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Performance Evaluation of a Condenser at a Combined Cycle Power Plant Using the LMTD Method

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Abstract

This study evaluates the performance of the condenser at the Cilegon Combined Cycle Power Plant (CCPP) using the Logarithmic Mean Temperature Difference (LMTD) method to measure the heat transfer rate. Routine maintenance carried out on the condenser in the form of cleaning the condenser water box and condenser tube from garbage and crust on the condenser tube wall. Currently, condenser maintenance follows a routine schedule that is tied to steam turbine maintenance, without taking actual condenser performance into account. This can lead to inefficiencies and unnecessary downtime. The goal of this research is to assess the heat transfer rate of the condenser before and after maintenance to judge its effectiveness. Data on temperature changes were gathered in June 2023, before maintenance, and again in July 2023, after an overhaul. The analysis shows that the heat transfer rate increased from 51,362,294.48 kcal/h to 127,246,219.7 kcal/h, while the LMTD value rose from 0.76°C to 1.86°C. Based on these results, the study suggests a new approach to maintenance that focuses on performance. Specifically, maintenance should be done when the heat transfer rate drops below 110,000,000 kcal/h. This approach will help ensure the condenser works at its best, improve the plant's overall efficiency, and prevent the need for unnecessary maintenance. By aligning maintenance with performance data, the plant can boost output while lowering costs and downtime.

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1. Introduction

In the modern era of globalization, the industrial sector has expanded rapidly, leading to a substantial increase in electricity demand. Electricity has become essential for both household and industrial needs. To meet this growing demand, various power plants, including combined cycle power plants (CCPPs), have been developed. In Indonesia, the Cilegon combined cycle power plant is a notable example, featuring two gas turbines (GT 1.1 and GT 1.2) with a capacity of 240 MW each, along with a single steam turbine of 260 MW capacity. A critical component of the steam turbine system is the condenser, a heat exchanger that converts steam output from the turbine into feedwater, which is then recycled to produce steam.

Like other heat exchangers, the condenser requires regular maintenance to ensure optimal performance [1]. In CCPPs, the heat transfer rate within the condenser is a key factor that influences the overall efficiency of the system, as shown in Figure 1. The Logarithmic Mean Temperature Difference (LMTD) method is commonly used to analyze heat exchangers, including condensers, as it effectively calculates heat transfer rates by accounting for the varying temperature differences between hot and cold fluids throughout the heat exchanger.

At the Cilegon CCPP, routine maintenance of the condenser includes patrol inspections and annual cleaning of the condenser water box and tubes to remove debris and scale that accumulate on the tube walls. This buildup, often caused by seawater, can reduce the efficiency of heat transfer if left unchecked. However, the maintenance schedule is typically aligned with steam turbine maintenance cycles, without considering actual condenser performance [2]. As a result, maintenance may be performed ineffectively. The temperature difference between the cooling water entering and exiting the condenser, along with the hot fluid from the turbine, can be calculated using the LMTD method, allowing for a precise determination of the condenser's heat transfer rate [3]. To improve

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maintenance strategies, the heat transfer rate should be analyzed before and after maintenance, ensuring it is carried out when performance begins to decline.

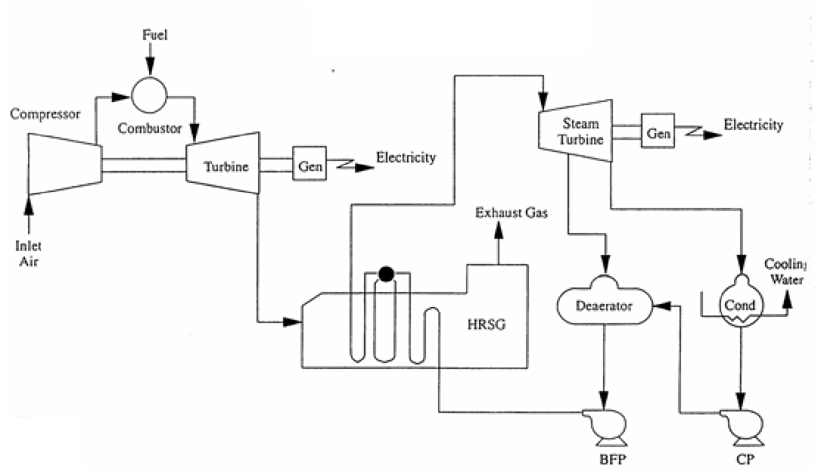

Figure 1. Schematic diagrams combined cycle power plant

The LMTD method is particularly relevant in the context of CCPPs, where the heat recovery steam generator (HRSG) plays a pivotal role in utilizing the exhaust heat from gas turbines to generate steam for the steam turbine cycle. The efficiency of this process is significantly affected by the temperature differences involved in the heat exchange process. highlight that modern CCPPs can achieve efficiencies exceeding 60% due to the effective recovery of exhaust heat, which underscores the importance of optimizing heat transfer in the condenser section of the HRSG [4].

