NeuroQuantology | June2022 | Volume 20 | Issue 6 | Page 1198-1208 | doi: 10.14704/nq.2022.20.6.NQ22116

Performance Analysis of the Natural Draft Hybrid (Wet/Dry) Cooling Tower

A.K. Abdullah[1*], M.Q. Ahmed[2], M.S. Qasim[3]

Abstract

This study has evaluated the thermal performance of a natural draft hybrid cooling tower based on Iraqi weather conditions because of their similarities in geometry and thermodynamics. Using the concepts of similarity, heat, and mass transmission, the rig's dimensions (top shell diameter, bottom shell diameter, shell height) are given to imitate real-world working circumstances. There will be a hybrid cooling tower model and the necessary testing equipment designed and built. Hybrid cooling systems that integrate air-cooled heat exchangers and water spray facilities in a natural draft hybrid cooling tower were simulated using physical models (NDHCT).This research aims to investigate the performance of a natural draft hybrid cooling tower utilizing an appropriate approach. This method looks at how the type of fill, the size of the nozzle hole, and the rate at which hot water flows through a cooling tower affect its performance. The following were the model's specs: diameter at the top (98 cm), diameter at the bottom (56 cm), and height (131 cm). There were three parts to the 200 tests: 64 for different water flow rates, 120 for different types of filling, and 58 for different nozzle holes. There were three examples of film and three examples of splash fills. The heights of the film were 5, 10, and 15 cm, and the heights of the splash fills were 5, 10, and 15 cm. The tower's range, approach, effectiveness, and Merkel number were all looked at to figure out how well it worked. Between the Merkel number and the ratio of the mass flow rate of water to air, the 18th new experimental relationship was suggested. And when compared to other works.

Key Words: Iraqi Weather, Splash Fill, Natural Draft Hybrid Cooling Tower, Film Fill.

DOI Number: 10.14704/nq.2022.20.6.NQ22116 **NeuroQuantology2022;20(6):1198-1208**

Introduction

Cooling towers are commonly employed in the electricity, refrigeration, and air conditioning sectors to drain heat from warm water into the atmosphere [1]. Dry and wet varieties can be distinguished based on contact[2]. A third way to categorize them is based on the force of airflow, which might be mechanical or natural [3]. Cooling water from the condenser in thermal power plants and certain inland nuclear power plants is vital to the operation of natural-draft wet cooling towers. There is a direct correlation between cooling tower capacity and the total power generation capability. The filling zone is where 70% of the heat extraction capacity is found in previous research [4]. The filling zone's thermal performance must be thoroughly investigated as a result. When removing heat from a facility, either heat exchangers (direct contact) or cooling towers are used (direct contact). Wet or dry working fluids can be used (wet). Water has a far higher specific heat than air; it is often favoured in large systems. Natural draft dry cooling towers (NDDCT) are less efficient [5]. When ambient temperatures are high, hybrid cooling pre-cools the air by employing tiny amounts of water. A hybrid cooling tower may be operated in either dry or wet mode depending on the ambient temperature and water supply, resulting in increased plant efficiency and power generation. Compared to typical wet cooling towers, hybrid cooling towers use far less water. A Free-For-All Draft Heat and mass transfer are generally utilized in conjunction in a wet cooling tower (NDWCT) to reduce the temperature of the water.

Corresponding author: A.K. Abdullah
Address: [1*2]Middle Technical University, Technical Engineering College, Baghdad, Iraq; [3]Mech.Eng.Dept.,MustansiryahUniversity, College ofEngineering,Baghdad, Iraq.
[1*]E-mail:al6815514@gmail.com

The amount of water that needs to be cooled is spread out in the tower by spray nozzles over splash or film fills. This allows a lot of water to be exposed to the outside air in a short amount of time. Air from the outside is either forced up mechanically by fans or naturally by the buoyancy force created by the various weights of hot, humid air and cold, dry air. The differential creates this buoyant force in pressure between the upper side of the tower and the bottom. While air and water move, heat moves from one to the other when they come into direct contact. This process evaporates some of the water in the water, making it less dense. The cold water in the reservoir under the tower shell is used to cool the main system. In a hybrid cooling design, water is added to the air that comes into a dry cooling tower to help it cool down. People who use evaporative cooling can cool things down to as low as a temperature that can be reached by evaporation, which is called the "wet-bulb temperature." The cooler air then takes in more heat through the heat exchangers, making the process more efficient. A hybrid cooling tower allows the tower to work in a wider range of temperatures than before [6]. The tower can be built more cheaply (and in a smaller space), producing more power over its lifetime. It takes a lot of hot water and cold air to fill the packing before the small drops of water do. In large towers, the spray zone can account for up to 15% of the heat thrown out. The second zone is the fill zone or packing zone, the main zone for removing heat from the body. This zone is called the "fill zone." After putting in a lot of big-sized droplets and waterfalls. The area that is filled with water is called the rain zone. About(10% to 20%) of the heat and mass that moves through tall buildings comes from the rain zone. If you use different packing, the surface area will be different.

Fill is better for mechanical cooling towers than natural cooling towers[7]. Fills with less pressure drop are better for natural cooling towers. You can use the trickle fill type if you have a mechanical or natural tower. In the cooling tower, they are exposed to airflow at the top[8]. This hurts the cooling tower's ability to work. In the experiment, the water temperature that comes out of the cooling tower can rise to (3°C) because of the air that comes into contact with it. So, the air temperature in small cooling towers can be carefully chosen [9][10]. It was done in Iraqi weather to do experiments, which are hot and dry in summer and wet in winter. The trickle fill was (10 cm). The mass flow rate of water has changed from (0.8 to 2.4) gpm, and the crosswind hasn't changed. Tower range, cooling capacity, and air temperature change are bigger in winter than in summer when relative humidity changes [11].

A natural draft hybrid cooling tower (NDHCT) combines dry and wet cooling sections inside a single cooling tower. Therefore, hybrid cooling tower components have the benefits of both cooling towers and use less water while keeping the same heat load rejection capability. Either individually or concurrently, hybrid cooling towers can be employed for water saving[12]. A balance may be established by raising the load on the dry cooling unit and lowering the load on the wet cooling unit. If conditions permit, water use can be reduced by running the dry cooling system at full capacity. Figure (1) depicts the natural draft hybrid cooling tower's design.

