Evaluation of forced cooling tower thermal performance

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Yassin Mohammed Mustafa, Adnan Mohammed Hussein
Kirkuk Technical Engineering College/ Northern Technical University
.Renewable energy research center Kirkuk, Northern Technical University, Iraq
Corresponding author: Email: yassen.mohamdegs2022@ntu.edu.iq

Abstract

This article discusses an experimental analysis of the heating effectiveness of a forced cooling tower (WCT) using dimensions (15X15X80) cm, as well as the effect of water inlet temperatures (60, 50, 55, 40, 45, 35) degrees Celsius, different air velocities (2.15, 15.3, 4) m/s, and water flow rates (4, 6, 8, 10) liters/min, where the current work addressed an experimental investigation of the efficacy of the evaporative cooling tower. for pure water. Using cardboard packaging with holes and inclined divisions of (15X15X60) cm, which provides a uniform distribution of water to augment the surface area for heat and mass transmission process, the experimental Results indicated the thermal performance, cooling rate (range), approach, and tower efficacy, and cooling capacity are affected by, he elements listed above, as well as the fact that raising the temperature of the incoming water water increases the cooling rate, increasing the approach increases the water flow rate, and decreasing the efficacy. At a temperature rise of (55, 60) Celsius and a flow rate of 4 liters/min, the cooling rate rose by 5%, while the efficiency improved by 6%.

Keywords: cooling tower, performance , effectiveness. pure water .

Nomenclature

Q_L	Heat capacity (Kw)	Eff %	effectiveness
Cp_w	Specific heat ($J/\ kg\ .K$)	Tdbi	dry-bulb temperature of incoming air, [^oC]
$m_l^{\cdot}$	liquid flow rate, [$kg.\ s\ -1$]	Tdbo	dry-bulb temperature of exhaust air , [^oC]
ΔT	water temperature difference, [^oC]	Twbi	Inlet air wet-bulb temperature , [^oC]
$m_a^{\cdot}$	air flow rate, [$kg.\ s\ -1$]	Twbo	wet-bulb temperature of exhaust air , [^oC]
Tw_i	inflow water temperature , [^oC]	Cp_a	heat capacity of air, [$J.\ kg-1\ .K\ -1$]
Tw_o	discharge water temperature , [^oC]	V	Flow rat (L /min)
a	Area of fan m^2	A	Area of cooling tower m^2
wct	Wet cooling tower	D	Diameter of fan inch

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1. Introduction

Technical literature originally described the cooling tower in the late 19th century. Power stations, petrochemical plants, oil refineries, and central air conditioning systems employ cooling towers. In industrial operations, water transfers heat from coolant or heat exchangers to cooling towers. The cooling tower dissipates heat from water through thermal exchange and convection.to the air. This is called evaporative cooling because the tower is packed with high-quality, waterproof hardwood panels, aluminium, or plastic for a wide surface area. To cool water, spray nozzles or a thin coating of water (film) covering the tower pad enhance the interface between water and air, exposing more water to the air entering the tower. Thus, cooling towers transport thermal energy transfer from the water to the external environment by lowering its temperature to the wet bulb temperature[1].

Evaporative cooling towers are categorised according to their mechanisms for heat extraction from incoming water and subsequent atmospheric discharge, as well as the water circulation methods employed within them. They can be either open or closed. Open cooling towers can be classified as either natural or mechanical, utilising spray as its operational mechanism. Water cascades from the tower's apex across an extensive surface area, facilitating enough interaction with the ambient air, resulting in the evaporation of a segment of the flowing water , so directly transferring heat to the environment [2-3].

Numerous historical applications exist for Alternative means of evaporative heat removal, including cooling towers, industrial processes, refrigeration cycles, and power generation, generate substantial quantities of waste heat. Cooling towers and other evaporative cooling devices function by exposing water to air that is not fully saturated. Mass transfer happens when a gas and a liquid exhibit differing vapors pressures. The air becomes increasingly hot and humid as water evaporates and cools [4-6].

The three main categories of cooling towers are characterized by their configurations: parallel, crossflow, and counterflow. In wet cooling towers, the processes of mass transfer and heat transfer occur within the fill, spray, and rain zones. Two principal types of cooling systems incorporate fans, utilizing both mechanical and natural airflow for cooling purposes [7-9] .

A cooling tower is an apparatus. That reduces the thermal measurement of a fluid by transferring thermal energy from the fluid to the surrounding air [10].

Wet cooling towers are the exclusive mechanism for transferring waste heat in industrial thermodynamic cycles. Administering and improving their account is challenging. Air and water transmit mass and heat in distinct manners. This research investigated atmospheric mass. The effects of flow rate of water, temperature of hot water, and fill stage number on cooling tower performance were evaluated. We highlight phase numbers and their correlation with packing density. The results indicated a clear correlation with the efficiency factor. Heating water impedes air mass movement and filling. There are methods to achieve the highest score. Induced draft wet cooling tower [11-12].

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Kloppers and Krüger [13] investigated the efficiency of heat transport in both natural and used wet cooling towers under pressure to assess the influence of the Lewis factor. International trade agreements are said to serve as a model for efficiently coordinating thermal and mass-energy exchange.

The performance of a WCT flow meter is assessed using exergy analysis and the principles of the second law of thermodynamics, focussing on the effects of inlet temperature and humidity. The research examines a cooling tower using a closed cross-flow design, characterised by a finned tube arrangement. The research is based on experimental and numerical methodologies. The researchers performed a comparison analysis to assess the relative advantages of bare tube and finned tube designs in terms of thermal efficiency. Furthermore, the study investigated the impact of spray-type rotary packing on the counter flow dynamics of forced draft. The article is named "Wireless Charging Technologies" and was written by Lavasani et al [14].

Evaluated the efficacy of trickle, film, and splash completes a compelled draught humidification cooling tower. By considering the air and water mass flow rates, researchers were able to build robust correlations for performance metrics utilising experimental data. Additionally, a Non-Dominated Sorting Genetic Algorithm was employed to optimize the forced draught Shahali et al., [15].

Ning et al., [16] conducted a research to investigate the influence of spray-type rotational packing on the thermal performance of a counter flow mechanical water-cooling tower. They determined that employing a more rapid rotary jet filling technique might enhance the heat transfer process. They subsequently conducted an experimental study to ascertain the impact of packing or nozzle configuration on the thermal performance of the WCT.

2. Determinants of Cooling Tower Operational Effectiveness

The effectiveness of a cooling tower is determined by a variety of factors. Key parameters that affect this effectiveness include the rate of water circulation, the volume of air flow, the cooling capacity, the conditions of the surrounding air, the temperature of the water, and the design of the tower, which encompasses its dimensions, components, and materials. Critical aspects also include scale, mobility, proximity, and the wet bulb temperature [17].

