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Effect of Operating Temperature on the Perfomance Effectiveness of Cooling Tower in a Phosphoric Acid Concentration Unit

Manuscript Information

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Abstrak

Cooling Tower memainkan peran penting dalam sistem pendinginan industri dengan mengurangi suhu air melalui perpindahan panas dan penguapan. Kinerjanya sangat memengaruhi efisiensi proses, terutama pada unit konsentrasi asam fosfat. Studi ini bertujuan untuk mengevaluasi kinerja menara pendingin berdasarkan suhu operasi dan membandingkan kondisi operasi aktual dengan spesifikasi desain. Data primer berupa suhu air masuk dan keluar, suhu bola basah, kelembaban, dan laju aliran air dikumpulkan melalui pengamatan lapangan langsung dan dianalisis menggunakan parameter rentang, pendekatan, efektivitas, dan kehilangan panas. Hasil menunjukkan penurunan signifikan dalam kinerja aktual relatif terhadap kondisi desain: rentang aktual adalah 5,7°C, lebih rendah dari nilai desain 14°C, sedangkan pendekatan aktual adalah 13,4°C, lebih tinggi dari nilai desain 6°C. Efektivitas menara pendingin hanya mencapai sekitar 30%, jauh di bawah nilai desain 70%, menunjukkan penurunan substansial dalam kemampuan perpindahan panas. Penurunan ini disebabkan oleh kerak pada sistem distribusi air, distribusi air yang tidak merata di seluruh media pengisi, dan penurunan kinerja kipas. Temuan ini memberikan dasar untuk mengevaluasi parameter operasi menara pendingin dan dapat mendukung upaya untuk meningkatkan efisiensi sistem pendinginan di industri asam fosfat.

Kata Kunci:
Cooling Tower, Efektivitas, Range, Approach, Asam Fosfat.

Abstract

Cooling towers play a crucial role in industrial cooling systems by reducing water temperature through heat transfer and evaporation. Their performance significantly affects process efficiency, particularly in phosphoric acid concentration units. This study aims to evaluate cooling tower performance based on operating temperature and to compare actual operating conditions with design specifications. Primary data inlet and outlet water temperature, wet-bulb temperature, humidity, and water flow rate were collected through direct field observation and analyzed using the range, approach, effectiveness, and heat loss parameters. The results show a significant decline in actual performance relative to the design condition: the actual range was 5.7°C, lower than the design value of 14°C, while the actual approach was 13.4°C, higher than the design value of 6°C. Cooling tower effectiveness reached only about 30%, far below the design value of 70%, indicating a substantial reduction in heat-transfer capability. This decline was attributed to scaling on the water distribution system, uneven water distribution across the fill media, and reduced fan performance. These findings provide a basis for evaluating cooling tower operating parameters and can support efforts to improve cooling-system efficiency in the phosphoric acid industry.

Keyword:
Cooling Tower, Effectiveness, Range, Approach, Phosphoric Acid.

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INTRODUCTION

Utility systems in the chemical industry, particularly cooling water systems, play an essential role in sustaining production continuity (Naik et al., 2017)(Bamimore & Enibe, 2021). Cooling water serves as the primary heat-transfer medium that keeps process temperatures within their operating limits, thereby maintaining both process efficiency and equipment reliability. A cooling tower is a heat-exchange device that uses water and air as its working media; it lowers water temperature through direct contact with air, causing part of the water to evaporate and release latent heat to the atmosphere (Rahman, 2022)(Tower et al., 2025)(Ghoddousi et al., 2021). By enabling the cooling water to be recirculated rather than discharged, the cooling tower significantly improves both water and energy utilization efficiency across the plant (Enggal Nurisman et al., 2020). Because cooling towers are typically installed at the interface between multiple process units, their performance has a direct and immediate influence on downstream operations, including concentration, distillation, and reaction processes that depend on stable cooling-medium temperatures.