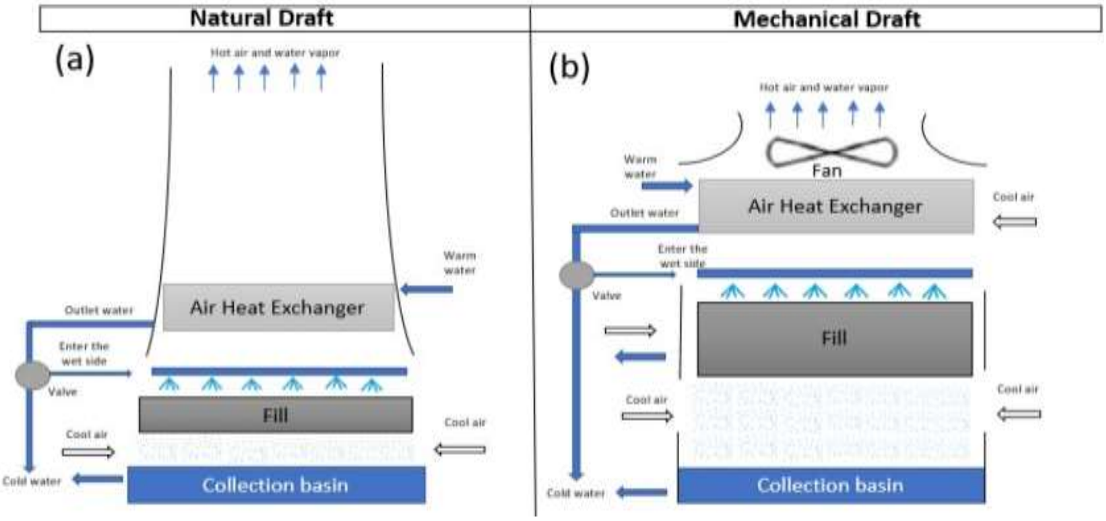

Figure 1. The schematic of a natural and mechanical draft hybrid cooling tower[13]

Similarity Criterion

To be similar, the model test has to meet the following criteria: geometric, kinematic, dynamic, and thermal. The (NDHCT) model was used at a scale of 1:100 to the real tower. The water distribution system is made up of two main pipelines and several smaller pipelines that connect to them. According to the principle of kinematic similarity, the model tower's air velocity ratio must be the same as that of the prototype, that is,

$$\left(\frac{v_{to}}{v_{cw}}\right)_p=\left(\frac{v_{to}}{v_{cw}}\right)_m \qquad (1)$$

Where v_{to}denotes air velocity at the tower's top outlet, v_{cw}Denotes crosswind velocity at the tower's outlet height, and (P) and (m) are the prototype and model towers, Due to the Reynolds number's inverse relationship with the model scale and the (Froude number's) direct relationship with the model scale's square root, the (Reynolds) and (Froude number's) similarities can not be met in the same model test. The driving force of buoyancy and the inertial force of crosswinds are the primary components in this model test, while the viscous force plays a minor role. As a result, it is not the Reynolds number that must be met, but the density Froude number similarity.

$$\Delta \mathrm{Fr} =\left(v_{to} /\sqrt{(\Delta\rho_a \ / \rho_i \ * g * L)}\right)_P =\left(v_{to} / \sqrt{(\Delta\rho_a/\rho_i \ * g * L)}\right)_M (2)$$

The ρ_i represents the density of the air in the cooling tower (kg/m3). The $\Delta\rho=\rho_a- \rho_i$; ρ_a Represents the density of the air outdoor the cooling tower. Whereas the $\Delta\rho$ represents the difference density (kg/m3), L (m) is the cooling tower's effective height, and g is the gravity acceleration (9.81 kg/m^2sec). The real-size hyperbolic tower was constructed using the following equationsof the generating curve as represented in Figure 2:

$$4R^2/d_T^2\text{-}Z^2/b^2=1 \qquad (3)$$

$$\mathrm{b}=d_T Z_H/\sqrt{({d_H}^2-{d_T}^2)} \qquad (4)$$

$$\mathrm{b}=d_T Z_U/\sqrt{({d_U}^2-{d_T}^2)} \qquad (5)$$

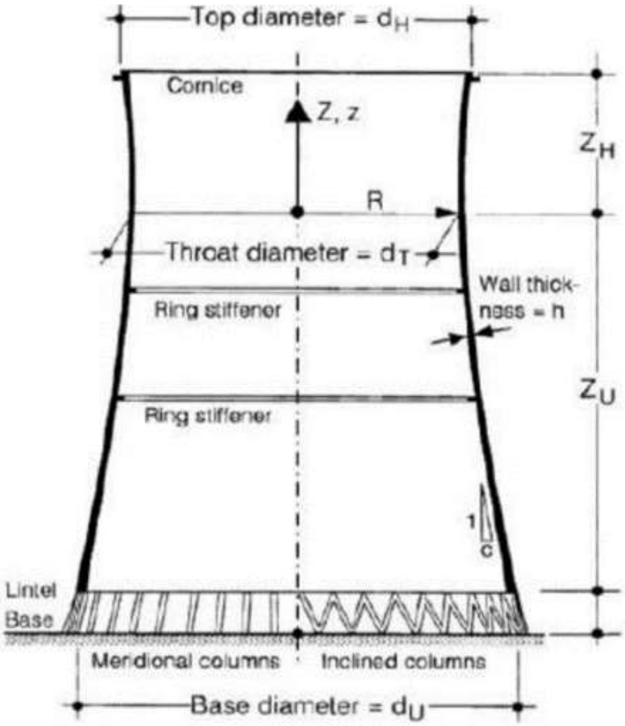

Figure 2. Tower shell design[14]

Where;

d_U base diameter (98 cm)
d_T throat diameter (53.5 cm)
d_H top diameter (58.17 cm)
z_H height from throat to top (102.5cm)
z_U height from base to throat (28.5cm)
R radius at any height Z (cm)

In this experiment, the ratio of water flow to airflow and the drop in water temperature was kept the same between the prototype and the model. So, the water flow rate was changed to be between 6 and 9 l/min, which for the prototype is between 10 and 15.3 l/min. The input water temperature was set to (40, 45, 50, and 55 °C) to get a bigger drop in water temperature, which is more like what happens in real life. The crosswind speed in this hot model test should be about 1/10 of it based on dynamic similarity. The lower fan makes six different crosswind speeds: 0, 0.3, 0.6, 0.9, and 1.2 m/s. This equation should be used to figure out the crosswind speeds created by the upper fan [15].

$$V_{cw}/V_{cwref}=(Z/Z_{ref})^{\ 0.2} \qquad (6)$$

So, the crosswind speed from the upper fan is about twice as fast as the crosswind speed from the blower fan, which is (0, 0, 1, 1, 8, and 2.4 m/s). All of the crosswind speeds listed below are from the lower fan.

Experimental Apparatus and Procedure

1. Description of Test Rig

The rig for the natural draft hybrid cooling tower (NDHCT) utilized in this study was constructed in Baghdad using resources from Middle Technical University/Technical Engineering College-Baghdad under a resemblance criterion for an actual tower previously constructed in Australia. The experimental portion of the research includes developing similarity criteria, rig regulations, building procedures, and fill preparation, providing a comprehensive understanding of the rig's components, measuring instruments, and experimental technique. The first stage in conducting tests is designing and building an appropriate rig to imitate real towers' geometrical properties and stresses. This comprises modelling and constructing (or planning for the construction of) the following; A cooling tower with a hyperbolic shape. Fillers for packaging. Heaters imitate the presence of a load. Pipes, connectors, valves, pumps, reservoirs, and nozzles comprise the piping system. A heat exchanger and fans are utilized to simulate the movement of the wind.

