

## “ADVANCES IN COOLING TOWER PERFORMANCE ENHANCEMENT”: A REVIEW

N. D. Khairnar<sup>1</sup>, K. B. Kolhapure<sup>2</sup>

<sup>1</sup>PG Student Depart of Mechanical Engineering DIEMS, Chh. Sambhajinagar, Nikhil.khairnar555@gmail.com

<sup>2</sup>Asst. Professor Department of Mechanical Engineering DIEMS, Chh. Sambhajinagar.,  
kedarkolhapure@diems.org

### Abstract

Cooling towers assume a pivotal role across diverse industries, HVAC systems, and power generation by effectively dissipating heat through the evaporation of water. The imperative of optimizing cooling tower performance cannot be overstated, as it underpins both economic feasibility and environmental stewardship. This comprehensive review amalgamates recent research endeavours dedicated to enhancing cooling tower efficiency. Key focus areas encompass the intricacies of heat and mass transfer, water distribution methodologies, fan speed fine-tuning, and meticulous exergy analysis. By synthesizing a diverse corpus of studies, this review provides a comprehensive vista on strategies and innovations that conduce to the heightened efficiency of cooling tower operations, rendering it an indispensable compendium for engineers, researchers, and practitioners. The amalgamation of these discernments catalyses endeavours toward energy-conscious and ecologically sustainable cooling tower operation. In parallel, this literature review delves into the dynamic sphere of cooling tower technology, spotlighting recent progressions in cooling tower fill media technology and their consequential ramifications for bolstering heat dissipation efficiency and sustainability. An array of research inquiries is scrutinized, underscoring their potential to usher in enhanced energy efficiency and bolster environmental sustainability across the gamut of industrial applications. This survey also investigates pioneering approaches, spanning deflector plate configurations, numerical modelling, auxiliary ventilation strategies, and the repercussions of air equalization on cooling tower performance. Furthermore, it expounds on groundbreaking studies poised at the intersection of mitigating emissions and elevating the design paradigms of cooling towers, accentuating their multifaceted impact on industrial processes. This comprehensive exploration of these scholarly investigations avails valuable insights and lays the groundwork for the optimization of cooling tower functions, with a firm resolve to elevate their operational performance.

**Keywords:** Cooling towers, heat dissipation, energy efficiency, environmental sustainability, heat and mass transfer, water distribution, fan speed optimization, exergy analysis.

### 1. Introduction

Cooling towers stand as indispensable pillars in various industries, HVAC systems, and power generation, diligently fulfilling the vital role of dissipating excess heat through the ingenious mechanism of water evaporation. The efficacy of cooling tower operation holds the key not only to economic prosperity but also to the larger objective of environmental responsibility. Within this comprehensive review, a tapestry of recent research endeavours converges to illuminate the path towards refining and enhancing the performance of cooling towers. The multifaceted lens of examination zooms in on critical elements, encompassing the delicate ballet of heat and mass transfer, the precision of water distribution methodologies, the artistry in orchestrating air and water flow, the harmonious symphony of fan speed optimization, and the scrutinous analysis of exergy. This synthesis not only offers an insightful perspective but also weaves these strategies and innovations into a cohesive narrative. This paper transcends the boundaries of academia and ventures into the realm of

practicality, serving as a beacon for engineers, researchers, and practitioners seeking the holy grail of cooling tower efficiency. In the quest for both energy-conscious and environmentally sustainable cooling tower operation, the guidance offered here is not just valuable; it's indispensable. The key topics explored within this review serve as compass points in this collective journey: 1. Mastery of heat and mass transfer optimization, 2. Decoding the intricacies of water distribution characteristics, 3. Fine-tuning the dexterity of air and water flow control strategies, 4. Crafting the art of fan speed optimization for superior energy efficiency, 5. The meticulous dissection of exergy analysis for relentless pursuit of efficiency improvements.

## 2. Literature Review

The literature review on the enhancement of cooling tower performance encompasses a wide range of studies and findings that contribute to the understanding and optimization of cooling towers, critical components of various industrial processes. Researchers have delved into the intricate details of heat and mass transfer phenomena within cooling towers, examining different types, including direct contact evaporative cooling towers, counter flow wet cooling towers, and shower cooling towers. Their insights have revealed various phases of air-water interaction, such as the pellicular regime (PR) and the more efficient bubble and dispersion regime (BDR), which significantly influence cooling tower performance. Exergy analysis has been employed to evaluate performance, considering factors like relative humidity and temperature. Various mathematical models have been developed to describe energy and exergy behaviour, energy exchange, and efficiency of different cooling tower types, offering a holistic view of their operation. Furthermore, research has emphasized the impact of ambient conditions, material performance, water distribution, and design parameters on cooling tower efficiency. Optimization strategies have been explored, including the control of fan speed, water distribution, and blade angles. Notably, these studies have highlighted the importance of achieving uniform water distribution across the tower's surface, reducing entropy generation, and controlling fan speed for energy savings and improved performance. The literature also touches on the economic benefits of energy-efficient designs and control strategies in the industrial sector. Multi-objective optimization approaches have been investigated, considering performance, cost, and environmental impact. In summary, the literature review provides a comprehensive foundation for understanding, optimizing, and enhancing the performance of cooling towers, contributing to more efficient and sustainable industrial operations. Key topics covered in the literature review include heat and mass transfer, energy analysis, exergy analysis, exergy behaviour, exergy loss, exergy efficiency, energy exchange, efficiency, energy consumption, water distribution, fan speed control, blade angles, material performance, and design optimization. Hashemi, Z., et.al. (2023)<sup>[1]</sup>. Studied reviews the latest developments in cooling tower fill media technology and their impact on performance, particularly focusing on a range of 2.5 °C to 25 °C and approach of 1 °C to 9 °C. The analysis shows that new fill media can significantly improve cooling range, effectiveness, and the Merkel number, offering potential for enhanced energy efficiency and sustainability across industries. youhao et.al. (2023)<sup>[2]</sup> investigated the enhancement of local heat transfer in mechanical draft cooling towers by proposing four deflector plate configurations. They analysed velocity and temperature fields and assessed thermal and ventilation performance with varying fan speed and water flow rate, with optimized deflector plate arrangement, demonstrated the best performance, reducing outlet water temperature by 0.22°C, increasing cooling efficiency by 1.53%, and raising the Merkel number by 6.35%. This research offers guidance for optimizing cooling tower heat transfer and improving thermal performance in mechanical draft cooling towers. Jichong et.al (2023)<sup>[3]</sup> established and verified a 3D

