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Ageless Steam, New Life: How Strategic Upgrades Revitalized Kamojang Unit 4 Geothermal Power Plant

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ABSTRACT

Kamojang is the oldest geothermal area and the first to be developed in Indonesia. Geothermal exploration began in 1970s through a collaboration between the governments of Indonesia and New Zealand. Development accelerated in 1983 due to the area's substantial geothermal resources and the presence of dry steam fluid. Following successful steam field development, three power plant units totaling 140 MW were commissioned and operated by another company. In 2003, PT Pertamina Geothermal Energy Tbk (PGE) began constructing its own power plant at Kamojang, with an installed capacity of 60 MW. Today, Kamojang Unit 4 is the oldest power plant operated by PGE, having been in continuous operation for nearly 20 years. Despite regular overhauls and preventive maintenance, performance degradation has been observed in recent years—primarily due to elevated condenser pressure and the unit's inability to reach its maximum output. In response, a major overhaul was carried out in 2024, including the replacement of the turbine rotor and the filler packs in the cooling tower. This study aims to evaluate the plant's performance post-overhaul by comparing key operational parameters before and after the upgrades. The evaluation was conducted in accordance with ASME PTC 46 to assess overall plant performance and CTI 105 to verify the cooling tower's performance. The results indicate a significant improvement in system performance, particularly in turbine efficiency, condenser pressure, and cooling tower effectiveness—approaching or even exceeding the original design specifications. Overall, the unit now operates reliably at full load with enhanced efficiency, supporting stable and sustainable energy generation.

1 INTRODUCTION

Kamojang is recognised as one of the oldest geothermal fields in Indonesia, dating back to 1926 as Volcanological Section of the colonial Geological Survey of Indonesia (GSI) drilled three exploration wells (Hochstein & Sudarman, 2008). Exploration continued in the 1970s under a cooperation program between the Governments of Indonesia and New Zealand, leading to the commissioning of the first three geothermal units in the 1980s with a combined capacity of 140 MW, operated by PT. Perusahaan Listrik Negara (PLN) Indonesia Power. In 2008, PT Pertamina Geothermal Energy Tbk (PGE) commissioned Unit 4, a 60 MW dry-steam plant designed and constructed using modern steam-turbine technology. Since then, the unit has operated continuously for more than two decades, supplying renewable power to the West Java grid. In 2015, PGE commissioned Unit 5, a 35 MW power plant, as the latest development in the utilisation of geothermal energy in Kamojang.

After prolonged operation under geothermal steam conditions, the turbine and auxiliary cooling systems of Unit 4 gradually exhibited thermodynamic performance degradation. Routine monitoring and a comprehensive performance test conducted before the 2024 overhaul indicated increased condenser pressure and reduced net power output compared with design expectations, despite stable steam supply. Aging geothermal steam turbines suffer performance decline mainly due to increased steam consumption (caused by erosion, corrosion, scale deposits, non-condensable gases affecting flow), mechanical damage (including stress corrosion cracking, corrosion fatigue, and blade deterioration), and lower inlet steam pressure due to aging of geothermal wells (Sakuma et al., 2006).

To maintain reliability and recover lost performance, a major overhaul was carried out in 2024, involving the installation of a new turbine rotor and the refurbishment of the cooling-tower filler pack. This work was part of PGE's broader asset-integrity and reliability program, aimed at restoring the unit's mechanical and thermal efficiency. The new turbine rotor shaft and interstage were coated with a tungsten carbide layer to enhance erosion resistance, which had been identified as the primary degradation mechanism in previous overhauls. The manufacturer also implemented a minor modification to the seal-fin configuration on the rotor interstage to

improve steam-flow characteristics. In the cooling tower, 50% of the fill pack was replaced to ensure optimal airflow while minimising the overall overhaul duration.

A rigorous assessment of the overhaul outcomes necessitates the use of established and uniform testing procedures to ensure consistency and comparability of results. Accordingly, standardised performance-evaluation protocols were applied during the pre- and post-overhaul verification stage. The ASME PTC 46 standard, which provides comprehensive guidelines for determining overall power-plant performance, was employed to quantify the unit's thermal and electrical efficiency following the intervention. In parallel, cooling-tower performance was evaluated in accordance with CTI 105, the industry benchmark for field testing of evaporative heat-rejection systems. These methodologies provide a reliable and objective basis for determining the effectiveness of the refurbishment activities.

