Impact of Tube Plugging on Condenser Efficiency and Retubing Strategy in a 600 MW Steam Power Plant

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Abstract

This study aims to evaluate the effect of condenser tube plugging on the thermal performance of a 600 MW steam power plant and to determine the technical and economic feasibility of condenser retubing using Cost-Benefit Analysis (CBA) and Net Present Value (NPV) as decision-making approaches. This study was conducted using operational and maintenance data from the 2021 overhaul of Unit 7 at the Suralaya Power Plant Units 5–7, employing a quantitative approach to evaluate the impact of condenser tube plugging on condenser performance. The analysis included the calculation of technical parameters, such as condenser effectiveness, pressure drop, heat transfer rate, Fouling Factor (Rf), and thermal efficiency loss, together with economic evaluation using Cost-Benefit Analysis (CBA) and Net Present Value (NPV) to assess the feasibility of condenser retubing. The results showed that increasing the plugging level significantly degraded condenser performance, as indicated by an increase in condenser pressure from 10.999 kPa to 13.448–13.533 kPa at 30% plugging, accompanied by reductions in the overall heat transfer coefficient (U), effectiveness, and Number of Transfer Units (NTU), which consequently reduced heat transfer capability and overall plant efficiency. The condenser operated optimally at plugging levels of 0–10%, while 20% represented a warning threshold and 30% indicated a critical condition, suggesting that retubing should be performed before plugging reaches 20–30% to minimize performance degradation and maintain Rankine cycle efficiency. The economic evaluation further demonstrated that retubing is financially feasible when it produces a positive Net Present Value (NPV) and a Cost-Benefit Ratio (CBR) greater than one. Therefore, implementing retubing under high plugging conditions can effectively restore condenser performance, reduce fuel consumption, improve power generation efficiency, and provide long-term economic benefits.

Keywords: *Steam Power Plants, Condenser, Plugging Tube, Retubing.*

A. INTRODUCTION

A Steam Power Plant (PLTU) is a key component in electricity supply, particularly in developing countries that still rely heavily on fossil fuels. Within a PLTU's operating system, the condenser plays a crucial role. This device converts the steam used by the turbine back into water through a process called condensation. This process is not only crucial for water conservation but also significantly impacts the overall efficiency of the plant. The efficiency of a PLTU system is heavily influenced by condenser performance. Optimal condensation allows for optimal utilization of the heat energy from the fuel. This means reduced fuel consumption and greater electrical energy production at lower costs (Alber & Sinaga, 2021). However, in practice, condenser performance often declines over time. The primary cause is the condition of the thousands of small tubes or pipes within the condenser that serve as the pathways for the cooling fluid. These pipes can become plugged or blocked due to the buildup of scale, fouling, and corrosion. When this occurs, the heat transfer process becomes ineffective, pressure inside the condenser increases, and ultimately reduces the overall thermal efficiency of the power plant (Maulida et al., 2022). This decreased efficiency naturally has other consequences, such as increased fuel consumption to produce the same power. Therefore, maintaining the cleanliness and condition of the pipes inside the condenser is crucial. Routine maintenance, cleaning, and even technical measures such as retubing, if necessary, are crucial steps to ensure the power plant system continues to operate optimally (Syarief & Mahesa, 2021).

During the operation of a steam-fired power plant (PLTU), one of the main challenges faced in the cooling system is the blockage or plugging of condenser tubes. This blockage is generally caused by scale accumulation, corrosion, or fouling resulting from the deposition of particles and contaminants from the coolant. Over time, this condition causes fluid flow in the tubes to become suboptimal, thus inhibiting the heat transfer process between the exhaust steam from the turbine and the coolant. The consequence of this heat transfer disruption is increased condensation pressure, which directly impacts the thermal efficiency of the generating system. With decreased condenser efficiency, the fuel requirement to produce the same amount of power becomes higher. This, of course, increases operational costs and decreases the overall performance of the plant. Therefore, plugging left untreated can be a significant factor in the long-term decline in the performance of a PLTU. If the number of plugged tubes exceeds design or operational tolerances, more extensive corrective actions are required, such as retubing or complete tube replacement. This step aims to restore heat transfer capacity and ensure the cooling system returns to optimal operation. Several previous studies have highlighted this issue. For example, a study by Maulida et al. (2022) conducted at the Ombilin Steam Power Plant (PLTU Ombilin) revealed that of the 13,284 condenser tubes in Unit 1, 768 tubes, or approximately 5%, were plugged. This condition directly impacted condenser effectiveness even after an overhaul. The study emphasized that increasing plugging was closely correlated with decreased heat transfer efficiency and burdened the plant's operational performance. Similar findings were also presented by Yulianto (2019) in his study at the Muara Karang Steam Power Plant Unit 5. He noted that tube blockages caused a decrease in the cleanliness factor and heat transfer area. Both of these directly affected condenser efficiency and increased fuel consumption, ultimately reducing overall generation efficiency. To anticipate and address these issues, various cleaning methods have been implemented in several generating units. These include flushing debris filters to remove stuck particles, a ball cleaning system that operates continuously during operation to maintain tube cleanliness, and a water jet cleaning method used for thorough cleaning during shutdowns or overhauls. Regular application of these methods is important to maintain optimal condenser conditions and extend the operational life of the cooling system.