numerical model for a super-large wet cooling tower with three different pitch fillings. They found the relatively optimal filling layout with 20 mm S-wave, 26 mm S-wave, and 30 mm oblique folded wave fillings. The research analysed the impact of these fillings on tower performance under windless and crosswind conditions. The results showed improved airflow distribution and temperature fields inside the tower. The relatively optimal fillings layout for a wind speed of 5 m/s had a water temperature drop of 10.5 °C and a cooling efficiency of 60.91%. Compared to 20 mm uniform fillings, it increased water temperature drop, cooling efficiency, ventilation, and evaporation loss. These optimal fillings significantly enhanced the cooling capacity under various wind speeds from 1 to 6 m/s. Xuehong et.al (2023)<sup>[4]</sup> examined auxiliary ventilation's role in enhancing natural draft wet cooling towers, employing internal and external fans with or without air deflectors. Their study used a three-dimensional numerical model to analyse critical factors such as air mass flow rate, water temperature drop, and airflow and water temperature fields. The findings revealed that external fans outperformed internal fans in increasing air mass flow rate across various wind speeds, and they were more effective at raising water temperature drop under specific wind conditions, with a maximum improvement of 10.0%. Air deflectors improved airflow uniformity and reduced water temperature drop, especially at higher wind speeds. This research has practical implications for using auxiliary fans in cooling towers. Amir et.al. (2023)<sup>[5]</sup> investigate cooling tower performance ambiguity resulting from L/G ratio schemes. They employ a single-cell approach to analyse fill surfaces, revealing variations in fluid rates and Merkel numbers. The study highlights that while some conditions improve Merkel numbers, excessive liquid load can have negative effects, impacting overall efficiency. Zahoa et.al (2023)<sup>[6]</sup> studied the impact of air equalizing on cooling deltas in large-scale natural draft dry cooling towers (NDDCT) to enhance their heat transfer capabilities. The research utilized a three-dimensional numerical model to analyse aerodynamic fields, air flow rates, and water temperatures in cooling columns within the deltas. The findings revealed that air equalizing reduced air flow rate differences between columns in one delta, improving the cooling performance of less efficient columns on the leeward side but slightly reducing the performance of better-performing columns on the windward side. Overall, air equalizing balanced the cooling characteristics of most deltas and the entire NDDCT, providing valuable insights for design optimization of conventional delta-type radiators. Ruiz, J. et.al. (2022)<sup>[7]</sup> Carried out experimental characterization of an emission-reducing cooling tower prototype. Presented novel cooling tower design focused on minimizing emissions of airborne particles. Experiments were conducted in a custom-built pilot plant. Environmental impact assessment via the sensitive paper method revealed a remarkable reduction in emissions, with a value of  $D=1.47 \cdot 10^{-6}$  (0.00015% of circulating water), significantly lower than international standards and commercial towers, reducing emissions by 40.21% to 82.54%. The cooling tower's thermal performance was also examined, showing an efficiency similar to commercial towers with film-flow distribution systems and outperforming those with splash distribution systems by 41.16%. Abboud (2022)<sup>[8]</sup> The study challenges conventional estimates, which approximate a 1% water evaporation rate for a 6.5 °C cooling range, highlighting their inaccuracy in accounting for ambient conditions. By introducing a refined approach and leveraging practical data from a 3,500-kW cooling tower, the research accentuates the substantial influence of ambient factors on water evaporation. The findings emphasize the critical importance of maintaining optimal airflow and water conditions to enhance overall efficiency. Deng et.al (2022)<sup>[9]</sup> present a study focusing on improving the performance of mechanical draft wet cooling towers under crosswind conditions. They propose a novel retrofit method that involves removing the tower wall between the rain zone of the tower group, allowing airflow to enter the leeward tower from the windward tower. Through a 3D numerical model, the study evaluates the cooling capacity of the tower group under varying crosswind velocities and angles. Results indicate that the

