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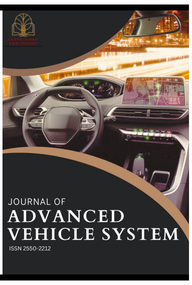

Thermal and Energy Performance Analysis under Off-Design Conditions of Open Recirculating Cooling Tower at PT Petrokimia Gresik

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ABSTRACT

This study analyzes the deviation of normal operating conditions from design parameters in the Open Recirculating Cooling Water System at PT Petrokimia Gresik Production Unit III A, and its implications for thermal performance, energy efficiency, and water quality control strategy. Operational data were collected during a field internship in February 2026 [10]. Three cooling tower units were examined: T-6520 (5 cells, Power Generation Plant), T-6530 (4 cells, process plant), and T-6510 (2 cells, ammonium sulfate plant). Under normal operating conditions, the recirculating flow rate decreases by 16.5% for T-6520 and T-6530 (from 6,000 to 5,010 m^3/hr) and by 13.3% for T-6510 (from 2,000 to 1,735 m^3/hr). Although cooling efficiency remains unchanged at 76.0% and 71.4%, the total heat duty of the system decreases from 158.6 MW under design conditions to 133.2 MW under normal conditions, a difference of 25.4 MW. The coefficient of performance decreases proportionally: T-6520 from 47.6 to 39.7 (a reduction of 16.5%) and T-6530 from 52.8 to 44.1 (a reduction of 16.5%), despite no change in electrical power consumption. The evaporation loss formula applied in field practice at PT Petrokimia Gresik yields a coefficient approximately 2.1 times greater than the standard ASHRAE formula, reflecting the higher relative humidity of Indonesia's tropical climate. Retention time increases under normal conditions, with T-6520 rising from 53 to 63 hours (an increase of 18.9%) and T-6530 from 69 to 83 hours (an increase of 20.3%), indicating elevated risks of $CaCO_3$ scale formation and biofilm growth, thereby confirming the need to maintain a consistent chemical treatment program.

1. Introduction

An open recirculating cooling water system is a critical infrastructure component in petrochemical industrial operations, serving as an auxiliary system that directly supports the thermal management of process equipment and power generation units. At PT Petrokimia Gresik Production Unit III A, this system is operated through three cooling tower units, namely T-6520, T-6530, and T-

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6510, which collectively handle the heat rejection demands of the entire production area. T-6520 specifically serves the Power Generation Plant (PG Plant), where the utility unit operates a boiler with a thermal capacity of approximately 65 MW. Process and utility heat is absorbed by the cooling water through heat exchangers and subsequently dissipated to the atmosphere via T-6520. The cooling water pump and fan motors operate at a medium voltage of approximately 6 kV, and the pump system is operationally interlocked with the power generation unit, requiring coordinated operation between the utility and power generation divisions to maintain system continuity at Production Unit III A [10].

In industrial practice, it is common for actual operating conditions to differ from the original design values. Design conditions represent the target parameters established at full capacity during the engineering phase, whereas normal operating conditions reflect the practical state of the system as observed during regular field operations. Although individual deviations may appear modest, their combined implications for thermal performance, energy efficiency, and water quality management can be significant and systematic [4,8]. The two most widely used thermal performance indicators are cooling efficiency (η) and approach temperature (AT) [15]. In addition, heat duty (Q) and the coefficient of performance (COP) serve as comprehensive indicators of the energy efficiency of the cooling system [2,6].

Studies that explicitly connect the deviation of normal operating conditions from design parameters with implications for heat duty, COP, and chemical treatment strategy in Indonesian petrochemical cooling tower systems remain scarce in the existing literature. This research addresses that gap through a quantitative analysis based on data from the Handbook Demin Water and Cooling Tower of PT Petrokimia Gresik Utilitas Pabrik 3A [10]. The main contributions of this study are: (1) the quantification of deviations in Q and COP between design and normal operating conditions across all three cooling tower units; (2) the validation of the field-derived evaporation loss formula applied in practice at PT Petrokimia Gresik against the standard ASHRAE formula, including a theoretical explanation of why tropical climate conditions yield a higher evaporation coefficient; and (3) the demonstration of the relationship between increases in retention time under normal conditions and elevated fouling risk, which confirms that chemical treatment dosing must be maintained consistently, even when the cycle of concentration (CoC) remains at the target value of 5. A summary of representative studies related to off-design thermal performance evaluation, energy efficiency analysis, and water quality control strategies in industrial cooling tower systems is presented in Table 1. These studies serve as the theoretical foundation and comparative framework for the present research.

Table 1
Summary of representative studies on thermal performance and energy efficiency of open recirculating cooling tower systems under various operating conditions

Simulation Model	Key Feature	Method	Main Finding	Result	Reference
Al-Bloushi *et al.*, (2021)	Non-chemical biofouling mitigation in cooling towers using GAC biofiltration and ultrafiltration	Experimental & field studies	Biofouling can be suppressed without chemicals through multi-stage filtration	Microbial activity reduced by more than 90%	[1]
Blackburn *et al.*, (2020)	Real-time optimization of	Machine learning	Data-driven optimization reduces	Energy savings of 8 to 15%	[2]