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During the cooling process, heat transfer causes part of the circulating water to evaporate, which requires make-up water to maintain the mass balance of the system (Navarro et al., 2023)(Wahyu et al., 2023). This evaporation process is governed primarily by water temperature and airflow: the higher the water temperature and the better the airflow across the fill media, the higher the evaporation rate, and consequently the more effective the heat-rejection process becomes (Cahya et al., 2026). In addition to evaporation, the cooling process is accompanied by several water losses evaporation loss, drift loss, and blowdown that must be accounted for when evaluating cooling tower performance, since they are directly related to both cooling efficiency and water consumption (Enggal Nurisman et al., 2020). Accurately quantifying these losses is therefore a prerequisite for any meaningful performance evaluation, as unaccounted losses can mask the true extent of thermal degradation within the system.

A decline in cooling tower performance can raise process operating temperature, reduce heat-transfer efficiency, and increase energy consumption elsewhere in the plant (Firman Manahan Panjaitan, n.d.) Periodic performance evaluation is therefore necessary to ensure that the system continues to operate close to its design specification (Afshari & Dehghanpour, 2018). Although various studies have evaluated cooling tower performance using range, approach, and effectiveness parameters, research specifically addressing the effect of operating temperature on cooling tower effectiveness in a phosphoric acid concentration unit based on a direct comparison between design and actual field data remains limited. Furthermore, a comprehensive analysis linking performance degradation to its physical root causes, namely scaling, water maldistribution, and reduced fan performance, has not been widely discussed in the existing literature, leaving a gap between diagnostic parameters (range, approach, effectiveness) and the operational causes that drive them.

This study therefore aims to evaluate the effect of operating temperature on cooling tower effectiveness by comparing design data against actual field data, and to identify the operational factors responsible for the observed performance decline as a basis for recommending improvements to the cooling system. The novelty of this study lies in combining quantitative thermal-performance evaluation with a field-based diagnosis of the physical causes of degradation, which together provide a more actionable basis for maintenance and operational decision-making than parameter evaluation alone.

METHODS

This study used a quantitative approach, evaluating cooling tower performance by comparing design data against actual operating data. The research stages consisted of determining the research flow, identifying the research location, collecting data, analyzing data, and evaluating cooling tower performance using the range, approach, evaporation loss, drift loss, blowdown, make-up water, heat loss, and effectiveness parameters.

Research Location

The research was conducted on the cooling tower system that supports the cooling requirements of a phosphoric acid concentration unit within an industrial chemical plant. The object of the study was a multi-cell, forced-draft, counterflow cooling tower, which operates on the principle of countercurrent contact between the air and water streams to maximize the heat- and mass-transfer area between the two phases. This configuration was selected as the object of study because it represents the most common cooling tower type used in continuous chemical process units of this scale, and because preliminary field observation indicated that its actual performance had already deviated from its design specification, making it a representative case for evaluating temperature-dependent effectiveness loss. The general configuration of the cooling tower is presented in Figure 1.

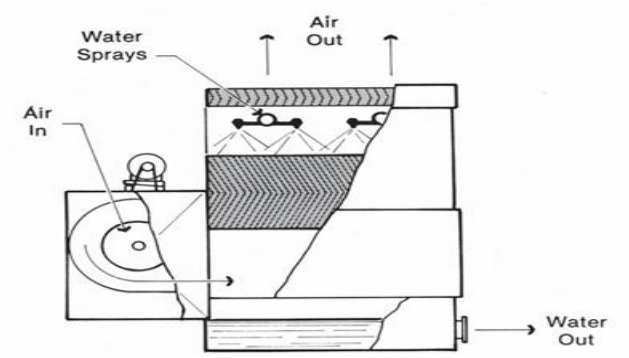


Figure 1. Forced draft cooling tower (Hensley, 2003)

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As shown in Figure 1, air is drawn mechanically through the fill media by an induced- or forced-draft fan while water is distributed from above through a spray or gravity distribution system, so that the two streams meet in a countercurrent pattern as the water falls through the fill. This arrangement is directly relevant to the performance issues discussed later in this study: because heat and mass transfer in a counterflow tower depend on even wetting of the fill surface and unobstructed airflow, any disruption to the water-distribution system (e.g., scaling) or to the fan (e.g., reduced rotational speed or fewer units in operation) directly reduces the effective air–water contact area, providing the physical basis for the effectiveness decline analyzed in Section 3.

