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Research Article

Types of Cooling Towers: A Review

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ABSTRACT

Cooling towers are indispensable in dissipating heat from industrial processes and HVAC systems, hence playing a significant role in operational efficiency and sustainability. This review describes the classification of cooling towers based on airflow mechanisms, methods of heat transfer, and applications. This study highlights recent developments in hybrid cooling systems that combine wet and dry cooling technologies for improved water conservation and thermal efficiency. Through the analysis of recent developments in the domain, this work describes innovative design considerations that optimize thermal performances by including environmental concerns; designs that are in the counterflow and crossflow configuration. These insights underline continuous improvements within cooling tower technologies in light of evolving industrial and ecological demands.

1. INTRODUCTION

Power generation, manufacturing, and the operations of data centers are just few of the industries that rely heavily on cooling towers for their cooling needs. In most cases, the working fluid is water, and the goal is to remove any surplus heat from the fluid and transfer it to the atmosphere. In order to transmit heat, a portion of the water evaporates, which then absorbs latent heat and causes the remaining water to cool down. This process is known as heat transfer. Following the cooling of the water, it is recirculated back into the process, which enables the process to continue. In order to keep the process efficiency at its highest possible level and reduce the amount of energy that is used, it is essential that cooling towers will operate reliably. If cooling towers are not optimized, it can result in higher energy expenditures, decreased output, and even the possibility of system failure. Additionally, particular attention is paid to the environmental implications that are involved with the operation of cooling towers, particularly with regard to the consumption of water and the emission of water vapor and pollutants within the environment[1].

2. IMPORTACNE OF COOLING TOWERS

Cooling towers are essential elements in several industrial and commercial operations, enhancing effectiveness, efficiency, and sustainability. The effective heat dissipation system guarantees that operations vital to industries like power generation and manufacturing remain within safe and suitable temperature limits. The technology not only mitigates equipment degradation due to overheating but also augments longevity and boosts the dependability of the integrated system. The energy efficiency of cooling towers substantially decreases operational expenditures. Cooling towers enhance effective heat exchange by employing natural resources, namely water and air. This method decreases dependence on energy-consuming cooling systems, potentially resulting in considerable economic and ecological consequences. This renders them indispensable for companies aiming to augment earnings while reducing their carbon footprint.

Moreover, cooling towers mitigate environmental issues by facilitating water reclamation and reducing thermal and aquatic pollution. Hybrid cooling systems and drift eliminators improve environmental sustainability, along with worldwide initiatives to save resources and mitigate ecological effect. Their capacity to operate well in diverse climates and applications, ranging from arid areas utilizing dry cooling systems to humid settings preferring wet cooling, illustrates their adaptability. The proliferation of corporate premises and the enhancement of urban infrastructure have escalated the

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requirement for effective cooling solutions, underscoring the persistent significance of cooling towers. As corporations shift towards more sustainable technologies, the role of cooling towers will evolve. The use of contemporary materials, advanced sensors, and automated control systems may improve their performance, making them more efficient and sustainable. This groundbreaking capacity reinforces their position as an essential element of industrial and commercial thermal management systems. Cooling towers are vital components in modern engineering and energy management, balancing operating efficiency, environmental responsibility, and adaptability. Their continuous enhancement and execution will be crucial in tackling the requirements of a swiftly evolving industrial and environmental context [8-9].

3. CLASSIFICATION OF COOLING TOWERS

Cooling towers can be classified based on several factors, including:

3.1 Based on air flow mechanism

1) Mechanical draft cooling tower

A mechanical draft cooling tower is an essential heat rejection technique frequently utilized in industrial and commercial settings. The primary role is to dissipate excess heat from processes such as energy generation, HVAC operations, and chemical synthesis into the ambient environment. Unlike natural draft cooling towers, mechanical draft cooling towers employ fans or blowers to improve air circulation inside the system, hence offering enhanced control and efficiency in cooling performance. Cooling towers are categorized into two main types: forced draft and induced draft, as seen in figure (1). In a forced draft setup, fans located at the tower's base drive air through the system. This configuration is appropriate for installations with spatial constraints but frequently need supplementary energy to counteract air resistance. In contrast, induced draft cooling towers utilize fans at the top to extract air through the system. This technique utilizes natural airflow dynamics to improve energy efficiency and facilitate large-scale activities. Mechanical draft cooling towers display differences in airflow configurations. Crossflow cooling towers provide horizontal air circulation over descending water, ensuring uncomplicated maintenance and moderate energy efficiency. Counterflow cooling towers, conversely, drive air upward against the water flow, leading to improved performance in compact configurations, but at a higher initial cost.
The operational principle of a mechanical draft cooling tower relies on evaporative cooling. Hot water from the industrial process enters the tower and is evenly distributed throughout the fill medium, increasing the surface area for air-water interaction. Fans promote air circulation inside the fill medium, hence improving heat transfer during water evaporation and cooling the remaining water. The cooled water collects in a basin at the bottom and is then recirculated into the system for reuse. The fundamental components of a mechanical draft cooling tower are fill media for enhanced heat transfer, fans for airflow circulation, drift eliminators to minimize water loss, and a water distribution system for uniform coverage. The tower's shell protects the inside components while enabling effective ventilation. Mechanical draft cooling towers provide significant advantages, including compactness, efficiency, and adaptability to various climatic conditions. They are widely employed in power generation facilities, petrochemical industries, and large HVAC systems in commercial buildings. When selecting a cooling tower, it is crucial to assess factors such as heat load, water flow rates, ambient temperatures, and energy efficiency to optimize performance and minimize operational expenses [10].

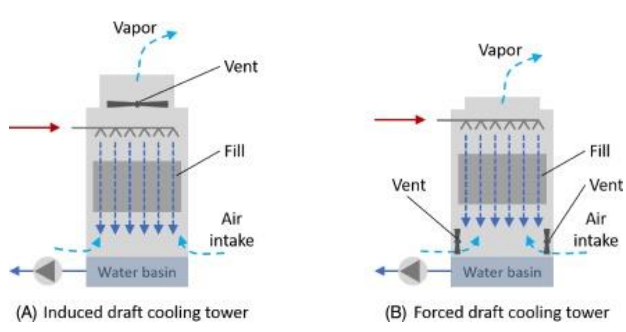

Fig.1. Mechanical draft cooling tower

Ruiz et al. [11] examined evaporation loss and drift deposition from mechanical draft wet cooling towers and created a drift deposition model to analyze the influence of Legionnaires' disease in urban settings. Their model predictions demonstrated strong concordance with the experimentally obtained facts. Fisenko et al. [12] established a mathematical model that enhances the efficiency of a mechanical draft wet cooling tower across varying meteorological conditions. Wetter [13] created a model employing a static mapping approach to examine the performance of a York cooling tower.

Sanchez [14] quantitatively forecasted the lifespan of droplets released by mechanical draft wet cooling towers and examined the concern of Legionnaires' illness.

A natural draft cooling tower is a cooling tower that utilizes the natural movement of air to enhance the cooling process, as seen in figure (2). In contrast to mechanical draft cooling towers that utilize fans or blowers for air movement, natural draft towers rely on the disparity in air density resulting from temperature variations between the heated water and the ambient air. This thermal buoyancy enables warm, wet air to ascend, subsequently being supplanted by colder air from the surrounding environment, therefore generating a passive circulation through the tower. The configuration of a natural draft cooling tower often exhibits a substantial, cylindrical form, commonly known as a hyperboloid design, which optimizes the vertical movement of air. The heated water from the industrial process is injected at the apex of the tower, where it is disseminated across fill media or splash bars. As the water flows down the tower, a portion evaporates, extracting heat from the residual water and therefore cooling it. The ascending warm air transports moisture, while the cooled water is gathered in a basin at the bottom for recirculation.

Natural draft cooling towers are especially efficient for large-scale applications, such as power stations, where substantial cooling capacity is required. They are frequently selected for their minimal running expenses, as they do not need energy-intensive fans. Nonetheless, the preliminary construction expenses may be considerably elevated owing to the dimensions and intricacy of the tower's design. Furthermore, natural draft towers need particular climatic conditions, including a consistent temperature differential between the water and the air, to operate well [15].While natural draft cooling towers are highly energy-efficient due to their reliance on natural forces, they tend to be less adaptable to changing heat loads compared to mechanical draft systems. They are also less common in urban environments due to their large size and visual impact. Nevertheless, they remain a preferred choice for industries where long-term operational savings and large-scale cooling are priorities.