	multi-cell evaporative cooling tower using machine learning and PSO	combined with PSO	energy consumption while maintaining thermal performance		
Biedunkova and Kuznietsov (2025)	Comprehensive assessment of scale formation, corrosion, and biological pollution in a cooling water supply system	Laboratory and field comprehensive assessment	A combined direct and indirect monitoring methodology effectively evaluates scale, corrosion, and biofouling	Stable pH reduces corrosion and scale rates by 60 to 80%	[3]
Wenzel and Fensterle (2023)	New energy performance indicators for cooling towers with climate and cooling demand normalization	KPI normalization framework	The new KPI framework enables fair efficiency comparisons across locations with different climate conditions	Standardized indicators validated across 12 locations	[4]
Leung and Cheng (2024)	Water and energy conservation through condensate reclamation in evaporative cooling towers	Water and energy conservation experiments	Atmospheric condensate recovery compensates for a portion of make-up water demand without wastewater treatment	Make-up water demand reduced by 15 to 25%	[5]
Mujtaba *et al.*, (2025)	Machine learning for cooling tower efficiency optimization in sustainable power generation	Gradient boosting and data-driven model	Data-driven model outperforms manual control in predicting COP and identifying optimal operating parameters	COP prediction accuracy exceeds 95%	[6]
Zhu *et al.*, (2025)	Energy-saving methods for industrial circulating cooling systems through cycle of concentration optimization	Cycle of concentration optimization	Optimizing cycle of concentration simultaneously reduces water consumption and pump energy	Water savings of 30-50%	[7]
Chatterjee and Rahman (2022)	Innovative approach to minimize blowdown in recirculating cooling water systems	Water balance and industrial CoC analysis	Blowdown optimization based on cycle of concentration significantly reduces make-up water consumption in recirculating systems	Water efficiency improved through optimal CoC control	[8]

ChemTreat (2025)	Integrated corrosion, scale, and biofouling control in industrial cooling water systems	Technical review of industrial treatment programs	No single treatment approach can address all problems; a holistic program is essential	Holistic programs result in 3 to 5 times longer mean time between failures	[9]

Based on the literature reviewed in Table 1, the explicit evaluation of COP in cooling tower studies within the context of Indonesian petrochemical industries remains limited [4,6,11,13]. Research by Biedunkova and Kuznietsov [3] and ChemTreat [9] demonstrates that water quality control forms the foundation of energy efficiency; however, neither study integrates heat duty and COP analysis within a unified evaluation framework. The present research addresses this gap by providing a quantitative analysis that connects off-design operating conditions, thermal performance deviation, and water quality control strategy within a single study.

2. Methodology

2.1 Research Flow Diagram

This study adopts a comparative quantitative analysis approach to evaluate the deviation of actual operating conditions from design parameters in the Open Recirculating Cooling Tower system at PT Petrokimia Gresik Production Unit III A. The research is organized into the following sequential steps. First, operational data were collected directly during a field internship conducted in February 2026 [10], covering design and normal operating parameters for all three cooling tower units (T-6520, T-6530, and T-6510). Second, the collected data were used as inputs for calculating a set of thermal performance and energy efficiency indicators, including cooling efficiency (η), approach temperature (AT), heat duty (Q), coefficient of performance (COP), evaporation loss (E), retention time (T), and specific power (SP), using the formulas described in Section 2.3. Third, the field-derived evaporation loss formula applied at PT Petrokimia Gresik was validated against the ASHRAE standard formula using the same input data, in order to assess its suitability for tropical operating conditions. Fourth, the calculation results under design and normal conditions were compared quantitatively to identify the magnitude and direction of deviations, and their implications for water quality and chemical treatment strategy were analyzed. The complete research sequence is illustrated in the flow diagram presented in Figure 1.

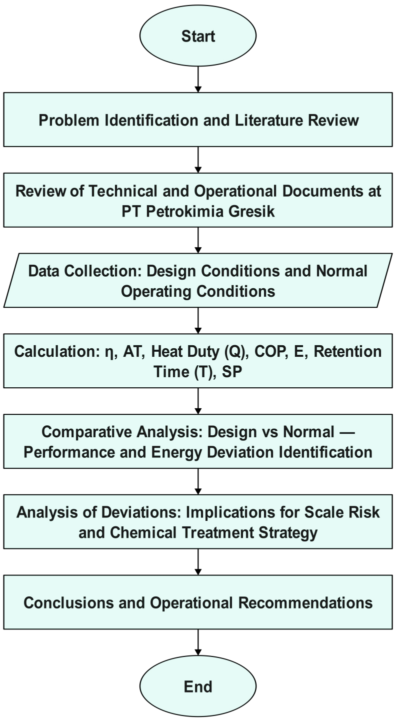

Fig. 1. Research flow diagram

2.2 Research Objects

This study examines three induced-draft, counter-flow cooling tower units with Douglas fir fill at PT Petrokimia Gresik Production Unit III A: T-6520 (5 cells, PG Plant area), T-6530 (4 cells, process plant area), and T-6510 (2 cells, ammonium sulfate plant area). Complete technical specifications, recorded during field internship observations, appear in Table 2.

Table 2
Technical specifications of cooling tower units at PT Petrokimia Gresik Unit III A [10]

Parameter	T-6520	T-6530	T-6510
Service Area	PG Plant (Power Generation)	Process Plant	AS Plant
Number of Cells	5 cells	4 cells	2 cells
Fan Power Absorbed	77.2 kW/cell	79.0 kW/cell	24.0 kW/cell
Pump Motor Rating	500 kW (3 units, ABC system)	500 kW (3 units, ABC system)	500 kW (3 units, ABC system)
Basin Holding Capacity (Design)	1,385 m³	1,748 m³	236 m³

2.3 Calculation Method

2.3.1 Cooling efficiency and approach temperature

Cooling efficiency (η) is defined as the ratio of the actual cooling range to the maximum temperature difference that can be thermodynamically achieved between the hot water inlet and the wet bulb temperature [4]. It is calculated using Eq. (1). Approach temperature (AT) is calculated using Eq. (2).

$$\eta = \left(\frac{T_{hot} - T_{cold}}{T_{hot} - T_{wb}}\right) \times 100\% \tag{1}$$

$$\mathrm{AT} = T_{hot} - T_{wb} \tag{2}$$

where T_{hot} is the hot water inlet temperature (°C); T_{cold} is the cold-water outlet temperature (°C); and T_{wb} is the wet bulb temperature (°C).