2.1: Thermal Load

The determination of the heat resistance coefficient and the design heat rejection load is essential prior to the selection of an appropriate cooling tower. The heat load reflects the necessary cooling capacity for the recirculating water within the tower. Te cooling area of the system is directly proportional to the product of the water circulation rate and the cooling range. The quantity of heat removed has a direct impact on both the cost and dimensions of the cooling tower, which is crucial for maintaining a low temperature necessitates a cooling tower, and a smaller tower results in reduced expenditures on maintenance and repairs [18].

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2.2. Wet Bulb Temperature

The thermometer coil in water indicates the ambient temperature, referred to as the 'wet bulb temperature.' A filament collects atmospheric moisture and radiates heat. Air circulates through the filament, vaporising water. The filament can discharge only a finite amount of moisture under conditions of elevated humidity. Dry bulb temperature (DBT) is a measurement obtained from a non-saturated thermometer. A table of air characteristics and a psychrometric chart can be utilised to The evaluation of air properties necessitates a comparison between wet and dry bulb temperatures. It is essential that the temperature of the components within our cooling tower remains below the external wet bulb temperature account the standard summer wet bulb temperature when constructing a tower system. Forced draft towers are advantageous due to elevated intake and reduced output air velocities. This mostly dictates the efficacy and dimensions of evaporative cooling towers. Constructing cooling towers for a designated function: Water must be recirculated to achieve 'nearly bulb humidity [19] .

2.3: Range and Approach

The thermometer coil displays the ‘wet bulb temperature’ in water. Air-moistured filaments emit heat. Air evaporates water through the filament. Under high humidity, the filament can only discharge so much moisture. Unsaturated thermometers measure dry bulb temperature (DBT). A psychrometric chart and air properties table may compare wet and dry bulb temperatures to determine air characteristics. Cooling tower objects should be colder than the outside wet bulb. Consider the average summer wet bulb temperature when developing a tower system. High input and low output air velocities favour forced draft towers. This largely influences evaporative cooling tower size and performance. Building cooling towers at ‘almost bulb humidity’ requires water recirculation [20].

2.4: Thermal efficiency

Thermal performance, the proportion of actual heat produced to theoretical maximum temperature is an important cooling tower performance parameter. The following equation defines closed-circuit cooling tower thermal efficiency [21].as in equation (1) :

$$\%Eff = \frac{Twi-T}{Twi-Twbi} \qquad (1)$$

Temp of the wet bulb is Twbi ºC temperature of cold water is Two ºC.

Twi is temperature of hot water °C, Approach= Water-wet bulb temperatures during cold.

Range = Temperature of Hot Water - Temperature of Cold Water, Thus, Equation shows cooling tower thermal efficiency (2):

$$\%\ \text{Eff.} = \frac{\text{Range}}{\text{Range} + \text{Approach}} \qquad (2)$$

3. Experimental setup

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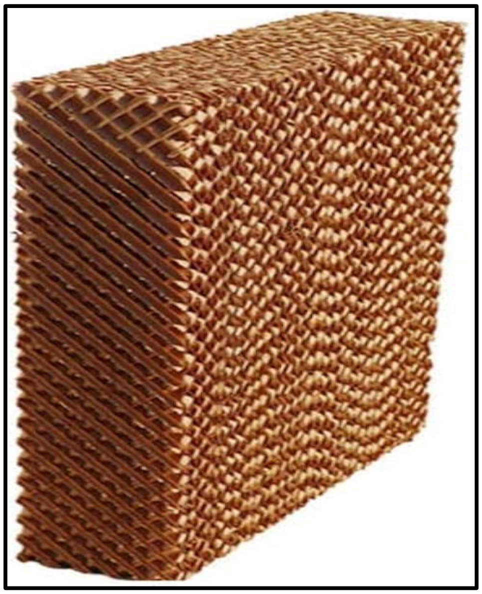
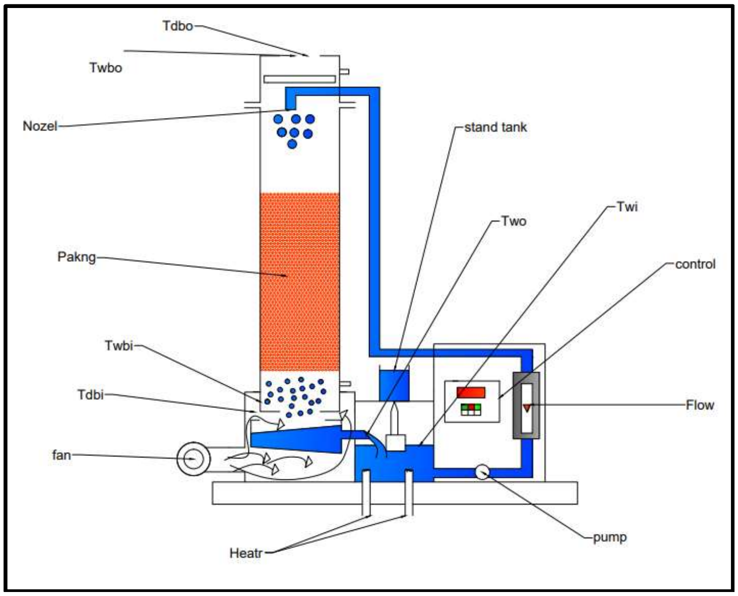
Laboratory-scale WCTs were employed for experiments. The plastic cooling tower is (80 x 15 x 15) cm. Figure 4 shows the cooling tower stacked with carton during tests. The packaging measurements are (60 x 15 x 15cm).



(a) packaging.



(b) schematic of equipment.

Figure 5. Experimental test system.

Figure 5 shows how a centrifugal fan moves air from the tower's base to its top. A digital thermometer measures entering and departing air dry and wet lamp temperatures. Setting control valves may also modify air and water flow rates. An electrical element in the water tank generates A 1000 W electric element within the water tank generates water at 35, 40, 45, 50, 55, 60 degrees Celsius with air flow rates of 2.15, 3.15, and 4 m/s. The demo setup contains a sensor to accurately regulate and The focus is on stabilizing the temperature of the hot water. A water pump is tasked with raising water to the cooling tower. Within the water cooling tower (WCT), the water tank heats the water, which is subsequently distributed to the packing through a spray nozzle. As the water is passed over the filling surfaces, a thin layer forms, increasing the contact area between the water and the air stream. Initial pilot studies suggest that evaporation from the tower results in a loss of some water.

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Table 1. The wet cooling component dimensions.

