A Comprehensive Review of Counter-Flow Wet Cooling Towers

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ABSTRACT

Cooling towers are critical components in various industrial and commercial applications, including power plants, refineries, and HVAC systems. They are designed to reject excess heat from processes by evaporative cooling, which involves the exchange of sensible and latent heat between water and air. This paper provides a comprehensive review of the literature on cooling towers, focusing on their modeling, performance analysis, and optimization. The review covers the evolution of mathematical models, from the fundamental Merkel model to more advanced approaches such as the Poppe model and the Effectiveness-NTU method. Additionally, the paper discusses the impact of operational parameters such as air and water flow rates, humidity, and temperature on cooling tower performance. The review also highlights recent advancements in cooling tower design and optimization, including using computational tools like MATLAB and GAMS. Finally, the paper identifies gaps in the current research and suggests future directions for improving cooling tower efficiency and sustainability.

***Keywords*:** *Cooling towers; Merkel model; Poppe model; evaporation loss; Effectiveness-NTU Method; Cooling Tower Performance*

Highlights

1. Mathematical models for cooling towers (Merkel model, Poppe model, Effectiveness-NTU model).
2. Factors affecting the performance of cooling towers, with a focus on operational variables.
3. Recent developments in the design of cooling towers.

INTRODUCTION TO COOLING TOWERS

The cooling tower is one of the important devices used for heat rejection. It is used to reject the excess heat in the fluids to the atmosphere of the gas. Cooling towers are efficient for cooling industrial water influx from moderate to nearly ambient temperatures. It is believed that cooling towers are preferred over other heat exchanger devices economically because they do not require another liquid, such as water, to cool the primary liquid; they use air to cool the fluids. Cooling tower operation depends on evaporative cooling and the exchange of sensible heat. The cooling tower's evaporative cooling results in the loss of a small quantity of evaporated water. The water comes into contact with the air in the tower's fill. When cold air comes into contact with hot water, sensible heat transfer occurs [1,2]. A large quantity of heat is transferred to the cold air through evaporative cooling, while about 25% of the heat is transferred through sensible heat [1].

Cooling towers are typically employed to dissipate heat (similar to a heat exchanger) that is released into the atmosphere during a heat exchange procedure, which cools hot water to a temperature near the wet-bulb temperature. These towers are indispensable components of power plants (including nuclear and steam power plants), as well as oil refineries, petrochemical plants, natural gas processing plants, food industry manufacturers, and air conditioning (HVAC) [3, 4]. The term "cooled tower" includes all equipment that expels direct heat (open circuit) and indirect heat (closed circuit) [5,6]. Open circuit cooling towers consist of a stream of water to be cooled and air currents in direct contact with one another. These towers are referred to as evaporative cooling because a small portion of the hot water

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is permitted to evaporate while a cold air current from the top produces saturated steam. Conversely, closed-circuit cooling towers utilize the reverse process. Antifreeze is required in closed-circuit cooling towers, but not in open-circuit towers

COOLING TOWER THEORY

A moist cooling tower, which is the most prevalent and effective variety of cooling towers, utilizes both sensible and latent heat transfer between the ambient air and the circulating water [7]. The advantage of a Wet cooling tower over an air-cooled heat exchanger is that it can utilize evaporative cooling instead of depending only on the temperature difference between the two media. A fraction of the heated liquid water undergoes evaporation, absorbing energy from the rest of the liquid water and causing a significant decrease in its temperature. This phenomenon may be used to improve the cooling process, as long as the air's moisture level is below saturation at the water's temperature. Even if the surrounding air is already saturated, it can still absorb more moisture if it is heated by contact with hot water. The evaporation-induced water loss is minimal compared to the overall water flow rate, although it is influenced by the specific operating circumstances. The average losses amount to about 1 to 3% of the flow rate of the circulating water, or 1% for every 7 K of range (water temperature change) [8, 9]. Furthermore, apart from the loss of heat via latent means, the direct interaction between the flowing water and the surrounding air also allows for the transmission of noticeable heat. In a conventional cooling tower, the transmission of latent heat is the main factor, but the specific proportion of latent heat transfer to sensible heat transfer varies depending on the operating circumstances.

As the water and airflow through the tower and come into contact, the water cools while the air warms up. The temperature difference between the cooled output water and the input air (wet bulb) is often known as the approach. The approach depends on the fluctuating wet-bulb temperature of the surrounding air, which is influenced by the season and time of day, as well as the desired cold water temperature. Increasing the heat transfer surface area between the water and air inside a cooling tower will reduce the temperature difference between the water exiting the tower and the wet-bulb temperature of the incoming air. In other words, the temperature of the cold water coming out will approach the wet-bulb temperature, thereby improving the cooling tower's efficiency. The range refers to the overall decrease in the water's temperature within the tower. Climate significantly impacts cooling tower performance. High humidity, reflected in elevated wet-bulb temperatures, reduces the effectiveness of evaporative cooling. Therefore, the cooling tower design must consider the anticipated climatic conditions, particularly peak wet-bulb temperatures. A well-designed tower should maintain sufficient cooling capacity such that the design wet-bulb temperature is exceeded only for a limited percentage of the typical hottest summer periods (3-5%). This necessitates a thorough assessment of climatic factors, including peak temperatures and humidity levels, in order to select appropriate cooling tower design parameters. [10, 11].