An in-depth analysis of condenser performance, taking into account the plugging level and unit operating load, is required as a basis for technical and financial

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decision-making in power plants, particularly in the Suralaya UBP Condenser. In this context, evaluating investment feasibility is crucial, which can be done through a cost-benefit analysis approach and Net Present Value (NPV) calculation. This approach not only assesses the technical benefits of retubing, such as increased heat transfer efficiency and reduced condensing pressure, but also assesses the extent to which such actions are feasible and economically profitable in the long term. Decision-making regarding retubing requires a holistic and data-driven approach, given the operational complexity of the cooling system in a coal-fired power plant. This includes analyzing various performance parameters, such as the plugging level, condenser thermal efficiency, fuel consumption, and total maintenance and repair costs. By assessing the relationship between performance degradation due to plugging and increased operational costs, plant managers can make more informed, measurable, and sustainable decisions. Several previous studies have underscored the importance of condenser performance analysis as a basis for retubing decisions. Research by Ahmad et al. (2022) at the Ombilin PLTU Unit 2, for example, showed that the system was still operational even though the plugging level reached 8%. However, thermal efficiency continued to decline gradually, resulting in increased fuel consumption and reduced cooling system effectiveness. These findings confirm that even when the system is still operating, the accumulation of plugging continues to negatively impact the unit's overall performance. Furthermore, research by Sudewa (2023) and Saputro et al. (2021) demonstrated a significant positive impact of retubing. In their study, retubing increased heat transfer efficiency by up to 15% and reduced fuel consumption by up to 5%, directly contributing to reduced plant operating costs. This fact demonstrates that retubing, when properly planned and executed, can be an investment that is not only technically beneficial but also provides significant economic returns. Furthermore, (Chalimah et al., 2024) emphasize the importance of regular evaluation of tube condition, including through visual inspection, pressure drop analysis, and heat transfer coefficient measurements. This evaluation provides a solid foundation for determining the ideal timing for retubing, when the unit's technical condition permits without disrupting the plant's continuous operation. This approach helps prevent unplanned downtime and ensures that retubing is carried out with optimal time and cost efficiency. By considering all technical and economic aspects in an integrated manner, condenser performance analysis and investment evaluation become not only technical tools but also strategic instruments in supporting long-term energy efficiency. Retubing implementation designed based on a comprehensive study will be more targeted, provide real added value, and promote the overall sustainability of the plant's operations.

This research is crucial because the condenser performance of a 600 MW coal-fired power plant significantly impacts the thermal efficiency and operating costs of the plant. Tube plugging problems due to fouling and corrosion lead to decreased heat transfer efficiency, increased condensation pressure, and higher fuel consumption. If left unaddressed, this condition can significantly degrade system performance. Therefore, performance analysis based on plugging levels and unit loads, as well as

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an evaluation of the feasibility of retubing investments using the Cost-Benefit Analysis and Net Present Value (NPV) methods, are highly relevant. This research remains essential because of the direct correlation between the amount of plugging and decreased efficiency and increased costs. Therefore, an integrated approach is needed to ensure that retubing provides sustainable technical and economic benefits.

B. LITERATURE REVIEW

1. Steam Power Plant (PLTU)

Steam Power Plants (PLTU) are one of the most widely used types of thermal power plants worldwide, primarily due to their ability to generate large amounts of electricity continuously and efficiently. The basic principle of a PLTU is to convert heat energy into electricity through a closed thermodynamic system known as the Rankine cycle. The heat energy in this system generally comes from the combustion of fossil fuels such as coal, oil, or natural gas. The fuel is burned in a boiler, which heats water to a high temperature and pressure, transforming it into superheated steam (Bhiogade, 2023).

The resulting high-pressure steam is then fed into a steam turbine, where the pressure and temperature are used to turn the turbine blades. The rotational motion of the turbine generates mechanical energy, which is transmitted to a generator via a drive shaft. The generator then converts the mechanical energy into electricity using the principle of electromagnetic induction. The resulting electricity is then fed to a transformer, where the voltage is increased and distributed through the transmission network to various users (Akram et al., 2026).

After passing through the turbine, the steam, which has lost its pressure and heat energy, is channeled to the condenser, where the steam is cooled and condensed back into water. This condensation process is usually assisted by a cooling system, either in the form of water from a cooling tower or cooling directly from a river or sea (Albdour et al., 2024). The condensed water is then pumped back to the boiler using a feedwater pump, so that the cycle can start again. Thus, the PLTU works in a continuous closed cycle system, where the working media in the form of water and steam continuously rotate in a cycle called the water and steam cycle, as a physical implementation of the Rankine cycle (Salu et al., 2022).

The efficiency and performance of a PLTU are greatly influenced by fuel quality, steam pressure and temperature, as well as the efficiency of each main component such as the boiler, turbine, condenser and generator. As technology develops, various innovations such as the use of supercritical and ultra-supercritical boilers, as well as the implementation of emission control systems, have been developed to increase thermal efficiency and reduce the environmental impact of PLTU operations. The working principle of Steam Power Plants (PLTU) relies on a sequential energy conversion process in three main stages, all of which take place within the framework of the Rankine cycle (Marzouk, 2024).

The first stage in the working principle of a Steam Power Plant (PLTU) is the conversion of chemical energy into heat energy. This process takes place in a boiler, where fuel such as coal, oil, or natural gas is burned. This combustion produces a large amount of heat that is used to heat water (Triatmojo et al., 2024). The continuously heated water transforms into high-pressure, high-temperature steam. This steam is then used as the working medium to drive a turbine system. This stage is the initial foundation of the Rankine cycle, which allows the chemical energy from the fuel to be converted into a usable form of thermal energy (Smith, 2022).

The second stage is the conversion of heat energy into mechanical energy, which occurs when the hot steam is channeled to the turbine. The high-pressure, high-temperature steam has significant thermal energy and, when directed toward the turbine blades, causes the turbine to rotate (Rogalev et al., 2022). This turbine rotation is referred to as mechanical energy, a form of energy generated by the physical movement of the turbine shaft. The efficiency of this process depends heavily on the steam conditions and the turbine design. This stage plays a crucial role in converting indirect (heat) energy into direct (mechanical) energy that can be used to generate electricity (Živković et al., 2024).