Data Colletion

This study used two types of data: design data and actual operating data. Design data were obtained from the operating specification documents, while actual data were obtained through direct field observation during one full operating shift, namely on 24 September 2025, when the system was operating under stable conditions. The parameters collected included inlet water temperature, outlet water temperature, wet-bulb temperature, dry-bulb temperature, water circulation rate, air humidity, fluid density, and other supporting parameters required for the cooling tower performance evaluation. The design and actual data are presented in Table 1 and Table 2, respectively.

Table 1. Cooling tower design parameters

Design Parameter	Value
Water circulation (m³/h)	2600
Inlet temperature (°C)	49
Outlet temperature (°C)	35
Wet-bulb temperature (°C)	29
Dry-bulb temperature (°C)	33,84
Approach ΔT (°C)	6
Range ΔT (°C)	14
Air humidity (%)	70
Fluid density (kg/m³)	991,46

Table 2. Cooling tower actual operating parameters

Actual Parameter	Value
Water circulation (m³/h)	2110,5
Inlet temperature (°C)	44,7
Outlet temperature (°C)	39
Wet-bulb temperature (°C)	25,6
Dry-bulb temperature (°C)	32
Approach ΔT (°C)	13,4
Range ΔT (°C)	5,7
Air humidity (%)	59
Fluid density (kg/m³)	991,45

Data validation was carried out by comparing the field observation results against the design data and by checking the consistency of operating parameters throughout the data-collection period, to ensure that the data used were representative of actual operating conditions and not distorted by transient fluctuations.

Data Analysis

The collected data were analyzed by comparing actual conditions against design conditions. This analysis involved calculating evaporation loss, drift loss, blowdown, make-up water, water mass flow rate, heat loss, range, approach, and cooling tower effectiveness using Equations (1)–(7). The calculated results were then compared with the design data and supported by relevant literature to evaluate the extent of performance decline and to identify the factors influencing cooling-system effectiveness.

Evaporation loss **(W_e)**

$$W_e = 0{,}00085 \; x \; 1{,}8 \; x \; Wc \; x \; \Delta T$$

Where:
We = evaporation loss (m³/h)
Wc = water circulation (m³/h)
ΔT = inlet water temperature (°C) − outlet water temperature (°C)

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Drift Loss **(W_d)**

$$W_d = 0.000002 \text{ x Wc}$$

Where:
Wd = drift loss (m³/h)
Wc = water circulation (m³/h)

Blowdown **(W_b)**

$$W_b = \frac{W_e}{(C.O.C - 1)}$$

Where:
We = evaporation loss (m³/h)
C.O.C = cycle of concentration, chloride ratio range 3–5

Make Up Water

$$W_m = W_e + W_d + W_b$$

Efektivitas kinerja *cooling tower*

$$\text{Efektivitas } \% = \frac{Range}{(Range + Approach)} x\ 100$$

Where:
Range = Tin − Tout
Approach = Tout − Twb

Laju alir massa air (ṁ)

$$\dot{m} = \rho \cdot Q$$

Where:
ṁ = mass flow rate (kg/s)
ρ = fluid density (kg/m³)
Q = volumetric flow rate (m³/h)

Heat Loss **(Q)**

$$Q = \dot{m}\ x\ Cp\ x\ \Delta T$$

Where:
Q = heat rejected (kJ/s)
ṁ = water mass flow rate (kg/s)
Cp = specific heat of water (4.18 kJ/kg·K)
ΔT = inlet water temperature (°C) − outlet water temperature (°C)

RESULTS AND DISCUSSION

Results

Field observation showed that the cooling tower serving the concentration unit was not operating according to its design specification, as indicated by an actual range value lower than, and an actual approach value higher than, their respective design values. This condition was associated with scaling in the water distribution system, water maldistribution, and a reduction in the number of fans in operation, which together limited the effectiveness of the heat-transfer process. These field observations are consistent with the calculated performance parameters presented below.

Cooling tower performance was evaluated by calculating evaporation loss, drift loss, blowdown, make-up water, water mass flow rate, heat loss, range, approach, and effectiveness for both the design and actual conditions. The results are presented in Table 3 and Table 4.