This paper reports the post-overhaul performance verification of Kamojang Unit 4 following the major maintenance executed in 2024. Through a comparative analysis of normalised operating data collected before and after the overhaul, the study quantifies the degree of performance restoration achieved. The findings illustrate how targeted, integrity-focused upgrade strategies can effectively mitigate aging-related degradation, thereby extending the service life of a mature geothermal unit while maintaining reliable and sustained power generation.

2 THEORY OVERVIEW

2.1 Power Plant Performance

In general, the performance parameters of a power plant consist of net power output, heat rate, and steam consumption rate. The net power output is determined by subtracting the total auxiliary power consumption from the generator's gross electrical output. This net output represents the amount of electrical energy sold to the customer, which is subsequently distributed to end users through the transmission and distribution network.

The heat rate is defined as the ratio of the energy input required to generate electricity to the amount of electricity produced over a given period. Common units for expressing heat rate include kcal/kWh, kJ/kWh, or Btu/kWh. This energy input is directly associated with the production cost of the electricity delivered to the customer. In geothermal power plants, production cost is fundamentally linked to the amount of steam required to produce electrical energy. Accordingly, the steam consumption rate—also referred to as the specific steam consumption (SSC)—is expressed in units of steam mass flow (kg/s) per unit of electrical output (kW).

However, SSC does not account for variations in the thermodynamic quality of the produced steam, such as changes in temperature, pressure, dryness fraction, or non-condensable gas (NCG) content. Steam production from geothermal wells may also vary over time as reservoir conditions evolve. For these reasons, heat rate can be used as a more representative performance indicator, as it inherently accommodates changes in the energy level of the produced fluid, including variations in temperature, pressure, dryness fraction, and NCG concentration.

The primary objective of power-plant performance testing is to demonstrate and validate that the unit is capable of achieving its guaranteed output under the design conditions specified in the contract. Because it is practically impossible to conduct testing under conditions that perfectly match the design parameters, correction curves are introduced. These correction curves enable the normalization of off-design operating conditions, providing mathematically adjusted performance values that reflect the equivalent design-condition output.

There are four parameters for the correction curves: Main Steam Pressure, Non-Condensable Gas (NCG) content, Ambient Wet-Bulb Temperature, and Generator Power Factor. Each curve supplied by the manufacturer contains separate formulations for values below and above the design point, ensuring accurate adjustment across a range of operating conditions.

2.2 Cooling Tower Performance

The cooling tower of Kamojang Unit 4 is an induced-draft type consisting of four towers arranged in a single row, with air inlets located on the front, rear, and lateral sides. The cooling-tower manufacturer provides characteristic performance curves that are used to determine and calculate the cooling tower's capability under varying operating conditions. These characteristic curves are provided for multiple operating conditions, specifically at water-flow rates of 90%, 100%, and 110% of the design value. The calculation of cooling-tower capability follows the CTI ATC-105 Standard. The assessment is conducted using the performance-curve method, through the following sequence of calculation steps:

1. Prediction of Cold-Water Temperature (TCW)

The cold-water temperature is first predicted by plotting the measured test data, the wet bulb temperature onto the cooling-tower performance curves provided for water-flow conditions of 90%, 100%, and 110% of design. Each curve yields a corresponding predicted cold-water temperature (TCW) for a given operating range.

