Thermal Performance Analysis of a Shell and Tube Condenser in Steam Power Plant

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Abstract. Steam power plant is one of plant of electricity needs that has great potential in energy supply and is an alternative to electricity needs in Indonesia. This study reviews the thermal performance of a steam power plant's condenser, focusing on its exergy efficiency and heat transfer rate over five different days. The results show a significant increase in exergy efficiency on day four, reaching 78.3% with a heat transfer rate of 175.39 kW. The lowest exergy efficiency was found on the first day of data collection, with a value of 32% and a heat transfer rate of 191.40 kW. This highlights the importance of condenser performance in achieving optimal energy efficiency. The heat transfer rate and exergy Condenser are affected by factors the cooling water temperature as coolant inlet fluid and the exhaust steam temperature as condensate outlet fluid.

**Keywords:** Steam Power Plant, Condenser, Heat Transfer Rate, Exergy

1. INTRODUCTION

Steam power plant is one type of energy conversion technology from fossil fuels into thermal energy in the combustion chamber by utilizing steam thermal energy converted into mechanical energy in steam turbines and from mechanical energy converted into electrical energy in generators. The condenser is one of the important components in a power plant which significantly affect the power generation and performance of unit in terms of heat rate [1]. The type of condenser in this steam power plant is shell and tube. Condensation is a phase changing process by withdrawing of the latent heat of evaporation [2]. Condensation heat transfer has a significant duty in many industrial processes, such as thermal power plant, heavy industry, cooling and air conditioning cycles [3].

Therefore, the condenser as a heat exchanger must be reviewed through the heat transfer rate performance analysis. Through analyzing the heat transfer rate of Condenser in steam power plants, opportunities for more efficient energy use and savings can be identified.

The weakness in the condenser's circulating water parameters may cause an energy generation restriction due to the low vacuum pressure in the condenser. Thus, it is essential to identify the optimal working parameters of the condenser to obtain

better efficiency from the termal power stations and enhanced performance from the Rankine power cycle [4-5]. Effect of condenser pressure on Rankine cycle. Figure 1 shows one cycle with the same condenser pressures. One condenser operates at atmospheric presuure and the other at less than atmospheric pressure.
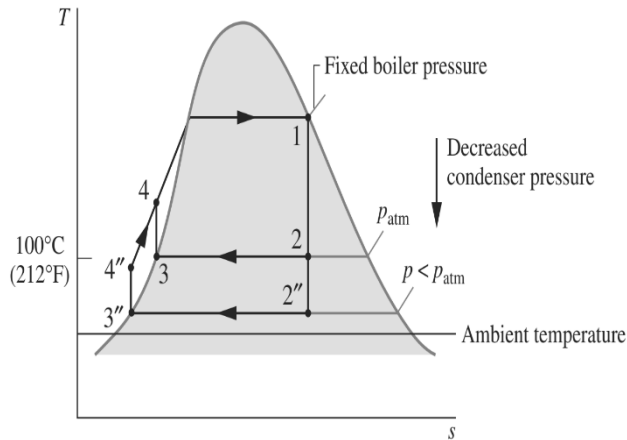
Figure 1 Effect of condenser pressure.

The temperature of heat rejection for cycle 1-2-3-4-1 condensing at atmospheric pressure is 100°C (212°F). The temperature of heat rejection for the lower-pressure cycle 1-2"-3"-4"-1 is correspondingly lower, so this cycle has the greater thermal efficiency. It follows that decreasing the condenser pressure tends to increase the thermal efficiency [6]. Heat transfer characteristics of condenser and its performances are examined using a modeling study by means of thermodyamic laws by changing key operating parameters of cooling water [7].

The performance analysis to define and to calculate thermal performance of a shell and tube condenser variation of (a) mass flow rate, temperature and pressure of exhaust steam inlet (b) temperature of coolant inlet, (c) mass flow rate and temperature of condensate outlet, (d) temperature of coolant outlet.

2. PROCESS DESCRIPTION

The process flow is based on the Rankine Cycle of a steam power plant with multiple feedwater heaters, with two systems of close feedwater heaters (high and low pressure heaters) and one system of open feedwater heaters (deaerators). The process flow is started by the superheated steam, which rotates turbine blades as mechanical energy at a rotation speed of 3000 RPM, and the turbine shaft is coupled with a generator.