System parts	N0	System parts	
Air fan (crystal) with a diameter of (6.35 cm	1	Cooling tower dimensions (15x15x80) cm	8
Flowmeter size with inner diameter (1.27) cm	2	Hot water basin dimensions (25x25x25) cm	9
T-type sensors	3	Cold water basin dimensions (30x30x10) cm	10
Water drain valve	4	Electric heater with a capacity of 1000 watts	11
Hot water inlet valve	5	Cardboard filling (package) dimensions (15 x 15 x 60) cm	12
Circuit breaker	6	water pump 0.37 Kw	13
air velocity meter	7	Temperature sensors	14

5.The Uncertainty Analysis

The analysis of the investigation indicates an error rate, detailed in Table 2, established through the equation provided below [22].

$$\omega_R = \sqrt{\left(\frac{\partial \phi}{\partial x_1} \times \Omega_1\right)^2 + \left(\frac{\partial \phi}{\partial x_2} \times \Omega_2\right)^2 + \cdots \ldots . . \left(\frac{\partial \phi}{\partial x_n} \times \Omega_n\right)^2} \quad (5)$$

Table 2. The ratio of uncertainty employed in the experiments.

Apparatus	characteristics	mistake
Sensor IAN76797	Temperatures	±2 ^{0}C
Digital Anemometer	Velocity	±(5%+0.5) m/s
Flow Meter	water Flow	+/- 5%

4. Results of the Experiment

The experimental study was performed at the Technical College of Engineering, Kirkuk, within the Research and Renewable Energy Centre, using the center's resources owing to the availability of suitable equipment and the establishment of operational parameters. All experiments were performed on the forced wet cooling tower to assess the thermal performance under various factors and operating situations.

4.1. Cooling range

In this section, three fundamental parameters—temperature difference, cooling efficiency, and characteristics of the tower—are introduced to evaluate the thermal performance of the water cooling tower (WCT). The water temperature differential (ΔT) is defined as the disparity between the temperatures of the incoming and outgoing water [23].

$$\Delta T = Twi - Two \quad (3)$$

In Figures (1, 2, 3), the horizontal axis denotes the water flow rate in liters per minute, while the vertical axis indicates the cooling range in degrees Celsius, with inlet water temperatures of 35, 40, 45, 50, 55, and 60 °C, and three distinct air velocities of 2.15, 3.15, and 4 m/s. The cooling range diminishes as the water flow rate increases. The cooling range diminishes due to heat and mass transfer being influenced by several variables, including a constant surface contact area between air and water and a nearly constant air flow rate. When the temperature of the incoming water rises, the cooling rage behavior increases, for example in Figure (1) the relationship between flow rate and cooling range at air velocity (2.15 m/s), temperature (55, 60) and flow rate (4L/min) the cooling range is (16.504, 18.104) Celsius. In Figure (2), with an air velocity of (3.15 m/s), temperature (55, 60°C) and flow rate (4L/min), the cooling range is (19.14, 24.4) degrees Celsius. In Figure (3), with air velocity (4 m/s), temperature (55, 60) and flow rate (4L/min), the cooling range is (20.4, 24.404) which also shows the effect of increasing air flow rates on the cooling range.

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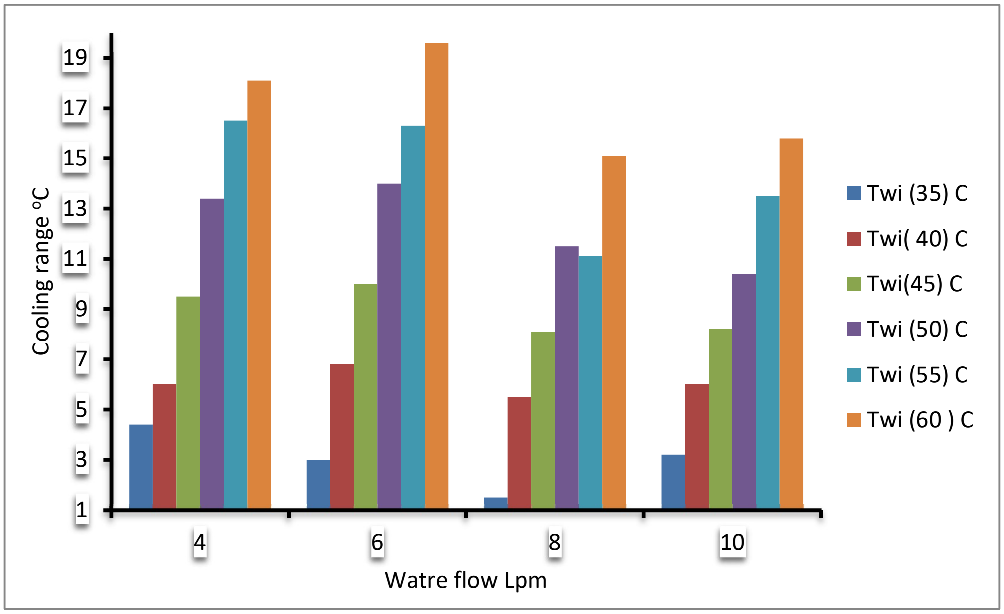

Figure 1. cooling range with flow rate (at an air velocity of 2.15 m/s)

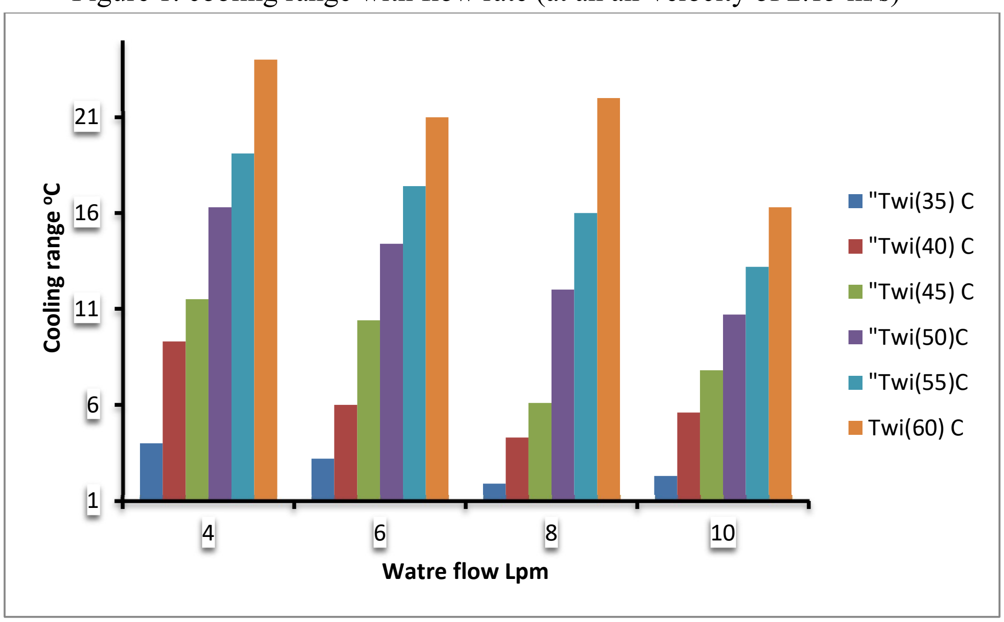

Figure 2 cooling range with flow rate (3.15 m/s air velocity).