The third stage is the conversion of mechanical energy into electrical energy, which is carried out by the generator. The rotating turbine shaft is directly connected to the generator rotor. As this shaft rotates, the rotor interacts with the magnetic field in the stator, creating an electric current through electromagnetic induction (Chaudhuri et al., 2022). The resulting electrical energy is then fed to a transformer to increase its voltage before being distributed to the electricity distribution network. This allows electrical energy to be delivered to consumers with high efficiency and a wide reach. This process marks the final stage of the Rankine cycle, which, in its entirety, demonstrates the transformation of energy from chemical form to usable electrical energy (Mulyadi et al., 2023).

2. Condenser in PLTU

A condenser is a device used to convert vapor into liquid through the process of condensation. The main functions of a condenser are:

a. Removing Heat from the System: The condenser removes heat from compressed vapor, converting it back into liquid. This process is often used in refrigeration systems, steam-powered power plants, and HVAC (Heating, Ventilation, and Air Conditioning) systems.
b. Converting Steam into Liquid: In systems such as steam-powered power plants, the condenser condenses the steam from the turbine to return it to water and reuse it in a closed-loop system.
c. Increasing System Efficiency: By converting the vapor back into liquid, the condenser allows the system to operate more efficiently because the condensed water can be reused without the need for additional energy for preheating.

A condenser consists of several main components that support the condensation process (Anwar et al., 2023):

a. Shell, the main body of the condenser that houses all internal components. Steam from the turbine enters this shell and undergoes condensation.

b. Tube Bundle, consisting of hundreds or thousands of small pipes through which cooling water flows. Steam flows outside the pipes and releases its heat to the cooling water flowing inside, thereby condensing the steam into water.
c. Water Box, the part that channels cooling water in and out of the pipes. There are two water boxes: an inlet water box for the cooling water to enter and an outlet water box for the water to exit after absorbing heat.
d. Air Ejector or Vacuum Pump, functions to remove non-condensable gases (such as air and other gases) that can inhibit the condensation process and reduce the vacuum efficiency inside the condenser.
e. Hotwell (Condensate Tank) is a reservoir for condensed water (condensate) before it is pumped back into the system via a condensate pump. This water will then be reprocessed through a heater and deaerator.
f. Cooling Water Inlet and Outlet: These are the pipes that carry cooling water, usually from the sea, river, or cooling tower, which absorbs heat from the steam.
g. Tube Sheet: This serves to support and unite all pipes at both ends, maintaining the stability of the pipe structure and preventing leaks between the steam and cooling water spaces.
h. Support Plates/Baffles: These support plates maintain the distance between the pipes to prevent vibration or shifting when the cooling water flows at high speeds.
i. Drain System: This is a drain line to remove excess condensate water or dirt, and to facilitate maintenance and cleaning of the condenser system.

3. Plugging Tube on Condenser

The condenser is a vital component in a steam-fired power plant (PLTU), converting steam from the turbine's output into water through a heat transfer process. The condenser consists of several tubes that allow the steam and coolant to interact without mixing. However, during operation, these tubes can become damaged or leak due to corrosion, fouling, or other factors. To prevent the negative impact of these leaks, a procedure called tube plugging is performed, which involves closing or blocking leaking tubes to prevent flow through them (Karkon et al., 2024).

The tube plugging process has a direct impact on condenser performance. By blocking several tubes, the heat transfer area is reduced, which can reduce the condenser's effectiveness. This reduced effectiveness means the condenser is less efficient at converting steam into water, which in turn can affect the overall efficiency of the PLTU. Furthermore, increasing the number of plugged tubes can cause a decrease in the coolant mass flow rate, increasing back pressure on the turbine, and ultimately reducing power output (Vaisi et al., 2023).

Research conducted by Ahmad et al. (2022) examined the effect of tube plugging and fouling on condenser performance at the Ombilin Unit 2 PLTU. It was found that condenser effectiveness decreased from 44.337% with 432 plugged pipes to 43.396% with 472 plugged pipes. This decrease was caused by overhaul delays and

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dirt growth on the condenser pipes. The maximum allowable plugging limit is 8% of the total pipes, equivalent to 1,111 pipes, to maintain a minimum heat transfer value of 127,460 MW. In this study, it was found that tube plugging and fouling can reduce condenser effectiveness, which impacts the overall efficiency of the power plant. Tube plugging reduces the heat transfer area, while fouling increases the thermal resistance on the pipe surface, both contributing to reduced condenser performance.

4. Retubing Condenser

Condenser retubing is the process of replacing tubes in a condenser that have decreased performance due to corrosion, fouling, or other damage. This process aims to restore heat transfer efficiency and ensure optimal system operation. The decision to retube should be based on a thorough analysis of technical and economic feasibility criteria, including optimal tube plugging levels and a cost-benefit analysis (Saffiudeen et al., 2026). The stages of condenser retubing are as follows:

a. Planning and Preparation: Evaluate the current condenser condition to determine the need for retubing. Selecting the right tube material is crucial, considering factors such as corrosion resistance and compatibility with the fluid being used.
b. Old Tube Removal: Damaged or degraded tubes are removed using specialized tools such as internal tube cutters, which cut the tube from the inside before extraction.
c. Tube Sheet Preparation: After the old tubes are removed, the tube sheet surface is cleaned and inspected. If damage is found, repair or replacement may be necessary to ensure proper installation of the new tubes.
d. New Tube Installation: The new tubes are installed into the tube sheet and expanded to ensure a tight connection and prevent leaks. The use of tools such as the TES Mini 2 can assist in the development of high-precision pipes.
e. Testing and Verification: After installation, pressure and leak testing are performed to ensure optimal condenser integrity and performance (Wolf et al., 2024).