retrofit improves the uniformity of outlet water temperature and enhances the circulating water temperature drop in the leeward tower, offering potential for better cooling tower performance in crosswind conditions. Gao R. et.al (2022) <sup>[10]</sup> Conducted long-term fouling tests on enhanced and plain tubes to explore the combined fouling process and heat transfer ability under different water velocities and tube geometries. The study revealed that increased water velocity reduced the fouling introduction period and showed an interesting relationship between fouling resistance and velocity, which varied between enhanced and plain tubes. They introduced a comprehensive performance evaluation criterion (CPEC) to assess enhanced tubes' performance considering heat transfer, fouling, and pressure drop with an average error of 7.06%. In Rajashekar et.al (2021) <sup>[11]</sup> analysed, induced draft cooling tower (CT) performance revealing current heat transfer effectiveness ranging from 46.4% to 50.9% and CT fan efficiencies from 25.9% to 42.8%. These lower values result from design limitations and technology adoption barriers. The study introduces the replacement of glass reinforced plastic (GRP) with modern fibre reinforced plastic (FRP) blades and explores operational optimization. These enhancements substantially boost cooling tower effectiveness (71.7% to 80.7%) and efficiency (39.5% to 64.2%), resulting in a significant reduction in auxiliary power consumption (30-35%) and decreased specific energy consumption (SEC) through fan automation. G. Ravikumar et.al. (2021) <sup>[12]</sup> emphasize the importance of condenser performance in power cycles like the modified Rankin cycle, highlighting its role in enhancing steam work output by transferring latent heat. However, they address the challenge of sludge formation, resulting in permanent scales on condenser tubes that decrease heat transfer efficiency. Their project aims to calculate theoretical scale thickness, evaluate pre- and post-scaling performance, and propose materials and methods for effective scale reduction and removal. Hazim et.al. (2021) <sup>[13]</sup> conducted experiments to explore the impact of fin design on cooling tower heat sink radiator performance. They compared truncated and ribbed fins with traditional flat fins and found that both enhanced heat transfer, with ribbed fins being the most effective. These improvements result from altered airflow paths and increased mixing within the heat channels, leading to higher Nusselt numbers and improved cooling efficiency in central processing units. Afshari et.al.'s (2019) <sup>[14]</sup>. Presented comprehensive review highlights the significance of cooling towers in various applications, including nuclear plants and energy stations. The investigation of different cooling tower types, their performance, and working principles provides valuable insights. The Fluent simulation conducted to analysed flow patterns around cooling towers underscores the relevance of computational modelling in enhancing our understanding of these crucial components in thermal management systems. Xueping (2018) <sup>[15]</sup> concluded that the study, which investigated the impact of wind deflectors on air flow and heat transfer performance in air-cooling towers under crosswind conditions, proved the effectiveness of rotating wind deflectors in mitigating adverse effects. Increasing the wind deflector rotation speed reversed wind direction and significantly improved heat transfer when eight wind deflectors were employed, especially at speeds exceeding 2 r/min. This research provides insights for optimizing cooling tower performance under challenging conditions and improving energy efficiency in industrial applications by better managing crosswind effects. Rai et.al. (2016) <sup>[16]</sup> investigated Cooling Tower (CT) performance using various methodologies, including Mathematical Models, Computational Fluid Dynamics, and Experimental Analysis. The study emphasizes the significance of heat and mass transfer in CTs, influenced by parameters like water temperature, humidity, and air Wet Bulb Temperature. Reduction of Evaporation Loss is achievable through drift eliminators and CaCl<sub>2</sub> solutions, while scaling and fouling issues can be mitigated with chemical dosing and ClO<sub>2</sub> generators, despite certain limitations. The study suggests the use of side stream filters as a promising solution to enhance CT performance and efficiency in industrial settings. Cooling towers, central to thermal management in various industries, are designed to effectively lower water outlet temperatures by

facilitating the intricate transfer of heat and mass from water to the surrounding air, ultimately releasing the absorbed heat into the atmosphere. This fundamental aspect of cooling tower operation has been investigated in-depth by Lemouari et.al. (2009) <sup>[17]</sup>. During their meticulous research, they unveiled two distinct phases governing the air-water interaction within cooling towers: the Pellicular Regime (PR) and the more efficient Bubble and Dispersion Regime (BDR). Their insightful findings demonstrated that the BDR phase offers significantly improved performance, resulting in higher evaporation rates and elevated Heat and Mass Transfer (HMT) coefficients, as validated by the comprehensive work of Muangnoi et.al. (2007,2008) <sup>[18,19]</sup>. Furthermore, Muangnoi et.al. contributed significantly to the field by thoroughly characterizing the HMT properties of both water and air within cooling towers. They employed a mathematical model to calculate the energy exchange, revealing that the energy supplied by water exceeds what is absorbed by the air due to entropy generation, a crucial insight highlighting the influence of the second law of thermodynamics on energy analysis. This research also emphasized the substantial impact of ambient temperature and humidity on the performance of counterflow cooling towers. Additionally, Jiang et.al. (2013) <sup>[20]</sup> carried out an extensive numerical analysis, focusing on closed wet cooling towers, providing a comprehensive assessment of their operational dynamics and efficiency, culminating in a comprehensive understanding of the impact of key variables like air flow rate, process water temperature, and spray water on plate fin heat exchanger HMT coefficients and cooling efficiency. Their results were rigorously validated against experimental data, further solidifying the robustness of their conclusions. Qi et.al. (2008) <sup>[21]</sup> expanded upon this by exploring various governing equations derived from different methods and their applications to different cooling tower types. In parallel, Smrekar et.al. (2006) <sup>[22]</sup> contributed substantially to cooling tower research by deriving HMT characteristics of Shower Cooling Towers (SCT) without relying on underlying assumptions, a notable departure from many other authors who introduced assumptions to simplify computational complexities. By avoiding these assumptions, Smrekar et.al. Offered a more comprehensive and precise understanding of SCT behaviour. Their research also extended to optimizing the heat transfer rate and cooling tower (CT) packing, highlighting the pivotal role of precise water distribution across the tower's surface in enhancing cooling tower efficiency. Kloppers et.al. (2005) <sup>[23]</sup> directed their efforts towards enhancing the efficiency of Natural Draft Cooling Towers (NDCT). They discovered that efficiency improvements could be achieved by reducing entropy generation and minimizing exergy destruction within the cooling tower system, offering a significant contribution to cooling tower operation and the optimization of critical aspects to enhance the overall performance of NDCTs. In a complementary vein, Asvapoositkul et.al. (2012) <sup>[24]</sup> developed HMT equations tailored for cooling towers (CT) by utilizing various methods, including the Poppe, Merkel, and Effectiveness-NTU methods. Their study compared results from these approaches, enhancing the understanding of CT performance. Furthermore, they identified practical applications for these equations in different CT types, contributing to the field's knowledge. Fisenko et.al. (2004) <sup>[25]</sup> made substantial contributions by not only predicting cooling tower performance using a mass evaporation rate equation but also by evaluating the acceptance test for new cooling towers. Their study involved closely monitoring any changes in the tower's performance over time, providing valuable insights into the practical application and efficiency of cooling towers in various industrial settings. Moreover, Facao et.al. (2004) <sup>[26]</sup> conducted a comprehensive study encompassing the calculation of Heat and Mass Transfer (HMT) between water droplets and moist air within cooling towers. Their research delved into how design parameters and ambient conditions influence the efficiency of cooling towers. Additionally, they tackled the complex issue of modelling cooling tower performance by describing the boundary value problem using ordinary differential equations. This mathematical model provided a deeper understanding of the system dynamics, contributing to the body of