The LMTD method is especially relevant in CCPPs due to the role of the heat recovery steam generator (HRSG) in converting exhaust heat from gas turbines into steam for the steam cycle. The efficiency of this process is highly dependent on the temperature gradients during heat exchange. In fact, modern CCPPs can achieve efficiencies of over 60% due to the effective recovery of exhaust heat, which underscores the importance of optimizing heat transfer in the condenser section of the HRSG [5].

However, while the LMTD method is widely used, its accuracy can be compromised under certain conditions. For instance, in non-insulated heat exchangers, heat radiation is often neglected, which can lead to significant errors. Research has shown that in some practical cases, these errors can reach up to 40%, particularly in systems with high surface emissivity and low ambient convection [6]. Similarly, Wong et al. have noted that the conventional LMTD method may not be suitable when heat radiation cannot be ignored, such as in smaller ducts or when the temperature difference between fluids is minimal [7]. Therefore, while the LMTD method remains useful, it must be applied cautiously, with possible corrections for radiation and other influencing factors to ensure accurate heat transfer rate calculations.

The performance of the condenser is also influenced by various operational parameters, including the pressure levels within the HRSG. Research has demonstrated that increasing the number of pressure levels within the HRSG can improve exergy efficiency, thereby reducing losses associated with heat transfer in the condenser [5]. This suggests that careful management of operational conditions can lead to enhanced heat transfer rates, which can be further analyzed using the LMTD method.

Moreover, the design and configuration of the condenser plays a significant role in determining the heat transfer rate. Studies have shown that different configurations of combined cycle plants can affect overall thermal efficiency, emphasizing the importance of optimal design choices to maximize heat recovery [8]. Additionally, advanced heat exchanger designs contribute to further improvements in thermal efficiency, as evidenced by research on power generation cycles such as the Rankine cycle, which is commonly used in condensers [9].

Experimental studies provide empirical data on heat transfer coefficients in condensers under various conditions, which can enhance the accuracy of LMTD calculations [10]. These studies indicate that the heat transfer coefficient is sensitive to changes in condensation pressure and flow rates—critical parameters in the LMTD method. The heat transfer rate in the condenser of a combined cycle power plant can be effectively analyzed using the LMTD method, which accounts for temperature differences and operational factors that influence heat exchange. By optimizing these factors, including HRSG design and operating conditions, significant improvements in the plant's thermal efficiency can be realized.

The objective of this research is to evaluate the performance of the condenser in a combined cycle power plant (CCPP) by analyzing its heat transfer rate using the Logarithmic Mean Temperature Difference (LMTD) method. The study aims to assess the effectiveness of routine maintenance activities, such as cleaning the condenser water box and tubes, in improving heat transfer efficiency. By comparing the heat transfer rates before and after maintenance, the research seeks to establish a performance-based maintenance schedule, ensuring that maintenance is conducted when the condenser's heat transfer rate falls below an optimal threshold, thereby enhancing the overall efficiency of the power plant.

2. Methods

2.1. Research stages

The analysis of the condenser follows several key steps. First, a literature review is conducted to identify relevant research and references on condenser performance and maintenance. Next, field observations are carried out to identify specific problems, which include taking photographs and recording parameters at the power plant. Interviews with technicians and operators help refine potential research topics. At the Cilegon Combined Cycle Power Plant, condenser maintenance is typically aligned with steam turbine maintenance, rather than being based on actual performance data.

The subsequent phase involves data collection, which includes recording the temperatures of the cold fluid entering and exiting the condenser, the steam fluid entering from the low-pressure turbine, and the hot fluid exiting the condenser. Data, collected from operator logs between June and July 2023, is then processed using the Logarithmic Mean Temperature Difference (LMTD) method to calculate the heat transfer rate [11], [12]. The final step involves analyzing the results to evaluate the change in heat transfer rates before and after maintenance, after which a comprehensive report is compiled.