Table 3. Calculated results design condition

Parameter	Calculated Result
Evaporation loss (m³/h)	55,692
Drift loss (m³/h)	0,0052
Blowdown (m³/h)	13,923
Make up water (m³/h)	69,620
Cooling tower effectiveness (%)	70
Water mass flow rate (kg/s)	716,054
Heat loss (kJ/s)	41903,506

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Table 4. Calculated results actual condition

Parameter	Calculated Result
Evaporation loss (m³/h)	18,406
Drift loss (m³/h)	0,0042
Blowdown (m³/h)	4,601
Make-up water (m³/h)	23,011
Cooling tower effectiveness (%)	30
Water mass flow rate (kg/s)	581,238
Heat loss (kJ/s)	13848,566

Comparing Table 3 and Table 4, every water-loss parameter under the actual condition is lower than under the design condition. Evaporation loss decreased from 55.692 m³/h (design) to 18.406 m³/h (actual), while blowdown decreased from 13.923 m³/h to 4.601 m³/h. This reduction lowered the make-up water requirement from 69.620 m³/h to 23.011 m³/h. The actual inlet water temperature was 44.7°C and the actual outlet temperature was 39°C, giving an actual range of 5.7°C lower than the design range of 14°C and an actual approach of 13.4°C, higher than the design approach of 6°C. Cooling tower effectiveness under the actual condition reached only 30%, compared with 70% under the design condition. Overall, every performance parameter evaporation loss, blowdown, make-up water, heat loss, water mass flow rate, and effectiveness was lower under the actual condition than under the design condition, which is consistent with a genuine loss of thermal capacity rather than a mere shift in operating point.

Discussion

Effectiveness is one of the primary parameters used to evaluate a cooling tower's ability to reduce cooling-water temperature. Based on the results, actual effectiveness reached only 30%, compared with a design value of 70%. This gap indicates a substantial decline in the tower's capacity to reject heat to the surroundings. Cooling tower effectiveness is illustrated in Figure 2.

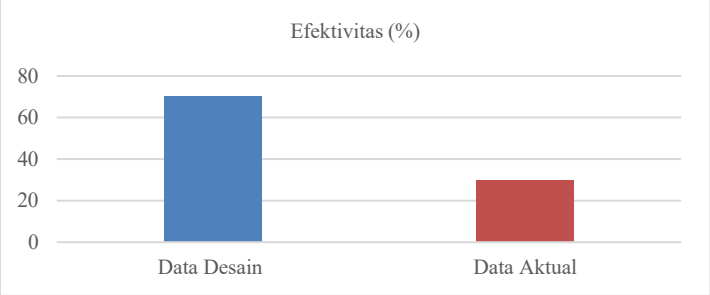


Figure 2. Comparison of cooling tower effectiveness between design and actual conditions

As shown in Figure 2, actual effectiveness reached only about 43% of the design effectiveness. Rahayu (2025) explained that, this value is also well below the typical range of an optimally performing cooling tower, approximately 78–82%. This indicates that heat transfer between water and air was not proceeding optimally, so that a portion of the heat that should have been rejected to the atmosphere remained in the circulating water, resulting in a higher outlet temperature than the design specification. The magnitude of this gap effectiveness at less than half of the design value signals that the degradation is unlikely to be explained by normal seasonal variation in ambient conditions alone, and instead points toward a persistent mechanical or fouling-related cause, which is examined further below. Operating temperature has a substantial influence on cooling tower effectiveness. Inlet water temperature, outlet water temperature, and wet-bulb temperature are the primary parameters that determine the system's heat-transfer capability, as shown in Figure 3.