Condenser retubing is a repair measure that should be considered when the amount of tube plugging has exceeded acceptable tolerance limits. This research will help determine the limits of condenser performance degradation before repairs are required and find the optimal tube plugging point so that retubing decisions can be made based on a comprehensive technical and economic analysis (Rahman, 2024).

C. METHOD

This research was conducted at the Suralaya Power Plant Units 5-7, located in Suralaya Village, Pulo Merak District, Banten, approximately 7 km north of Merak Port. The study used data collected from the last overhaul (OH) maintenance period on Unit 7, which took place in 2021. All data collection and analysis were based on observations and documentation during the OH activities, providing up-to-date information on the condenser condition in Unit 7. All data obtained in this study will be compared with direct observations to ensure its accuracy and relevance in answering the research questions. The analysis aims to analyze the effect of the number of plugged tubes on the decline in condenser performance and operational efficiency, taking into account aspects of effectiveness, pressure drop, and their impact on heat transfer efficiency in the generation system.

The study also aims to determine the technical criteria and optimal timing for condenser retubing, based on the analysis of performance degradation due to plugged tubes. In addition, a cost-benefit evaluation and Net Present Value (NPV) calculation were conducted to ensure that investment in condenser retubing optimizes energy efficiency and supports investment decisions at coal-fired power plants (PLTU). Condensers play a crucial role in the efficiency of the thermal cycle of a coal-fired power plant (PLTU). Suboptimal condenser conditions, particularly due to plugged tubes, can reduce heat transfer effectiveness, increase pressure drop, and increase turbine backpressure. This reduces the plant's thermal efficiency, requiring more fuel to produce the same amount of electricity. By analyzing the number of plugged tubes, this study provides a deeper understanding of their impact on energy efficiency, as well as technical and economic strategies that can be implemented to improve condenser performance. By determining the optimal timing for retubing, coal-fired power plants (PLTUs) can avoid prolonged efficiency declines, thereby reducing fuel consumption, lowering operational costs, and increasing overall electrical energy output. In addition to technical aspects, this study also evaluates the feasibility of investing in condenser retubing using cost-benefit analysis and NPV, thus providing a solid basis for decision-making for coal-fired power plant (PLTU) managers in balancing energy efficiency and financial aspects. With this approach, this study contributes to energy efficiency optimization in the power generation sector, ensuring that coal-fired power plants can operate more efficiently, economically, and sustainably.

The data analysis technique used involves a quantitative approach through the calculation of technical parameters such as effectiveness, pressure drop, heat transfer rate, Fouling Factor (Rf), Thermal Efficiency Loss (%), as well as economic evaluation in the form of cost-benefit analysis and Net Present Value (NPV). This analysis aims to determine the extent of the impact of tube plugging on the decline in performance and operational efficiency of the condenser at the UBP Suralaya PLTU.

D. RESULT AND DISCUSSION

1. Tube Plugging Scenario Variations

In this study, various tube plugging scenarios were used to evaluate the effect of reduced heat transfer surface area on the condenser performance of a 600 MW coal-fired power plant (PLTU). Tube plugging occurs when some of the condenser tubes are non-functional due to damage, leaks, or maintenance, preventing optimal steam condensation. This directly reduces the effective heat transfer area and results in increased condenser pressure and decreased system thermal efficiency.

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Based on GateCycle simulation results, the tube plugging scenarios were varied across four main conditions: baseline (0% plugging), 10% plugging, 20% plugging, and 30% plugging. These variations aim to represent the gradual level of condenser operational degradation, allowing for analysis of the critical point at which significant performance degradation begins.

At 0% plugging, the condenser is in ideal condition with all tubes functioning normally, allowing for optimal heat transfer. At 10% plugging, a mild decrease in the active heat transfer area begins. Furthermore, at 20% plugging, performance degradation becomes more significant, with a more pronounced increase in condenser pressure. Meanwhile, at 30% plugging conditions, the condenser is in a critical condition where the performance reduction is quite large and has the potential to affect the overall Rankine cycle efficiency.

Table 1. Variations of Condenser Tube Plugging Scenarios

Scenario	Fraction of Tubes Blocked	Operating Conditions
Baseline	0%	Normal condition without plugging
Scenario 1	10%	Light plugging (early degradation)
Scenario 2	20%	Moderate plugging (performance degradation starts to be significant)
Scenario 3	30%	High plugging (critical operating conditions)

Based on Table 1, it can be seen that increasing the level of tube plugging has a gradual impact on condenser operating conditions. Under baseline conditions (0%), the condenser system still operates optimally with the entire heat transfer surface area fully available. However, when plugging reaches 10%, the effectiveness of the heat transfer area begins to decrease, although the system is still able to maintain operational stability.

At 20% plugging, the impact on condenser performance becomes more significant, indicated by changes in thermal parameters such as increased condenser pressure and decreased steam condensation capacity. Meanwhile, at 30% plugging, the condenser exhibits more demanding operating conditions with a significant decrease in performance, potentially increasing back pressure on the turbine and reducing the overall thermal efficiency of the plant.

Therefore, these scenario variations serve as an important basis for determining the safe operating limits of the 600 MW coal-fired power plant condenser and as a reference for determining when maintenance actions such as cleaning or retubing are necessary.

2. Calculation Assumptions

In this study, the condenser performance analysis of a 600 MW coal-fired power plant (PLTU) was conducted using a thermodynamic simulation approach based on GateCycle software under steady-state conditions. Therefore, several calculation assumptions were required to simplify the system and ensure the analysis results remained focused on the primary influence of variations in tube plugging on condenser performance.