The condensing steam turbine has been used to rotate the turbine. The first extraction flows to the high-pressure heater. The second extraction flows to the deaerator, and the third extraction flows to the low-pressure heater. The exhaust steam

energy leaving the turbine will flow into the condenser for the condensation process from the vapor phase to the liquid phase. The water output from the condenser circulating into the cooling tower is going through the cooling process. The cooling water is pumped by the circulating water pump and flows to the condenser to absorb heat and exhaust steam. The condensate from condensation is collected in a hotwell and then pumped by a condensate pump to a low-pressure heater to be reheated before it is flowed into the deaerator.

The type of condenser is a shell and tube. The simplest form of a horizontal shell and tube type condenser with various components. One fluid stream flows through the tubes while the other flows on the shell side, across or along the tubes. In a baffled shell and tube heat exchanger, the shell side stream flows across pairs of baffles and then flows parallel to the tubes as it flows from one baffle compartment to the next. The Schematic of the condenser is as illustrated in Figure 2.

Exhaust steam inlet

Coolant Outlet   **Coolant inlet**

Condensate Outlet
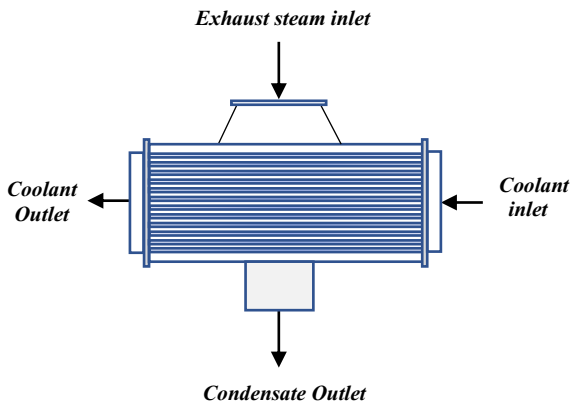
Figure 2 Shell and tube heat exchanger

2.1. Heat Transfer Rate

Heat transfer rate is the most important quantity in the selection of a heat exchanger. The heat exchanger should be capable of transferring heat at the specified rate in order to achieve the desired temperature change of the fluid at the specified mass flow rate. Two special types of heat exchangers commonly used in practice are condensers and boilers. An ordinary fluid absorbs and releases a large amount of heat at a constant temperature during a phase-change process, as shown in Figure 3.
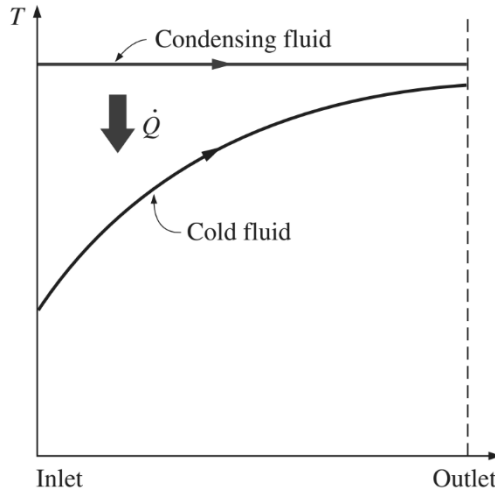
Figure 3 Process of Condensation and Fluid Temperature Change in a Condenser

In heat exchanger analysis, a condensing fluid is conveniently modeled as a fluid whose heat capacity rate is infinity. The rate of heat transfer in a heat exchanger can also be expressed into Newton's Law of cooling as :

$$\dot{Q} = UA_s \Delta T_{lm} F \qquad (1)$$

Where $\dot{Q}$ is heat transfer (kW), U is the overall heat transfer coefficient (W/(m².°C), A_s is the heat transfer area (m²), and ΔT_{lm} is an appropriate average temperature difference between the two fluids (°C), F is correction factor. The step to calculate the heat transfer rate as :

1. The overall heat transfer coefficient :

$$U = \frac{1}{\frac{1}{h_i} + \frac{1}{h_o}} \qquad (2)$$

a. Determine the inside convection coefficient

$$h_i = \frac{k}{D_h} N_u \qquad (3)$$

b. Determine the Nusselt Number

$$N_u = \frac{hD_h}{k} = 0{,}683 Re^{0,466} Pr^{1/3} \qquad (4)$$

c. Determine Reynolds Number

$$R_e = \frac{V_m D_h}{v} \qquad (5)$$

d. Determine the mean velocity

$$V_m = \frac{m_{exhaust\,steam}}{\rho A_c} \qquad (6)$$

e. Determine Area Surface

$$A_s = \pi DL \qquad (7)$$

f. Determine Log Mean Temperature Difference
$$\Delta T_{lm} = \frac{\Delta T_1 - \Delta T_2}{\ln\left(\frac{\Delta T_1}{\Delta T_2}\right)} \qquad (8)$$

g. Determine Factor Correction

The determination of the heat transfer rate heat shell and tube heat exchangers using Correction Factor F charts in Figure 4 [8] and using the equation :

$$P = \frac{t_2 - t_1}{T_1 - t_1} = \frac{T_{h,out} - T_{h,in}}{T_{c,in} - T_{h,in}} \qquad (9)$$

h. Determine the outside convection coefficient (h_o)
Follow the equation (4) to (6).