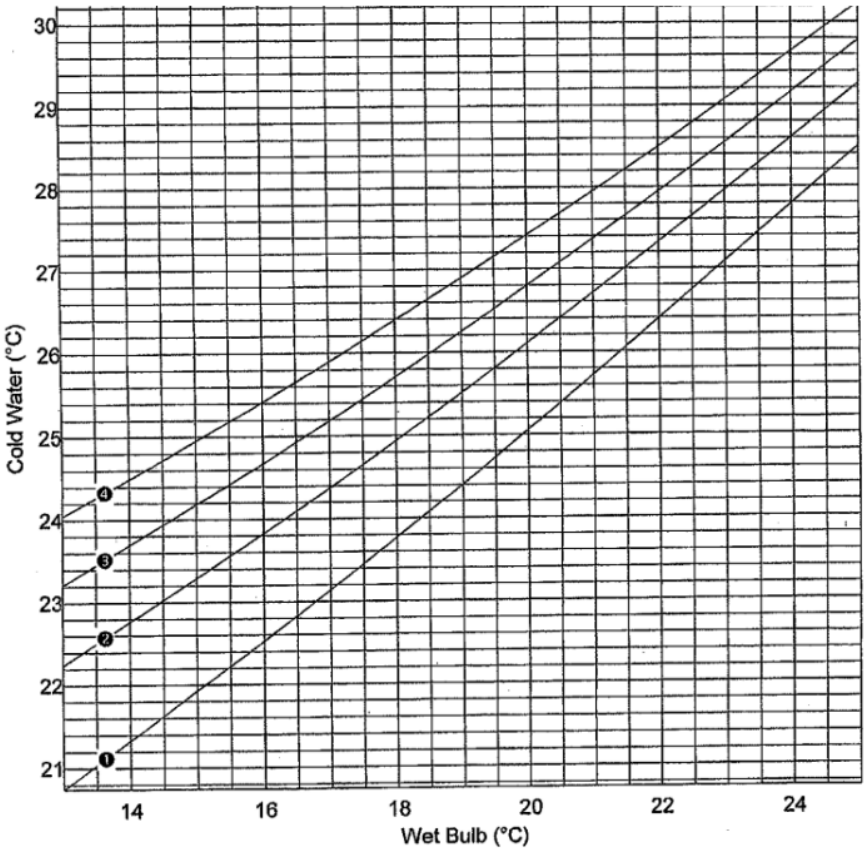


Figure 1. Example of performance curve provided, used for predicting cold-water temperature from wet bulb temperature data

2. First Cross-Plot

The data from previous step then can be plotted as a composite performance curve of range vs predicted cold-water temperature in each water flow rate. The test range value is then projected onto this curve. The output of this step is the predicted cold-water temperature at each of the three flow-rate conditions, thereby generating a consistent set of TCW predictions for further analysis.

3. Second Cross-Plot

With known range, the data of the curve are then plotted on a new set of axes, with water-flow rate on the x-axis and cold-water temperature on the y-axis. In this representation, the water-flow rate becomes a function of the thermal range, producing a predicted water-flow value denoted as $Q_{w,pred}$. The predicted cooling-water flow rate $Q_{w,pred}$ is subsequently compared with the actual flow rate measured during testing. To ensure that the test conditions are comparable to the design conditions, an adjustment is applied using fundamental heat-transfer principles. This adjustment yields the adjusted water-flow rate $Q_{w,pred}$.

For induced-draft cooling towers, the air properties relevant to the adjustment correspond to the discharge conditions downstream of the fan. Therefore, both design and test-condition air properties must be established. The design air properties are first determined using a heat-balance approach. According to the heat-balance principle, the heat absorbed by the air must equal the heat rejected by the circulating water. This relationship is expressed as follows:

$$h_o = \left(\frac{L}{G}\right) \times C_{pw} \times (T_{hw} - T_{cw}) + h_i \quad (1)$$

L : Water mass flow rate (kg/h)

C_{pw} : Specific heat of water = 4.186 kJ/kg°C

T_{hw} : Hot water temperature (°C)

T_{cw} : Cold water temperature (°C)

G : Dry-air mass flow rate through the cooling tower (kg/h)

h_o : Outlet air enthalpy from the tower (kJ/kg)

h_i : Inlet air enthalpy to the tower (kJ/kg)

Calculate the value of h_i using the pressure and temperature data at design conditions. Assuming that the discharge air is in a saturated-vapor state, the density and specific volume can be obtained from psychrometric tables. To determine the discharge-air condition during the test, the following equation is used:

$$\left(\frac{L}{G}\right)_t = \left(\frac{L}{G}\right)_d \times \left(\frac{Q_{wt}}{Q_{wd}}\right)^{\frac{1}{3}} \times \left(\frac{\rho_t}{\rho_d}\right)^{\frac{1}{3}} \times \left(\frac{v_t}{v_d}\right) \quad (2)$$