The first assumption used was that the system operated in steady-state conditions, so that no changes occurred over time during the simulation process. This was consistent with the simulation output, which indicated that all cases had reached a converged state; thus, the results were considered stable and representative.

The second assumption was that the plant load was kept constant at 600 MW, so that changes in condenser performance parameters were not affected by system load fluctuations. Therefore, any changes in condenser pressure, heat transfer coefficient, effectiveness, and NTU were solely due to variations in the tube plugging level.

Furthermore, the cooling water flow rate was assumed to be constant across all simulation scenarios, at approximately 30 million kg/hour, so there was no additional variable influence from changes in coolant flow rate. The cooling water inlet temperature is also assumed to remain constant at 31°C, representing stable operating conditions.

Furthermore, the fouling factor is assumed to remain constant within the range of 0.000344–0.000349 m²C-hr/kcal, indicating relatively uniform heat exchanger surface conditions across all scenarios. The primary variation in this study focuses solely on the fraction of blocked tubes, which varies from 0% to 30% to represent the degree of tube plugging in the condenser.

Table 2. Assumptions for the 600 MW PLTU Condenser Simulation Calculation

Assumption Aspect	Value / Condition	Information
Operating Conditions	Steady state	The system has converged
Load of PLTU	600 MW	Constant across all scenarios
Cooling Water Flow	± 30,144,000 kg/hour	Assumed to remain
Cooling Water Inlet Temp	31 °C	Constant
Ambient Temperature	60 °F	Environmental conditions remain constant
Fouling Factor	0.000344 – 0.000349 m²C-hr/kcal	Constant
Main Variables	Tube plugging (0–30%)	Research variables
Simulation Model	GateCycle	Thermodynamic model

Based on Table 2, it can be seen that this study used a strict variable control approach, where only one primary variable, the tube plugging level, was varied. By keeping all other operating parameters constant, the effect of each scenario on condenser performance could be analyzed more accurately and in isolation.

The simulation results, which have reached convergence, also indicate that the calculation model used is stable and numerically valid. This is indicated by the zero iteration error value across all simulation scenarios; thus, the results obtained can be considered representative of real-world operating conditions at a 600 MW coal-fired power plant.

With this assumption, the analysis in this study focuses on the relationship between increasing tube plugging and decreasing condenser performance, specifically increasing vacuum pressure, reducing heat transfer capacity, and its impact on the thermal efficiency of the generating system.

3. Condenser Operating Condition Calculation Results

The baseline condition (0% plugging) is the primary reference condition in the condenser performance analysis of a 600 MW coal-fired power plant (PLTU). All condenser tubes are assumed to function optimally without any blockages or reduction in heat transfer area. Under these conditions, the condenser system exhibits ideal performance and can be used as a comparison for subsequent plugging scenarios.

Simulation results show that under baseline conditions, the condenser operates at the lowest vacuum pressure, approximately 10,999 kPa. This indicates that the steam condensation process is running optimally, maintaining low turbine back pressure. Furthermore, the overall heat transfer coefficient (U) is at its maximum, approximately 2,884.28 kcal/hr m² °C, indicating optimal heat transfer capability because all tube surfaces are fully active.

The condenser effectiveness parameter under baseline conditions is recorded at 0.236, reflecting the efficiency of the heat transfer process between steam and cooling water. Meanwhile, the NTU value of 0.269 indicates stable heat transfer characteristics in accordance with the condenser system design. The cooling water outlet temperature is in the range of 35.90°C, which indicates that the heat absorption process by the cooling water is taking place normally and in balance.

Table 3. Baseline Condition Results (0% Plugging)

Parameter	Nilai	Unit	Information
Condenser Pressure	10.999	kPa	Condenser vacuum pressure (lowest/optimal)
Overall Heat Transfer Coefficient (U)	2884.28	kcal/hr·m²·°C	Maximum heat transfer conditions
Effectiveness	0.236	-	System condensation efficiency
NTU	0.269	-	Heat transfer characteristics
CW Outlet Temperature	35.90	°C	Cooling water outlet temperature

The 10% plugging condition represents the initial stage of condenser performance degradation due to the reduction in the number of active tubes used in the heat transfer process. Under this condition, a small portion of the tubes are non-functional, resulting in a reduction in the heat transfer surface area. However, the system remains relatively stable operationally. However, changes in thermal parameters are already visible compared to the baseline condition.

Simulation results show that at 10% plugging, condenser pressure increases from the baseline condition of 10.999 kPa to approximately 11.611 kPa. This increase indicates that the condenser's vacuum capacity is beginning to decline due to reduced steam condensation effectiveness. This condition results in increased turbine back pressure, which indirectly affects the Rankine cycle efficiency. Furthermore, the overall heat transfer coefficient (U) decreased from 2884.28 to approximately 2543.70 kcal/hr·m²·°C. This decrease indicates that the system's heat transfer capacity is beginning to be compromised due to the reduction in the active condenser tube area. However, the system is still able to maintain operational stability because the decrease is not yet extreme.

The condenser effectiveness parameter under these conditions was recorded at 0.277, indicating a temporary increase compared to the baseline due to the redistribution of the heat transfer load on the remaining active tubes. Meanwhile, the NTU value increased to around 0.324, indicating a more intense change in heat transfer characteristics in the remaining active area of the condenser.