2.3.2 Evaporation loss — field formula of PT Petrokimia Gresik

The evaporation loss formula applied in field practice at PT Petrokimia Gresik, as documented in the operational handbook [10], is given by Eq. (3). This formula differs from the standard ASHRAE formula ($E = 0.00085 \times R \times \Delta T$), and its accuracy relative to operational data is validated in Section 4.2.

$$E = \left(\frac{\Delta T}{5.6}\right) \times \left(\frac{R}{100}\right) \tag{3}$$

where E is the is the evaporation loss (m^3/hr); ΔT is the cooling range (°C); and R is the recirculating flow rate (m^3/hr).

2.3.3 Heat duty

Heat duty (Q) represents the total thermal energy rejected by the cooling tower system per unit time. It is a fundamental parameter in the energy balance analysis of industrial cooling systems [6] and is calculated using Eq. (4).

$$Q = \dot{m} \times Cp \times \Delta T \tag{4}$$

where $\dot{m}$ is the mass flow rate (kg/s), determined as $\rho \times \frac{R}{3{,}600}$; ρ = 995 kg/m^3 at the operating temperature; and Cp = 4.186 kJ/(kg·°C).

2.3.4 Coefficient of performance

The coefficient of performance (COP) of a cooling tower is the ratio of the rate of heat rejection (Q, in kW) to the total electrical power consumed by the system (P_{total}, in kW) [2][6]. A higher COP indicates a more energy-efficient system. It is calculated using Eq. (5).

$$COP = \frac{\mathrm{Q}}{P_{total}} \tag{5}$$

where $P_{total} = P_{fan} + P_{pump}$ (kW).

2.3.5 Retention time

Retention time (T) is the average duration water remains within the circulating system. A longer retention time increases the risk of scale formation and biofilm growth [3][9]. The safe limit established by PT Petrokimia Gresik is less than 300 hours [10]. The theoretical formula for retention time is given by Eq. (6), and the actual values recorded in the field operational data are presented in Table 3.

$$T = \frac{\mathrm{H}}{(\mathrm{B+D})} \tag{6}$$

where T is the basin holding capacity (m^3); B is the blowdown rate (m^3/hr); and D is the drift loss (m^3/hr).

2.3.6 Specific power

Specific power (SP) is the electrical power consumed per unit of cooling water flow rate. It serves as a relative indicator of energy efficiency across different units [2] and is calculated using Eq. (7).

$$SP = \frac{\mathrm{P}}{\mathrm{R}} \tag{7}$$

where SP is in in W/(m³/hr); P is the motor power (W); and R is the recirculating flow rate (m³/hr).

2.3.7 H_2SO_4 dosage for pH control

The required dosage of 98% H_2SO_4 to maintain target M-Alkalinity of the circulating water within the pH range of 7.5 to 8.5 is calculated using Eq. (8) [10].

$$\mathrm{H_2SO_4}\ (L/hr) = \frac{[(A\times C-B)\times D]}{(1.8\times 1{,}000)} \tag{8}$$

where A is the M-Alkalinity of make-up water (ppm as $CaCO_3$); B is the target M-Alkalinity of the circulating water; C is the cycle of concentration; and D is the blowdown rate (m³/hr).

3. Results

3.1 Design and Normal Operating Data

Design and normal operating condition data for all three cooling tower units, recorded during field observations at PT Petrokimia Gresik Production Unit III A, appear in Table 3. These data provide the primary input for all thermal performance and energy efficiency calculations throughout this study. Thermal parameters remain identical between conditions for all units: hot water temperature (T_{hot}), cold water temperature (T_{cold}), cooling range (ΔT), and wet bulb temperature (T_{wb}). This confirms preserved thermal quality per unit volume of circulating water under normal conditions. Recirculating flow rate (R) decreases significantly: T-6520 and T-6530 by 16.5% (6,000 to 5,010 m³/hr), T-6510 by 13.3% (2,000 to 1,735 m³/hr). Evaporation loss remains stable at 1.70% of recirculating flow across all units and conditions, governed by ΔT rather than absolute flow rate. Cycle of concentration (N) consistently maintains target value of 5. Retention time increases under normal conditions: T-6520 from 53 to 63 hours (18.9%), T-6530 from 69 to 83 hours (20.3%), both well below 300-hour operational safe limit. These increases carry implications for water quality control strategy discussed in detail in Section 3.6.