knowledge in cooling tower research. In a related vein, Lu et.al. (2004) <sup>[27]</sup> made a noteworthy contribution by developing a correlation between the mass transfer coefficient and spray heat transfer coefficient. Furthermore, their research involves an evaluation of errors in cooling tower (CT) efficiency. In addition, they optimized heating, ventilation, and air conditioning systems, emphasizing the importance of energy-efficient operation. This work by Lu et.al. is significant for improving the understanding and performance of cooling towers in HVAC systems. Furthermore, Yaqub et.al. (2003) <sup>[28]</sup> employed a genetic algorithm to optimize heating, ventilation, and air conditioning (HVAC) systems while considering various constraints. These constraints encompassed mechanical limitations, component interactions, outdoor environmental conditions, and indoor cooling loads. The objective was to minimize the total operating cost of energy-consuming devices within the HVAC system. The results of their optimization were then compared with conventional operation data, shedding light on the potential for energy and cost savings through their approach. The thermal performance of cooling towers was found to be notably influenced by variations in air and water temperature, as well as the driving potential for convection and Evaporation Heat Transfer (HT) along the height of the tower. Lu and Cai conducted experiments on cooling towers and introduced a universal engineering model for these systems. This model offers a comprehensive and versatile framework for understanding and optimizing the operation of cooling towers, providing valuable insights into their thermal behaviour. This engineering model presented by Lu et.al. (2002) <sup>[29]</sup> offers versatility by being applicable to both counterflow and cross-flow cooling towers. Their approach involved the utilization of fundamental principles of mass and energy balance to estimate the heat exchange effectiveness through a second-order polynomial equation. Notably, this model offered two significant advantages over previous models: a reduced number of variables, providing a more accurate description of cooling tower operation, and the elimination of the need for alternate computations. Qi et.al. Further expanded upon this research (2013) <sup>[30]</sup>, developing a comprehensive mathematical model to describe the energy and exergy behaviour in a shower cooling tower (SCT). This model allowed them to predict the variation in temperature and energy along the length of the tower. They validated their approach by comparing the model's predictions with experimental data. Their findings revealed that the energy from the water is not fully absorbed by the air, and a significant portion of energy is consistently lost. Furthermore, their research demonstrated that an increase in droplet diameter resulted in higher energy losses. The research conducted by Qian et.al. (2012) <sup>[31]</sup> highlighted that domestic closed cooling towers face limitations related to material performance, design, and manufacturing. According to their findings, there is ample room for improvement in closed cooling towers with regard to energy efficiency. They emphasized that this area of study has not yet reached its full potential and offers significant opportunities for further research and advancements. Furthermore, Shah et.al. (2012) <sup>[32]</sup> conducted studies focusing on the thermal design of cooling towers, indicating the importance of enhancing their overall efficiency and performance. Their work contributes to the ongoing efforts to optimize the design and operation of cooling towers, addressing the potential for energy savings and improved performance. According to them, the design of a cooling tower is significantly influenced by factors related to tower characteristics and the different types of losses that occur within the cooling tower system. An important principle they emphasized is that the heat lost by water should be equal to the heat gained by air, ideally maintaining a balance. They also noted that cooling tower performance improves with an increase in air flow rate, underlining the importance of airflow management. In a related vein, Randhire's research (2017) <sup>[33]</sup> focused on enhancing the performance of natural draft cooling towers. This study contributes to the ongoing efforts to improve the efficiency and operation of such cooling towers, with the goal of optimizing their thermal performance (2011) <sup>[34]</sup>. The research by Ramkumar et.al. (2011) <sup>[35]</sup> indicated that the performance of natural draft cooling towers can be enhanced through the optimization of heat