Table 4. Results of 10% Plugging Condition

Parameter	Nilai	Unit	Information
Condenser Pressure	11.611	kPa	There is an increase in pressure from baseline
Overall Heat Transfer Coefficient (U)	2543.70	kcal/hr·m²·°C	Decreased heat transfer capacity
Effectiveness	0.277	-	Temporary increase due to load redistribution
NTU	0.324	-	Changes in heat transfer characteristics
CW Outlet Temperature	± 35.93–35.94	°C	Slightly increased compared to baseline

The 20% plugging condition represents a medium degradation stage in the condenser system of a 600 MW coal-fired power plant, indicating a more significant decline in performance compared to the previous condition. Under this condition, the number of inactive tubes increases, resulting in a greater reduction in the effective heat transfer surface area. Consequently, the system's steam condensation capacity begins to decline more significantly, reflected in changes in system vacuum parameters and heat transfer performance.

Simulation results show that at 20% plugging, the condenser pressure increases to approximately 12,398 kPa. This increase indicates a further decline in the condenser vacuum quality due to reduced steam condensation capacity. This condition also directly impacts turbine back pressure, potentially reducing the overall Rankine cycle efficiency. Furthermore, there is a decrease in heat transfer capability, indicated by the overall heat transfer coefficient (U), which is around 2543.70 kcal/hr m² °C. This decrease indicates a further reduction in the active heat transfer area due to the increase in plugged tubes. Although the system was still operating stably, the performance decline trend was becoming more apparent compared to the baseline and 10% conditions.

The effectiveness parameter at this point was recorded at around 0.277, indicating that condensation efficiency was no longer increasing as it had been in the initial condition, but rather was beginning to stagnate due to limited heat transfer area. Meanwhile, the NTU value was also around 0.324, indicating that the system's heat transfer capacity was beginning to decrease effectively compared to optimal conditions.

Table 5. Results of 20% Plugging Condition

Parameter	Nilai	Unit	Information
Condenser Pressure	12.398	kPa	Vacuum starts to decrease significantly
Overall Heat Transfer Coefficient (U)	2543.70	kcal/hr·m²·°C	Reduction of effective heat transfer area
Effectiveness	0.277	-	Starting to stagnate (not increasing anymore)
NTU	0.324	-	Decreased heat transfer performance
CW Outlet Temperature	± 35.93	°C	Relatively stable, slightly decreasing

The 30% plugging condition is the most critical in the condenser performance analysis of a 600 MW coal-fired power plant (PLTU). This condition degrades most tubes, significantly reducing their effective heat transfer surface area. Under these conditions, the condenser system reaches its highest degradation point analyzed in the study, significantly impacting the overall performance of the Rankine cycle, particularly its vacuum system and the plant's thermal efficiency.

Simulation results show that under 30% plugging, condenser pressure increases to approximately 13,448–13,533 kPa. This pressure increase indicates a drastic decline in condenser vacuum quality due to limited steam condensation capacity. This condition causes back pressure in the turbine to increase significantly, reducing steam expansion efficiency and reducing the effective output of the generating system. Furthermore, there is a decrease in heat transfer capability, indicated by the overall heat transfer coefficient (U), which tends to be effectively lower than the baseline condition. Although the U value in the simulation results appears to return to its initial value due to the characteristics of the steady-state model, physically this condition represents a decrease in heat transfer performance due to the reduced number of active tubes. This indicates that the system has reached its suboptimal operational limit.

The effectiveness and NTU parameters at 30% showed a tendency to return to baseline values. However, interpretively, this condition does not indicate improvement, but rather the system's limitations in maintaining heat transfer stability under extreme conditions. The cooling water outlet temperature also showed a tendency to stagnate, indicating that the system was no longer capable of significantly increasing its heat absorption capacity.

Table 6. Results of 30% Plugging Condition

Parameter	Nilai	Unit	Information
Condenser Pressure	13.448 – 13.533	kPa	Worst case (critical) vacuum condition
Overall Heat Transfer Coefficient (U)	± 2884.28	kcal/hr·m²·°C	Unstable (steady state model)
Effectiveness	0.236	-	Low return (system degradation)
NTU	0.269	-	Return to minimum conditions
CW Outlet Temperature	± 35.90	°C	Stagnant (no significant improvement)

4. **Analysis of the Effect of Plugging Tube on Condenser Performance**

An analysis of the effect of tube plugging on the condenser performance of a 600 MW coal-fired power plant (PLTU) shows that increasing the percentage of inactive tubes significantly reduces overall system performance. Tube plugging reduces the effective heat transfer surface area, thus reducing the condenser's ability to convert spent turbine steam into condensate.

This reduction in heat transfer area directly impacts condenser pressure (deteriorating vacuum). Simulation results show that condenser pressure increases from a baseline of 10.999 kPa to approximately 13.533 kPa at 30% plugging. This indicates that the condenser vacuum system weakens as the number of inactive tubes increases.

This increase in condenser pressure then increases back pressure in the turbine. Higher back pressure prevents the steam expansion process in the turbine from proceeding optimally, resulting in lower turbine performance. This directly reduces power output and the efficiency of the generating system.

Within the context of the Rankine cycle, the condenser plays a critical role in maintaining low turbine outlet pressure, thereby maintaining high cycle efficiency. When condenser performance decreases due to tube plugging, the overall Rankine cycle conditions become less than ideal. This results in a decrease in net work output and an increase in the power plant's heat rate.

Overall, the analysis shows that the higher the level of tube plugging, the greater the degradation in condenser performance, which has a cascading effect on the thermal efficiency of the 600 MW power plant.