Table 3
Design and normal operating condition data collected at PT Petrokimia Gresik Production Unit III A

Parameter	T-6520 Design	T-6520 Normal	T-6530 Design	T-6530 Normal	T-6510 Design	T-6510 Normal	Unit
Thermal Conditions							
Hot Water Temperature (T_{hot})	39.5	39.5	41	41	41	41	°C
Cold Water Temperature (T_{cold})	30	30	31	31	31	31	°C
Cooling Range (ΔT)	9.5	9.5	10	10	10	10	°C
Wet Bulb Temperature (T_{wb})	27	27	27	27	27	27	°C
Flow Rate and Capacity							
Recirculating Water (R)	6,000	5,010	6,000	5,010	2,000	1,735	m³/hr
Basin Holding Capacity (H)	1,385	1,335	1,748	1,748	236	236	m³
Water Balance							
Evaporation Loss (E)	102	85.2	102	85.2	34	29.5	m³/hr
E as Percentage of R	1.70	1.70	1.70	1.70	1.70	1.70	%
Total Blowdown (B)	25.5	21.5	12	10	8.5	7.4	m³/hr

Drift Loss (D)	12	10	N/A	N/A	4	3.5	m^3/hr
Make-Up Water (M)	N/A	106.5	N/A	106.5	42.5	36.5	m^3/hr
Cycle of Concentration and Retention Time							
Cycle of Concentration (N)	5	5	5	5	5	5	N/A
Retention Time (T)	53	63	69	83	28	32	hr

3.2 Validation of Evaporation Loss Formula

This section validates the evaporation loss formula applied in field practice at PT Petrokimia Gresik, as specified in Eq. (3), against the ASHRAE standard formula ($E = 0.00085 \times R \times \Delta T$). Both formulas were applied to the design operating condition of T-6520 ($R = 6{,}000\ \mathrm{m^3/hr}$; $\Delta T = 9.5$°C), and the results were compared against the actual value observed in the field [10].

Applying the ASHRAE standard formula to the design operating condition of T-6520 (R = 6,000 m^3/hr; ΔT = 9.5°C) yields a result of 48.45 m^3/hr. Applying the PT Petrokimia Gresik field formula using Eq. (3) under the same conditions yields 101.8 m^3/hr, which closely matches the actual field value of 102 m^3/hr [10]. The ASHRAE formula therefore underestimates the actual evaporation loss by approximately 53%, while the field formula provides a result that is consistent with the operational data recorded on-site.

The same validation was applied to the normal operating condition of T-6520 (R = 5,010 m^3/hr), where Eq. (3) yields 84.97 m^3/hr, consistent with the field-recorded value of 85.2 m^3/hr [10]. The effective coefficient derived from the PT Petrokimia Gresik formula is approximately 0.00179, which is about 2.1 times greater than the ASHRAE coefficient of 0.00085. This discrepancy is attributed to the higher relative humidity characteristic of Indonesia's tropical climate [14][16][20], which increases the fraction of water evaporated per degree of cooling range relative to the temperate climate baseline underlying the ASHRAE standard. This finding has practical significance for the accurate planning of make-up water requirements and blowdown rates in tropical petrochemical facilities.

3.3 Thermal Performance and Energy Efficiency: Design vs Normal

3.3.1 Cooling efficiency and approach temperature

Cooling efficiency (η) and approach temperature (AT) were calculated for all three units using Eq. (1) and Eq. (2), respectively, based on the operating data presented in Table 3.

For T-6520, with $T_{hot} = 39.5°\mathrm{C}$, $T_{cold} = 30°\mathrm{C}$, and $T_{wb} = 27°\mathrm{C}$, the cooling efficiency is calculated as $\eta = \left(\frac{39.5-30}{39.5-27}\right) \times 100\% = 76.0\%$, and the approach temperature is AT = 30 – 27 = 3.0°C. For T-6530 and T-6510, with $T_{hot} = 41°\mathrm{C}$, $T_{cold} = 31°\mathrm{C}$, and $T_{wb} = 27°\mathrm{C}$, the results are $\eta = \left(\frac{41-31}{41-27}\right) \times 100\% = 71.4\%$, and AT = 31 – 27 = 4.0°C.

A significant finding is that cooling efficiency remains identical under both design and normal operating conditions for all three units. This is because the thermal parameters governing the calculation, namely the cooling range (ΔT) and the wet bulb temperature (T_{wb}), remain unchanged between the two conditions [19]. As a result, the deviation in flow rate under normal conditions does not affect the thermal quality of the cooling process per unit of water flow. However, as demonstrated in the following subsection, the reduction in recirculating flow rate (R) under normal conditions substantially reduces the total heat rejection capacity of the system.

3.3.2 Heat duty

Heat duty (Q) was calculated for all three units under both design and normal operating conditions using Eq. (4), with water density ρ = 995 kg/m³ and specific heat Cp = 4.186 kJ/(kg·°C). Mass flow rate for each unit derived first from volumetric recirculating flow rate (R), then combined with cooling range (ΔT) to determine total thermal energy rejected per unit time. Results show heat duty decreases proportionally with recirculating flow rate reduction under normal conditions while cooling range remains unchanged.

T-6520 heat duty decreases from 66.0 MW (design) to 55.1 MW (normal), a 16.5% reduction matching its flow rate drop from 6,000 to 5,010 m³/hr. T-6530 heat duty falls from 69.5 MW to 58.0 MW (16.5% reduction) despite 10°C cooling range. T-6510 heat duty declines from 23.1 MW to 20.1 MW (12.9% reduction), consistent with 13.3% flow reduction. System total heat rejection capacity drops from 158.6 MW to 133.2 MW, a 25.4 MW deficit across Production Unit III A.

T-6520 normal condition heat duty of 55.1 MW adequately supports the utility boiler's 65 MW thermal output at PG Plant area, confirming sufficient capacity for power generation despite design deviation. However, reduced margin between cooling capacity and boiler demand heightens vulnerability to further flow reductions from pump degradation or heat exchanger fouling. Thus, maintaining recirculating flow rates near design values and monitoring heat exchanger tube cleanliness become essential for sustaining effective heat rejection capacity.