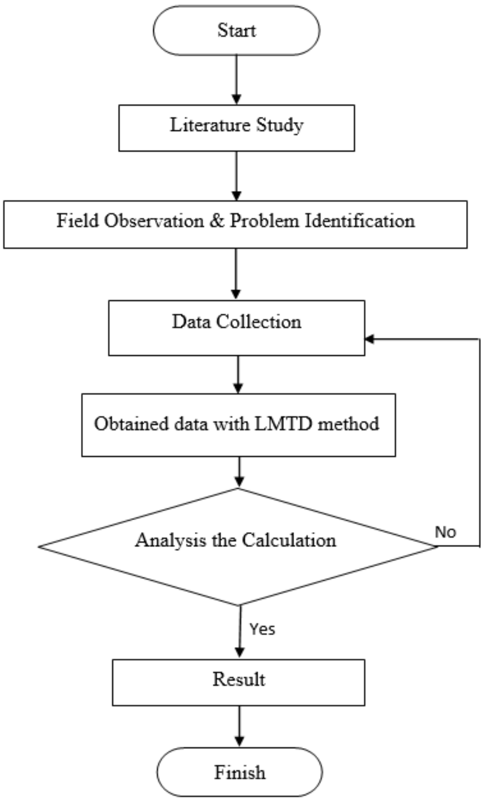

Figure 2. Research flowchart

2.2. Condenser specification

The table provides key specifications of the condenser at the Cilegon Combined Cycle Power Plant, as shown in Table 1 [11]. Built in November 2005, the condenser has a cooling surface area of 23,070 m^2, which is critical for facilitating efficient heat exchange. The vacuum pressure within the condenser is maintained at 0.074 Bar Abs, which helps improve steam condensation and overall plant efficiency. Weighing 420 tons, the condenser is made of titanium, a material known for its high corrosion resistance, especially in seawater environments, ensuring durability and longevity.

The tubes within the condenser, with an outer diameter of 22.23 mm and an average thickness of 0.5115 mm, are designed to withstand the high flow rates and pressure differentials inherent in the system. The velocity of the fluid inside the tubes is 2.0 m/s, which ensures optimal heat transfer without causing excessive pressure drop. The large number of tubes, 21,796 in total, provides a vast surface area for heat transfer, contributing significantly to the condenser's efficiency in converting steam into water. These specifications are indicative of a robust design aimed at maximizing thermal efficiency and reliability in the power plant's operation.

Table 1. Condenser specification

Description	Specification
Year built	2005
Cooling surface area	23070 m^2
Condenser vacuum	0,074 Bar Abs
Weight	420 Ton
Velocity in tubes	2,0 m/s
Material	Titanium
Outside diameter of tube	22,23 mm
Number of tubes	21796
Average tube thickness	0,5115 mm

2.3. LMTD (Log Mean Temperature Difference)

The Logarithmic Mean Temperature Difference (LMTD) method is used to calculate the average temperature difference between the inlet and outlet fluids in a heat exchanger, which allows for determining the heat transfer rate. This method is particularly useful when the fluid temperatures at both the entry and exit points are known. The LMTD formula provided in the manual is as follows [11].

$$\mathrm{LMTD} = \frac{(\mathrm{Th_{out}} - \mathrm{Tc_{in}}) - (\mathrm{Th_{out}} - \mathrm{Tc_{out}})}{\ln \frac{(\mathrm{Th_{out}} - \mathrm{Tc_{in}})}{(\mathrm{Tho_{out}} - \mathrm{Tc_{out}})}} \tag{1}$$

Where, LMTD is Logarithmic Mean Temperature Difference, $\mathrm{Th_{out}}$ is the hot fluid temperature entering the condenser, $\mathrm{Tc_{in}}$ is the cold fluid temperature entering the condenser, and $\mathrm{Tc_{out}}$ is the cold fluid temperature exiting the condenser.

2.4. Overall heat transfer coefficient

The overall heat transfer coefficient represents the total thermal resistance between two fluids involved in heat transfer. It can be defined as the combined effect of individual heat transfer coefficients and correction factors that account for various system conditions. The formula for calculating the overall heat transfer coefficient, as provided in the manual, is as follows [11].

$$\mathrm{U} = \mathrm{U_1 x F_w x F_m x F_c x 4{,}882} \tag{2}$$

Where U is an overall heat transfer coefficient, U_1 is the uncorrected heat transfer coefficients, F_w is the inlet water temperature correction factor, F_m is the tube material and gauge correction factor, F_c is the cleanliness factor (°C), and the conversion factor is set as 4,882 Kcal/m^{3}h°C.