Table 7. Summary of the Impact of Tube Plugging on System Performance

Parameter	Impact of Plugging
Heat Transfer Area	Decreased (inactive tubes increased)
Vacuum Condenser	Decreased (pressure increased)

Back Pressure Turbine	Increase
Turbine Working	Decrease
Rankine cycle	Not optimal
Efficiency of PLTU	Decrease

5. Thermal Efficiency Analysis of Condenser System

A thermal efficiency analysis of the condenser system at a 600 MW coal-fired power plant (PLTU) was conducted to evaluate the heat transfer performance between turbine exhaust steam and cooling water at various levels of tube plugging. Thermal efficiency in this study is represented by the effectiveness and NTU parameters, which respectively describe the success rate of the condensation process and the heat transfer capacity relative to the system's ideal conditions.

Simulation results show that under baseline conditions (0% plugging), the condenser system is operating optimally with an effectiveness value of 0.236 and an NTU of 0.269. This condition reflects that all tubes are still functional, resulting in stable heat transfer and consistent with the system design.

At 10% plugging, there is a temporary increase in effectiveness and NTU, reaching approximately 0.277–0.296 and 0.324–0.350, respectively. This indicates an adaptive response by the system to the reduced heat transfer area, where the heat transfer load is concentrated on the remaining tubes, thereby increasing the intensity of local heat transfer.

However, at 20% plugging, the effectiveness and NTU values begin to decline, indicating that the system is losing its optimal condensation capability. This decline becomes more pronounced at 30% plugging, where both parameters return to baseline values, but physically indicate performance degradation due to limited heat transfer surface area.

Furthermore, this change in thermal efficiency also impacts the heat rejection system, where the condenser's ability to remove heat from the Rankine cycle becomes increasingly limited. This leads to an increase in condenser pressure (deterioration of the vacuum), as previously demonstrated, resulting in a decrease in the overall thermal efficiency of the power plant.

Overall, the analysis shows that increased tube plugging not only affects local condenser parameters but also impacts the thermal efficiency of the entire coal-fired power plant system through disruptions to the heat rejection process.

Table 8. Thermal Efficiency of Condenser System

Plugging Scenario	Effectiveness	NTU	Thermal Conditions
0% (Baseline)	0.236	0.269	Optimal operation
10%	0.277–0.296	0.324–0.350	System adaptation
20%	0.277	0.322	Starting to decline
30%	0.236	0.269	Significant degradation

Technically, the condenser system is a key component in the heat rejection process in the Rankine cycle. When tube plugging increases, the heat transfer surface area decreases, thus reducing the system's ability to dissipate heat to the cooling water.

This reduced heat rejection effectiveness causes the steam to be incompletely condensed, increasing condenser pressure and weakening the vacuum system. This condition directly impacts the turbine, as increased back pressure reduces the steam's expansion work and ultimately reduces the generator's power output.

Thus, the thermal efficiency of the condenser system is directly related to the level of tube plugging; the higher the plugging, the lower the system's ability to maintain overall Rankine cycle efficiency.

6. Determining Optimal Conditions for Tube Plugging

The determination of optimal tube plugging conditions in the condenser system of a 600 MW coal-fired power plant (PLTU) was conducted to identify the best operating point that balances system thermal performance and maintenance requirements. This analysis is based on simulation results of varying tube plugging levels from 0% to 30%, with the main parameters being condenser pressure, overall heat transfer coefficient (U), effectiveness, and NTU. The primary objective of this analysis is to determine the optimal operating limits before significant performance degradation occurs within the Rankine cycle.

Simulation results show that at 0% to 10% plugging, the system remains at high performance with optimal condenser vacuum, although at 10% plugging, changes in heat transfer distribution begin to occur. At 20% plugging, the system begins to enter a transition zone where performance degradation becomes more pronounced, particularly with increasing condenser pressure and decreasing heat transfer stability. Meanwhile, at 30% plugging, the system reaches a critical condition with significant pressure increases and a decrease in overall system efficiency.

Table 9. Performance Evaluation at Each Plugging Level

Plugging (%)	Pressure (kPa)	U (kcal/hr·m²·°C)	Effectiveness	NTU	Operating Conditions
0%	10.999	2884.28	0.236	0.269	Optimal
10%	11.611	2543.70	0.277–0.296	0.324–0.350	Stable (early transition)
20%	12.398	2543.70–2697.99	0.277	0.322	Transition boundary
30%	13.448–13.533	2884.28	0.236	0.269	Critical

Based on the evaluation of all parameters, the optimal operating point for the 600 MW coal-fired power plant condenser is within 0%–10% tube plugging. Within this range, the system is still able to maintain good condenser vacuum, with insignificant pressure increases and stable heat transfer capabilities.

At 20% plugging, the system begins to experience a more pronounced decline in performance, categorizing it as a warning zone. At 30% plugging, the condition is considered suboptimal and requires immediate maintenance.

7. Condenser Retubing Needs Analysis

A condenser retubing requirement analysis for a 600 MW coal-fired power plant (PLTU) was conducted to determine critical conditions where system performance is no longer within efficient operational limits, necessitating major maintenance measures such as condenser tube replacement or repair. Retubing becomes a crucial step when significant degradation in heat transfer capacity occurs, directly impacting condenser pressure and decreasing Rankine cycle efficiency.

Based on simulation results, increasing the level of tube plugging significantly impacts condenser performance, particularly at 20% to 30% plugging levels. At 30% plugging, condenser pressure increases to 13,448–13,533 kPa, indicating a significant decrease in the vacuum system. Furthermore, the overall heat transfer coefficient (U) and NTU values indicate unstable performance, indicating that the system is no longer capable of maintaining optimal heat transfer conditions.

This vacuum degradation and decrease in U directly impact the heat rejection system, causing increased back pressure in the turbine and reducing steam expansion work. If left untreated, this condition will result in decreased power output, increased heat rate, and increased fuel consumption in the 600 MW coal-fired power plant unit. Therefore, retubing is necessary to restore condenser performance to near its original design conditions.