2. The Present Work's Assumptions

Experiments will be done on a natural draft hybrid cooling tower (NDHCT) model. The study can only be done if certain assumptions and simplifications are made, such as that the cooling tower works at steady-state conditions and that there are no thermal loads, such as conduction across the shell wall, the addition of make-up water, net heat exchanges with the environment, and pump head gain. Wind speed stays the same, and air and water flow rates remain the same across the tower's cross-sectional area. As a counterflow tower, the thermodynamic parameters of the air and water flows fluctuate upwards and are supposed to remain constant throughout the tower's interior cross-section.

3. Procedures for Experiments

The experimental method begins in August 2020, during hot and dry weather in Iraq (summer). An investigation aims to determine the effect of When a parameter is modified, it is investigated individually, while the remaining parameters are fixed. The tests began with (2) mm nozzles and a packing fill thickness of (5,10,15) cm. The water inlet temperature was set to (40,55°C), and the water flow rate was varied (from 3 to 13.5 L/min). Before capturing any data, the system is brought to steady-state conditions. This is accomplished when the water temperature. Wind speed was changed from 0 to 1.2 m/s at the tower's base and from 0 to 2.4 m/s at the top. Output achieves a steady value (with the input temperature already set at 40 to 55°C). The results of each test are recorded twice; the first time when the water flow rate increased and the second time when it decreased. The method is repeated with film fill and splash fill. The following parameters are monitored throughout these experimental tests: Water mass flow rate, water inlet and outlet temperatures in the dry part (heat exchanger), and water inlet and outlet temperatures in the wet section.The humidity and temperature of the air at the tower's inlet and outlet, the pressure drop along with the tower's height, the air velocity at the tower's outlet, and the wind velocity. The experimental setup and testing procedures are illustrated in fig (3).

1-Makeup water
2.Float valve
3.Fill packing
4. Water distribution nozzle
5. .Heat exchanger
6. U-tube monometer
7. Water flow meter
8.Water thermocouple inlet
9. Regulate valve.
10. Hot water pump
11. Gate valve
12. Main water tank
13. Electric element heater
14. Cold water pump.
15. Water thermocouple outlet
16. strainer.
17. Cold water tank.
18. Drain water tank
19. Water thermocouple inlet dry section.
20. supports
21. Dry and wet bulb temperature inlet
22. Dry and wet bulb temperature outlet
23. Air thermocouple inlet dry section.
24. Air thermocouple outlet dry section.

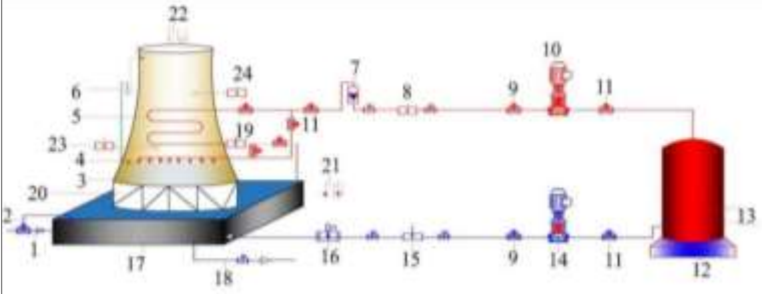

Figure 3. The main parts of a natural draft hybrid cooling tower rig

During experimental tests, many parameters have to be measured like water flow rate, water temperature, air(dry-wet) bulb temperature, relative humidity, pressure drop, airflow rate, and wind velocity. To achieve these measurements, the following devices are required. Table (1) lists the details of the measuring instruments used in the experimental studies.

Table 1. Specification of measuring instruments

NO.	Instruments	Supplier	Type	Range	Accuracy
1	Adigital thermpmeter	(Lutron:BTM-4208SD)	Air and wate temperature (°C)	(-50-1370)	±0.1 °C
2	Humitity meter	(BENETECH:GM-1363B)	Relative humidity(%)	(0-100)	±5%
3	Flow metrr	(ZYIA INSTRUMENT COMPANY)	Water flow rate(L/min)	(3-70)	±2%
4	Anemometer	Lutron:BTM-4208SD	Air velocity(m/sec)	(-0.2- 20)	±5%
5	Manometer	Eisco	Pressure drop(mmH2O)	(0-30)	±2%

4. Performance Parameters

From an energy analysis viewpoint, the following parameters are used to determine a cooling tower's performance:

Cooling range: is the difference in temperature between the inlet and outlet states of the water. The temperature differential between the cooling tower's input and outlet can be used to determine the range:

$$CR=T_{cw.in}-T_{cw.out} \qquad (7)$$

Effectiveness (Thermal efficiency): Thermal efficiency, which may be defined as the ratio of the cooling tower's actual heat output to its maximum theoretical heat output, is essential for cooling towers.

$$\varepsilon=\frac{T_{cw.in}-T_{cw.out}}{T_{cw.in}-T_{awb.in}} \quad (8)$$

Cooling capacity: The amount of heat rejected or dissipated is the product of the water flow rate, its specific heat, and the difference in temperature between the water and the air around it.

$$q= \dot{m}_{cw}C_{p.cw}CR \qquad (9)$$

Mass transfer coefficient: The mass transfer coefficient can be found by balancing the enthalpy of an elementary transfer surface [16].

$$m_{air}dh_a= \alpha_m\ (i_i\ -i_{air})\ (10)$$

Results and Discussion

The results will be broken down into three groups: one group will look at how to fill thickness, type of fill, water flow rate change, and wind velocity affect the results. This is the only thing that hasn't been controlled. Wind velocity is controlled by directing two fans to the bottom and top of the tower, and there are no fans inside the tower shell to make it move more air. During the study of tower parameters, effectiveness, tower range, tower capacity, and air humidity have been examined. Film and splash fill are two types of fill used in the study. Through the following comparison, the best type will be found. The comparison looked at a lot of different things, like how thick the tower was and how fast the wind was coming from the side.