3.3.3 Coefficient of performance

The coefficient of performance (COP) was calculated using Eq. (5) for both design and normal operating conditions across all three cooling tower units. Total power consumption (P_{total}) comprises fan motor power plus operational pump power. Results show T-6520 at 1,386 kW, T-6530 at 1,316 kW, and T-6510 at 1,048 kW. These values remain constant between conditions because electrical equipment operates at fixed rated capacity regardless of recirculating flow rate.

Applying Eq. (5) with heat duty values from Section 3.3.2 yields: T-6520 COP decreases from 47.6 (design) to 39.7 (normal), a 16.5% reduction; T-6530 from 52.8 to 44.1 (16.5%); T-6510 from 22.1 to 19.2 (12.9%). These reductions mirror the heat duty pattern exactly. COP decreases proportionally with heat duty because P_{total} remains unchanged across conditions. This confirms cooling tower energy efficiency depends primarily on recirculating flow rate rather than thermal parameters. T-6510 exhibits the lowest COP due to its oversized 500 kW pump motor serving reduced flow capacity, yielding 500 W/(m³/hr) specific power versus 166.7 W/(m³/hr) for T-6520 and T-6530.

3.4 Comparative Visualization: Design vs Normal

Figure 2 through Figure 4 present comparative bar charts of heat duty, COP, and retention time between design and normal operating conditions for all three units. The visualizations are derived from the calculation results presented in Sections 3.2 and 3.3.

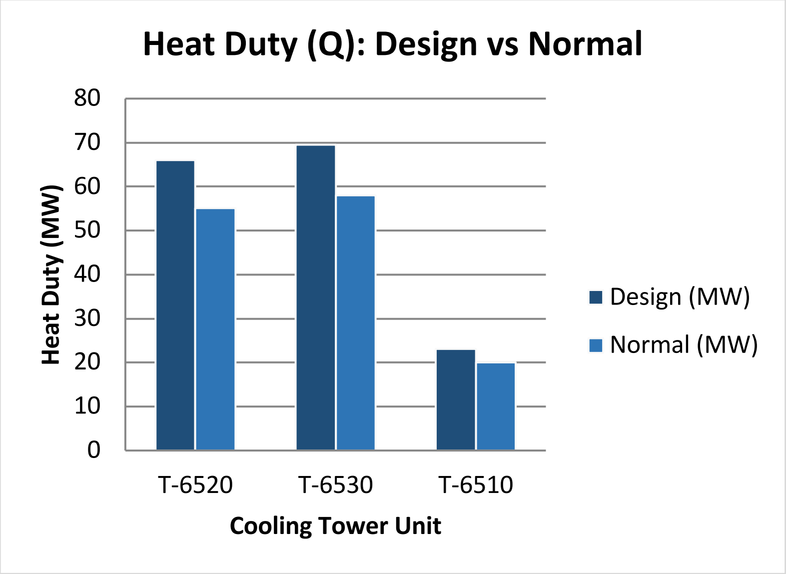

Fig. 2. Comparison of heat duty (Q) between design and normal conditions: dark blue bars represent design conditions; light blue bars represent normal conditions (MW)

Figure 2 presents a comparative visualization of heat duty (Q) across all three cooling tower units under design and normal operating conditions. The chart reveals a consistent and proportional reduction in heat rejection capacity for every unit during the transition from design to normal conditions. T-6520 decreases from 66.0 MW to 55.1 MW (16.5% reduction), T-6530 from 69.5 MW to 58.0 MW (16.5%), and T-6510 from 23.1 MW to 20.1 MW (12.9%).

The design condition proves superior because higher recirculating flow rates enable proportionally greater heat extraction from process equipment per unit time at identical cooling range (ΔT). This superiority stems not from thermal efficiency differences per unit flow, which remain constant across conditions, but from circulating a larger water mass overall.

The gap between design and normal heat duty represents an irrecoverable thermal deficit without flow rate increases. For T-6520 specifically, the normal condition heat duty of 55.1 MW adequately supports the utility boiler's 65 MW thermal output, yet reduced margins limit buffer capacity against process upsets or seasonal temperature rises. Thus, maintaining recirculating flow rates near design values emerges as the primary strategy for preserving system-level heat rejection performance.

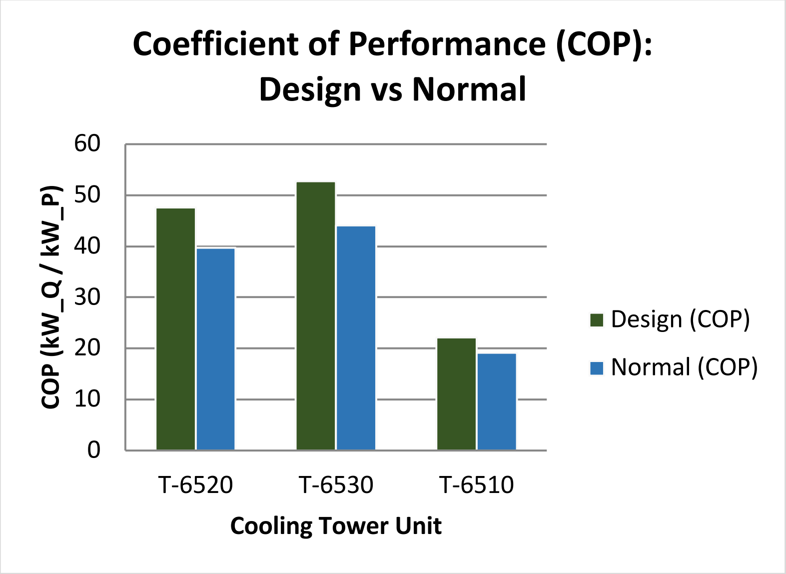

Fig. 3. Comparison of COP between design and normal conditions: dark green bars represent design conditions; blue bars represent normal conditions

