water quantity required at different working condition is obtained when the inlet temperature of the circulating water is 18.5℃ and the back pressure is the set value \( P \), as shown in Figure 2.
Figure 2. Change of Circulating Water Amount with the Navigational Speed.

Among them, the corresponding relation between circulating water flow and speed under common working conditions 1–4 is as follows,

Table 1. Circulating Water Quantity Required for Each Working Condition under Back Pressure P

| Condition No. | 1    | 2    | 3    | 4    |
|---------------|------|------|------|------|
| Speed V/ top speed (%) | 66.73 | 51.98 | 44.23 | 36.42 |
| Circulating water D/ maximum flow (%) | 38.89 | 22.41 | 16.81 | 12.54 |

3. Dynamic operation of condenser and related equipment

3.1. Dynamic Response of Condenser Back Pressure when Exhaust Volume Changes

Based on the above principles, a simulation model is established by Matlab to simulate the back pressure response of the condenser when the exhaust volume changes. Since the change of exhaust steam volume is caused by the change of speed, step change of speed is used instead of step change of exhaust steam volume in the simulation of this section. The dynamic response results of condenser back pressure when the speed step is ±5% under various working conditions are obtained, as shown in Figures 3 and 4.

Figure 3. Back Pressure Change at Speed +5%.

Figure 4. Back Pressure Change at Speed -5%.

Through the dynamic simulation analysis of various working conditions, it can be found that there are certain differences in the dynamic response of the condenser back pressure when the exhaust volume...
is disturbed under different working conditions. Table 2 is a summary of the speed step ±5% gain and time constant under different working conditions according to the dynamic simulation results of various working conditions. It can be seen that the gain and time constant of the system change greatly with the working conditions when the exhaust volume is disturbed, and the system has obvious nonlinear variable parameter characteristics.

Table 2. Speed Step 5% Gain and Time Constant under Different Working Conditions

| Condition No. | +5% gain  | -5% gain  | +5% time constant(s) | -5% time constant(s) |
|---------------|-----------|-----------|----------------------|----------------------|
| 1             | 4393.30   | 3381.02   | 3                    | 3                    |
| 2             | 4279.30   | 3765.33   | 4                    | 4                    |
| 3             | 4362.29   | 3936.47   | 5                    | 5                    |
| 4             | 4416.29   | 3877.18   | 7                    | 7                    |

3.2. Dynamic Response of Condenser Back Pressure when Circulating Water Inlet Temperature Changes

The back pressure response of the condenser when the circulating water inlet temperature changes is simulated, and the dynamic response results of the condenser back pressure when the circulating water inlet temperature step is ±5% under various working conditions are obtained, as shown in figs. 5 and 6.

Figure 5. Back Pressure Change at Circulating Water Inlet Temperature +5%.

Figure 6. Back Pressure Change at Circulating Water Inlet Temperature -5%.

There are some differences in the dynamic response of condenser back pressure when circulating water inlet temperature is disturbed under different working conditions. Table 3 summarizes the gain and time constant of circulating water inlet temperature step ±5% under different working conditions according to the dynamic simulation results of various working conditions. It can be seen that the gain and time constant of the system change greatly with the working conditions when circulating water inlet temperature is disturbed, and the system has obvious non-linear variable parameter characteristics.

Table 3. Circulating Water Inlet Temperature Step 5% Gain and Time Constant under Different Working Conditions

| Condition No. | +5% gain  | -5% gain  | +5% time constant(s) | -5% time constant(s) |
|---------------|-----------|-----------|----------------------|----------------------|
| 1             | 832.7559  | 805.7179  | 5                    | 5                    |
| 2             | 852.2881  | 824.8702  | 7                    | 7                    |
| 3             | 863.5562  | 835.8943  | 9                    | 9                    |
| 4             | 875.8771  | 847.9029  | 12                   | 12                   |

3.3. Dynamic Response of Condenser Back Pressure with Change of Circulating Water Valve Opening

The back pressure response of condenser is simulated when the opening of circulating water valve changes. Since the change of circulating water valve opening will directly cause the change of
circulating water flow rate, the following changes of circulating water flow rate replace the change of circulating water valve opening. Figures 7 and 8 are the simulation results of dynamic response of condenser back pressure when the circulating water flow rate step is ±5%.

