Steady-state Operational Characteristics for Condenser and Correlative Equipment

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Abstract. Effective control of condenser backpressure and outlet supercooling plays important role in thermal deaeration process. The backpressure model of condenser is established to analyse the pressure and temperature impact of circulating water flow, circulating water temperature and suction capacity of air ejector. The steady-state control characteristics and ability of the above factors to backpressure are analyzed.

1. Introduction
The condenser is an important heat transfer equipemnt in the steam turbine thermodynamic system, playing the role of a cold source, reducing steam exhaust temperature, and improving the heat efficiency of the cycle.[1] The condenser system is composed of condenser, condensate pump, circulating pump and air ejector.[2] Fig.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]

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°C.

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,

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

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,

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

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

\[
K = 1095.5 \sqrt{v} \cdot \sqrt{T} + 17.8 \cdot 0.9 \cdot 0.83 \left( 0.7 + 0.3 \frac{R'}{R} \right) 
\]

3. Steady-state operation of condenser and related equipment
3.1 Circulating water flow demand of the condenser at each steady-state operating point
Based on the above principle, by using Matlab programming to iterate the circular water flow D, the circulating water amount required by each working condition to meet the back pressure changes with the ship speed as shown in figure 2.

![Figure 2. Change of Requirement and Actual Circulating Water Amount with the Inlet Pressure of Circulating Water.](image)

When the actual circulating water amount is greater than requirement, the back pressure of condenser will be lower than set point if the circulating water amount or swept volume of air ejector is not adjusted. The back pressure of the condenser can be stabilized at set point through proper adjustment of the circulating pump to change the circulating water quantity or the swept volume of air ejector.

### 3.2 Steady-state performance of condenser back pressure

#### 3.2.1 Effect of inlet temperature of circulating water on the back pressure of condenser.

When the swept volume of air ejector is fixed, the amount of circulating water required in each condition is different under different inlet temperature of circulating water. Without regulating the circulating water flow, there is difference between the back pressure of the condenser and the rated inlet temperature of circulating water at different inlet temperature.

The condenser back pressure is obtained by steady state calculation, as shown in figure 3, corresponding to circulating water inlet temperature at 4 °C, respectively, 8 °C, 12 °C and 16 °C, 18.5 °C, 20 °C and 24 °C, 28 °C.

![Figure 3. Change of the Inlet Temperature of Circulating Water with Condenser Back Pressure](image)

#### 3.2.2 Effect of adjustment of swept volume on the back pressure of the condenser.

When the air ejector is involved in the regulation, the air content in the condenser will be increased by turning down the air
ejector, and a certain air partial pressure will be generated. At this moment, the back pressure of the condenser will be composed of steam partial pressure and air partial pressure.

The regulation of the air ejector can control the air partial pressure. In extreme cases, when the air ejector is completely closed, the air partial pressure will increase to atmospheric pressure. Therefore, when the air ejector is involved in the regulation, the back pressure of the condenser can maintain the set point under the condition of insufficient of circulating water. When the circulating water is sufficient, the circulating water flow is controlled by adjusting the circulating water valve, so that the back pressure of the condenser is also controlled at the set point.

Therefore, when the inlet temperature of the circulating water is different, the back pressure of the condenser is controlled at the set point by adjusting the opening of the circulating water valve and the valve of the air ejector at each working condition.

3.3 Steady-state performance of condensate supercooling of the condenser

3.3.1 Effect of inlet temperature of circulating water on the condensate supercooling of condenser
If the air ejector is not working, the air content in the condenser is zero. Under different inlet temperature of circulating water, the supercooling degree of condensate is calculated as shown in table 1.

| Inlet temp. | Supercooling degree (°C) | Condition No. | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|-------------|--------------------------|---------------|---|---|---|---|---|---|---|
| 4°C         | 2.52 1.84 0.41 0 0 0 0   |               |   |   |   |   |   |   |   |
| 8°C         | 2.61 1.99 0.65 0 0 0 -   |               |   |   |   |   |   |   |   |
| 12°C        | - - 0.91 0 0 0 -         |               |   |   |   |   |   |   |   |
| 16°C        | - - 1.18 0 0 0 -         |               |   |   |   |   |   |   |   |
| 18.5°C      | - - 1.36 0 0 0 -         |               |   |   |   |   |   |   |   |
| 20°C        | - - 1.46 0.07 0 0 -     |               |   |   |   |   |   |   |   |
| 24°C        | - - - 0.50 0 0 -        |               |   |   |   |   |   |   |   |
| 28°C        | - - - 0.94 0.04 0 -     |               |   |   |   |   |   |   |   |