Q : Fan motor power (kW)

Among all parameters, only the values of ρ_t and v_t are not directly available. These two parameters are obtained through an iterative procedure. The iteration begins by assuming a temperature to estimate the corresponding density and dynamic viscosity. These estimated values are then used to calculate the enthalpy (using Equation (1)) and compare it with the enthalpy from the fluid-property tables. Once convergence is achieved, the resulting parameters are used to determine the $\left(\frac{L}{G}\right)_t$ value. The $\left(\frac{L}{G}\right)_t$ value is then used to calculate $Q_{w,adj}$ using the following equation:

$$Q_{w,adj} = Q_{wt} \times \left(\frac{W_d}{W_t}\right)^{\frac{1}{3}} \times \left(\frac{\rho_t}{\rho_d}\right)^{\frac{1}{3}} \quad (3)$$

The final step is to determine the cooling-tower capability using the following equation:

$$\mathrm{C} = \frac{Q_{w,adj}}{Q_{w,pred}} \times 100 \quad (4)$$

3 METHODOLOGY

The performance verification of Kamojang Unit 4 was conducted immediately before and after the 2024 overhaul to quantify the effect of turbine-rotor replacement and cooling-tower refurbishment on overall plant performance. The methodology followed internationally recognized test codes to ensure accuracy, comparability, and reproducibility.

3.1 Test Standards and Scope

The overall plant performance was evaluated in accordance with ASME PTC 46: Performance Test Code for Overall Plant Performance, which defines procedures for determining thermal efficiency, gross and net output, and associated corrections. The cooling-tower evaluation followed Cooling Technology Institute (CTI) ATC-105, which establishes measurement and data-correction methods for field testing of evaporative cooling equipment.

Testing covered:

- Steam-turbine and generator output characteristics,
- Condenser pressure and heat-rejection performance, and
- Cooling-tower range, approach, and effectiveness.

All measurements were carried out at steady operating conditions representative of base-load operation.

3.2 Data Acquisition and Parameters

3.2.1 Data Acquisiton for Power Plant Performance Test

Data acquisition was carried out using the following methods:

1. Data retrieval from the DCS.
2. Direct recording of environmental conditions and data from locally installed field instruments, probes, and portable measuring devices.
3. Secondary data obtained from equipment manufacturer performance curves, heat balance diagrams, and calculations.

3.2.2 Data Acquisiton for Cooling Tower Performance Test

Performance data acquisition of the cooling tower was conducted pre and post overhaul, following the guidelines specified in the CTI ATC 105 standard. The data collection process was carried out for a minimum of two hours and included measurements of key parameters such as cooling water inlet and outlet temperatures, air humidity, air velocity, and other relevant operating conditions. Measurements were performed using calibrated instruments in accordance with applicable standards to ensure data accuracy and reliability. Data acquisition was conducted by installing humidity sensors in the cooling tower cells and temperature sensors on the cooling water inlet and outlet lines, with all readings recorded directly into a computer. Wind speed was measured using a portable anemometer. During the testing process, the wind speed was observed to be around 2.0 m/s. This value is below the maximum ambient wind speed specified in the CTI ATC 105 standard, which is 6.5 m/s.

3.3 Normalization and Analysis Approach

The results of performance test were normalized to the design baseline. Pre- and post-overhaul results were each normalized to the design baseline. The percentage change in each performance index was calculated to evaluate relative improvement.

Several performance indicators were analyzed to determine the overhaul success. Besides the overall power plant performance, the performances of the three main components—turbine, condenser, and cooling tower—were analyzed. Overall, the performance parameters analyzed in this study are: main steam flow, gross and net power output, Net Plant Heat Rate (NPHR), Specific Steam Consumption (SSC), turbine steam flow, turbine shaft power, isentropic turbine efficiency, turbine heat rate, condenser percent heat load, condenser expected absolute pressure, cooling tower range, cooling fan power, cooling tower approach, cooling tower effectiveness, and cooling tower capability.

The analysis was done by comparing the normalized pre- and post-overhaul performance parameters to see the effects of turbine rotor replacement and cooling tower filler replacement.