1. Cooling Tower Range

Figure 4 shows the influence of water flow rate on the cooling tower range for various inlet water temperatures. The cooling tower range decreases when the water flow rate increases for each inlet temperature value. For instance, if the water inlet temperature is between 40 and 55°C and the water flow rate is between 3 and 13.5 L/min, the cooling tower ranges between (5.69 and 11.63°C) and (4.15 and 8.74°C). Splash fill behaves similarly to film fill, as seen in Figure 5, except that the range of splash fill is slightly higher than that of film fill. With a water inlet temperature of (40–55°C) and a water flow rate of (3–13.5 L/min), the cooling tower temperature ranges are (6.68–12.56°C) and (4.8–10.17°C. The cooling tower range must decrease when the water mass flow rate increases to maintain a constant cooling load. Due to the increased heat and mass transfer coefficients, the cooling towers' range decreases as the water's mass flow rate increases. The effects of air flow rate on cooling tower range are presented in Figures 6, 7, and 8. When the airflow rate is increased for each value of the water flow rate, the cooling tower's operating range expands. With a water flow rate of 6 L/min and airflow rates of 44.7 and 158.6 m3/hr, respectively, the cooling tower range is between 10.4°C and 17.8°C. As seen in figure 6, the optimum range for splash fill at height (15 cm) is the same in all fill types. Due to an increase in airflow, the amount of water evaporated per unit of air rises, and the fill height rises due to the air's capacity to break up droplets of water into films. Eventually dropping to the next element below. Figs. 7 and 8 show the effect of increasing water flow rate (9 L/min) and (12 L/min) on the range. It can be demonstrated that increasing the water flow rate results in a decrease in range due to decreased heat transfer caused by insufficient time for the heat exchanger. The change in the cooling water range as a measure of the water to air mass flow rate ratio ($\dot{m}_w / \dot{m}_a$) for various airflow rates is seen in figures 9, 10, and 11. As seen in figure 9, the best cooling water range is achieved at the lowest ($\dot{m}_w/\dot{m}_a$) values. The range of cooling water available reduces as the water flow rate ($\dot{m}_w/\dot{m}_a$) increases. This decrease is most pronounced at the lowest airflow rate or the highest ($\dot{m}_w/\dot{m}_a$) ratio, as seen in Figure 10. For example, with a water flow rate of (6 L/min) and a water to air mass flow rate ratio of (5.25) and (0.887), the cooling tower range is (10.4°C and 18.25°C) for splash fill at the height of (15 cm), respectively, which is the best range for all types of fills, as seen in Figure 9. As a result, the mass flow rate of air and water directly affects the range of a cooling tower. Figures 10 and 11 show the variation in range with increasing water to air mass flow rate ratios (9 L/min and 12 L/min, respectively). As the water flow rate increases, the mass flow rate ratio increases, and the range decreases.

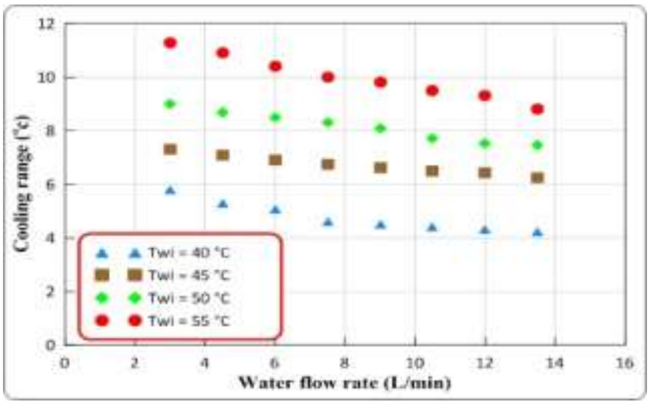

Figure 4. Cooling range based on water flow rate for variable inlet water temperature with film fill (15 cm)

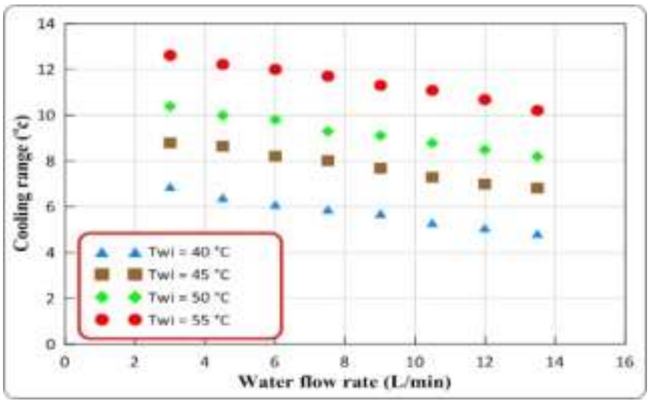

Figure 5. Cooling range based on water flow rate for variable inlet water temperature with splash fill (15 cm)

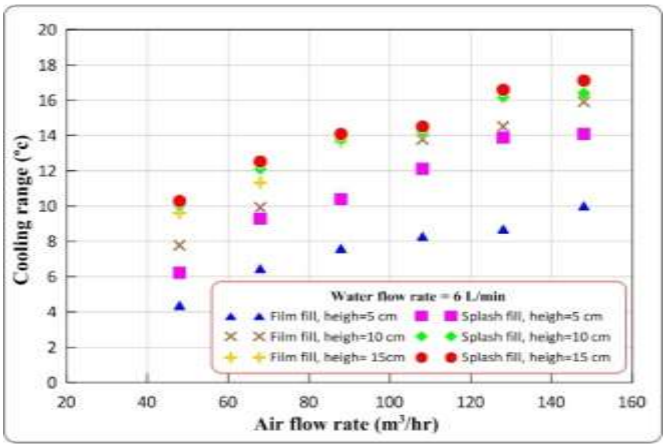

Figure 6. The cooling range for different fill types is based on the airflow rate

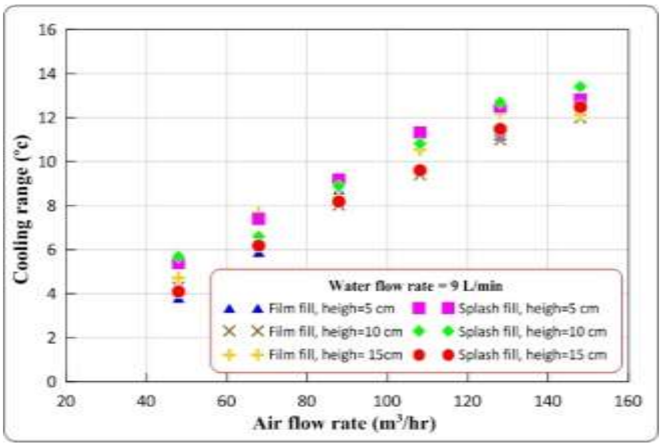

Figure 7. The cooling range for different fill types is based on the airflow rate

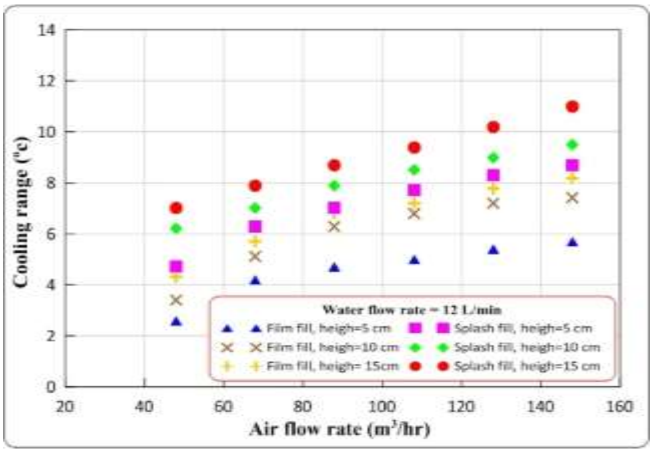

Figure 8. The cooling range for different fill types is based on the airflow rate