LITERATURE REVIEW

Merkel (1925) [13] presented the first simplifying assumption mathematical model for cooling tower analysis. Although this model is basic in the knowledge of heat and mass transfer in cooling towers, it ignores some important considerations, such as heat transfer resistance in the water layer. Under some working conditions, **Nahavandi et al. (1975)** [14] showed that the Merkel model might cause mistakes of up to 12%. By considering water evaporation losses, the researchers created a fresh method that increases the analytical accuracy. Based on a more thorough investigation of cooling towers, **Sutherland (1983**) [15] demonstrated that applying the Merkel model might cause under-sizing of the tower by 5–15%. The study also looked at how tower performance was affected by atmospheric pressure; NTU rises with increasing pressure. Introduced the Effectiveness-NTU approach for tower analysis cooling **in 1989, Jaber and Webb** [16] Their research revealed that this approach can be implemented to all kinds of flow (counter-flow, cross-flow, and parallel flow) and fits rather nicely with heat exchanger design theory. The results show when calculating the required NTU for water cooling from 35 ° C to 30 ° C with a humid air temperature entering 25°C, the following results were obtained: Using the LMED method: K_mA/m_w=0.76 and Using efficacy method-NTU: K_mA/m_w=0.74. Developed a mathematical model based on experimental data to examine cooling tower performance in **Dreyer and Ernes (1996)** [17]. The model forecasts transfer characteristics and pressure drop across packing materials; the outcomes revealed that the model fairly forecasts trends in transfer and pressure drop. Proposed an enhanced model that considers heat transfer resistance in the water layer, improving the analysis's accuracy.

Khan and Zubair (2001) [18] The new model, according to the results, lowers tower efficiency error by up to 15%. **Khan et al. (2003)** [19] present a detailed model for analyzing the thermal performance of counter-flow cooling towers, validated against existing literature data. The key finding is that evaporation dominates heat transfer in cooling towers and accounts for up to 90% of all heat transfer at the tower top. The research also revealed that raising the water flow rate lowers general heat transfer efficiency. Examined how fouling affected cooling tower performance with **Khan and Zubair (2004)** [20]. The findings revealed that especially in medium-sized towers, fouling accumulation lowers tower efficiency. Developed a model to examine the effect of material accumulation on cooling tower performance, **Queshi et al. (2004)** [21]. The findings revealed that material buildup might lower tower efficiency by up to 6.5%. Comparatively to the Merkel and Poppe models, **Kloppers and Kroger (2004**) [22] found that the Poppe model is more accurate in examining saturated air. The study advised applying the same approach for the analysis of tower performance as well as fill. **Kloppers and Krüger (2005)** [23] tested several models of mechanical and natural draft cooling towers. Less exact models such as Merkel and NTU produce similar outlet water temperature forecasts, according to the findings. Developed a model to examine water evaporation in cooling towers (**Papaefthimiou et al., 2006)** [24]. The findings revealed that raising the inlet air temperature lowers cooling efficiency by 3% due to low evaporation, increases the rate of water flow to air reduces the total water temperature by 2%, and reduces the cooling efficiency by 2.5%. **Ren et al. (2006)** [25] developed an analytical framework for the study of cooling tower performance. The model lowers the relative error to less than 2% when compared to numerical integration, according to the findings.