4 RESULTS AND DISCUSSION

4.1 Overall Power Plant Performance

Table 1. Overall power plant performance parameter pre- and post-overhaul

Parameter	Compared to Design Value	
	Pre-Overhaul	Post-Overhaul
Turbine Steam Flow	-10,29%	1,90%
Turbine Shaft Power	-18,83%	1,17%
Isentropic Efficiency	-11,87%	-3,88%
Turbine Heat Rate	13,39%	4,01%
Main Steam Flow	-5,60%	6,51%
Gross Power Output	-23,00%	-1,23%
Net Power Output	-24,37%	-1,96%

A significant increase was observed in the Main Steam Flow indicator following the overhaul activity, increasing by 12,11%. The increase directly contributed to the rise in the Gross Power Output, which increase 21.77% after overhaul, slightly lower than the design value (1.23% lower than design value).

The Net Power Output also showed a substantial increase, from -24.37% pre- to -1.96% post-overhaul, closely aligning with the design value. These corrections indicate that the system has recovered performance levels close to the original design specification, albeit with minor deviations.

Theoretically, an increase in Main Steam Flow correlates with the steam generation capacity and the integrity of the steam path. The post-overhaul performance improvement is directly linked to major overhaul activities, including turbine rotor replacement, cooling tower package structure replacement, cooling tower nozzle cleaning, condenser cleaning, and auxiliary component repairs. These actions helped resolve previous operational constraints, such as condenser pressure approaching the alarm limit, which had previously restricted optimal loading. With the cooling tower and condenser now capable of handling a greater volume of condensable steam, the plant can operate at higher efficiency and accommodate a larger steam flow to the turbine.

From a thermal efficiency perspective, the Net Plant Heat Rate (NPHR) improved significantly, decreasing from 30.79% pre- to 0.90% post-overhaul, approaching the design target. Similar improvements were observed in the Specific Steam Consumption, which decreased toward its design value from 32.21% to 2.00%, indicating more efficient steam utilization after overhaul. Overall, the plant's performance showed substantial improvement after the overhaul, achieving values that closely approach the design guarantees.

Although the test results were corrected to design conditions, a direct comparison between pre- and post-overhaul performance cannot be made straightforwardly. This is due to differences in load conditions during the two tests, where the plant tended to operate with a higher Net Plant Heat Rate (NPHR) at lower loads. This phenomenon is typical for power plants, as thermal efficiency generally decreases at loads below optimal capacity.

4.2 Turbine Performance

The turbine performance was evaluated based on isentropic efficiency and turbine heat rate. Using data obtained from the Distributed Control System (DCS) and the application of energy balance equations, the turbine efficiency was calculated. The calculated turbine efficiencies under design, pre-, and post-overhaul conditions are presented in the table below. In this calculation, the generator efficiency was assumed to be 98%, which represents the standard value for power plant generators.

Table 2. Turbine Performance Parameters pre- and post-overhaul

Parameter	Compared to Design Value	
	Pre-Overhaul	Post-Overhaul
Turbine Steam Flow	-10,29%	1,90%
Turbine Shaft Power	-18,83%	1,17%
Isentropic Efficiency	-11,87%	-3,88%
Turbine Heat Rate	13,39%	4,01%

Based on the available data, the turbine performance after the overhaul showed a significant improvement compared to the pre-overhaul condition. One of the main performance indicators is the increase in isentropic efficiency, which rose 7.99% after the overhaul. This improvement is primarily attributed to the turbine rotor replacement carried out during overhaul, which enhanced the efficiency of converting thermal energy into mechanical energy. The post-overhaul isentropic efficiency value falls within the optimal performance range for geothermal turbines, reported to be between 81% and 85% by Moon and Zarrouk (2012). Therefore, the turbine performance post-overhaul can be categorized as good.

In addition, the turbine steam flow increased 12.19% from pre- to post-overhaul, indicating the turbine's improved ability to process a larger amount of steam following the overhaul. This contributed to an increase in

turbine shaft power, which reached 101.17% of the design value. The Turbine Heat Rate also improved from 13.39% pre- to 4.01% post-overhaul compared to the design value, reflecting a reduction in the energy required to generate a unit of power. These performance enhancements underscore the success of the rotor replacement conducted during the overhaul in restoring turbine efficiency and improving the overall power plant performance.