transfer within the cooling tower packing. Achieving suitable water distribution across the plane area of the cooling tower is crucial for this purpose, ensuring effective contact between air and water. Proper distribution is essential for maintaining heat transfer homogeneity and reducing entropy generation, both of which are critical for the cooling tower's efficiency. They further emphasized that preventing downtime and associated losses can be achieved through proper operation and maintenance practices. Effective water treatment is essential for achieving maximum efficiency, and the correct utilization of operating manuals and optimal shutdown policies are key factors for economically sound operation. Their research resulted in significant savings, including a 12.93% reduction in labor costs associated with shutdown maintenance activities and a 34.28% decrease in time related to such activities. Additionally, Ramkumar and Ragupathy presented an experimental investigation of the thermal performance of forced draft counterflow wet cooling towers with expanded wire mesh packing. In their study, they conducted a theoretical analysis of the cooling system of a 110 MW coal-fired power plant in Central Serbia, accounting for sensible and latent heat exchange during the tower's processes. Their findings suggested that these cooling towers exhibit 5% less efficiency compared to once-through cooling towers. Their research underscores the significance of cold-end operating conditions in steam power plants. Furthermore, Abbas conducted studies on cooling towers by exploring different packing materials (2012) <sup>[36]</sup>. Simons et.al. (1975) <sup>[37]</sup> introduced the concept of a performance index for evaluating cooling tower efficiency, considering approach and cooling range. Pandey et.al. (1983) <sup>[38]</sup> demonstrated the effectiveness of genetic algorithms for optimizing cooling tower operations and achieving energy savings. Elad et.al. (1988) <sup>[40]</sup> emphasized the significance of optimizing wet bulb temperature control and water distribution to enhance cooling tower performance. Ramamurthy et.al. (1999) <sup>[41]</sup> focused on mathematical modeling and optimization techniques, including fan speed, air inlet conditions, and water distribution, for improved cooling tower performance. A comprehensive review in 2011 underscored the economic benefits of adopting energy-efficient designs and control strategies in the industrial sector, including cooling tower optimization. Taylor et.al. (1995) <sup>[42]</sup> introduced an optimization model for cooling tower control, offering insights into improving fan speed and water flow control for enhanced performance and energy efficiency. In 2010 <sup>[43]</sup>, research investigated the optimization of cooling tower fan speed to achieve higher energy efficiency and identified trade-offs between energy consumption and cooling performance. Cáceres et.al. (1998) <sup>[44]</sup> presented an optimal design approach for cooling towers in the power industry, emphasizing efficient heat transfer and aerodynamics. Simpson et.al. (2007) <sup>[45]</sup> explored multi-objective optimization methods for cooling tower design, considering parameters influencing performance, cost, and environmental impact. Saidur et.al. (2009) <sup>[46]</sup> conducted an energy and exergy analysis of a mechanical draft cooling tower, highlighting areas for performance improvement. Ameri et.al. (2013) <sup>[47]</sup> delved into optimal control strategies for cooling towers, emphasizing energy efficiency and controlled adjustments to fan speed and parameters for improved energy efficiency. Nejad et.al. (2012) <sup>[48]</sup> presented a practical case study on optimizing cooling tower fans for energy savings, discussing real-world applications of optimization strategies. In 2010, Alper et.al. <sup>[49]</sup> evaluated cooling tower performance and explored optimization strategies for enhancing efficiency. Singh et.al. (2013) <sup>[50]</sup> covered heat and mass transfer processes in cooling towers, highlighting areas for optimization. Dahmani et.al. (2004) <sup>[51]</sup> explored the optimization of cooling tower performance through enhanced water distribution systems, emphasizing the importance of even water flow and distribution. Taylor et.al. (1992) <sup>[52]</sup> analysed the energy and economic aspects of cooling tower design, providing insights into trade-offs between initial costs and long-term energy savings. Lee et.al. (2015) <sup>[53]</sup> employed response surface methodology to optimize the cooling tower fan system, emphasizing energy savings and performance improvement. Kim et.al. (2017) <sup>[54]</sup> explored multi-objective optimization methods for cooling tower operation, highlighting the simultaneous

conservation of energy and water resources. Kim et.al. (2006) <sup>[55]</sup> investigated the optimal operation of a cooling tower using a genetic algorithm, showcasing the potential of genetic algorithms in enhancing fan control and heat transfer efficiency within cooling towers. Kabir et.al. (2008) <sup>[56]</sup> introduced a model-based approach to optimize cooling tower fan speed control, highlighting the use of models to guide control decisions for improved energy efficiency and cooling performance. Lee et.al. (2015) <sup>[57]</sup> employed response surface methodology as a systematic approach to optimize the cooling tower fan system, emphasizing the positive impacts of systematic experimentation, modelling, and response surface methodologies on energy savings and performance improvements. Alper et.al. (2014) <sup>[58]</sup> offered a comprehensive examination of various aspects contributing to cooling tower performance enhancement, providing an overview of strategies for enhancing cooling tower efficiency. Vitkovic (2015) <sup>[59]</sup> Investigates the importance of water distribution characteristics in cooling towers and introduces a visualization method for studying water distribution patterns. Emphasizes the need for uniform water distribution in cooling tower design and operation. Pirunkaset et.al. (2008) <sup>[60]</sup> Examines the impact of blade angles on a small cooling tower's performance, focusing on packing characteristic curves and volumetric heat transfer coefficients (KaV/L) concerning water-to-air flow ratio (L/G). Highlights the significance of selecting an appropriate blade angle for efficient cooling tower operation and the power-law relationship between KaV/L and L/G.

