Analysis of the energetic and exergetic performance in condensers of thermal generation plant

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Abstract. In the present study, the influence of the flow parameters of the cooling water on the operating conditions of the condenser is evaluated. The above, by simulating codes that represent the thermal behavior of the equipment. The study focuses on the influence of the temperature and the flow rate of the cooling water on the pressure, heat transfer coefficient, and exergy efficiency of the condenser. Additionally, mathematical correlations are made between these operating variables. The study shows that the flow of cooling water causes a reduction in the condenser pressure. However, it does improve its heat transfer capacity. On the other hand, a 2 °C increase in temperature produces a 6% increase in condenser pressure. Pressure levels above 8.5 kPa cause a considerable reduction in the energy and exergetic efficiency of the condenser. Similarly, the exergetic efficiency of the condenser is also affected by heat losses to the environment. Additionally, the increase in temperature allows the condenser to operate at a higher exergy efficiency. Finally, the development of the correlations carried out can become a tool for evaluating the performance of the condenser under different operating conditions.

1. Introduction

Steam condensers are one of the main equipment that significantly affects the performance and power generation process of a power plant. The loss of efficiency in the condenser can lead to an overall reduction in the entire energy process [1,2]. The influencing parameters on the performance of a steam condenser are temperature, cooling water, flow rate, heat transfer area, tube bundle fouling, and air leakage. Some of these parameters, such as flow rate and condenser pressure, vary depending on the load to which the equipment is subjected. Others are dependent on the intake system, such as the temperature of the cooling water. Due to these changes in operating conditions, the performance of the condenser is subject to variations during its operating process. Additionally, these variations in operating conditions cause changes in the heat rate of the turbine cycle and in power generation.

Researchers and designers of condensers have developed studies that improve their efficiency in relation to their flow distributions, geometric configuration, and type of material [3,4]. Currently, studies have focused on investigating the effect of flow conditions (temperature and velocity) and the effect of vacuum in the condenser [5-9]. Generally, the study of the condenser performance is carried out by means of correction methods or effectiveness methods [10,11]. Zhao et al. [12] investigated the performance of a condenser using pressure and cleaning factor indices. Laković et al. [13] studied the influence of the temperature and speed of the cooling water on the efficiency of the condenser. Anozi et al. [14] investigated the effect of the condenser flow on the cycle efficiency of the entire plant. Ayoola et al. [15], raised the use of programming to optimize the operation in thermal power plants. Qureshi and Zubair [16] showed that fouling thickness has a direct effect on the performance of the condenser.
and the evaporative cooler. The results obtained show that fouling can cause performance losses greater than 70% in the condenser. Putman and Harpster [17] investigated the effect of condenser back pressure on the economic cost of the process. Previous studies involved the use of mathematical models to calculate thermal balances and heat transfer coefficients [18]. The use of these models has been proposed for the analysis of condenser performance in relation to various characteristics such as materials, flow rates, and fouling [19]. Additionally, efforts have been made to implement to evaluate the performance of a condenser based on parameters such as the heat transfer coefficient, flow rates, and flow velocity, and in general, under non-design operating conditions. However, this type of analysis requires high geometric detail information, which is not always available. Due to the above, the present study aims to develop mathematical correlations that allow the cooling water flow conditions to be related to the pressure, heat transfer coefficient, and efficiency characteristics of a steam surface condenser. The above, to obtain a tool for evaluating the thermal behavior of the condenser from basic operating conditions such as the parameters of flow and temperature of the cooling water.

2. Methodology

For the study, the main two-step tube and shell vapor condenser used in a thermal power station were analyzed. The capacity of the hot well is 41 m$^3$, and the condensation surface area is 18135 m$^2$. Figure 1 shows the arrangement of the condenser flows.

![Figure 1. Flow distribution in the steam condenser.](image)

The steam originated in the turbine enters the condenser (1), it is subsequently condensed by the surface of the tube bundle (2) and accumulates in a liquid state in the hot well. Inlet (3) enters the cooling water, runs through the entire body of the condenser until it reaches the return box, which changes the direction of flow by 180°. Again, the flow of water runs through the body of the equipment until its exit in (4). Due to the characteristics of steam condensers, four operating conditions are assumed; steady-state flow, no heat transfer to the condenser, no work is done inside the condenser, and the effects of kinetic and potential energy are negligible. Considering the previous assumptions, the main thermodynamic equations are defined for the analysis of the steam condenser. The logarithmic mean temperature difference (LMTD) method was used to consider the condenser performance. Therefore, heat transfer is defined as shown in Equation (1).