4.3 Condenser Performance

The condenser performance was evaluated based on its ability to condense turbine exhaust steam and maintain pressure stability. The comparison of condenser performance before and after the overhaul with respect to the design conditions is presented in the table below.

Table 3. Condenser Performance Parameters pre- and post-overhaul

Parameter	Compared to Design Value	
	Pre-Overhaul	Post-Overhaul
Cooling Water Inlet Temperature	12,67%	-1,68%
Condenser Pressure	-6,56%	-9,88%
Percent Heat Load	-17,82%	-8,98%

According to the performance test data summarized in the table above, the condenser exhibited significant improvements in several operating parameters after the overhaul. The cooling water inlet temperature decreased 14.35% from pre- to post-overhaul, 1.68% lower than design condition. This reduction contributed to a decrease in condenser pressure from -6.56% to -9.88% of the design value. These results indicate that the condenser operated more efficiently after the overhaul, supported by improved cooling water conditions. Additionally, the percent heat load increased 8.84% after the overhaul, 8.98% lower than the design value demonstrating the condenser's enhanced capacity to handle a higher thermal load.

Although the condenser pressure pre-overhaul was relatively high, this condition does not necessarily indicate poor condenser performance. At that time, the condenser received cooling water with a considerably higher temperature (12.67% higher than design condition), which naturally resulted in higher condenser pressure. Therefore, condenser performance cannot be evaluated solely based on instantaneous operating parameters. A proper comparison of pre- and post-overhaul performance should refer to the condenser performance curve.

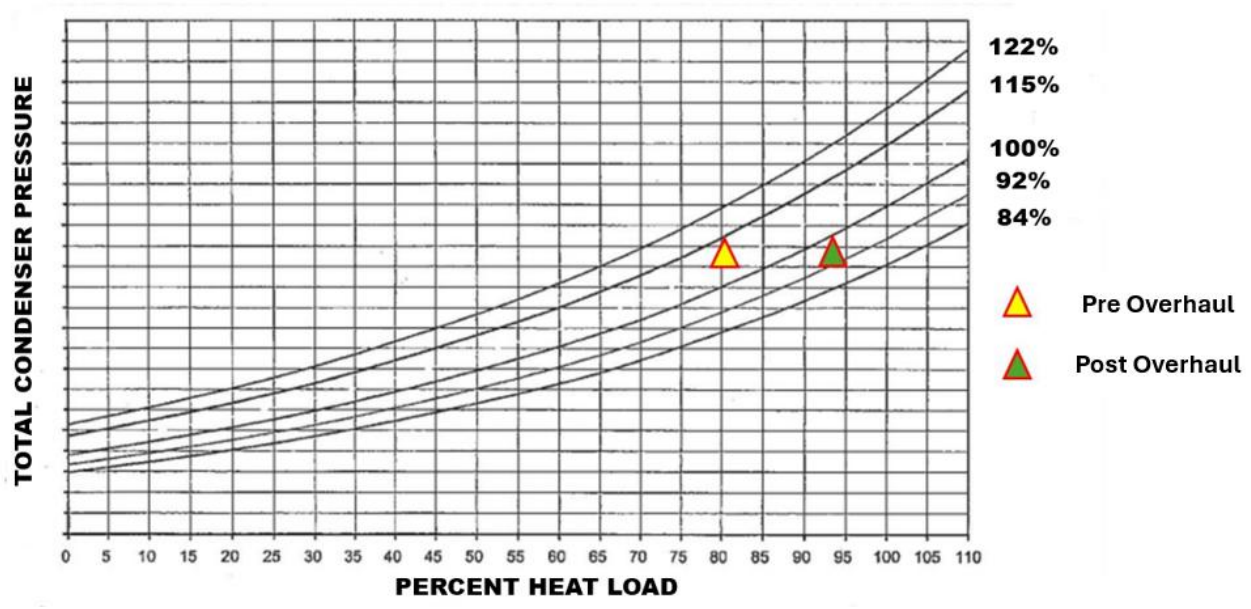


Figure 2. Comparison of pre- and post-overhaul conditions of condenser operation on performance curve