(b) Two-shell passes and 4, 8, 12, etc. (any multiple of 4), tube passes
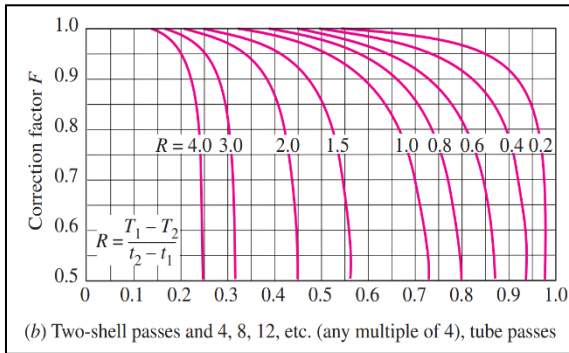
Figure 4 Correction Factor F Charts

2.2. Exergy Analysis

The exergy analysis defined as the maximum theoretical work obtainable from an overall system consisting of a system and the environment as system comes into equilibrium with the environment [6]. The exergy analysis method is well-matched

for furthering the objective of using more efficient energy sources, because it allows the location, cause and size of wastes to be recognized [3].
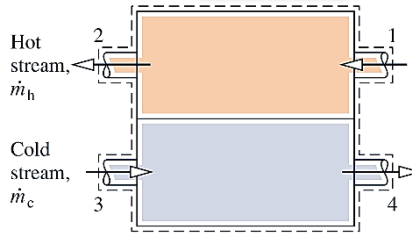
Figure 5 Heat exchanger system boundary

Regarding the hot stream as supplying the exergy increase of the cold stream as well as the exergy destroyed, we can write an exergetic heat exchanger efficiency as [6]:

$$\eta = \left(\frac{ef_3 - ef_2}{ef_1 - ef_4}\right) \qquad (10)$$

Where η is an exergetic heat exchanger efficiency, *ef* is the flow exergy between inlet and exit. The step to calculate an exergy heat exchanger efficiency as :

1. Exergy of exhaust steam

$$ef_1 = m_1(h_1 - h_0) - T_0(s_1 - s_0) \qquad (11)$$

2. Exergy of coolant inlet

$$ef_2 = m_2(h_2 - h_0) - T_0(s_2 - s_0) \qquad (12)$$

3. Exergy of coolant outlet

$$ef_3 = m_3(h_3 - h_0) - T_0(s_3 - s_0) \qquad (13)$$

4. Exergy of condensate outlet

$$ef_4 = m_4(h_4 - h_0) - T_0(s_4 - s_0) \qquad (14)$$

2.3. Data Analysis

The main objective of this reseacrh is to investigate the thermal performance analysis of condenser through heat transfer rate and exergy analysis of heat exchanger. The data was taken in five different days respectively at 1st to 5th September, 2023. The nominal operating parameters of a shell and tube condenser is shown in Table 1.

| Parameters Unit		The operating parameters of condenser				
		1	2	3	4	5
Input (*exhaust steam inlet*)						
Mass flow rate	(T/hr)	41.2	42.5	40.5	41.7	42.9
Temp.	(°C	45	46	53	54	48
Press.	(Mpa)	-0,09	-0,09	-0,09	-0,09	-0,09
Input (*coolant inlet*)						
Temp.	(°C)	25	26	25	25	26
Output (*condensate outlet*)						
Mass flow rate	(T/hr)	41.2	42.5	40.5	41.7	42.9
Temp.	(°C)	34.7	35.2	37.2	34.8	34.5
Output (*coolant oulet*)						
Temp.	(°C)	27.5	29.5	30.2	31.2	29.5

Table 1. The operating parameters of condenser

3. Result and Discussion

The exergy efficiency and heat transfer rate are shown in Table 2. The result shows that the highest efficiency has 78.3% and the highest heat transfer rate has 192.17 (kW)

Research Date	Exergy Efficiency (%)	Heat Transfer Rate (kW)
1	32	191.4
2	43.4	192.17
3	68	183.86
4	78.3	175.39
5	43	191.89