Figure 3 presents the COP comparison across all three units under design and normal operating conditions, calculated using Eq. (5). The chart reveals a pattern that exactly mirrors Figure 2: the percentage decrease in COP matches the percentage decrease in heat duty for each unit at 16.5% for T-6520 and T-6530, and 12.9% for T-6510. This precise correspondence occurs because total electrical power consumption (P_{total}) remains fixed between conditions, so the COP numerator (Q) changes proportionally while the denominator stays constant.

The design condition proves superior in COP terms for every unit since the same electrical power investment produces substantially higher thermal energy rejection. For T-6520, the design COP of 47.6 versus normal COP of 39.7 means each kilowatt of electrical input rejects approximately 7.9 kW more thermal energy under design conditions. This gap represents a quantifiable loss of energy efficiency entirely attributable to reduced recirculating flow rate, not thermal process degradation.

Among the three units, T-6530 achieves the highest COP under both conditions (52.8 design, 44.1 normal) due to its high cooling range (10°C) combined with moderately lower power consumption than T-6520. T-6510 consistently records the lowest COP (22.1 design, 19.2 normal) because of its disproportionately large pump motor rating (500 kW) relative to smaller recirculating flow capacity. This structural mismatch yields a specific power of approximately 500 W/(m^3/hr) for T-6510 under design conditions, compared to 166.7 W/(m^3/hr) for T-6520 and T-6530, suggesting that pump resizing or operational strategy review could meaningfully improve overall system energy efficiency.

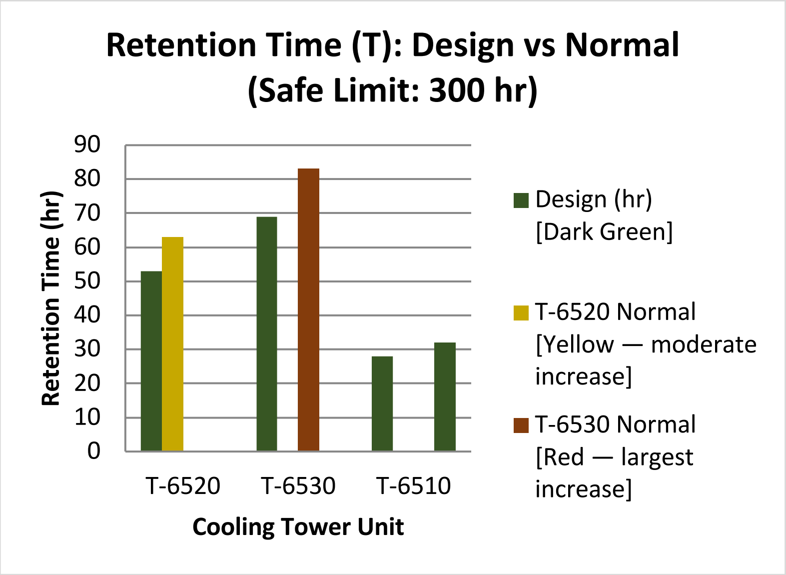

Fig. 4. Comparison of retention time between design and normal conditions: dark green bars represent design conditions; yellow and red bars indicate elevated risk under normal conditions (safe limit: 300 hr)

Figure 4 presents the retention time comparison across all three units and reveals a pattern inverse to those in Figures 2 and 3: heat duty and COP decrease under normal conditions, while retention time increases. This inverse relationship stems from reduced blowdown and drift loss rates under normal operating conditions, both of which drop proportionally with lower recirculating flow rates and thus extend average water residence time in the basin. T-6530 shows the largest increase, rising from 69 hours under design conditions to 83 hours under normal conditions (a 20.3% change). T-6520 rises from 53 to 63 hours (18.9%), and T-6510 from 28 to 32 hours (14.3%). Although all values stay well below the 300-hour operational safe limit set by PT Petrokimia Gresik [10], the upward trend holds important qualitative implications for water quality management.

Under design conditions, shorter retention times displace dissolved ions such as Ca^{2+} and HCO_3^- more frequently through fresh make-up water, thereby lowering the probability of supersaturation and scale deposition. Higher turnover rates also disrupt microorganism growth more effectively. Under normal conditions, extended retention time allows the same mass of dissolved minerals and microbial nutrients to persist longer in the system, heightening risks of $CaCO_3$ precipitation and biofilm formation on heat exchanger surfaces [18] even when cycle of concentration (CoC) holds at the target of 5. This pattern proves especially significant for T-6530, which records both the highest retention time increase (20.3%) and Polycrin A-491 weekly consumption (88 kg/week), indicating that chemical dosing adjusts implicitly to elevated biofouling risk. The finding thus reinforces that chemical treatment dosing requires maintenance at full prescribed levels irrespective of CoC target achievement, as retention time drives fouling risk independently of CoC.