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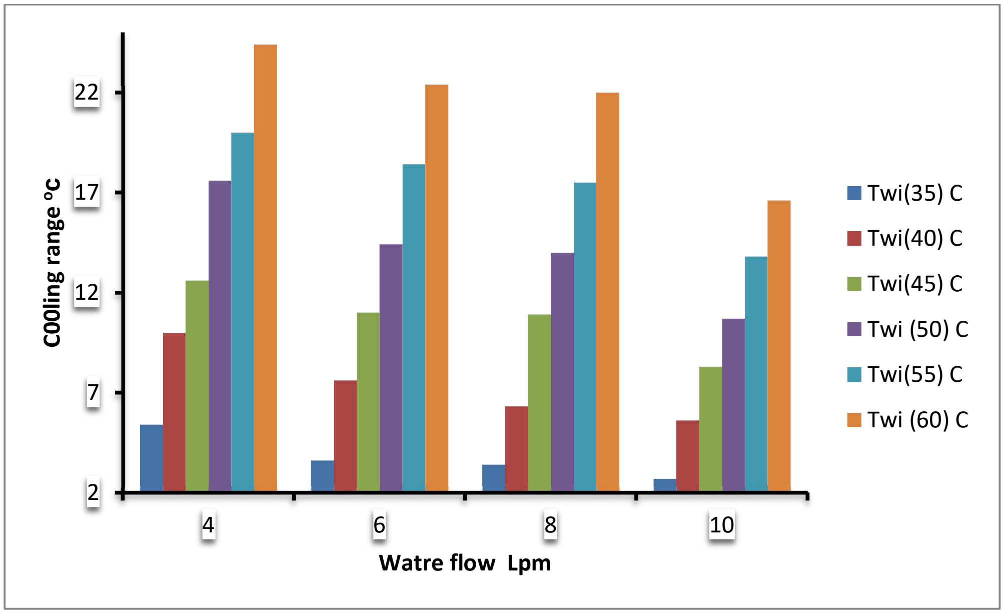

Figure 3. cooling range with flow rate (With an airspeed of 4 m/s).

4.2. Tower approach

The calculation of the tower approach involves determining the difference between the output water temperature and the input wet bulb temperature of the air (Twout – T airwbi). In Figures (4, 5, 6), the horizontal axis represents the water flow rate measured in liters per minute, while the vertical axis illustrates the tower approach for inlet water temperatures of 35, 40, 45, 50, 55, and 60 degrees Celsius, across three varying air velocities (2.15, 3.15, and 4 m/s). An increase in the water flow rate correlates with a rise in the tower approach value; likewise, higher input water temperatures lead to an upward shift in the tower approach curve. The outlet water temperature is directly affected by the inlet water temperature, indicating that an increase in the latter results in a proportional increase in the former. For instance, in Figure (4), with an inlet water temperature of (40, 60) degrees Celsius, a flow rate of (4, 6) liters/minute, and an air velocity of (2.15 m/s), the tower approach values are (7.4, 12.506) degrees Celsius. In Figure (5), with the same inlet temperatures and flow rates but an air speed of (3.15 m/s), the tower approach values are (5.304, 10.706) degrees Celsius. Figure (6) shows that with an inlet temperature of (40, 60) degrees Celsius, a flow rate of (4, 6) liters/minute, and an air speed of (4 m/s), the tower approach values are (3.204, 10.106). This data illustrates the significant impact of varying air speeds on the tower approach. To achieve optimal performance, it is essential to cool the water to match the wet bulb temperature of the incoming air.

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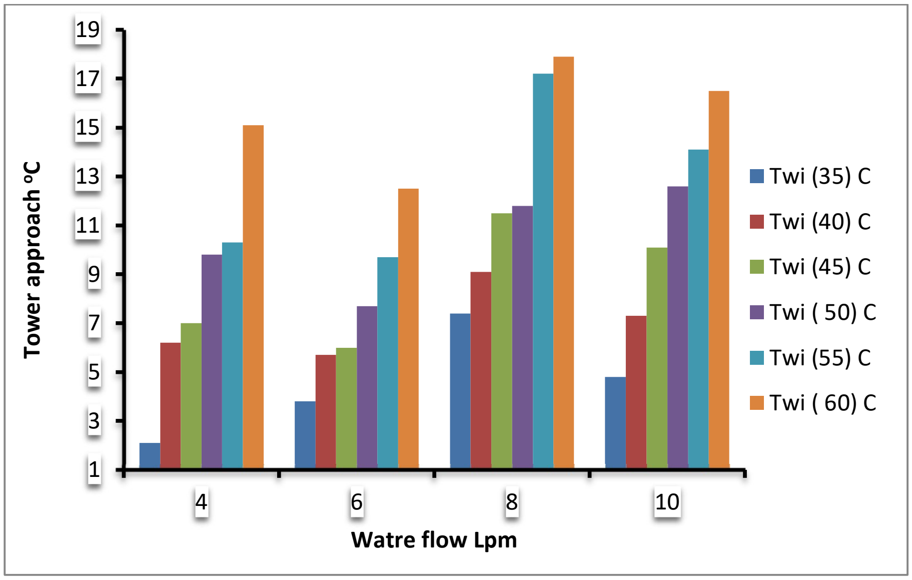

Figure 4. approach with flow rate (at an air velocity of 2.15m/s).