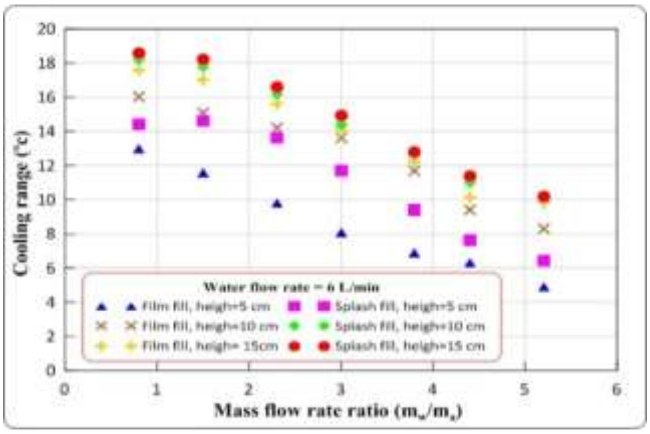

Figure 9. The cooling range for different fill types is based on the mass flow rate ratio

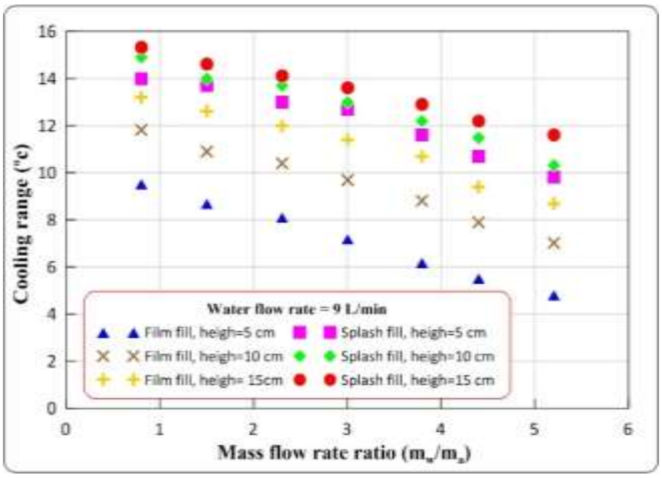

Figure 10. The cooling range for different fill types is based on the mass flow rate ratio

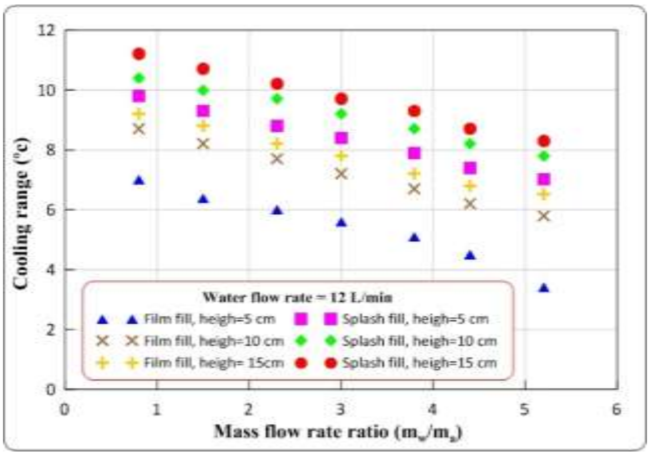

Figure 11. The cooling range for different fill types is based on the mass flow rate ratio

2. Cooling Tower Effectiveness

This study examines the impact of air and water mass flow rate on the effectiveness of a cooling tower. The ratio of the amount of energy that is actually transferred to the amount of energy that could be transferred through the cooling tower. Eqn, (8), Determines how effective the tower is. For example, in Figure 12, we can see how the effectiveness of a cooling tower can change with the amount of water poured into it for splash fill at different temperatures.The cooling tower's capability to function decreases with increasing water flow rate for any given value of water inlet temperature. For example, if the water inlet temperature is between 40 and 55°C and the water flow rate is between 3 and 13.5 L/min, the cooling tower effectiveness is 15.35 %, 28.49 %, and 7.4 %, 7.4 %, and 16.4 %, respectively. This is shown in Figure 13, which shows that film fill and splash fill both works the same way. For film fill, however, it works better than splash fill. Another thing to keep in mind is that for splash fill, if the water inlet temperature is (40 or 55°C) and the water flow rate is (3 or 13.5 l/min), cooling tower effectiveness is 18.3%, 32.82%, and 16.3%, 23.26%, respectively. As a result, the cooling tower's efficacy increases as the water to air mass flow rate ratio $(\dot{m}_w/\dot{m}_a)$ is lowered. As seen in Figure 13, for a 6 L/min water flow rate. As an example, consider a $(\dot{m}_w/\dot{m}_a)$ ratio of (5.21); the efficacy is computed as (37.69 5%. Where the water mass flow rate remains constant and the air mass flow rate decreases, the effectiveness is determined as a $(\dot{m}_w/\dot{m}_a)$ ratio of (0.89). (77.6 %). The highest efficacy for splash fill is achieved at 15 cm, as seen in Figure 13. This indicates that when the $(\dot{m}_w/\dot{m}_a)$ ratio drops, and effectiveness improves for each water mass flow rate value. Thus, while the mass flow rate of water remains constant, the mass flow rate of air plays a critical role in determining the cooling tower's efficacy. The change in cooling tower efficacy as a function of the water to air mass flow rate ratio for various air mass flow rates is depicted in figures 14, 15, and 16. These images show that cooling tower efficacy declines as the ratio $(\dot{m}_w/\dot{m}_a)$value grows$\dot{m}_w/\dot{m}_a$. Whereas the efficacy of water flow rate (9 L/min) reaches (61.31%) at a mass flow rate ratio $(\dot{m}_w/\dot{m}_a)$ of (0.89) for splash fill at the height of (15 cm), as seen in figure 13. According to figure 15, the highest efficacy (55.46 %) occurs when the mass flow rate ratio $(\dot{m}_w/\dot{m}_a)$ is 0.98, and the water flow rate is 12 L/min. This indicates that as the water flow rate increases, the efficacy of the cooling tower decreases. The highest cooling tower effectiveness is reached at the lowest $(\dot{m}_w/\dot{m}_a)$ ratio values.

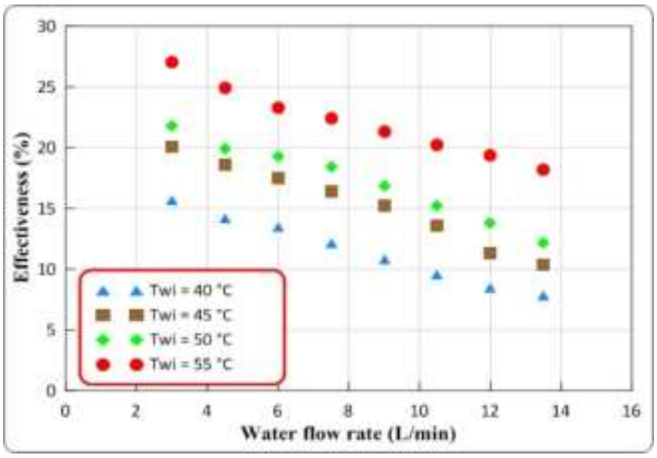

Figure 12. Effectiveness of circulating water flow rate for varying inlet water temperature with film fill (15 cm)