Jin et al. (2007) [26] present a simplified model for the study of cooling tower performance. With an error rate of 5.6%, the findings revealed that the model could highly precisely forecast tower performance. **Qi et al. (2008)** [27] created a better mathematical model for the study of cooling tower performance. Particularly in the analysis of water mass loss, the results revealed that the new model is more accurate than previous ones. **Ren et al. (2008)** [28] investigated cooling tower water evaporation. The results revealed that the model is sensitive to the saturation level of the inlet air; lower wet-bulb temperatures boost cooling capacity by 2.25%, while the overall water temperature decrease diminishes with a higher water-to-air mass flow ratio by 3.5%. Developed a model for heat and mass transfer analysis in cooling towers under **Klimanek et al. (2009)** [29] With less than 1% of errors, the model proved consistent with the Poppe model. **Costello et al. (2009)** [30] examined cooling tower performance under constrained running conditions. The optimal performance requires a water-to-air flow rate ratio (L/G) less than 1.0, according to the findings. Using Visual Studio. .NET, **Panjeshi et al. (2010)** [31] developed a model for cooling tower design. Raising the wet-bulb air temperature increases the outlet water temperature, according to the findings. **Ragupathy et al. (2011)** [32] investigated how well-expanded wire mesh packing cooled towers. The results revealed that vertical packing performs better than horizontal packing. **Rubio-Castro et al. (2011)** [33] developed a Poppe model-based optimization method for cooling tower design. Results showed that the evaporation rate using the Merkel method was 1.156 kg/s When using poppe 0.8425 kg/s, the evaporation rate decreased by 27% when using poppe. Developed a technique using operational data for cooling tower performance analysis, **Pan et al. (2011)** [34]. Changing fan positions revealed that power output might rise by up to 260 kW. **Rao et al. (2011)** [35] optimized the design of cooling towers using the artificial bee colony algorithm. According to the results, the algorithm could raise tower efficiency by up to 10.5%. **Picardo and Variyar (2012)** [36] devised a condensed approach for computing cooling tower packing height. Rising excess airflow lowers packing height by 3.5%, according to the findings. **Khamis et al. 2014** [37] Designed fresh correlations for a study on cooling tower performance. The findings revealed that these relationships might enhance operational tower performance. **Nasrabadi et al. (2014a)** [38] investigated low-temperature process cooling tower use. The model could forecast outlet water temperatures with an accuracy of 0.29°C for low-temperature processes and 0.57 °C for high-temperature operations, according to the findings. **Nasrabadi et al. (2014b)** [39] looked at temperate climate cooling tower performance. The studies revealed that towers do better in dry environments. **Singh et al. (2016)** [40] investigated varying fill types' performance in cooling towers. At 25.9%, wire mesh packing offers the best efficiency according to the findings. **Llano-Restrepo et al. (2016)** [41] created a mathematical model for the analysis of cooling tower performance. The model's predictions of mass transfer coefficients revealed accuracy. **Zhou and Ding (2017)** [42] investigated how packing affected Mechanical draft wet cooling towers (MDWCTs cooling tower performance. The findings revealed that packing lowers outlet water temperature by up to 1.5°C. **Forero et al. (2018)** [43] investigated how well wood splash packing cooled towers. Higher water-to-air flow ratios cause a marked drop in tower efficiency, according to the findings. **Mishra et al. (2019)** [44] investigated how adding silica gel mesh to cooling tower performance affected it. The mesh increases the cooling range by up to 2°C, according to the results. Investigated mass and heat transfer in evaporative cooling systems by **Jes et al. (2019)** [45] Analytical solutions found in the results fit numerical solutions rather nicely.

Muthukumar et al. (2019) [46] investigated how well subtropical cooling towers performed. The findings revealed that water loss might reach 4050 liters hourly. **Mustafa Kilic et al. (2020)** [47] present a numerical analysis of a novel cooling tower design incorporating swirling jets to reduce evaporation loss and enhance efficiency. A reduction in air inlet temperature from 40°C to 10°C. decreases evaporation loss by 62% and 81%, respectively. Similarly, decreasing the Reynolds number from 8500 to 3900 also significantly reduces evaporation loss (30%) but leads to a cooling effectiveness decrease (28. 5%). **Shublaq et al. (2020)** [48] investigated how filters (Four types of filters were tested: metal aluminum board, fiberglass, folded primary filters, and glass pocket filters) might help to lower water evaporation loss in cooling towers. The findings revealed that metal filters cut water loss by 17%. **BamiMore et al.**

(2021) [49] investigated how cooling tower performance varied with inlet water temperature. Rising water temperature reportedly increases air moisture content. **Navarro et al. (2022)** [50] assessed inverted cooling tower performance. The Poppe model yields more accurate findings than the Merkel model, according to the results. **Kumar et al. (2023)** [51] investigated how well Celdek-packed cooled towers. The packing increases tower efficiency by up to 58%, according to the findings. Examined the effects of fouling and weather on cooling tower performance **in 2024 Arefimanesh and Heyhat** [52]. The data revealed that fouling lowers water consumption and raises the outlet water temperature. **Navarro et al. 2024** [53] Expected cooling tower performance in concentrated solar power plants compared to theoretical models. The Poppe model turns out to be more accurate than the Merkel model.

SUMMARY

The literature review examined various aspects of the induced draft counter flow wet cooling tower, particularly the factors influencing the system's thermal performance. Many researchers have concentrated on developing established mathematical models such as Merkel, Poppe, and the efficiency method. These models were studied and validated for their accuracy and precision using experimental and theoretical data. Factors affecting the cooling tower's performance were explored, including changes in operating conditions like inlet and outlet water temperature, dry bulb air temperature, wet bulb temperature, water and air flow rates, humidity, air velocity, type and height of fill, cooling tower height, fouling, and the Lewis number. Additionally, some researchers employed programming software, including MATLAB, GAMS, and C++, to analyze these factors. Most of the data used were theoretical and experimental.

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