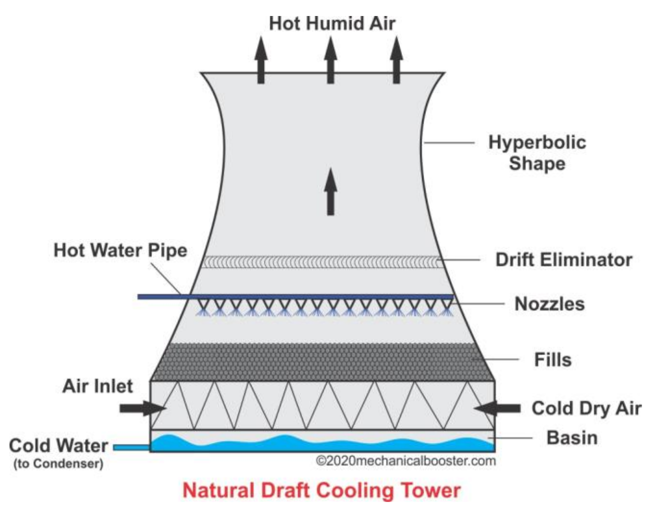

Fig.2. Natural draft cooling tower

Kloppers and Kroger [16] investigated effects of the Lewis factor on thermal energy transfer performance of natural and forced draft WCTs. They explained the relation between the Lewis factor and the Lewis number (ratio of thermal diffusivity to diffusion coefficient). They concluded that in the cases of relatively warm and humid inlet ambient air, effects of the Lewis factor on the performance assessment of WCTs decrease. In addition, after enhancing the Lewis factor, the temperature of outlet water and water evaporation rate decrease, while the heat rejection rate increases. Smrekar et al. [17] showed that the efficiency of natural draft cooling tower could be increased through optimization of the thermal energy transfer across the CT. They analyzed the water transportation mechanisms across the CT and subsequently suggested correlations in order to find an optimum ratio of water to air flow rates. Furthermore, the experimental study of ceramic tile packing and its influence on the CT performance was first carried out by Elsarrag [18]. l-Waked and Behnia [19] investigated the influence of wind break walls on the thermal performance of natural draft wet cooling towers under cross-wind through the three dimensional CFD modeling. Eventually, it was concluded that the NDWCT performance could be enhanced by installing solid walls at the entry of the NDWCT. In addition, Lemouari et al. [20] carried out experiments on heat transfer performance of a cooling tower with different parametric studies and yielded a similar model to that of Gharagheizi [21].

3.2 Based on Heat Transfer Mechanism

1) Wet Cooling Towers

In wet cooling towers, water is sprayed or trickled over fill media, increasing the surface area for heat transfer. Air passing through the tower causes water evaporation, effectively carrying away the heat as shown in figure (3). This method achieves excellent cooling efficiency and is widely used in industrial and HVAC systems. However, it requires a significant water supply and may result in drift (small water droplets escaping into the atmosphere) [22]. To mitigate these, drift eliminators are often installed. Wet cooling towers are unsuitable for regions with water scarcity or strict environmental regulations.

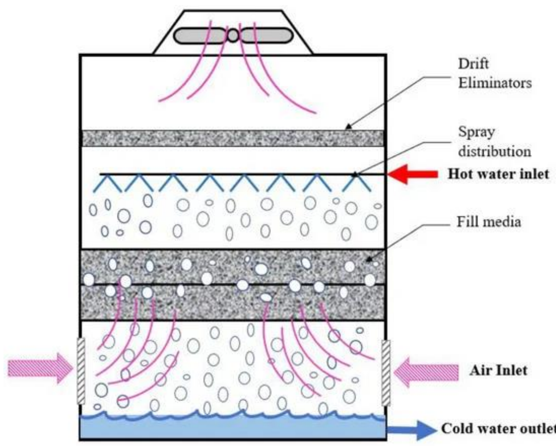

Fig.3. Wet cooling tower

Alavi et al. [23] examined the efficacy of heat transfer in counter-flow NDWCT in both cross-wind and windless situations using a wind-creator apparatus to replicate the authentic properties of the natural wind speed profile. This research examined the impact of water flow rate, crosswind velocity, fill thickness, and inlet water temperature on the variance and efficacy of water temperature. Saad et al. [24] conducted an experimental investigation on the performance of a natural wet cooling tower. The impacts of fill type, nozzle diameter, and water flow rate were analyzed. The model's measurements were: top outlet diameter (370 mm), bottom diameter (680 mm), and height (850 mm). Three examples were examined for film and splash fills. The thickness for film fill types was 60, 90, and 120 mm, but for splash fill, it was 30, 45, and 60 mm. The performance criteria of the tower, including temperature range, approach, efficacy, and Merkel number, were examined. Zhigang et al. [25] performed a three-dimensional numerical simulation to examine the thermal performance of a large-scale NDWCT with varying fan diameters and speeds. The findings indicated that an increased fan diameter resulted in enhanced cooling efficiency and improved air flow homogeneity. They determined that the utilization of a fan improves the efficiency of the cooling tower.