$$Q = k \cdot A \cdot dTm,$$  \hspace{1cm} (1)

where $Q$, $k$, and $A$, are the heat transfer rate, the heat transfer coefficient, and the total area of the tube bundle. Considering the law of conservation of energy inside the condenser, the relations of the heat transfer rates for the hot flow and the cold flow are obtained. The heat flow absorbed by the cooling water is defined according to Equation (2).
\[ Q_{34} = \dot{m}_3 (h_4 - h_3) = \dot{m}_3 C_p (T_4 - T_3), \]  
\[ (2) \]

Similarly, the heat flow given off by steam is defined according to Equation (3).

\[ Q_{156} = \dot{m}_1 h_1 + \dot{m}_5 h_5 - \dot{m}_6 h_6, \]  
\[ (3) \]

where \( \dot{m}, C_p, T \) and \( h \), are the mass flow, specific heat, temperature, and enthalpy of the flow. Based on the above equations, the energy efficiency of the condenser is stable as indicated by Equation (4).

\[ \eta_{\text{ener}} = \frac{\dot{m}_3 C_p (T_4 - T_3)}{\dot{m}_1 (h_2 - h_1)}. \]  
\[ (4) \]

The exergy balance inside the condenser is defined based on the following Equation (5) to Equation (7).

\[ \sum \dot{m}_{\text{in}} S_{\text{in}} - \sum \dot{m}_{\text{out}} S_{\text{out}} + \dot{\sigma} = 0, \]  
\[ (5) \]

\[ \sum \dot{m}_{\text{in}} e_{\text{in}} - \sum \dot{m}_{\text{out}} e_{\text{out}} - \dot{E}_d = 0, \]  
\[ (6) \]

\[ e = h - h_0 - T_0 (S - S_0), \]  
\[ (7) \]

where the in and out subscripts indicate the inlet and outlet flows. \( \dot{E}_d \) is the destruction of exergy due to irreversibility. \( T_0, h_0 \) and \( S_0 \) are the temperature, enthalpy, and entropy in environmental conditions, respectively. Based on Equation (5) to Equation (7), exergy efficiency is defined as shown in Equation (8).

\[ \eta_{\text{exer}} = \frac{\dot{m}_3 e_4 - \dot{m}_4 e_3}{\dot{m}_1 e_1 - \dot{m}_2 e_2}. \]  
\[ (8) \]

For the analysis of the efficiency of the steam condenser, the historical record of its operating conditions was used, which shows the state of the flows at the inlet and outlet. All these data were organized for a subsequent numerical simulation through the development of programming codes. The simulation of the codes was carried out using the MATLAB software.

For the study of the condenser, three load conditions were selected, P1, P2, and P3, respectively. In each of these conditions, the turbine operated at different power levels. Table 1 shows the turbine power for each condition.

| Table 1. Condenser operating conditions. |
|-----------------------------------------|
| Load | Turbine power range (MW) |
| P1   | 60 - 76                  |
| P2   | 76 - 92                  |
| P3   | 92 - 108                 |

3. Results

3.1. Effect of cooling water flow

Figure 2 shows the effect of the flow of the cooling water on the heat transfer coefficient and the Figure 3 show the pressure of the condenser. The results obtained show that the flow of the cooling water produces an increase in the heat transfer coefficient and a reduction in the condenser pressure. For the flow range studied, there was no significant change in condenser pressure. The increase in the heat transfer coefficient may be a consequence of the increase in the flow velocity of the water.
The results obtained show that the rise in the turbine load produces an increase in the pressure levels and in the heat transfer coefficient of the condenser. On average, the P3 load shows a 2.1% and 4.28% increase in the condenser pressure, when compared to the P2 and P1 load levels, respectively. In the case of the heat transfer coefficient, load P3 shows a rise of 20% and 35% compared to loads P2 and P1. From the analysis carried out, a correlation was found between the heat transfer coefficient and the flow of the cooling water, which was defined as $k = -0.0001 \text{m}^2 + 0.0289 \text{m} - 0.8084$, $k = -0.0001 \text{m}^2 + 0.0292 \text{m} - 0.4595$ and $k = -0.0001 \text{m}^2 + 0.0287 \text{m} - 0.0584$, for the load conditions P1, P2, and P3, respectively.

Similarly, the mathematical relationship between the condenser pressure and the flow of the cooling water was established, defined as $P = 0.00002 \text{m}^2 - 0.0048 \text{m} + 9.2181$, $P = 0.00002 \text{m}^2 - 0.0045 \text{m} + 9.4205$ and $P = 0.00002 \text{m}^2 - 0.0046 \text{m} + 9.5181$ for the load conditions P1, P2, and P3, respectively.