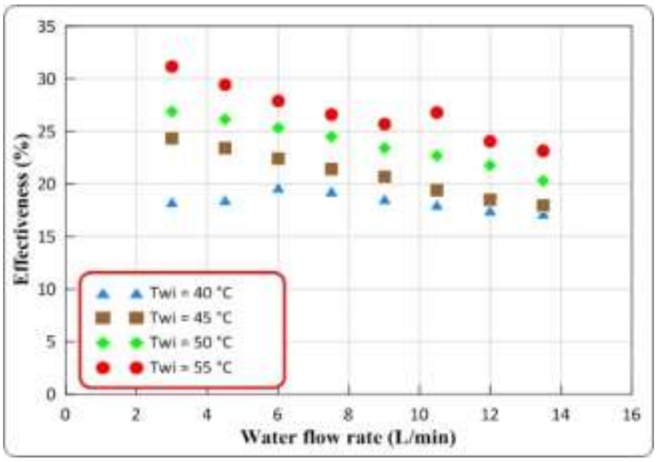

Figure 13. Effectiveness of circulating water flow rate for varying inlet water temperature with splash fill (15 cm)

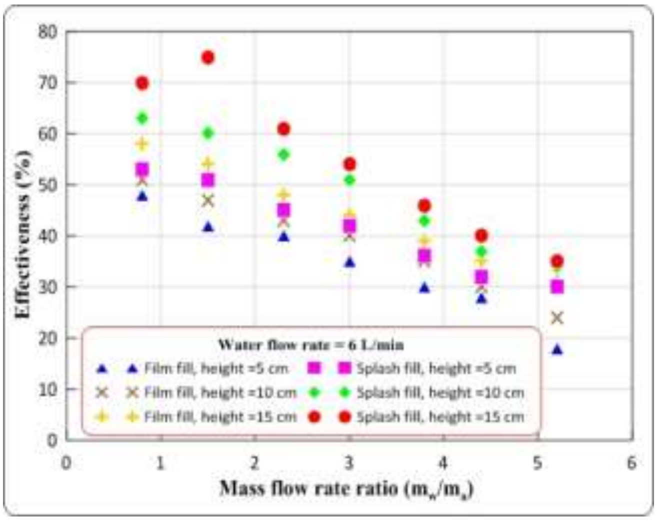

Figure 14. Effectiveness for different fill types based on mass flow rate ratio

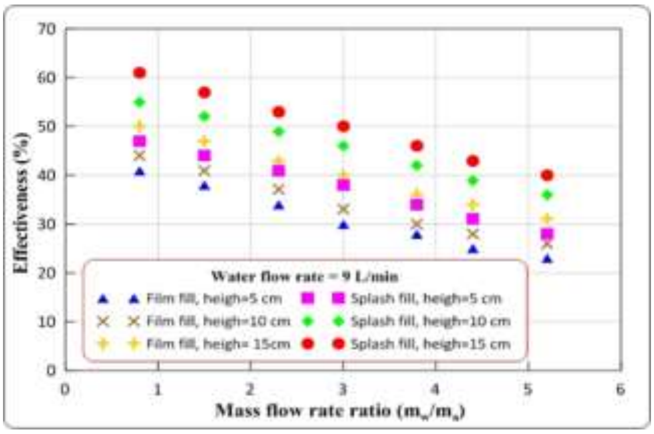

Figure 15. Effectiveness for different fill types based on mass flow rate ratio

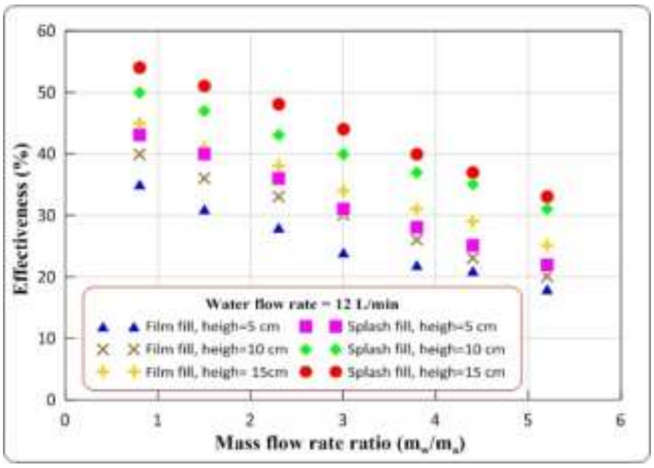

Figure 16. Effectiveness for different fill types based on mass flow rate ratio

3. Cooling Tower Approach

The connection between approach and water flow rate for splash fill due to varying inlet water temperatures is demonstrated in figure 17. As water flow rates increase, the exit water temperature approaches the wet-bulb temperature, as seen in this figure. The increase in outlet water temperatures occurs due to an increase in water flow rate, and these outcomes are acquired as a result of an increase in hot water. Figure 18 shows that the approach increases somewhat less than form splash fill because heat transmission in film boards serves two purposes. The first stage is to break up large water droplets into smaller ones, increasing the air-water contact area. The second goal is to delay the droplets' descent and so lengthen their stay in the tower. Water should be chilled to the same temperature as the air wet bulb entering the system, theoretically possible for infinite packing heights.

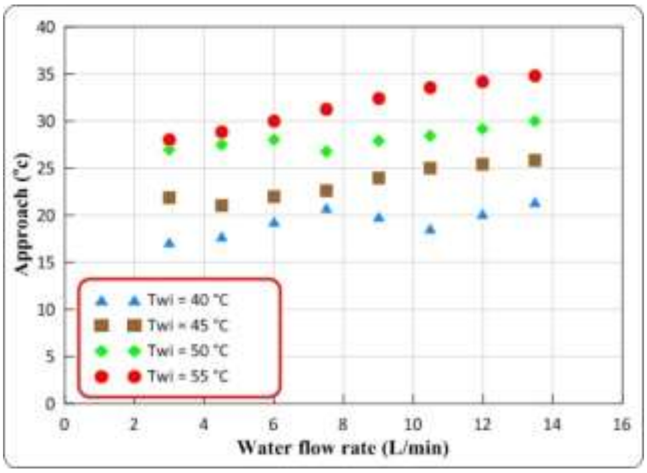

Figure 17. Approach with circulating water flow rate for different inlet water temperatures. (splash fill=15 cm)

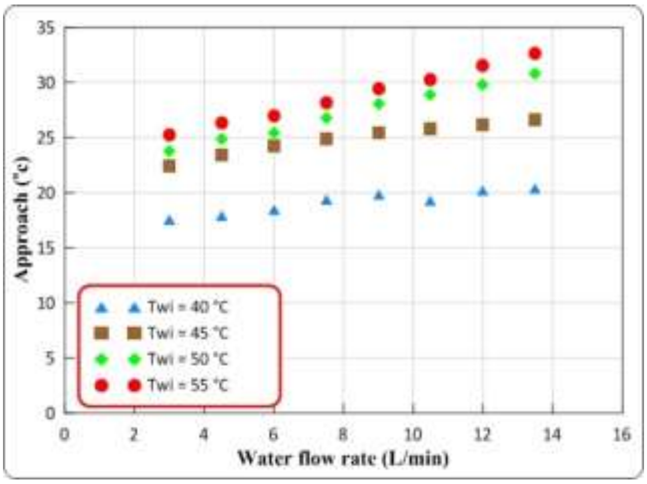

Figure 18. Approach with circulating water flow rate for different inlet water temperatures. (film fill=15 cm)

4. Variation of Outlet Water Temperature

Figure 19 shows the relationship between outlet water temperature and water flow rate for various inlet water temperatures used for splash fill at the height of 15 cm. Water temperature increases with increasing water flow rate for each value of water input temperature, and this is due to heat and mass transfer in the tower. For varied inlet water temperatures, film fill at a fill spacing of 15 cm behaves differently from splash fill, as seen in Figure 20, where exit water temperature increases as water flow rate increases.