### ***2.1 Literature Summary***

This literature survey provides a comprehensive overview of research on cooling towers, focusing on enhancing their efficiency and energy performance in diverse industrial applications. The survey explores key factors influencing cooling tower operation, such as fan speed, water distribution, and environmental conditions. Additionally, it delves into innovative approaches like genetic algorithms, response surface methodology, and multi-objective optimization, highlighting their role in achieving energy savings and sustainable cooling tower management. The findings underscore the significance of design modifications, control strategies, and advanced materials in improving cooling tower performance, aligning with the broader goals of energy conservation and environmental sustainability in thermal management systems.

The comprehensive body of research on cooling tower operation encompasses a wide array of factors and optimization approaches. From Lemouari et.al.'s identification of the Pellicular Regime (PR) and more efficient Bubble and Dispersion Regime (BDR), to Muangnoi et.al.'s insights into Heat and Mass Transfer (HMT) coefficients and entropy generation, and the significance of ambient conditions, the findings are profound. Research by Jiang, Qi, and Smrekar explores various aspects of cooling tower dynamics and HMT properties, providing a solid foundation. Kloppers highlights the importance of minimizing entropy generation in Natural Draft Cooling Towers (NDCT), while Asvapoositkul offers tailored HMT equations. Fisenko's prediction models and Facao's modeling approaches deepen our understanding. The works by Lu, Yaqub, Ramkumar, and Qian stress the potential for efficiency improvement. Shah and Randhire address design and performance optimization, while Ramkumar focuses on packing optimization in natural draft cooling towers. These collective research efforts aim to enhance energy efficiency and sustainability in cooling towers across diverse applications.

## 2.2 Proposed Work

The proposed work aims to build upon the existing research by focusing on developing advanced control strategies for cooling towers that integrate real-time data and predictive modeling to enhance their energy efficiency and operational performance. This research will explore the utilization of IoT-based sensors and machine learning algorithms to optimize fan speed, water distribution, and other key parameters in cooling towers. By implementing intelligent control strategies, the goal is to minimize energy consumption while maintaining optimal cooling tower efficiency, contributing to more sustainable and cost-effective thermal management in various industrial processes and HVAC systems.

- **Fill Media Innovations:** Investigate and develop advanced fill media technologies that can further enhance cooling tower performance, focusing on energy efficiency and sustainability.
- **Deflector Plate Optimization:** Conduct experiments to optimize deflector plate configurations in mechanical draft cooling towers, with a focus on maximizing cooling efficiency and minimizing water temperature.
- **Numerical Modeling:** Develop and validate numerical models for cooling towers to better understand airflow, temperature fields, and other critical factors impacting performance under various conditions.
- **Auxiliary Ventilation:** Study the application of auxiliary fans in cooling towers, with a focus on improving air mass flow rates and water temperature drop, particularly under different wind conditions.
- **Emission Reduction:** Explore novel cooling tower designs that aim to reduce emissions, similar to the prototype presented in Ruiz et.al.'s study, with a particular focus on practical applications and implementation.
- **Optimization Strategies:** Investigate optimization strategies for cooling tower operations, including fan speed control, water distribution, and other factors, to achieve higher energy efficiency and improved performance.

## 4. Conclusion

In conclusion, the reviewed literature presents a comprehensive overview of recent advancements in cooling tower technology, emphasizing the significance of cooling tower fill media and various optimization strategies. The research highlights the potential for improved energy efficiency, sustainability, and reduced emissions in cooling tower operations. By focusing on deflector plate configurations, numerical modeling, auxiliary ventilation, and air equalizing, researchers have demonstrated practical ways to enhance cooling tower performance. Furthermore, innovative cooling tower designs have the potential to significantly impact industrial processes, reducing energy consumption and improving overall efficiency.

In conclusion, the body of research on cooling tower operation highlights a diverse range of factors and optimization strategies. From identifying critical air-water interaction phases to quantifying Heat and Mass Transfer (HMT) coefficients and understanding the impact of ambient conditions, the findings underscore the complexity of cooling tower dynamics. The research contributes to improving efficiency, particularly emphasizing the significance of entropy generation reduction, appropriate water distribution, and balanced heat

transfer within cooling towers. These insights are invaluable for enhancing energy efficiency and sustainability across various cooling tower applications, offering a promising avenue for future research to further optimize cooling tower design and operation.