3.3.2 Effect of adjustment of swept volume on condensate supercooling of the Condenser
The air content in the condenser can be changed by adjusting the swept volume of the air ejector, and the air partial pressure is then changed. This allows the total back pressure of air and steam in the condenser to be maintained at the set points. The supercooling degree of condensation water under various working conditions was calculated in steady state, as shown in table 2.

| Condition No. | Supercooling degree (°C) | 3 4 5 6 |
|---------------|--------------------------|--------|
| Air mass fraction | 0.0071 0.0096 0.0110 0.0110 | |

When the air ejector is involved in regulating the back pressure of the condenser, under different inlet temperature of circulating water, through steady-state calculation, the condensation water supercooling degree under different inlet temperature of circulating water is respectively obtained, as shown in table 3.
It can be observed from table 3 that when the inlet temperature of circulating water changes within the range of 4-28, the increase of air partial pressure caused by the air ejector adjustment has little influence on the supercooling degree of condensate, which can be basically ignored.

| Condition No. | 1  | 2  | 3  | 4  | 5  | 6  | 7  |
|---------------|----|----|----|----|----|----|----|
| Inlet temp.   | 4°C| 2.75| 2.15| 1.73| 1.13| 0.72| 0.23| 0.00|
|               | 8°C| 2.69| 2.09| 1.72| 1.12| 0.72| 0.23| -   |
|               | 12°C| -  | -  | 1.71| 1.11| 0.71| 0.22| -   |
|               | 16°C| -  | -  | 1.70| 1.10| 0.70| 0.21| -   |
|               | 18.5°C| -  | -  | 1.69| 1.09| 0.70| 0.21| -   |
|               | 20°C| -  | -  | 1.66| 1.09| 0.69| 0.20| -   |
|               | 24°C| -  | -  | -   | 1.07| 0.68| 0.19| -   |
|               | 28°C| -  | -  | -   | -   | 0.99| 0.66| 0.17| -   |

It can be observed from table 3 that when the air ejector participated in regulating the back pressure of the condenser, compared with table 1, the condensation water undercooling degree of each working condition increased but not obvious. The reason is that the air pressure has a great influence on the heat transfer coefficient of the condenser. When it increases slightly, the heat transfer coefficient of the condenser will drop sharply. The decrease of heat transfer coefficient will lead to the increase of circulating water demand, thus the excess degree of circulating water flow in the downgrade flow condition will be greatly reduced, and the steam partial pressure will be significantly increased, at this time, the proportion of air partial pressure in the total back-pressure is very small. Therefore, the increase of air partial pressure caused by the air ejector participation in regulating the back pressure of the condenser has little influence on the supercooling degree of the condensate, which can be basically ignored.

4. Conclusions
When the actual circulating water flow is greater than requirement, the air partial pressure can be increased by controlling the air ejector, so that the back pressure of the condenser is controlled at the set point. When air volume is increased by adjusting the air ejector to control back pressure, Adjusting air ejector leads to the increasement of air pressure but the supercooling degree of the condensate was not significantly affected in the circulating water inlet temperature of 4 °C~28°C range. It can be concluded that it is feasible to control the back pressure of the condenser by regulating the swept volume of air ejector.

Nomenclature

\[ W_{\text{tot}} \text{ thermal load, J/s} \]
\[ K \text{ heat transfer coefficient, } \frac{W}{(m^2 \cdot ^\circ C)} \]
\[ A \text{ average heat transfer area, } m^2 \]
\[ D \text{ circulating water flow, J/s} \]
\[ t_s \text{ temperature of steam, } ^\circ C \]
\[ t_{in} \text{ inlet temperature of the circulating water, } ^\circ C \]
\[ t_{out} \text{ outlet temperature of the circulating water, } ^\circ C \]
\[ v \text{ average flow rate of cooling water, } m/s \]
\[ \tau \quad \text{average temperature of cooling water, } ^\circ\text{C} \]
\[ R \quad \text{rated load of condenser, J/s} \]
\[ R' \quad \text{condenser load, J/s} \]

References
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