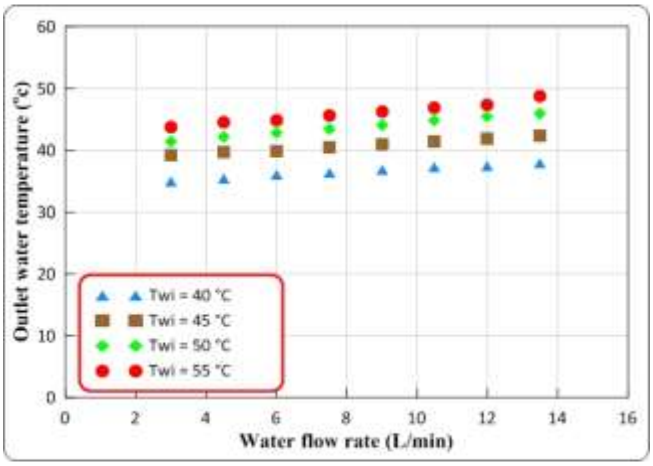

Figure 19. Water temperature at the outlet and water flow rate for different inlet water temperatures (15 cm splash fill)

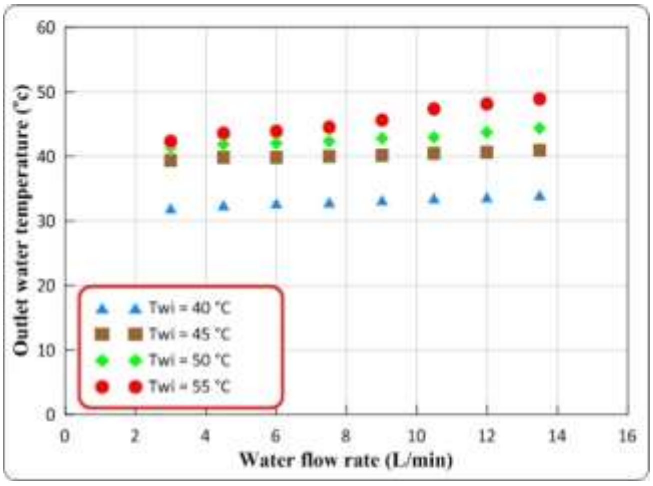

Figure 20. Water temperature at the outlet and water flow rate for different inlet water temperatures (15 cm film fill)

5. Merkel Number

Merkel number (Me) is used to measure the cooling tower's heat transfer capacity. Merkel number decreases due to increasing mass flow rate ratio with different fill types for water flow rates of 6L/min, 9L/min, and 12L/min, respectively. Figures (21, 22, and 23) show that splash fill at (15 mm) has the greatest Merkel value of all fill types. The table summarizes the empirical relationships (2). As a result, tower characteristics increase as air mass flow rate increases and water flow rate decreases. This number decreases as the water flows towards the bottom of the tower and reaches its minimum value when the water exits. This is because the evaporation process extracts the necessary heat for evaporation from the remaining water, cooling it and lowering its enthalpy.

Table 2. Empirical relation for the transfer characteristic of fills

Fill type	Empirical relation	Correlation R^2
Film, height=5cm	Me=0.9455($\dot{m}_w$ / $\dot{m}_a$)^(-0.323)	0.968
Film, height=10cm	Me=1.3618 ($\dot{m}_w$ /$\dot{m}_a$)^(-0.305)	0.9485
Film, height=15cm	Me=2.0941 ($\dot{m}_w$ / $\dot{m}_a$)^(-0.365)	0.9867
Splash,height=5cm	Me=2.0229 ($\dot{m}_W$/$\dot{m}_a$)^(-0.186)	0.6953
Splash, height=10cm	Me=1.4811 ($\dot{m}_w$ / $\dot{m}_a$)^(-0.616)	0.9998
Splash, height=15cm	Me=1.5058 ($\dot{m}_w$ / $\dot{m}_a$)^(-0.533)	0.8614
Film, height=5cm	Me=1.1212 ($\dot{m}_w$ /$\dot{m}_a$)^(-0.241)	0.9861
Film, height=10cm	Me=1.2894 ($\dot{m}_w$ / $\dot{m}_a$)^(-0.126)	0.7942
Film, height=15cm	Me=1.7962 ($\dot{m}_w$ / $\dot{m}_a$)^(-0.143)	0.8158
Splash, height=5cm	Me=1.1333 ($\dot{m}_w$ / $\dot{m}_a$)^(-0.221)	0.9073
Splash, height=10cm	Me=1.2946 ($\dot{m}_w$ / $\dot{m}_a$)^(-0.247)	0.9647
Splash, height=15cm	Me=1.7786 ($\dot{m}_w$ / $\dot{m}_a$)^(-0.251)	0.6439