2.5. Heat transfer surface area

The heat transfer surface area refers to the actual area where heat transfer occurs within the condenser. The equation used to calculate this surface area is as follows [13].

$$A_{act} = \pi x d_o x N x L \tag{3}$$

Where d_o is the outer diameter of condenser tube (mm), N is the number of condenser tubes, and L is the effective length of condenser tube (mm).

2.6. Heat transfer rate

Heat transfer rate refers to the amount of heat energy transferred between two systems or objects over a given time. This transfer can occur via three main mechanisms: conduction (direct contact between objects), convection (through the movement of fluids such as air or water), or radiation (via electromagnetic waves). The rate of heat transfer is typically measured in units such as watts (W) or calories per second. The formula used to calculate the heat transfer rate is as follows [13].

$$Q = U.A.LMTD \tag{4}$$

Where Q is the heat transfer rate (W), U is the overall heat transfer coefficient, and A_{act} is the actual heat transfer surface area (m^2).

3. Results and Discussion

3.1. LMTD value and heat transfer rate before maintenance

The data collected in June 2023 shows varying LMTD values and corresponding heat transfer rates before condenser maintenance. The Logarithmic Mean Temperature Difference (LMTD) values range from 1.30 to 1.74°C, while the heat transfer rate (Q) varies from 89,444,665.92 kcal/h to 119,845,353.78 kcal/h.

Higher LMTD values, such as 1.74°C, correspond to higher heat transfer rates, such as 119,845,353.78 kcal/h, indicating a more efficient heat exchange process. On the lower end, LMTD values of 1.30°C correlate with lower heat transfer rates, like 89,444,665.92 kcal/h, showing that the condenser's performance was suboptimal prior to maintenance. The relatively consistent LMTD values around 1.5°C and heat transfer rates near 104,868,250 kcal/h suggest a steady, though not optimal, performance for most of the pre-maintenance period.

Table 2. LMTD value and heat transfer rate before maintenance

Tc_{in} (°C)	Tc_{out} (°C)	Th_{out} (°C)	LMTD	Q (kcal/h)
31.4	33.9	34.5	1.52	104,868,250.79
31.4	33.9	34.5	1.52	104,868,250.79
31.3	33.9	34.5	1.55	106,994,488.34
31.9	33.7	34.3	1.30	89,444,665.92
31	33.5	34.1	1.52	104,868,250.79
30.8	33.4	33.9	1.43	98,164,655.12
30.7	33.3	33.8	1.43	98,164,655.12
30.8	33.3	33.9	1.52	104,868,250.79
30.9	33.5	34	1.43	98,164,655.12
31	33.6	34.2	1.55	106,994,488.34
31.4	33.7	34.2	1.34	91,968,433.92
31.3	34.2	34.8	1.64	113,276,054.79
31.5	34.2	34.8	1.58	109,104,069.30
31	33.8	34.5	1.74	119,845,353.78
31.1	33.7	34.2	1.43	98,164,655.12
30.5	33.1	33.7	1.55	106,994,488.34
30.5	33	33.7	1.64	113,314,009.57
30.7	33.2	33.9	1.64	113,314,009.57
30.6	33	33.7	1.61	111,102,343.39

3.2. LMTD value and heat transfer rate after maintenance

Post-maintenance data collected in July 2023 reveals a noticeable improvement in both LMTD values and heat transfer rates. The LMTD values now range from 0.75 to 1.85°C, and the heat transfer rate varies from 51,362,294.48 kcal/h to 127,246,219.66 kcal/h. A significant increase in the highest LMTD value, reaching 1.85°C, corresponds with the highest heat transfer rate of 127,246,219.66 kcal/h, indicating a marked improvement in condenser efficiency after the maintenance work.

Notably, the post-maintenance data includes lower LMTD values, such as 0.77°C, associated with lower heat transfer rates of 52,858,332.46 kcal/h, likely reflecting operational variability. However, the majority of LMTD values hover above 1.2°C, indicating that the system operates more efficiently than before maintenance, with heat transfer rates exceeding 100,000,000 kcal/h in most cases. The data suggests that the maintenance significantly enhanced the condenser's performance by reducing fouling and improving overall heat transfer.