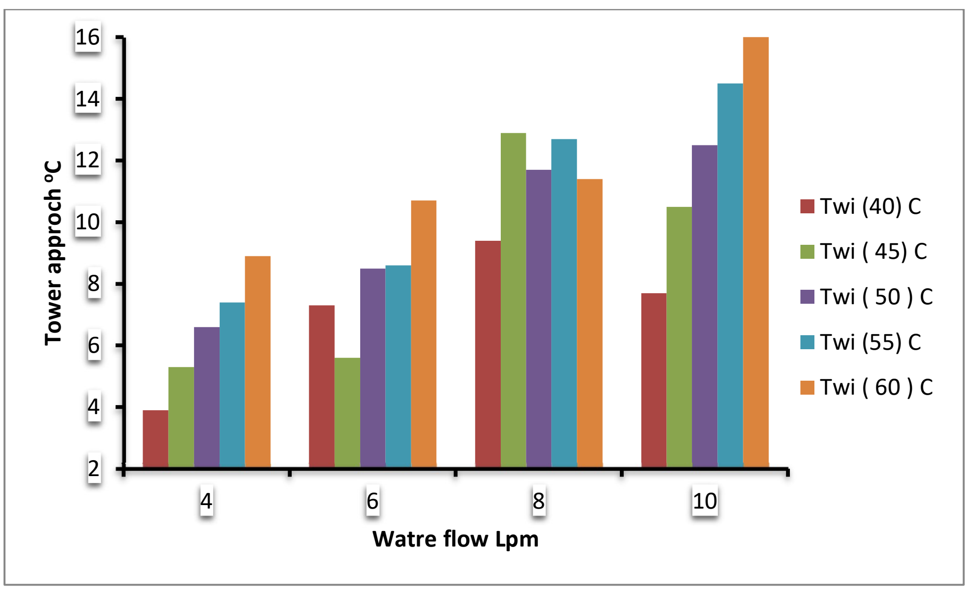

Figure 5. approach with flow rate (3.15 m/s).

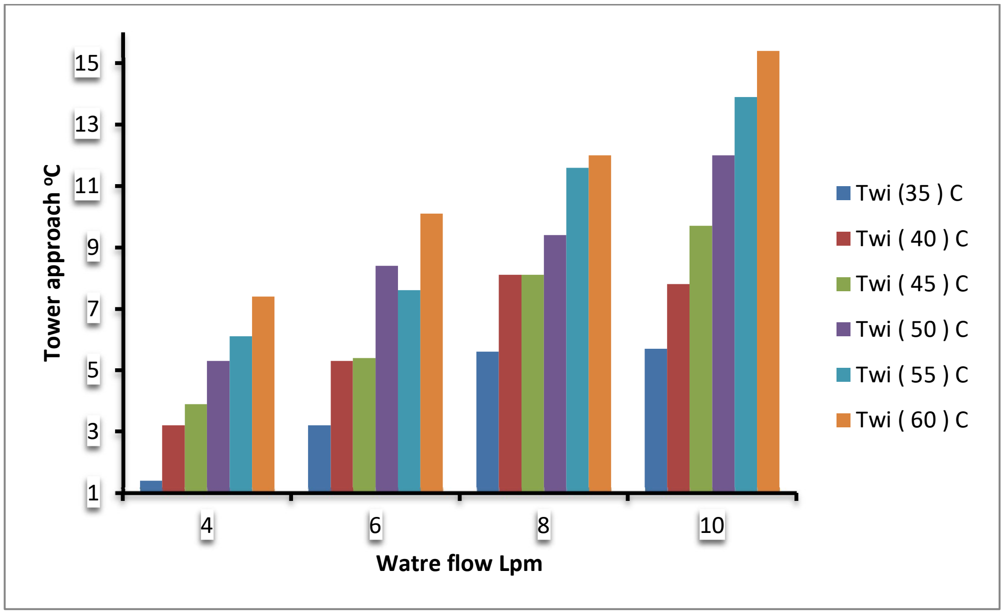

Figure 6. approach with flow rate at 4 m/s air speed.

4.3. Cooling tower effectiveness

The effect of using various flow rates (4, 6, 8, 10) L/min, water inlet temperatures (35, 40, 45, 50, 55, 60) °C and varied air velocities (2.15, 3.15, 4) m/s was investigated and the findings revealed that the greater the flow rate, the lower the tower efficiency. The efficiency The parameter ε, representing the efficiency of the cooling tower, is defined as the ratio of the energy transferred in practice to the highest possible energy transfer that can be realized. Consequently, the tower efficiency is derived from equation (1).

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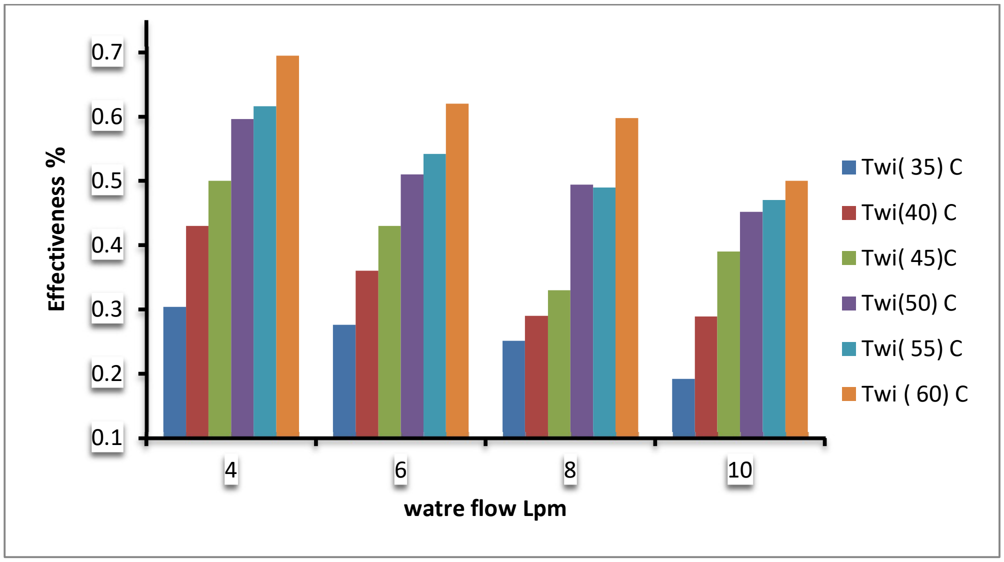

Figure 7. tower efficacy with flow rate at a velocity of 2.15 m/s.

Figures (7, 8, 9) show the efficiency at the input water temperature. The x-axis illustrates the rate of water flow in liters per minute, in contrast to the y-axis. denotes the efficiency (ε). For example, in figure (7) at inlet water temperature (40°C), flow rate (6, 8 liters/min) and air velocity (2.15) m/s (0.544, 0.377), in Figure (8), at water inlet temperature (60°C), flow rate (6, 4 liters/min) and air velocity (3.15), the tower efficiency is (0.729, 0.671). In Figure (9), Under conditions of a water intake temperature of 55°C, a flow rate of 6.4 liters per minute, and an air speed of 4 m/s, the system functions effectively. The effectiveness of the tower is (0.766, 0.708), which illustrates that the change in air speed leads to a change in effectiveness.