![Figure 7. Back Pressure Change at Circulating Water Inlet Temperature +5%](image1)

![Figure 8. Back Pressure Change at Circulating Water Inlet Temperature -5%](image2)

From the above results, it can be seen that there are certain differences in the dynamic response of the condenser back pressure when circulating water flow is disturbed under different working conditions. Table 4 is a summary of the gain and time constant of circulating water flow step ±5% under different working conditions according to the dynamic simulation results of various working conditions. It can be seen that the gain and time constant of the system change greatly with the working conditions when circulating water flow is disturbed, and the system has obvious non-linear variable parameter characteristics.

| Condition No. | +5% gain  | -5% gain  | +5% time constant(s) | -5% time constant(s) |
|---------------|-----------|-----------|----------------------|----------------------|
| 1             | -55.0339  | -48.5200  | 3                    | 3                    |
| 2             | -99.7407  | -87.5705  | 6                    | 5                    |
| 3             | -136.8029 | -119.6589 | 7                    | 7                    |
| 4             | -190.5345 | -163.8729 | 10                   | 9                    |

3.4. Dynamic Response of Condenser Back Pressure with Air Ejector Valve Opening Change

In order to stabilize the back pressure of the condenser at 24kPa under various working conditions, an air extractor can be used to participate in the adjustment. Therefore, it is necessary to analyse the dynamic characteristics of the air extractor adjustment under gravity flow working conditions. The back pressure response of condenser is simulated when the valve opening of air extractor changes. Since the change of the valve opening of the air extractor will directly cause the change of the air extraction volume of the air extractor, the change of the air extraction volume of the air extractor is used below to replace the change of the valve opening of the air extractor. Perform a -5% step on the extraction volume of the air extractor under each working condition. Figures 9, 10 and 11 are respectively the step response curves of the air partial pressure, steam partial pressure and total back pressure of the condenser.
Figure 9. Change of air partial pressure when pumping volume -5% step.

Figure 10. Change of steam partial pressure when pumping volume -5% step.

Figure 11. Change of back pressure when pumping volume -5% step.

From the above results, the gain and time constant of the pumping rate step -5% under different working conditions can be obtained as shown in Table 5. It can be seen that the gain and time constant of the system will change to a certain extent with the working conditions when the pumping rate is disturbed, but the change range is not large. Therefore, it can be concluded that the non-linear variable parameter characteristic of the system is not obvious when the ejector is adjusted, and the non-linear variable parameter characteristic of the system can be ignored.

Table 5. The gain and time constant of the total back pressure response under various working conditions with the pumping volume step -5%

| Condition No. | gain | time constant(s) |
|---------------|------|------------------|
| 1             | 4.44 | 10               |
| 2             | 3.57 | 11               |
| 3             | 3.13 | 50               |
| 4             | 2.5  | 70               |

4. Conclusions
Through the analysis in this chapter, it can be seen that when the back pressure of condenser is controlled by adjusting the opening of circulating water valve, the gain and time constant of condenser and its related equipment under step disturbance change greatly with the working condition, and the time constant under low working condition is about 10 times of that under high working condition, which shows that the system has obvious non-linear variable parameter characteristics. When the air extractor
is used to control the back pressure of the condenser, the time constant of the back pressure response is
about 60~90s when the air extraction volume changes step by step. Although the gain and time constant 
of the system will change to a certain extent with the working conditions, the change range is not large,
the nonlinear variable parameter characteristics of the system are not obvious, and the nonlinear variable 
parameter characteristics of the system can be ignored. In addition, compared with the time constant of 
the back pressure response when the circulating water pump is used for control, the time constant of the 
system when the air extractor is used for control is obviously larger than the time constant when the 
circulating water pump is used for control, and the back pressure response when the condenser is 
controlled by the air extractor is slower than that when the circulating water pump is used for control.

Based on the above analysis results, in order to achieve a good control effect, the above dynamic 
characteristics of the condenser and its related equipment need to be considered when designing the 
control law.

Nomenclature

- \( W_{\text{tot}} \) thermal load, J/s
- \( K \) heat transfer coefficient, \( w/(m^2 \cdot ^\circ \text{C}) \)
- \( A \) average heat transfer area, \( m^2 \)
- \( D \) circulating water flow, J/s
- \( t_s \) temperature of steam, \( ^\circ \text{C} \)
- \( t_{in} \) inlet temperature of the circulating water, \( ^\circ \text{C} \)
- \( t_{out} \) outlet temperature of the circulating water, \( ^\circ \text{C} \)
- \( v \) average flow rate of cooling water, \( m/s \)
- \( T \) average temperature of cooling water, \( ^\circ \text{C} \)
- \( R \) rated load of condenser, J/s
- \( R' \) condenser load, J/s

References

[1] Wan, H., Yao, Y.T., Pan, Y., Sun, J.H. (2008) Research of condensate depression and its 
    control system., 33(1): 80–83,110.
[2] Sun, Z. (2004) Nuclear Power Component. Harbin Engineering University Press, Harbin.
[3] Xue, R.J. (2002) Research on Real-time Simulation of Dynamic Characteristics of Marine 
    Condensation-steam Equipment. Harbin Engineering University, Harbin.
[4] Li X., Deng B., Tao W.Q. Study on Three-dimensional Numerical Simulation of Shell-and-
    tube Heat Exchangers with Finned Rod Bundles. Journal of Engineering Thermophysics, 
    2005, (2): 316～318
[5] Li Y., etc. Study on the Influence of Condenser Cooling Water Temperature and Flow Rate 
    on Condensate Sub- cooling Degree, Turbine Technology, Vol.51 No.3 2009: 210～213