3.2. Effect of condenser pressure
Figure 4 shows the influence of pressure on the energy and the Figure 5 show the energetic efficiency of the condenser. It is observed that the energy and exergetic efficiency of the condenser is reduced with increasing pressure levels of the condenser. This is attributed to the fact that at high-pressure levels, higher fuel consumption is required to reach the load conditions. Additionally, the rise in pressure favors the development of enthalpy, which reduces energy generation. For the analyzed pressure range, it was observed that the reduction in condenser efficiencies is further accentuated for pressure levels above 8.5 kPa.

3.3. Effect of heat loss on the condenser
Figure 6 shows the effect that heat loss has on the exergy efficiency of the condenser. The results obtained show a negative relationship between heat loss and exergy efficiency. In general, a decreasing linear correlation was observed between these two variables. The results indicate that a 10000-kW loss causes an 8% reduction in exergy efficiency. Which shows the importance of minimizing heat losses to the environment.
3.4. Effect of the temperature cooling water
In addition to the effect of the flow of the cooling water, the impact of its temperature on the condenser conditions is evaluated. The results are shown in Figure 7. The Figure 7(a) show the effect of cooling water temperature on the heat transfer coefficient and the Figure 7(b) show effect of cooling water temperature on the condenser pressure. It was observed that an increase in the temperature of the cooling water causes the condenser pressure levels to increase. This is attributed to the lower heat adsorption capacity of water. On average, the results show that an increase of 0.5 °C causes a 1.5% increase in condenser pressure. For this same temperature rise, an average increase of 10% in the heat transfer coefficient was observed.

The correlation found between temperature and pressure corresponds to an exponential relationship, defined as $P = 1.9586e^{0.0415T}$, $P = 2.8165e^{0.0360T}$, and $P = 4.088e^{0.0292T}$ for the load conditions P1, P2, and P3, respectively. Additionally, it was found that the increase in temperature caused an increase in the heat transfer coefficient. The mathematical relationship between these two variables is established.

**Figure 4.** Effect of condenser pressure on the energy efficiency.

**Figure 5.** Effect of condenser pressure on the exergy efficiency.

**Figure 6.** Relation between the exergy efficiency of the condenser with the heat losses.
as \( k = 0.0058T^2 - 0.2491T + 2.7932 \), \( k = 0.0018T^2 - 0.0043T + 0.8232 \), and \( k = 0.0058T^2 - 0.2491T + 3.5932 \) for the load conditions P1, P2, and P3, respectively. For the studied temperature range, it was found that the variation of the heat transfer coefficient was 0.31 kW/m²K to 1.97 kW/m²K. Finally, the effect of the temperature of the cooling water on the exergy efficiency of the condenser is analyzed.

The Figure 8 shows the results obtained. In the Figure 8(a) it is observed that the temperature increase allows increasing the exergetic efficiency of the condenser. For the temperature range between 27 °C and 35 °C, an exergetic efficiency range of 20% - 65% is achieved. The improvement in exergy efficiency is perceived by quantifying the loss of exergy as a function of the temperature of the cooling water. This relationship is shown in Figure 8(b). The results show that the increase in temperature caused a reduction in the destruction of exergy. On average, an increase of 2 °C produces a 1.64% decrease in exergy destruction.

![Figure 7](image_url1)  
**Figure 7.** Effect of cooling water temperature on (a) heat transfer coefficient and (b) condenser pressure.

![Figure 8](image_url2)  
**Figure 8.** Effect of cooling water temperature on (a) exergy efficiency and (b) destruction of exergy.
4. Conclusions
In the present study, the performance analysis of a steam surface condenser of a thermoelectric power station was performed. This investigation describes the influence of the parameters of the cooling water on the operating conditions and on the performance of the condenser. Increases in the flow of the cooling water cause a reduction in the pressure levels of the condenser. In general, a 20 kg/s increase in water flow produces a 1% reduction in pressure. The correlations made show that the increase in the temperature of the cooling water allows inducing an increase in the condenser pressure and in the heat transfer coefficient. The analysis of the influence of condenser pressure on energy and exergy efficiency showed that high pressures cause a considerable reduction in condenser efficiencies. Being a critical case, pressures above 8.5 kPa. The results showed that heat losses in the surface condenser cause a proportional reduction in exergy efficiency. Therefore, it is appropriate to implement methodologies to reduce heat loss to the environment. Additionally, the results obtained show that it is possible to achieve a reduction in exergy destruction by operating with higher temperatures in the cooling water. In general, the increase of 1 °C causes a 12% increase in the exergy efficiency of the condenser. However, excessive temperature rise can cause an incomplete condensation process. The development of the correlations carried out can lead to a guide, which allows the operator to obtain optimal working conditions in the condenser, since the flow and temperature of the cooling water are easily controllable parameters.

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