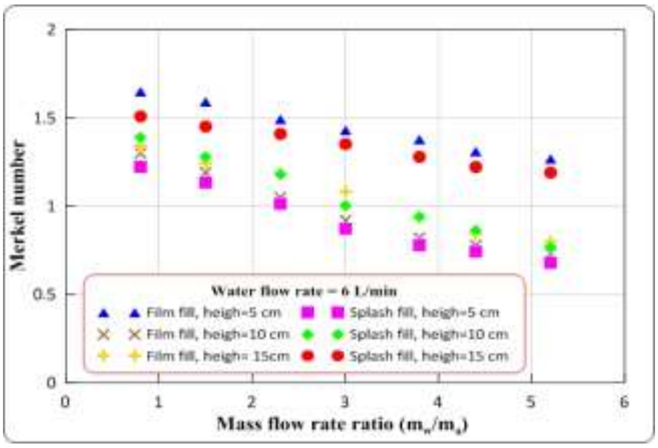

Figure 21. Merkel number with mass flow rate ratio for different fill types

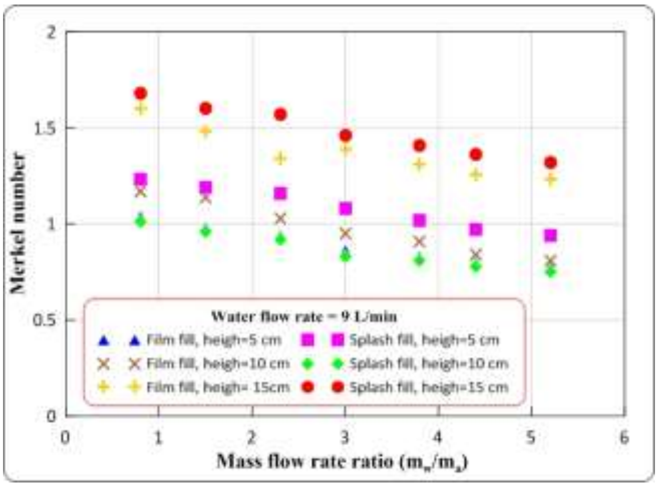

Figure 22. Merkel number with mass flow rate ratio for different fill types

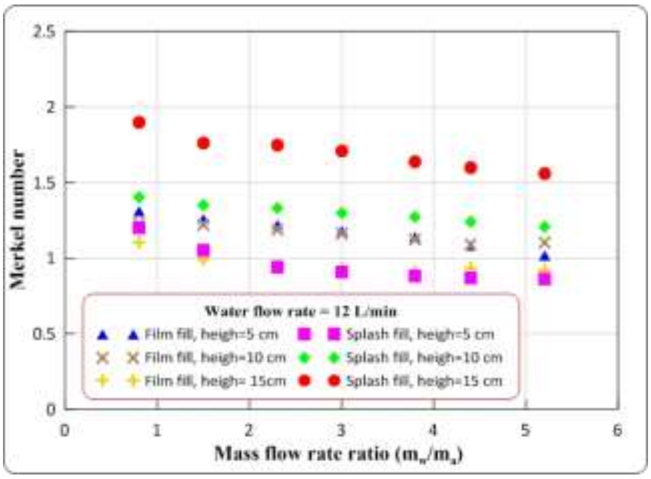

Figure 23. Merkel number with mass flow rate ratio for different fill types

Conclusions

The following findings are obtained from the experimental and theoretical analyses:

1. Laboratory experiments demonstrate that the value of ($\dot{m}_w/\dot{m}_a$) increases, (Me) decreases. The empirical relationships between (Me) and($\dot{m}_w/\dot{m}_a$) for various fill types are represented in table (1).
2. The tower characteristic improves when the cooling range increases and the tower approach

is reduced while maintaining the same tower volume.

3. Increasing the air mass flow rate $(\dot{m}_a)$ decreases the outlet water's temperature, whereas increasing the water mass flow rate $(\dot{m}_w)$ increases the outlet water's temperature.
4. Increasing the air mass flow rate $(\dot{m}_a)$ decreases the outlet air's wet bulb temperature, increasing the water mass flow rate $(\dot{m}_w)$ increases the outlet air's wet-bulb temperature.
5. The mass and heat transfer rate are fastest at the top of the tower. When the inlet water temperature goes up, the mass and heat transfer rate between the water and the bulk air goes up. When the wet-bulb temperature of the inlet air goes up, the mass and heat transfer rate go down. The relationship between how fast mass and heat move can also lead to the same conclusion.

References

M. Gao, C. Guo, C. Ma, Y. Shi, and F. Sun, “Thermal performance for wet cooling tower with different layout patterns of fillings under typical crosswind conditions,” Energies, vol. 10, no. 1, 2017, doi: 10.3390/en10010065.

H. Fugmann, B. Nienborg, G. Trommler, A. Dalibard, and L. Schnabel, “Performance evaluation of air-based heat rejection systems,” Energies, vol. 8, no. 2, pp. 714–741, 2015, doi: 10.3390/en8020714.

R. Fang, D.G. Cacuci, and M. Badea, “Predictive Modeling of a Paradigm Mechanical Cooling Tower Model: II. Optimal Best-Estimate Results with Reduced Predicted Uncertainties,” Energies, vol. 9, no. 9, 2016. doi: 10.3390/en9090747.

M. Goodarzi and P. Mohammadi, “Comparative Analysis on Thermal Performance of Different Natural-Draft Dry Cooling Towers Under Crosswind Condition,” vol. 1, no. 1, pp. 39–48, 2017, doi: 10.22060/mej.2017.12314.5310.

W. Wang, H. Zhang, P. Liu, Z. Li, J. Lv, and W. Ni, “The cooling performance of a natural draft dry cooling tower under crosswind and an enclosure approach to cooling efficiency enhancement,” Appl. Energy, vol. 186, pp. 336–346, 2017, doi: 10.1016/j.apenergy.2016.02.007.

Y. Huang, L. Chen, X. Huang, X. Du, and L. Yang, “Performance of natural draft hybrid cooling system of large scale steam turbine generator unit,” Appl. Therm. Eng., vol. 122, pp. 227–244, 2017, doi: 10.1016/j.applthermaleng.2017.04.120.

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.

X. Li, H. Gurgenci, Z. Guan, and Y. Sun, “Experimental study of cold inflow effect on a small natural draft dry cooling tower,” Appl. Therm. Eng., vol. 128, pp. 762–771, 2018, doi: 10.1016/j.applthermaleng.2017.09.071.

B.A. Qureshi and S.M. Zubair, “A complete model of wet cooling towers with fouling in fills,” Appl. Therm. Eng., vol. 26, no. 16, pp. 1982–1989, 2006. doi: 10.1016/j.applthermaleng.2006.01.010.

W. Li, YingYuan, F. Sun, R. Liu, and X. Chen, “The effect of air parameters on the evaporation loss in a natural draft counter-flowwet cooling tower,” Energies, vol. 13, no. 23, 2020, doi: 10.3390/en13236174.

Q. Saleh Mahdi and M.R. Al - Hachami, “Performance Comparison for NDWCT Using Trickle Fill at Different Weather Conditions,” Int. J. Eng. Trends Technol., vol. 19, no. 3, pp. 134–139, 2015. doi: 10.14445/22315381/ijett-v19p223.

Z. Nourani, A. Naserbegi, S. Tayyebi, and M. Aghaie, “Thermodynamic evaluation of hybrid cooling towers based on ambient temperature,” Therm. Sci. Eng. Prog., vol. 14, no. March, p. 100406, 2019, doi: 10.1016/j.tsep.2019.100406.

S. Ghoddousi, A. Anderson, and B. Rezaie, “Analysis of windbreaker combinations on steam power plant natural draft dry cooling towers,” Eur. J. Sustain. Dev. Res., 5(3),em0161, 2021, doi: 10.21601/ejosdr/10952.

E.C. Wai-fah, “Gould, P.L. and Kratzig, W.B. ‘Cooling Tower Structures,’” 1999.

K. Wang, F. zhong Sun, Y. bin Zhao, M. Gao, and L. Ruan, “Experimental research of the guiding channels effect on the thermal performance of wet cooling towers subjected to crosswinds - Air guiding effect on cooling tower,” Appl. Therm. Eng., vol. 30, no. 5, pp. 533–538, 2010. doi: 10.1016/j.applthermaleng.2009.10.015.

J. Facão and A. C. Oliveira, “Thermal behaviour of closed wet cooling towers for use with chilled ceilings,” Appl. Therm. Eng., vol. 20, no. 13, pp. 1225–1236, 2000. doi: 10.1016/S1359-4311(99)00096-4