2) Dry Cooling Towers

Dry cooling towers, or dry coolers, are cooling towers that utilize air to chill a working fluid without relying on water evaporation. They constitute a closed-circuit system, signifying that the working fluid is perpetually cycled through a heat exchanger and returned to the process. The heated working fluid, usually water or glycol, circulates via a series of tubes within the heat exchanger, as seen in figure (4). Fans circulate ambient air over the heat exchanger fins, which are affixed to the tubes. The thermal energy from the heated fluid is sent to the cooler air via the fins, therefore reducing the fluid's temperature. The cooled fluid is subsequently fed back into the process for reheating and recirculation. Dry cooling towers have several benefits. They are ecologically sustainable since they preserve water, particularly in areas experiencing water scarcity. They need minimal upkeep as water treatment and scaling prevention are unnecessary. Furthermore, they frequently exhibit diminished running expenses owing to decreased water and energy utilization. Moreover, they exhibit greater reliability as they are less prone to fouling and corrosion problems linked to water-based cooling systems. Nonetheless, dry cooling towers possess some drawbacks. They are often less efficient than wet cooling towers, as they depend exclusively on air for heat transmission. The initial expense of a dry cooling tower is generally more than that of a wet cooling tower owing to the intricate construction of the heat exchanger. Additionally, dry cooling towers need a bigger size to handle the considerable surface area of the heat exchangers [26].

Dry cooling towers are employed in many applications, such as power plants for condensing steam from turbines, industrial operations for chilling various fluids in manufacturing facilities, and data centers for dissipating heat produced by servers and other IT equipment. Although dry cooling towers have many benefits, their diminished efficiency and elevated initial expense need careful evaluation when choosing a cooling system.

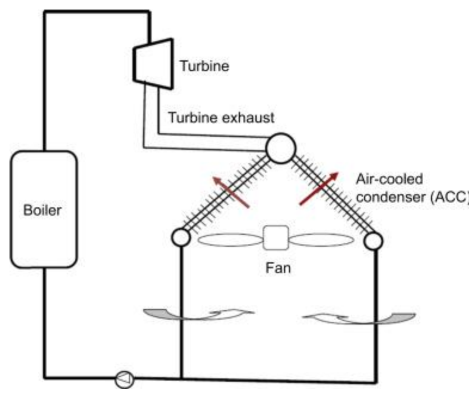

Fig.4. Dry cooling tower

3) Hybrid Cooling Towers

Hybrid cooling towers are a novel technology that integrates the advantages of both wet and dry cooling systems. These towers are engineered to enhance cooling efficiency while mitigating the constraints of each method. Hybrid cooling towers combine the concepts of wet evaporative cooling with dry air cooling to achieve a balance among water saving, cooling efficiency, and operational flexibility. This renders them especially appropriate for settings with fluctuating climatic conditions or operating requirements [27].

The operation of hybrid cooling towers incorporates both dry and wet cooling methods. In the desiccated part, the heated fluid is pre-cooled by air while traversing finned heat exchanger tubes, as seen in figure (5). This lowers the fluid's temperature without requiring water evaporation. The partially cooled fluid subsequently transitions to the wet portion, where it experiences evaporative cooling for additional temperature decrease. This dual-process system facilitates efficient operation while minimizing water use. In lower conditions or times of less heat demand, the dry portion alone suffices to fulfill cooling needs, hence conserving water completely. During elevated cooling needs, the wet part engages to enhance heat rejection. Hybrid cooling towers have several benefits. They markedly decrease water usage relative to conventional wet cooling towers, as the dry section can manage a portion of the cooling load. Furthermore, they sustain superior cooling efficiency under diverse environmental conditions by successfully using both processes. A further advantage is plume abatement, since hybrid systems can mitigate or eradicate visible water vapor plumes by decreasing dependence on evaporative cooling in colder conditions. Moreover, these systems exhibit significant adaptability and may be tailored to emphasize water conservation, efficiency, or cost-effectiveness based on particular requirements. Notwithstanding these benefits, hybrid cooling towers provide specific obstacles. Their initial installation expenses are elevated owing to their intricate design relative to traditional systems. Hybrid cooling towers are utilized in sectors where dependable and effective cooling is vital, and environmental factors are significant. These sectors encompass power generation facilities, chemical processing plants, and HVAC systems in regions where water shortages or plume mitigation is paramount. Urban places with stringent environmental laws also get advantages from hybrid systems, which mitigate issues associated with water use and visible emissions [28].