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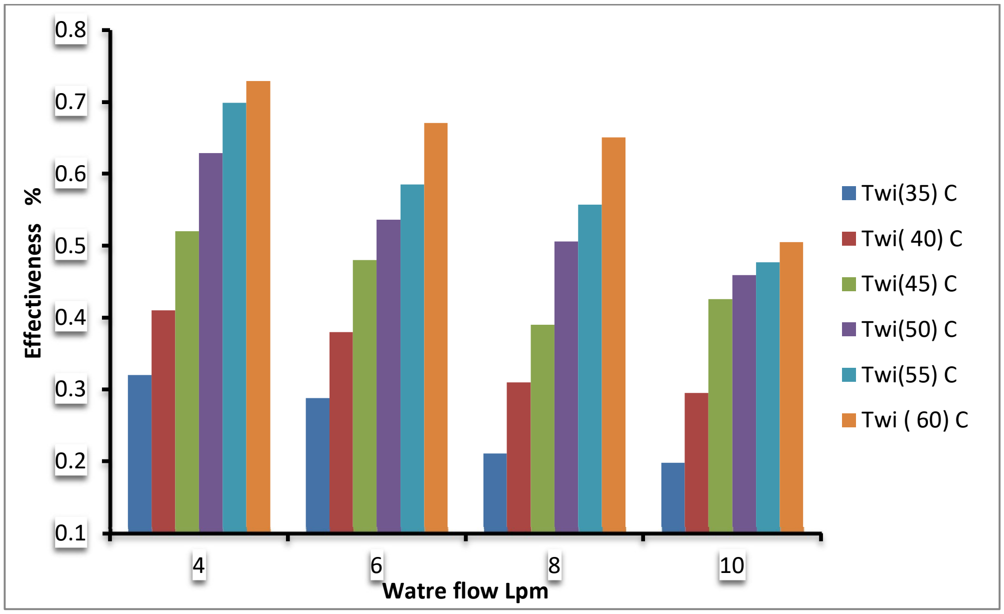

Figure 8: efficacy with flow rate at an air velocity of 3.15 m/s .

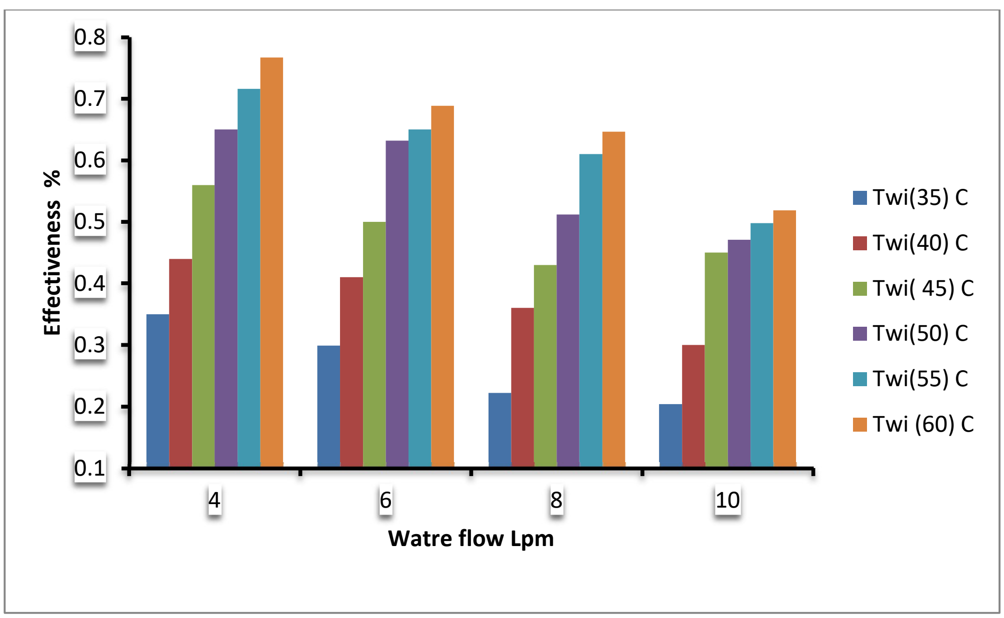

Figure 9: cooling tower efficacy with flow rate at 4 m/s.

4.4. The potential for heat removal.

Cooling capacity refers to the amount of heat discharged into the environment from the hot water entering the cooling tower. The outcome is obtained from the multiplication of the cooling

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range, water mass flow rate, and specific heat of water. Therefore, increasing any of these elements improves the cooling capacity. The tower's capacity is calculated using the equation [24].

$$q = \dot{m}_w * C_{p,w} * [\,(T_{water})_{,in} - (T_{water})_{,out}] \quad (4)$$

The cooling capacity refers to the quantity of heat that is expelled into the environment from the hot water that enters the cooling tower. This capacity is determined by the degree of cooling, the mass flow rate of the water, and the specific heat of the water. Enhancements in any of these parameters will lead to an increase in cooling capacity. Figures 10 through 12 illustrate the cooling capacity at various inlet water temperatures, specifically 35, 40, 45, 50, 55, and 60°C. In these figures, the x-axis denotes the water flow rate in liters per minute, while the y-axis indicates the cooling capacity measured in kilowatts (kW). An increase in water flow rate results in a larger contact surface area, thereby enhancing heat and mass transfer, which in turn leads to hotter and more humid air. The transfer of heat and mass from the hot water to the air increases the air's content, resulting in less dense air. Consequently, the rejected heat will rise with an increase in either the change in heat content or the air velocity at the tower's outlet. As the water flow rate rises, the cooling capacity also increases. However, at lower water flow rates for any given inlet water temperature, the cooling capacity values tend to converge. Conversely, as the water flow rate increases, the cooling capacity values begin to diverge.

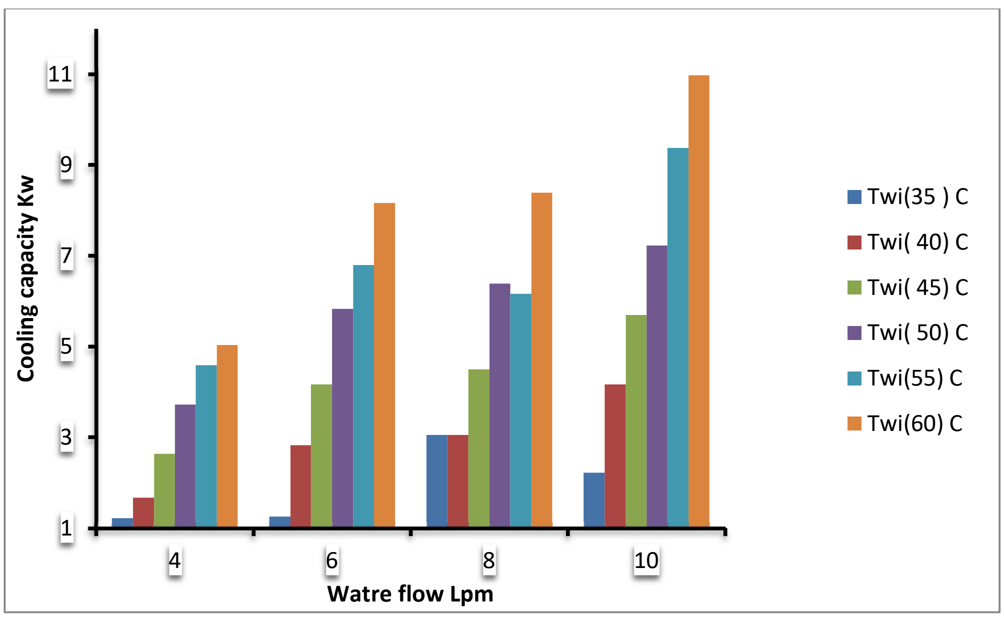

Figure 10. cooling capacity with flow rate (Q) at an air velocity of 2.15m/s.