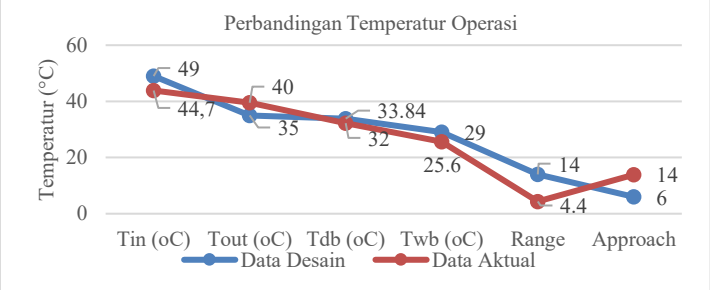


Figure 3. Comparison of cooling tower operating temperatures

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As shown in Figure 3, the actual outlet temperature remained higher than the design outlet temperature, which caused the range to decline and the approach to increase. A low range indicates that the cooling tower's capacity to reduce water temperature has become suboptimal, while an increased approach indicates that the outlet temperature is moving closer to the wet-bulb temperature, which is the theoretical thermodynamic limit the tower can approach but never fully reach. This pattern indicates that heat transfer between water and air was proceeding less effectively than designed (Engineering, 2025). As the approach value increases, the outlet temperature moves further from the ideal operating condition, and cooling-system effectiveness declines accordingly. The relationship between range, approach, and operating temperature is therefore a key diagnostic indicator of cooling tower performance, and the pattern observed here simultaneous range reduction and approach increase is the clearest available evidence that the loss in effectiveness originates in the air–water contact process itself, rather than in the water circulation rate alone.

Field observation indicates that the decline in cooling tower effectiveness was influenced by several operational factors: the formation of scaling, uneven water distribution (water maldistribution), and reduced fan performance. These three factors prevented the heat-transfer process between water and air from proceeding optimally, thereby reducing the cooling tower's capacity to lower water temperature. Scaling on the water distribution system obstructs water flow toward the fill media, resulting in uneven wetting of the fill surface. This condition reduces the contact area between water and air, which in turn reduces both heat transfer and evaporation. In addition, water maldistribution causes part of the fill media to remain insufficiently wetted, further reducing heat-transfer efficiency. This condition is consistent with the observed pattern of increasing approach and decreasing range under actual operating conditions, since both symptoms point to the same underlying cause: a reduction in effective wetted fill area rather than a change in the water or air flow rate itself.

According to Ahluriza, 2022 and Ghamdi et al., 2023 another factor contributing to the performance decline is the reduced number of fans in operation. A reduction in the air supply into the cooling tower lowers the water evaporation rate, thereby reducing the system's capacity to reject heat. The combined effect of scaling, water maldistribution, and reduced fan performance explains why the actual effectiveness fell far below the design condition, since each factor independently reduces the effective air–water contact area, and their simultaneous occurrence compounds rather than merely adds to the total performance loss. Taken together, these findings directly address the objective stated in the Introduction: the decline in cooling tower effectiveness is driven by the operating-temperature relationship between range and approach, and this relationship is itself the downstream consequence of three identifiable physical causes scaling, water maldistribution, and reduced fan performance rather than a single isolated fault. This link between the quantitative performance gap (Section 3.1) and its physical root causes (this section) is the core contribution of this study, and it indicates that restoring cooling tower performance requires simultaneous intervention on all three factors rather than addressing them individually. Regular maintenance of the fill media, water distribution system, water treatment program, and fan units is therefore necessary to restore cooling tower performance toward its design condition.

CONCLUSION

Based on the results of this study, operating temperature was shown to directly affect cooling tower effectiveness through its influence on the range and approach parameters: a lower actual range (5.7°C versus a design value of 14°C) combined with a higher actual approach (13.4°C versus a design value of 6°C) resulted in an actual effectiveness of only 30%, compared with a design effectiveness of 70%. This decline was corroborated by reductions in heat loss, evaporation loss, blowdown, and make-up water relative to the design condition, indicating that the heat-rejection and evaporation processes were not proceeding optimally. The performance decline was attributed to three identifiable operational factors: the formation of scaling, uneven water distribution (water maldistribution), and reduced fan performance, all of which reduced the effective air–water contact area within the cooling tower. These findings confirm that evaluating range, approach, heat loss, and effectiveness together provides a reliable basis for diagnosing cooling tower performance and for prioritizing maintenance interventions in phosphoric acid concentration units.

Recommendation

Based on these findings, cooling tower performance can be improved through periodic cleaning of the fill media, improvement of the water distribution system, scaling control through a water treatment program, and routine fan maintenance, so that the system can operate closer to its design condition. For future research, it is recommended that observations be conducted over a longer period and across varying operating

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conditions, using statistical analysis methods to strengthen the validity of the findings. Further research could also examine the effects of water quality, fouling mechanisms, and air-distribution optimization on cooling tower performance.

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