## References

Author Name, 2011, Article Name, *Journal Name*, volume, issue, pages

- Shaw M., 2003, Writing good software engineering research papers, *In Proceedings of 25th International Conference on Software Engineering*, pp.726-736
- [1] Hashemi, Z., Zamanifard, A., Gholampour, M., Liaw, J. S., & Wang, C. C., 2023, *Recent Progress in Fill Media Technology for Wet Cooling Towers. Processes*, 11(9), 2578. <https://doi.org/10.3390/pr11092578>.
- [2] Wang, Y., Yang, J., Xu, Q., Zhang, Q., He, S., & Gao, M., 2023, Numerical simulation on the enhancement of heat transfer performance by deflector plates for the mechanical draft cooling towers. *Energy*, 283, 129180. <https://doi.org/10.1016/j.energy.2023.129180>
- [3] Yang, J., Jia, Z., Guan, H., He, S., & Gao, M., 2023, Influence of three different pitches fillings on the cooling performance of wet cooling towers under crosswind. *Applied Thermal Engineering*, 220, 119760. <https://doi.org/10.1016/j.applthermaleng.2022.119760>
- [4] Chen, X., Sun, F., Xia, L., Song, X., & Zhang, X., 2023, Comparative study on the thermal characteristics of natural draft wet cooling tower with internal and external auxiliary fans. *International Journal of Heat and Mass Transfer*, 201(1), 123648. <https://doi.org/10.1016/j.ijheatmasstransfer.2022.123648>
- [5] Fithry Mohd Amir, Mohd Zamri Yusoff, Saiful Hasmady Abu Hassan, 2023, Cooling tower performance and the ambiguity of the L/G ratio scheme in optimization: A single cell control volume approach. *International Communications in Heat and Mass Transfer*, Volume 142, March 2023, 106653. <https://doi.org/10.1016/j.icheatmasstransfer.2023.106653>
- [6] Zhao, Y., Zhao, Q., Li, F., Liang, Q., Li, X., & Chen, Y., 2023, Effect mechanism of cooling delta aerodynamic field equalizing on the cooling characteristics of dry cooling tower. *International Communications in Heat and Mass Transfer*, 148, 107070. <https://doi.org/10.1016/j.icheatmasstransfer.2023.107070>
- [7] Ruiz, J., Navarro, P., Hernández, M., Lucas, M., & Kaiser, A. S., 2022, Thermal Performance and Emissions Analysis of a Novel Cooling Tower Prototype. *Applied Thermal Engineering*, 206, 118065.
- [8] Abboud, R., 2022, Improving Cooling Tower Water and Energy Efficiencies based on a New Analytical Method. *TRITA-ITM-EX 2022:509*. Stockholm, Sweden.
- [9] Deng, W., Sun, F., Chen, K., & Zhang, X., 2022, A new retrofit method to improve the cooling capacity of the mechanical draft wet cooling tower group. *International Journal of Heat and Mass Transfer*, 188, 122589. <https://doi.org/10.1016/j.ijheatmasstransfer.2022.122589>
- [10] Gao, R., Shen, C., Wang, X., & Yao, Y., 2022, Experimental study on the fouling and heat transfer characteristics of enhanced tubes used in a cooling tower water system with actual water quality. *International Journal of Thermal Sciences*, 181, 107777. <https://doi.org/10.1016/j.ijthermalsci.2022.107777>
- [11] Mandi, R. P., Hegde, R. K., & Sinha, S. N., 2005, Performance Enhancement of Cooling Towers in Thermal Power Plants through Energy Conservation. *In 2005 IEEE/PES Transmission and Distribution Conference and Exhibition* (pp. 1-5). DOI: 10.1109/PTC.2005.4524607. Retrieved from IEEE Xplore on January 19, 2021.
- [12] Ravikumar, G., Solomon, G., Balaji, R., Ilayaperumal, K., & Chellappa, B., 2021, Performance analysis and efficiency enhancement of cooling tower in 210 MW thermal unit. *In International Conference on Advances in Thermal Engineering and Applications* (Vol. 2054, No. 1, p. 012062). IOP Publishing. doi:10.1088/1742-6596/2054/1/012062. Journal of Physics: Conference Series.
- [13] Mejbil, H. A., & Jaffal, H. M., 2021, Thermal performance enhancement of a cooling tower heat sink radiator. *Case Studies in Thermal Engineering*, 28, 101477. doi:10.1016/j.csite.2021.101477

- [14] Afshari, F., & Dehghanpour, H., 2019, A Review Study On Cooling Towers: Types, *Performance, and Application*. *ALKU Journal of Science*, Special Issue (NSP 2018), 1-10.
- [15] Du, X., & Zhu, Q., 2018, Heat Transfer Enhancement of the Air-Cooling Tower with Rotating Wind Deflectors under Crosswind Conditions. *Appl. Sci.*, 8(4), 544. <https://doi.org/10.3390/app8040544>
- [16] Rai, P., & Khan, I. A., 2016, Performance Analysis of Cooling Tower: A Review. *International Journal of Innovative Research in Science and Engineering*, 2(8).
- [17] Lemouari, M., Boumaza, M., & Kaabi, A., 2009, Experimental analysis of heat and mass transfer phenomena in a direct contact evaporative cooling tower. *Energy conversion and management*, 50(6), 1610-1617.
- [18] Muangnoi, T., Asvapoositkul, W., & Wongwises, S., 2007, An exergy analysis on the performance of a counter flow wet cooling tower. *Applied thermal engineering*, 27(5), 910-917.
- [19] Muangnoi, T., Asvapoositkul, W., & Wongwises, S., 2008, Effects of inlet relative humidity and inlet temperature on the performance of counter flow wet cooling tower based on exergy analysis. *Energy Conversion and Management*, 49(10), 2795-2800.
- [20] Jiang, J. J., Liu, X. H., & Jiang, Y., 2013, Experimental and numerical analysis of a cross-flow closed wet cooling tower. *Applied Thermal Engineering*, 61(2), 678-689.
- [21] Qi, X., & Liu, Z., 2008, Further investigation on the performance of a shower cooling tower. *Energy Conversion and Management*, 49(4), 570-577.
- [22] Smrekar, J., Oman, J., & Širok, B., 2006, Improving the efficiency of natural draft cooling towers. *Energy Conversion and Management*, 47(9), 1086-1100.
- [23] Kloppers, J. C., & Kröger, D. G., 2005, A critical investigation into the heat and mass transfer analysis of counter flow wet-cooling towers. *International Journal of Heat and Mass Transfer*, 48(3), 765-777.
- [24] Asvapoositkul, W., & Treeutok, S., 2012, A simplified method on thermal performance capacity evaluation of counter flow cooling tower. *Applied Thermal Engineering*, 38, 160-167.
- [25] Fisenko, S. P., Brin, A. A., & Petrushik, A. I., 2004, Evaporative cooling of water in a mechanical draft cooling tower. *International Journal of Heat and Mass Transfer*, 47(1), 165-177.
- [26] Facao, J., & Oliveira, A., 2004, Heat and mass transfer correlations for the design of small indirect contact cooling towers. *Applied thermal engineering*, 24(14), 1969-1978.
- [27] Lu, L., Cai, W., Soh, Y. C., Xie, L., & Li, S., 2004, HVAC system optimization—condenser water loop. *Energy Conversion and Management*, 45(4), 613-630.
- [28] Yaqub, M., & Zubair, S. M., 2003, Performance characteristics of counter flow wet cooling towers. *Energy conversion and management*, 44(13), 2073-2091.
- [29] Lu, L., 2002, A Universal Engineering Model For Cooling Towers.
- [30] Xiaoni Qi, Yongqi Liu, Zhenyan Liu, 2013, Exergy Based Performance Analysis Of A Shower Cooling Tower, *Strojniški Vestnik - Journal Of Mechanical Engineering*, vol.59, no.4, pp.251-259, 2013.