The hybrid cooling system can limit the water consumption only to the periods when the ambient temperatures are too high. Heyns [29] introduced a forced draft hybrid dry/wet dephlegmator (HDWD) suitable for the small-scale power unit and investigated its performance. Owen [30] conducted a parametric investigation on the induced draft HDWD to improve the basic design proposed by Heyns. The steam-side pressure drop calculation was integrated by Anderson [31,32], and the more accurate thermal performance was predicted. Hu et al. [33] proposed a separated type of mechanical dry cooling and wet cooling system and calculated the performance during a year

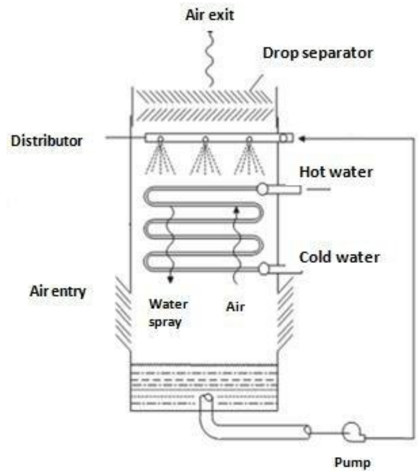

Fig.5. Hybrid cooling tower

3.3 Based on Application

1) Industrial Cooling Towers

These towers are designed to handle large heat loads typical of industrial processes, including power generation, petroleum refining, chemical manufacturing, and steel production. Industrial cooling towers often operate continuously and are engineered for durability under harsh operating conditions. They may be natural draft or mechanical draft, depending on the heat rejection requirements and site-specific constraints [34].

2) HVAC Cooling Towers

HVAC cooling towers are used to reject heat from water-cooled chillers in commercial and residential air conditioning systems. They are typically smaller than industrial towers and designed for intermittent operation. These systems are commonly found in hospitals, office buildings, and shopping malls, where maintaining indoor air quality and temperature control is critical [34].

3.4 Based on Airflow Configuration

1) Crossflow Cooling Towers

Crossflow cooling towers are a type of cooling tower where air flows horizontally across the falling water as shown in figure (6), creating a perpendicular interaction between air and water streams. This design allows for efficient heat exchange and easy access for maintenance. In a crossflow cooling tower, hot water enters through the top and is distributed over the fill media by gravity, using a network of nozzles. Meanwhile, air is drawn horizontally through the sides of the tower, either by natural draft or with the assistance of fans typically located at the top or sides. This configuration minimizes air pressure drops, making crossflow towers energy efficient. The exposed water distribution system also simplifies inspection and upkeep. Crossflow cooling towers are widely used in industries requiring substantial heat dissipation, such as power generation, chemical processing, and large-scale HVAC systems, due to their effective performance and ease of operation [35].

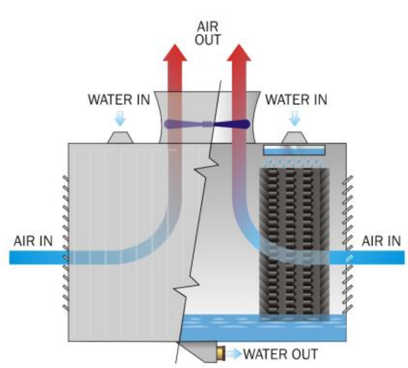

Fig.6. Cross flow cooling tower

Niitsu et al. [35] tested the performance of the plain and finned tubes, including the film heat transfer coefficient and air-water mass transfer coefficient. Experimental tests by Heyns and Kröger [36] showed the water-film heat transfer coefficient was a function of spray water temperature, spray water and air flow rates, while the air-water mass transfer coefficient was a function of air and spray water flow rates. Sarker et al. [37] assessed cross flow wet cooling towers CWCTs with staggered arranged bare-type or finned tubes, from the perspectives of cooling capacity, wet-bulb efficiency and pressure drop. Experimental tests showed that the fin-tube CWCT had better thermal performance although the pressure drop was higher than that of the bare-tube one. Zheng et al. [38] investigated the thermal behavior of an oval tube CWCT under different operating conditions. The results showed that the oval tube had a better combined thermal hydraulic performance.