Table 3. LMTD value and heat transfer rate after maintenance

Tc_{in} (°C)	Tc_{out} (°C)	Th_{out} (°C)	LMTD	Q (kcal/h)
30.5	33.2	33.5	1.17	80,776,582.18
30.6	33.1	33.2	0.77	52,858,332.46
30.7	33.6	34.2	1.64	113,276,054.79
30.6	33	33.9	1.85	127,246,219.66
30.4	32.8	33.3	1.37	94,051,314.59
30.4	32.9	33.2	1.12	77,103,397.99
30.4	32.9	33.2	1.12	77,103,397.99
30.7	33.1	33.2	0.75	51,362,294.48
30.3	32.8	33.5	1.64	113,314,009.57
30.2	32.7	33.1	1.26	86,934,589.76
30.2	32.7	33.2	1.40	96,116,444.73
30.4	32.9	33	0.77	52,858,332.46
30.5	33	33.2	0.96	66,169,067.70
30.5	32.8	33.4	1.46	100,562,671.83
30.3	32.5	33.1	1.43	98,381,597.51
32.3	34.8	35.2	1.26	86,934,589.76
31.6	34.2	34.5	1.15	78,947,217.07
31.3	33.9	34.3	1.29	88,890,755.62
31.3	34.6	35.2	1.76	121,448,285.94
31.5	34.2	34.6	1.32	90,831,471.43
31.4	34	34.5	1.43	98,164,655.12
31.5	34.1	34.5	1.29	88,890,755.62

3.3. Comparing the LMTD values and heat transfer rate before and after maintenance

Based on the data in Tables 3 and 4, there are notable changes in several parameter values following the maintenance of the condenser at the Cilegon Combined Cycle Power Plant. However, it remains important to compare the heat transfer rates before and after maintenance to establish a more solid foundation for future maintenance planning. The LMTD value before maintenance, specifically during the cleaning of the water box and condenser tubes, was 0.77°C, while after maintenance, the LMTD value increased to 1.85°C. This improvement is illustrated in Figure 3, which presents a graph of the LMTD values before and after the maintenance activities.

Before maintenance, the heat transfer rates were generally lower, and the LMTD values were more uniform, indicating reduced efficiency likely due to fouling and blockages within the condenser. After maintenance, the system's performance improved significantly, with the maximum heat transfer rate increasing from 119,845,353.78 kcal/h to 127,246,219.66 kcal/h. Although some lower post-maintenance LMTD values and heat transfer rates were observed, the overall data demonstrates a marked improvement in efficiency, most likely resulting from the cleaning of the condenser tubes, which enhanced the heat exchange process.

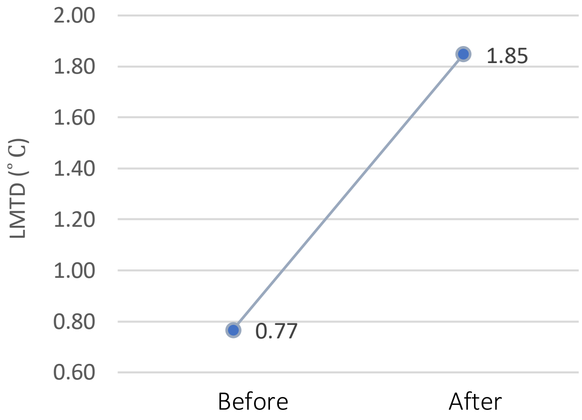

Figure 3. LMTD comparison before and after maintenance

After reviewing the calculation results and the LMTD graph, we proceed with the analysis of the heat transfer rate before and after maintenance. Prior to the maintenance activities, which involved cleaning the water box and condenser tubes, the heat transfer rate was recorded at 51,362,294.48 kcal/h. Following the maintenance, the heat transfer rate significantly increased to 127,246,219.7 kcal/h, as illustrated in Figure 4.