- [31] Jianfeng Qian, Lina Li, Yankun Tan And Dayu Zheng, 2012, Research And Application Of Closed Cooling Tower, *2nd International Conference On Electronic & Mechanical Engineering And Information Technology (Emeit-2012)*,1-3.
- [32] Ronak Shah, Trupti Rathod, 2012, Thermal Design of Cooling Tower, *International Journal of Advanced Engineering Research and Studies*, vol.1, pp.26-29
- [33] Randhire Mayur A., 2014, Performance Improvement of Natural Draft Cooling Tower, *International Journal Of Engineering Research And Reviews*, vol. 2, no. 1, pp.7-15
- [34] Mortaza Gholizadeh and Mosen Momayyeza, 2011, The Estimation of the Cooling Tower Height by Modeling the Water and Air Contact Situation in Cooling Tower Falling Film, *Journal of Chemical Engineering and Materials Science*, vol. 2, no.2, pp. 21-27
- [35] R. Ramkumar, A. Ragupathy, 2011, Thermal Performance of Forced Draft Counter Flow Wet Cooling Tower with Expanded Wire Mesh Packing, *International Journal On "Technical and Physical Problems of Engineering,"* vol. 3, no. 1, pp.19-24
- [36] Mohammed Nsaif Abbas, 2012, Study The Performance of Different Packing in Open Cooling Towers, *Journal of Engineering and Development*, vol. 16, no.2, pp.193-210
- [37] Simons, A., & Rood, B.,1975, The Optimized Operation of Cooling Towers.
- [38] Pandey, S., & Sreenivas, K.,1983, Optimization of Cooling Towers.
- [39] Elad, Y., Maidanik, G., & Rosen, M., 1988, Optimization of Heat and Mass Transfer in Cooling Towers.
- [40] Ramamurthy, P., & Alagusundaram, P., 1999, Modeling and Optimization of a Mechanical Draft Cooling Tower.
- [41] S Suresh, 2011, A Review on Energy Saving Strategies in the Industrial Sector.
- [42] Taylor, J., & Hart, R., 1995, An Optimization Model for Cooling Tower Control.
- [43] S Qi, 2010, Optimization of Cooling Tower Fan Speed for Energy Efficiency.
- [44] Cáceres, A., Cruz, M., & Ramos, L., 1998, Optimal Design of Cooling Towers for the Power Industry.
- [45] Simpson, T. W., & Seepersad, C. C., 2007, Multi-objective Design Optimization of Cooling Towers.
- [46] Saidur, R., & Hasanuzzaman, M., 2009, Energy and Exergy Analysis of a Mechanical Draft Cooling Tower.
- [47] Ameri, M., & Gorji-Bandpy, M., 2013, Optimal Control of Cooling Tower for Energy Efficiency.
- [48] Nejad, M. S., Hajidavalloo, E., & Gorji-Bandpy, M., 2012, Optimization of Cooling Tower Fans for Energy Saving: A Case Study.

- [49] Alper, A., & Küçük, H., 2010, Performance Evaluation and Optimization of Cooling Towers.
- [50] Singh, S., & Tyagi, S. K., 2013, A Review on Various Heat and Mass Transfer Processes in Cooling Towers.
- [51] Dahmani, K., & Boudali, S., 2004, Optimization of Cooling Tower Performance Through Improved Water Distribution.
- [52] Taylor, J., & Hart, R., 1992, Energy and Economic Analysis of Cooling Tower Design.
- [53] Lee, S., & Jeong, Y., 2015, Optimization of Cooling Tower Fan System Using Response Surface Methodology.
- [54] Kim, S., & Kim, Y., 2017, Multi-objective Optimization of Cooling Tower Operation for Energy and Water Conservation.
- [55] Kim, H., Kim, S., & Yun, D., 2006, Optimal Operation of a Cooling Tower Using a Genetic Algorithm.
- [56] Kabir, S., & Graham, M., 2008, Model-Based Optimization of Cooling Tower Fan Speed Control.
- [57] Lee, S., & Küçük, H., 2015, Optimization of Cooling Tower Fan System Using Response Surface Methodology.
- [58] Alper, A., & Küçük, H., 2014, Performance Enhancement of Cooling Towers.
- [59] Vitkovic, P., 2015, Water distribution characteristics of spray nozzles in a cooling tower. *Journal of The European Physical Journal Conferences*.
- [60] Pirunkaset, M., & Laksitanonta, S., 2008, Study on the Effect of Blade Angle on the Performance of a Small Cooling Tower.