2) Counterflow Cooling Towers

In this design, air flows upward against the downward flow of hot water as shown in figure (7), maximizing heat transfer efficiency. Warm water is distributed over fill material at the top, which increases surface area for heat exchange. Air is drawn upward by large fans, absorbing heat from the water through evaporation. The cooled water is then collected at the bottom and returned to the system for reuse. The counterflow arrangement enhances heat transfer by maximizing contact time between water and air. Counterflow cooling towers offer several advantages. They are highly efficient due to the large contact area between water and air, allowing more heat to be absorbed. The design also makes them compact, requiring less space compared to crossflow towers. They perform well in hot climates, as the countercurrent flow allows hotter water to encounter cooler air, improving heat absorption. Additionally, these towers are energy-efficient, requiring less fan power compared to other designs. However, counterflow cooling towers have some drawbacks. They tend to be more expensive to build due to their complex design and specialized materials. Maintenance can also be more challenging because of their vertical structure and complex airflow management. Noise from the large fans can be an issue in noise-sensitive areas [39].

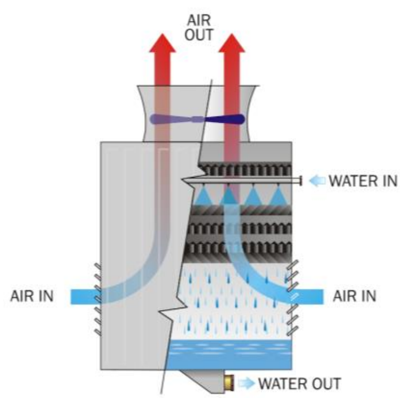

Fig.7. Counter flow cooling tower

Heyns and Kröger [40] examined the thermal-flow performance characteristics of evaporative coolers and established that the counterflow design results in superior heat transfer efficiency relative to alternative cooling tower configurations. Their studies indicated that counterflow towers provide superior cooling capability, since the hotter water interacts with colder air, facilitating more heat absorption from the water. Moreover, research indicates that the compact configuration of counterflow cooling towers renders them especially appropriate for scenarios with spatial constraints. Zheng et al. [37] examined the thermal efficiency of closed wet cooling towers utilizing oval tubes, demonstrating that counterflow systems may achieve superior efficiency while requiring less area compared to other designs, such as crossflow towers. The system's compactness, together with the countercurrent flow, enhances its performance under elevated thermal loads and in high-temperature environments. Nevertheless, notwithstanding their benefits, counterflow cooling towers has certain limits. A notable difficulty is the elevated initial installation cost. The intricacy of the design and the requirement for specialist materials for the fill and framework result in elevated initial expenses. Furthermore, these towers may provide greater maintenance challenges owing to their vertical configuration, necessitating more regular cleaning and oversight of interior elements such as the fill material and fans. Sarker et al. [37] investigated improvements in cooling capacity inside hybrid closed-circuit cooling towers, demonstrating that although counterflow towers exhibit great efficiency, they need meticulous maintenance to sustain maximum performance.

4. CONCLUSIONS

This study provides a comprehensive overview of the various types of cooling towers and their operational mechanisms. Mechanical draft cooling towers deliver controlled performance suitable for various industrial applications; however, natural draft systems excel in large-scale operations by minimizing energy consumption. Hybrid cooling towers demonstrate the combination of efficiency and sustainability, making them crucial for addressing water scarcity and environmental challenges. The findings underscore the importance of adopting advanced designs, such as crossflow and counterflow systems, to improve heat management efficiency. Future research should focus on integrating intelligent technologies, enhancing material durability, and investigating environmentally sustainable innovations to improve the sustainability and flexibility of cooling towers across various settings.

Conflicts Of Interest

The author's paper explicitly states that there are no conflicts of interest to be disclosed.

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