Table 2. The main result of exergy efficiency and heat transfer rate

The research is aimed to investigate performance of one of two identical condensers. The relationship of condenser exergy efficiency with the heat transfer rate is shown in Figure 6.
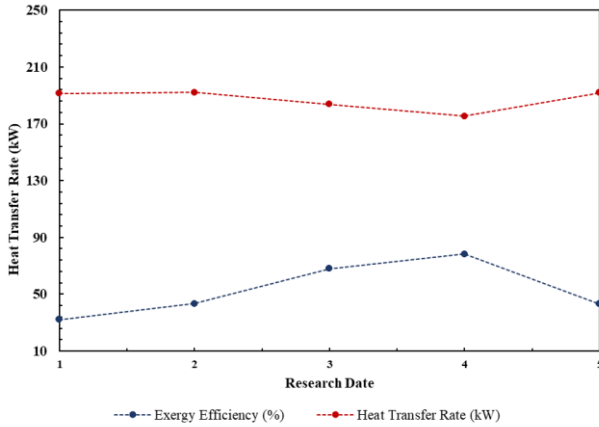

Figure 6 The relationship of condenser exergy efficiency and condenser heat transfer rate

The graph in Figure 6 shows fluctuating results, indicating that the lower heat transfer rates increase condenser exergy efficiency, with an average heat transfer rate of 186.94 kW and condenser exergy efficiency of 52.9 percent. The value of heat transfer rate is caused by heat rejection to the environment increases linearly with cooling water temperature, as the heat load of the condenser is directly proportional to temperature differences between the two mediums. Exergy destruction in the condenser is positively influenced by cooling water temperature incrementally and the irreversibility is reduced with cooling water enhancement. Heat rejection from the condenser is thermodynamically insignificant due to the heat source being close to the outside condition. Declining exergy destruction with increasing heat transfer indicates increased usable energy and cooling water temperature increases.

The analysis of fluid temperature can determine the effect of condenser exergy efficiency. The effect of variation temperature in the condenser and the exergy efficiency are shown in Figure 7.
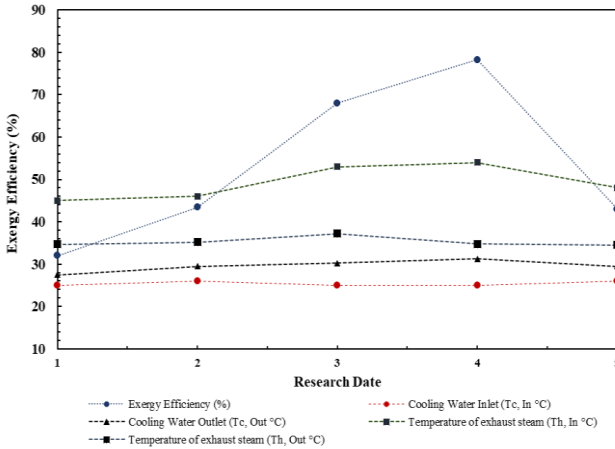
Figure 7 The effect of variation temperature in the condenser and the exergy efficiency

The condenser exergy efficiency calculation reveals a maximum of 78.3 percent with condenser operating conditions, including an exhaust steam temperature inlet and outlet of 54°C and 34.8°C respectively. The cooling water temperature inlet and outlet of 25°C and 31.2°C. The condenser is a crucial component in a turbine, responsible for extracting steam from low-pressure turbine exhaust and reducing turbine exhaust pressure to increase turbine output. It condenses the exhaust from the last stage, deaerator the accumulating condensate, and maintains a high vacuum.

The condenser is designed for condensation at the lowest possible pressure, near absolute vacuum, thereby increasing the turbine's thermal gradient. The cooling medium is cooling water from cooling tower and the tubes are kept clean to maintain heat transmission and prevent deposits of corrosive substances and mucous-producing bacteria. The condenser tubes are kept clean using cleaning balls from the tube cleaning system.

4. CONCLUSION

This study examines the impact of various factors on the performance of a thermal power station's condenser, including cooling water temperature, steam mass flow rate, heat transfer coefficient, condenser pressure, and heat transfer rate. The study highlights the influence of these parameters on the efficiency of the condenser, highlighting the importance of considering these factors in power plant performance.

The thermal assessment of steam condenser performance parameters is enhanced by increasing the cooling water temperature. The tubes were kept clean to maintain heat transmission and to get optimal work from the condenser. The change in steam flow rate does not significantly impact the performance of a condenser, but it directly impacts the energy destruction and heat load.

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