3.5 Summary of Performance Calculations

Table 4 presents a consolidated summary of all thermal performance and energy efficiency calculation results for design and normal operating conditions across all three cooling tower units. The table integrates all calculated metrics, including cooling efficiency, approach temperature, heat duty, COP, evaporation loss, and retention time, into a single structured reference that enables direct cross-unit and cross-condition comparisons. Each parameter appears alongside its deviation value, expressed as a percentage change relative to the design condition, to facilitate quantitative interpretation of system-level off-design behavior. The table organizes results by performance category to distinguish thermal parameters from energy efficiency and water balance parameters, reflecting the multi-dimensional nature of cooling tower performance evaluation [2][4][6]. Results for both conditions derive from the calculation procedures in Section 2.3, while retention time values come directly from field operational records [10].

Table 4
Summary of thermal performance and energy efficiency calculations under design and normal operating conditions

Performance Parameter	T-6520 Design	T-6520 Normal	T-6530 Design	T-6530 Normal	T-6510 Design	T-6510 Normal	Unit
Thermal Conditions							
Cooling Efficiency (η)	76.0	76.0	71.4	71.4	71.4	71.4	%
Approach Temperature (AT)	3.0	3.0	4.0	4.0	4.0	4.0	°C
Heat Duty $[\boldsymbol{Q = \dot{m} \times Cp \times \Delta T}]$							
Mass Flow Rate ($\dot{m}$)	1,658.3	1,385.4	1,658.3	1,385.4	552.8	479.8	kg/s
Heat Duty (Q)	66.0	55.1	69.5	58.0	23.1	20.1	MW
Deviation of Q from Design	N/A	Decreased 16.5%	N/A	Decreased 16.5%	N/A	Decreased 12.9%	
Coefficient of Performance $[\boldsymbol{COP = Q/P_{total}}]$							
Fan Power Absorbed	386	386	316	316	48	48	kW
Operational Pump Power	1,000	1,000	1,000	1,000	1,000	1,000	kW
Total System Power (P_{total})	1,386	1,386	1,316	1,316	1,048	1,048	kW
System COP	47.6	39.7	52.8	44.1	22.1	19.2	N/A
Deviation of COP from Design	N/A	Decreased 16.5%	N/A	Decreased 16.5%	N/A	Decreased 12.9%	
Evaporation Loss Using Field Formula: $\boldsymbol{E = (\Delta T/5.6) \times (R/100)}$							
Evaporation Loss (E)	101.8	85.0	107.1	85.0	35.7	30.9	m^3/hr
Retention Time $[\boldsymbol{T = H/(B + D)}]$							
Retention Time (field operational data [10])	53	63	69	83	28	32	hr
Deviation of T from Design	N/A	Increased 18.9%	N/A	Increased 20.3%	N/A	Increased 14.3%	

3.6 Implications of Retention Time Increase for Chemical Treatment Strategy

Table 5 presents a systematic analysis of the implications of retention time increases under normal operating conditions for the chemical treatment strategy of the system.

Table 5
Analysis of retention time increase implications for chemical treatment strategy

Parameter	T-6520 Design	T-6520 Normal	T-6530 Design	T-6530 Normal	Implication for Chemical Treatment
Retention Time (hr)	53	63	69	83	Increased by 10 to 14 hours relative to design
Deviation from Design	N/A	Increased 18.9%	N/A	Increased 20.3%	Longer water contact time with equipment surfaces
$CaCO_3$ Precipitation Risk	Low	Moderate	Low	Moderate	Higher likelihood of supersaturation occurring
Biofouling Risk	Low	Moderate	Low	Moderate	Extended microorganism growth period

Operational Consequence	Normal dosage	Increased vigilance required	Normal dosage	Increased vigilance required	Chemical treatment dosage must not be reduced

Three direct connections between the operational deviations identified in this study and the chemical treatment program can be established. First, T-6530 experiences the largest retention time increase of 20.3% and simultaneously receives the highest Polycrin A-491 consumption of 88 kg/week, indicating that the dosing program has implicitly accounted for elevated biofouling risk under actual operating conditions [17]. Second, the reduction in recirculating flow rate under normal conditions reduces the water velocity inside the heat exchanger tubes; if this approaches the minimum threshold of 0.3 m/s, the risk of scale deposition and slime growth increases significantly. Third, maintaining the chemical treatment program that preserves heat exchanger tube cleanliness is the only mechanism available to sustain the overall heat transfer coefficient at its baseline value without increasing the electrical power consumption of the system [3,9].

3.7 Chemical Treatment Program and Phosphate Passivation Layer

Table 6 summarizes the chemical treatment program observed during the field internship at Production Unit III A. The dosing levels recorded on-site [10] reflect operational practice that has been calibrated to account for actual retention time conditions higher than the original design values.

Table 6
Chemical treatment program observed and recorded during field internship at production unit III A