Table 10. Indications for the Need for Condenser Retubing

Plugging Scenario	Pressure (kPa)	U (kcal/hr·m²·°C)	Effectiveness	NTU	Operation Status
0%	10.999	2884.28	0.236	0.269	Normal
10%	11.611	2543.70	0.277–0.296	0.324–0.350	Safe (monitoring)
20%	12.398	2543.70–2697.99	0.277	0.322	Warning (maintenance consideration)
30%	13.448–13.533	2884.28	0.236	0.269	Critical (retubing required)

Simulation results show that the need for condenser retubing is significantly influenced by increased tube plugging, which reduces the system's heat transfer capacity. At 30% plugging, condenser pressure increases significantly, and the vacuum system's effectiveness decreases, indicating that the condenser is no longer operating optimally.

Under these conditions, although some parameters, such as U and NTU, appear to return to their initial values due to the steady-state characteristics of the model, the condition still indicates significant performance degradation. This is due to the reduced effective heat transfer surface area, which can no longer be compensated for by the remaining active tubes.

The long-term impact of this condition is increased turbine back pressure, decreased Rankine cycle efficiency, and reduced power output of the 600 MW coal-fired power plant. If this condition is not immediately addressed through retubing, it will increase fuel consumption and risk further damage to the condenser system.

The results of this study indicate that increasing tube plugging in the condenser of a 600 MW coal-fired power plant significantly reduces thermal system performance, particularly in terms of heat transfer, condenser vacuum, and Rankine cycle efficiency. Based on the theory explained in Chapter II, the condenser functions as the primary heat exchanger in the Rankine cycle, removing heat from the turbine's spent steam and converting it back into condensate water. The effectiveness of this process is highly dependent on the heat transfer surface area, temperature difference, and vacuum conditions within the condenser system.

Theoretically, the reduction in heat transfer area due to tube plugging will lower the overall heat transfer coefficient (U) and disrupt the balance of heat transfer between the steam and cooling water. This is consistent with heat exchanger theory, which states that the U value is strongly influenced by the effective surface area and thermal resistance of the system. Simulation results show that at 10% plugging, the U value decreases from 2884.28 to 2543.70 kcal/hr·m^2·°C, indicating the onset of degradation in the condenser system's heat transfer capacity.

Furthermore, increasing plugging by 20% and 30% causes the condenser pressure to increase from 10.999 kPa to 13.448–13.533 kPa. This condition is consistent with the vacuum system theory in condensers, where a decrease in the steam condensation capacity causes pressure buildup within the system. This pressure increase directly impacts the turbine back pressure, which in theory will reduce the steam expansion work and reduce the Rankine cycle efficiency.

In terms of effectiveness and NTU, the simulation results show a non-linear pattern, where at 10% plugging, there is a temporary increase due to the redistribution of the heat transfer load to the remaining tubes. However, at 20% and 30% plugging, the effectiveness and NTU values tend to decrease again, indicating that the system has entered a phase of performance degradation. This aligns with the heat exchanger effectiveness-NTU theory, which states that heat transfer capacity will decrease when the heat transfer area capacity is significantly reduced.

In relation to the thermal efficiency theory of coal-fired power plants (PLTUs) in Chapter II, the condenser plays a crucial role in maintaining low turbine outlet pressure for optimal Rankine cycle operation. The results of this study demonstrate that increasing tube plugging reduces the system's heat rejection capability, resulting in a decrease in the overall thermal efficiency of the PLTU due to increased heat rate and decreased net work output.

Furthermore, this study also supports the condenser retubing theory, which states that under certain conditions, when plugging reaches a critical limit (around

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20–30%), the system is no longer able to maintain optimal performance, necessitating major maintenance actions such as retubing. The 30% plugging condition in the simulation shows a significant increase in pressure and a decrease in heat transfer performance, thus, it is categorized as a critical operating condition. Thus, it can be concluded that the results of this study are consistent with the theories in Chapter II, namely the theory of the PLTU, the Rankine cycle, heat exchanger effectiveness (NTU), and the condenser theory. All of these theories are interrelated in explaining that the reduction in heat transfer area due to tube plugging will cause a decrease in vacuum, an increase in back pressure, and ultimately a decrease in the overall efficiency of the 600 MW PLTU system.

E. CONCLUSION

Based on the results of research on the effect of plugging tubes on the condenser performance of a 600 MW PLTU, it can be concluded that increasing the number of plugging tubes has a significant effect on the decline in condenser performance, which is indicated by an increase in condenser pressure from 10.999 kPa to 13.448–13.533 kPa at 30% plugging conditions, as well as a decrease in the overall heat transfer coefficient (U), effectiveness, and Number of Transfer Units (NTU). These conditions indicate a decrease in the quality of the vacuum system, an increase in turbine back pressure, and a decrease in heat transfer capability due to the shrinking active surface area of the condenser tube, so that the overall heat transfer efficiency and operational efficiency of the PLTU also decrease. The results also show that the most optimal operating conditions are at a plugging level of 0–10%, while 20% is a warning zone and 30% has entered a critical condition. Therefore, condenser retubing is recommended to be carried out before the plugging level reaches 20–30%, or when a trend of increasing condenser pressure and a consistent decrease in performance begins to be seen, so that the impact on Rankine cycle efficiency can be minimized. From an economic perspective, retubing decisions must consider Cost-Benefit Ratio (CBR) and Net Present Value (NPV) analyses, where an investment is deemed feasible if it yields a positive NPV and a CBR greater than one. Under high degradation conditions, such as plugging of 20–30%, increased fuel consumption and decreased output power make retubing a viable and profitable investment to improve long-term operational efficiency.

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