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For instance, at an inlet water temperature of 55.60°C, with flow rates of 6 and 8 liters per minute and an air velocity of 2.15 m/s, the cooling capacities are 6.7926 kW and 8.39049 kW, respectively, resulting in a difference of 1.59753 kW. Another example at an inlet water temperature of 55 and 60°C, with a water flow rate of 6.8 liters per minute and an air velocity of 15.15 m/s, yields cooling capacities of 6.7926 kW and 8.39049 kW. At an air velocity of 3 m/s, the cooling capacities are 9.08506 kW and 10.05576 kW, leading to a difference of 0.9707 kW. Additionally, at an inlet water temperature of 55 and 60 degrees Celsius, with a flow rate of 6 and 8 liters per minute and an air velocity of 4 m/s, the cooling capacities are 7.66813 kW and 15.2807 kW.

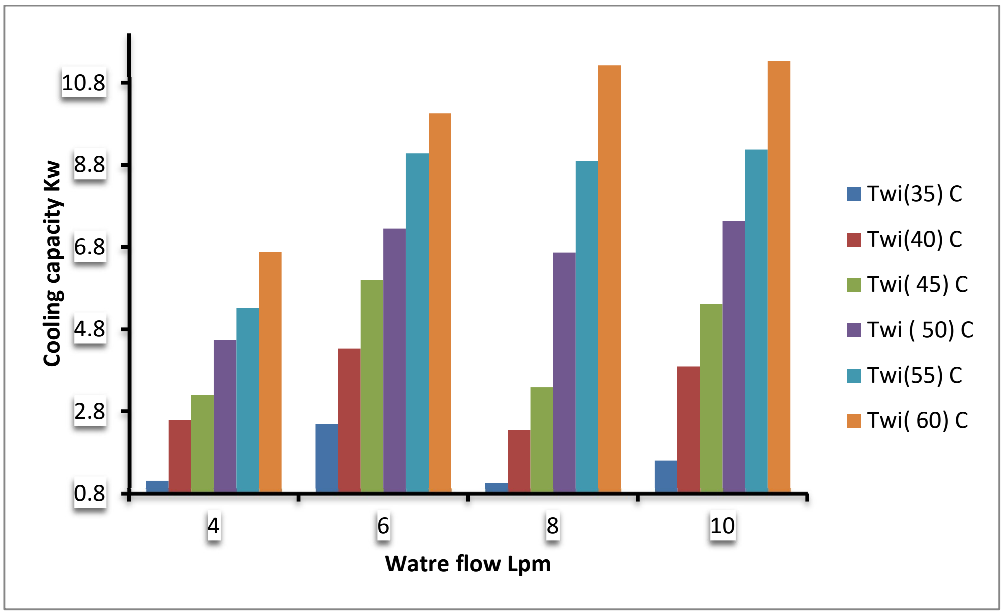

Figure 11. cooling capacity with flow rate at air velocity (3.15m/s).

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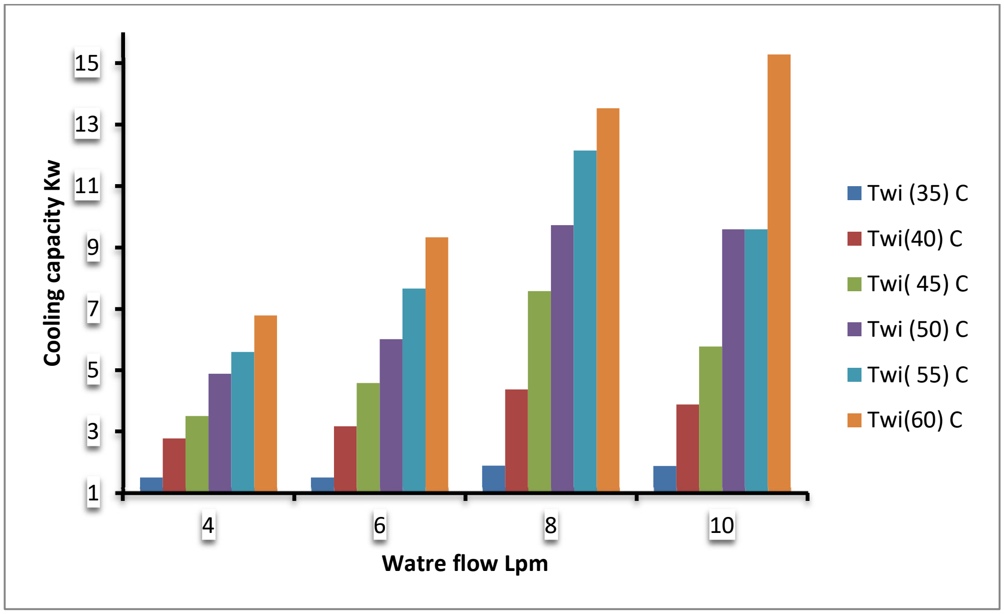

Figure 12 cooling capacity with flow rate at 4 m/s air velocity.

Conclusion

This study report examined the impact of elevated intake water temperatures, varying water flow rates, and differing air velocities, with the findings indicating the following:

1- An elevation in the input water temperature results in increased efficiency and cooling rate of the tower, which consequently affects the capacity and operational efficacy of the cooling tower.
2- The cooling capacity escalates with higher water flow rates into the tower.
3- As the water flow rates of the cooling tower rise, both the efficiency and the cooling rate of the tower decline.
4- The findings indicated that the maximum cooling tower efficiency, recorded at an With an air velocity of 4 m/s and a flow rate of 4 L/min, the efficiency achieved was 76.7%.