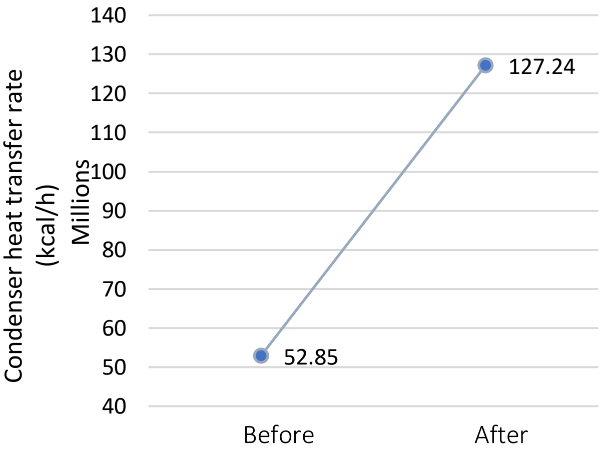

Figure 4. Trend of heat transfer rate before and after maintenance

The graphs in Figures 3 and 4 clearly demonstrate that the LMTD value is directly proportional to the heat transfer rate in the condenser. There is a significant difference in heat transfer rates before and after maintenance, indicating that the cleaning of water boxes and condenser tubes had a positive impact on the system's performance. The figures show the lowest heat transfer rate before maintenance and the highest rate after maintenance, providing clear evidence of improved efficiency, although variations in the steam turbine load were not considered.

The trend of the heat transfer rate, derived from data collected between June and July 2023, reflects operational fluctuations due to a limited gas supply from third parties and network demands in the Cilegon area. Typically, the steam turbine at the Cilegon CCPP operates at a load of 70 MW. Therefore, the data presented represents the heat transfer rates observed when the steam turbine was running at this load. Figure 5 below illustrates the heat transfer rate under these conditions.

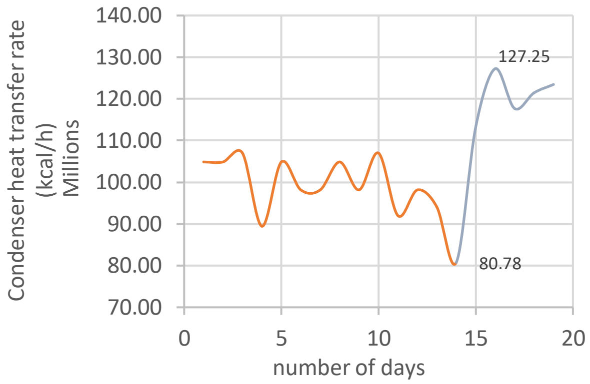

Figure 5. Trending heat transfer rate at a 70 MW steam turbine load

Analyzing the heat transfer rate graph of the Cilegon CCPP condenser unit, calculated using the LMTD method at a 70 MW load, the orange line represents the heat transfer rate before maintenance, while the blue line shows the rate after maintenance. Before maintenance, the heat transfer rate typically fluctuated between 90,000,000 and 110,000,000 kcal/h, with most values falling below 110,000,000 kcal/h. After maintenance, the heat transfer rate improved significantly, averaging between 110,000,000 and 125,000,000 kcal/h, with a peak value of 127,246,219.7 kcal/h. These findings are consistent with other research studies [14], [15], further validating the positive impact of maintenance activities.

According to the existing commissioning data, the heat transfer rate at a 70 MW load is 110,000,000 kcal/h. This suggests that performing periodic condenser maintenance, such as cleaning the water box and tubes, is most effective when the heat transfer rate drops below 110,000,000 kcal/h. Implementing this approach allows maintenance to be conducted as needed, rather than aligning it with the steam turbine's maintenance cycle, ensuring that the condenser continues to operate at optimal efficiency [11].

4. Conclusions

The analysis of the Cilegon Combined Cycle Power Plant (CCPP) condenser unit using the Logarithmic Mean Temperature Difference (LMTD) method highlights the critical impact of maintenance on heat transfer efficiency. Routine maintenance has proven effective, but it is evident that a performance-based approach would yield better results. Specifically, maintenance should be carried out when the heat transfer rate falls below 110,000,000 kcal/h. The data shows that before maintenance in June 2023, the LMTD value was 0.76, and the heat transfer rate was 51,362,294.48 kcal/h. After maintenance in July 2023, the LMTD value increased to 1.86, and the heat transfer rate peaked at 127,246,219.7 kcal/h. At a 70 MW steam turbine load, the heat transfer rate before maintenance ranged from 90,000,000 to 110,000,000 kcal/h, while post-maintenance, it improved significantly to a range of 110,000,000 to 125,000,000 kcal/h, with the highest value recorded at 127,246,219.7 kcal/h. These results emphasize that conducting maintenance when the heat transfer rate falls below the 110,000,000 kcal/h threshold ensures optimal condenser performance, improves overall plant efficiency, and reduces unnecessary downtime. By adopting this strategy, the CCPP can maintain high operational reliability and maximize energy efficiency.

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