Parameter	T-6520 Design	T-6520 Normal	T-6530 Design	T-6530 Normal	Notes
Corrosion and Scale Inhibitor					
Kurizet S-133 (KzS-133)	40-45 ppm	40-45 ppm	40-45 ppm	40-45 ppm	Scale and corrosion inhibitor
KzS-133 Consumption	23 kg/day	23 kg/day	23 / 8 kg/day	23 / 8 kg/day	Based on total blowdown rate
Kurizet S-611 (KzS-611)	20 ppm	20 ppm	20 ppm	20 ppm	Corrosion inhibitor
KzS-611 Consumption	10.3 kg/day	10.3 kg/day	10.3 / 3.6 kg/day	10.3 / 3.6 kg/day	Based on total blowdown rate
pH Control and M-Alkalinity Management					
H_2SO_4 98% Dosage	Calculated	Calculated	Calculated	Calculated	Target pH = 7.5 to 8.5 per operational SOP [10]
Biological Fouling Control: Biocide Program					
Cl_2 Gas (residual)	0.5-1.0 ppm	0.5-1.0 ppm	0.5-1.0 ppm	0.5-1.0 ppm	Injected 2 to 3 hours per day
Cl_2 Daily Consumption	15 kg/day	15 kg/day	15 / 5.2 kg/day	15 / 5.2 kg/day	T-6520/T-6530 versus T-6510
Polycrin A-491	50 ppm/week	50 ppm/week	50 ppm/week	50 ppm/week	Slime inhibitor
Polycrin A-491 Consumption	67 kg/week	67 kg/week	88 / 12 kg/week	88 / 12 kg/week	T-6530 receives highest dose corresponding to its greatest retention time increase

Field Observation: Phosphate Passivation Layer (*Phosphate Passivation Film*): During the field internship at Production Unit III A, it was directly observed that the metal surfaces within the cooling water system are maintained with a controlled phosphate passivation layer. This layer forms through the interaction of phosphate ions in the circulating water with the metal surface and functions as an additional barrier against corrosion. The thickness of this layer is critical: a layer that is too thin provides insufficient protection against corrosion, while a layer that is too thick may serve as a substrate for biofilm growth, since phosphate is one of the primary nutrients for microorganisms [3,9,17]. Periodic inspection is therefore carried out to ensure that the phosphate layer remains within the limits specified in the operational SOP. This practice is consistent with the operational records obtained during the internship [10], which identify phosphate as a key microorganism nutrient source in the cooling water system, requiring careful concentration management as part of an integrated water quality program.

4. Conclusions

This study has demonstrated that the transition from design to normal operating conditions in the Open Recirculating Cooling Tower system at PT Petrokimia Gresik Production Unit III A produces a consistent, quantifiable set of performance deviations governed primarily by the reduction in recirculating flow rate. The central finding shows that while the thermal quality of the cooling process, expressed through cooling efficiency (η) and approach temperature (AT), remains unchanged at 76.0% for T-6520 and 71.4% for T-6530 and T-6510, the total heat rejection capacity decreases significantly. Specifically, the total heat duty drops from 158.6 MW under design conditions to 133.2 MW under normal conditions, representing a reduction of 25.4 MW due to the 16.5% decrease in recirculating flow rate for T-6520 and T-6530, and the 13.3% decrease for T-6510. This confirms that the system's heat rejection capability depends fundamentally on flow rate rather than thermal limitations.

The proportional relationship between flow rate reduction and COP reduction represents another key finding. The COP of T-6520 decreases from 47.6 to 39.7 (a 16.5% drop), T-6530 from 52.8 to 44.1 (also 16.5%), and T-6510 from 22.1 to 19.2 (12.9%), while electrical power consumption stays constant across all cases. Consequently, energy costs for cooling remain fixed even as thermal output declines, indicating a systematic loss of energy efficiency under normal conditions. T-6510 appears structurally disadvantaged in COP terms because of its oversized pump configuration, which yields a specific power of approximately 500 W/(m^3/hr) compared to 166.7 W/(m^3/hr) for T-6520 and T-6530.

Validation of the evaporation loss formula provides a finding with practical significance for tropical industrial facilities. The field formula applied at PT Petrokimia Gresik produces results closely matching field-recorded values (101.8 vs. 102 m^3/hr under design conditions for T-6520), whereas the ASHRAE standard underestimates evaporation loss by about 53%. The effective coefficient of the field formula (0.00179) proves approximately 2.1 times greater than the ASHRAE coefficient (0.00085), a difference attributed to Indonesia's high ambient relative humidity. Thus, the ASHRAE formula, based on temperate climate assumptions, proves unsuitable as a direct tool for planning make-up water requirements and blowdown rates in tropical petrochemical environments.

The most operationally critical finding involves the increase in retention time under normal conditions, which contrasts with reductions in heat duty and COP. T-6530 experiences a 20.3% increase (from 69 to 83 hours), T-6520 a 18.9% rise (from 53 to 63 hours), and T-6510 a 14.3% increase (from 28 to 32 hours). Although all values stay well below the 300-hour safe operational limit, longer water residence heightens risks of $CaCO_3$ supersaturation, scale deposition, and biofilm growth on heat exchanger surfaces. Three key links connect these retention time increases to chemical treatment needs: the correlation between T-6530's largest increase and its highest Polycrin A-491 consumption (88 kg/week); the tie between reduced flow velocity and the minimum threshold for corrosion inhibitor effectiveness; and the influence of heat exchanger tube cleanliness on sustaining heat transfer coefficient and COP without added power. Maintaining full chemical dosing levels, regardless of cycle of concentration achievement, thus qualifies as essential operational practice.

For future research, several directions merit consideration. First, this study covers only one observation period in February 2026, so longitudinal monitoring across seasons could assess how variations in ambient wet bulb temperature influence performance deviations. Second, incorporating heat exchanger fouling resistance (R) as a metric would quantify scale and biofouling impacts on heat transfer over time. Third, computational fluid dynamics (CFD) or machine learning models, as shown in recent literature, could enable predictive control of flow rates and dosing at PT Petrokimia Gresik, potentially recovering lost energy efficiency. Finally, comparing the field evaporation formula (coefficient 0.00179) across Indonesian tropical sites would clarify if it applies broadly or remains site-specific.

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