According to the condenser performance documentation, the relationship between condenser pressure and cooling water temperature under design conditions can be expressed through a defined correlation. By applying this correlation, the expected condenser pressure under various design scenarios can be estimated. The comparison between the measured condenser pressure and the expected (design) condenser pressure indicates that both pre- and post-overhaul operating points were relatively close to the design curve. This suggests that the higher condenser pressure observed before the overhaul was primarily due to operational conditions—particularly the elevated cooling water temperature—rather than an actual decline in condenser performance. The operating position and performance of the condenser before and after the overhaul with respect to the performance curve are illustrated in the figure above.

4.4 Cooling Tower Performance

The performance of the cooling tower was evaluated both before and after the overhaul. The comparison of cooling tower capability values across several parameters—namely, cooling range, approach, and effectiveness—is presented in the table below.

Table 4. Cooling Tower performance parameters pre- and post-overhaul

Parameter	Compared to Design Value	
	Pre-Overhaul	Post-Overhaul
Cooling Range	-13,33%	-3,14%
Approach	100,77%	28,27%
Effectiveness	-18,10%	-5,27%
Capability	-26,28%	0,03%
Fan Driver Power	-13,18%	-2,63%

A significant improvement was observed in the cooling tower capability following the overhaul. Prior to the overhaul, the cooling tower capability reached only 73.72%, whereas after the overhaul, it increased markedly to 100.03%. This improvement can be attributed to several factors, including maintenance activities performed during the overhaul and operational pattern adjustments that influenced cooling tower performance.

The first parameter analyzed was fan driver power. Before the overhaul, the fan driver power was notably low, 13.18% lower than the design value. Based on available information, there were no technical failures in the motor, measuring instruments, gearbox, or blade angle, and no repair activities were identified that could have affected power readings. Therefore, the low fan power was most likely caused by restricted air intake, primarily due to dirty fill packs. Fouling on the fill packs reduced the air cross-sectional area and increased the density of the hot water passing through relative to the air, thereby decreasing the airflow rate. This condition reduced the workload of the blades and motor, resulting in lower motor power consumption.

The reduced airflow rate led to a decrease in direct contact heat transfer between the hot water and cooling air, which negatively affected both the approach and range parameters during the pre-overhaul testing. Consequently, the cooling tower capability prior to the overhaul was limited to 73.72%.

During the overhaul, fill pack replacements were carried out on several cells of the cooling tower, which increased the effective heat transfer surface area. These improvements enhanced both the range and approach parameters, leading to an overall increase in cooling tower capability to 100.03% after the overhaul. The current capability level is adequate to support full-load plant operation.

5 CONCLUSION

Based on the performance test results conducted before and after the overhaul, it can be concluded that the maintenance and repair activities carried out during the overhaul have had a significant positive impact on the performance of several major power plant components. The key findings from this performance evaluation are summarized as follows:

- After the overhaul, the Net Plant Heat Rate (NPHR) decreased 29.89%, only 0.90% higher than the design value. This reduction indicates a significant improvement in the plant's thermal efficiency. The Specific Steam Consumption (SSC) also showed improvement, decreasing 30.21%, reflecting more efficient steam utilization. Furthermore, the plant's Gross Power Output increased from 21.77%, 1.23% less from the design value. Overall, the system demonstrated a notable enhancement in performance, operating near the commissioning NPHR curve, which indicates that the power plant has successfully optimized its thermal energy utilization following the overhaul.

- The turbine performance improved significantly following the rotor replacement, as evidenced by the increase in isentropic efficiency from 75% pre- to 81.8% post-overhaul, approaching the optimal operating range of 81–85%.

- The cooling system improvements, including condenser cleaning, successfully reduced the condenser pressure by 3.32%. Although the condenser performance has not yet fully returned to commissioning conditions, it is now adequate to support full-load plant operation.

- Cooling tower capabilities increased by 26.31%, back to its design value. The main contributing factor is the replacement of filler packs, which is indicated by the increased fan driver power. This indicates that more air is being pulled by the fan due to less restriction on the filler packs.

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