References

[1] K.M. Azeez, A.F. Hameed, A.M. Hussein. Nanofluid heat transfer augmentation in a double pipe heat exchanger. AIP Conference Proceedings 2213, 020059 (2020).
[2] Iqbal, M., and J. W. Stachiewicz. "Influence of tube orientation on combined free and forced laminar convection heat transfer." (1966): 109-116.
[3] K.M. Azeez, Z. Ibrahim, A.M. Hussein. Thermal conductivity and viscosity measurement of ZnO nanoparticles dispersing in various base fluids, Journal of Advanced Research in Fluid Mechanics and Thermal Science, vol. 66, Issue 2, 2020.

مجلة العلوم والتطـبيقات الهـندسية

Journal of Science and Engineering Application

ISSN 2521-3911

[4] Hussein, A.M., Bakar, R.A., Kadirgama, K., Sharma, K.V. Heat transfer enhancement with elliptical tube under turbulent flow TiO2-water nanofluid. THERMAL SCIENCE, 20, (2016) 1, pp. 89-97.

[5] Ibrahim, Z.A., Jasim, Q.K., Hussein, A.M. The Impact of Alumina Nanoparticles Suspended in Water Flowing in a Flat Solar Collector. J. of Adv.Res.in Fluid Mech.&Ther.Sci. 65, (2020), 1, pp.1-12.

[6] Hussein, A.M., Dawood, H.K., Bakar, R.A., Kadirgama, K. Numerical study on turbulent forced convective heat transfer using nanofluids TiO2 in an automotive cooling system. Case Studies in Thermal Engineering 9 (2017), pp.72–78.

[7] Kaska, S.K., Khalefa, R.A., Hussein, A.M. Hybrid nanofluid to enhance heat transfer under turbulent flow in a flat tube. Case Studies in Thermal Engineering 13 (2019) pp.100398.

[8] Hussein, A.M. Thermal performance and thermal properties of hybrid nanofluid laminar flow in a double pipe heat exchanger. Exp. Ther. and Fluid Sci. 88 (2017) pp. 37–45.

[9] F. Al-Juwayhel, H. El-Dessouky, H. Ettouney, and M. Al-Qattan, "Experimental evaluation of one, two, and three stage evaporative cooling systems," *Heat Transf. Eng.*, vol. 25, no. 6, pp. 72–86, 2004, doi: 10.1080/01457630490486292.

[10] M. Rahmati, "Effects of ZnO/water nanofluid on the thermal performance of wet cooling towers," *Int. J. Refrig.*, vol. 131, no. March, pp. 526–534, 2021, doi: 10.1016/j.ijrefrig.2021.03.017.

[11] J. Ruiz, P. Navarro, M. Hernández, M. Lucas, and A. S. Kaiser, "Thermal performance and emissions analysis of a new cooling tower prototype," *Appl. Therm. Eng.*, vol. 206, p. 118065, 2022.

[12] X. Fan *et al.*, "An experimental study of a novel dew point evaporative cooling tower based on M-cycle," *Appl. Therm. Eng.*, vol. 190, no. March, p. 116839, 2021, doi: 10.1016/j.applthermaleng.2021.116839.

[13] J. C. Kloppers and D. G. Kröger, "The Lewis factor and its influence on the performance prediction of wet-cooling towers," *Int. J. Therm. Sci.*, vol. 44, no. 9, pp. 879–884, 2005, doi: 10.1016/j.ijthermalsci.2005.03.006.

[14] A. Mirabdolah Lavasani, Z. Namdar Baboli, M. Zamanizadeh, and M. Zareh, "Experimental study on the thermal performance of mechanical cooling tower with rotational splash type packing," *Energy Convers. Manag.*, vol. 87, pp. 530–538, 2014, doi: 10.1016/j.enconman.2014.07.036.

[15] P. Shahali, M. Rahmati, S. R. Alavi, and A. Sedaghat, *Experimental study on improving operating conditions of wet cooling towers using various rib numbers of packing*, vol. 65, no. 2016. Elsevier Ltd, 2016. doi: 10.1016/j.ijrefrig.2015.12.004.

[16] T. Ning, D. Chong, M. Jia, J. Wang, and J. Yan, *Experimental investigation on the performance of wet cooling towers with defects in power plants*, vol. 78. Elsevier Ltd, 2015. doi: 10.1016/j.applthermaleng.2014.12.032.

[17] S. He, Z. Guan, H. Gurgenci, K. Hooman, Y. Lu, and A. M. Alkhedhair, "Experimental study of the application of two trickle media for inlet air pre-cooling of natural draft dry cooling towers," *Energy Convers. Manag.*, vol. 89, pp. 644–654, 2015, doi: 10.1016/j.enconman.2014.10.031.

[18] M. Rahmati, S. R. Alavi, and M. R. Tavakoli, "Experimental investigation on performance

enhancement of forced draft wet cooling towers with special emphasis on the role of stage numbers," *Energy Convers. Manag.*, vol. 126, pp. 971–981, 2016, doi: 10.1016/j.enconman.2016.08.059.

[19] N. Gilani and F. Parpanji, "Parametric study on the outlet water temperature in a shower cooling tower and its application in different Iranian provincial capitals," *Int. J. Therm. Sci.*, vol. 124, no. March 2017, pp. 174–186, 2018, doi: 10.1016/j.ijthermalsci.2017.10.017.

[20] H. Wei, T. Wu, Z. Ge, L. Yang, and X. Du, "Entransy analysis optimization of cooling water flow distribution in a dry cooling tower of power plant under summer crosswinds," *Energy*, vol. 166, pp. 1229–1240, 2019.

[21] M. Hosoz, H. M. Ertunc, and H. Bulgurcu, "Performance prediction of a cooling tower using artificial neural network," *Energy Convers. Manag.*, vol. 48, no. 4, pp. 1349–1359, 2007, doi: 10.1016/j.enconman.2006.06.024.

[22] J. Tissot, P. Boulet, A. Labergue, G. Castanet, F. Trinquet, and L. Fournaison, "Experimental study on air cooling by spray in the upstream flow of a heat exchanger," *Int. J. Therm. Sci.*, vol. 60, pp. 23–31, 2012.

[23] J. C. Kloppers and D. G. Kröger, "A critical investigation into the heat and mass transfer analysis of counterflow wet-cooling towers," *Int. J. Heat Mass Transf.*, vol. 48, no. 3–4, pp. 765–777, 2005, doi: 10.1016/j.ijheatmasstransfer.2004.09.004.

[24] M. Rahmati, S. R. Alavi, and M. R. Tavakoli, *Étude Expérimentale Sur Le Transfert De Chaleur Dans Les Tours De Refroidissement Humides À Tirage Mécanique Par Thermographie Infrarouge*, vol. 88. Elsevier Ltd, 2018. doi: 10.1016/j.ijrefrig.2017.11.031.