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Research Article

Experimental and numerical analysis of the forced draft wet cooling tower

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ABSTRACT

Cooling towers are essentially large boxes designed to maximize the evaporation of water. The inlet water temperature and water to air mass flow rate ratio (L/G) significantly affect the performance of the cooling tower. The number of a transfer unit (NTU), Merkel number (Me), Lewis number (Le), and efficiency of the cooling tower define the performance of the forced cooling tower. In this research paper, different inlet water temperatures ranging from 28 °C to 42 °C and (L/G) ranging from 0.5, 1, and 1.5 were used to investigate the performance of the forced cooling tower. Mathematical modeling equations were used to calculate NTU, Me, Le, and efficiency at different inlet water temperatures and (L/G). Engineering equation solver (EES) software was used to solve these mathematical modeling equations. Further, an experimental investigation was carried to find forced cooling tower performance at different inlet water temperatures and (L/G), and results were compared with the theoretical results. The results revealed that increasing the inlet water temperature, NTU, Me, Le, and efficiency increased and were directly related to each other. Further, NTU and efficiency were increased by increasing (L/G). At the same time, the Me and Le reduced with (L/G). Finally, an acceptable and better agreement has been obtained between experimental and theoretical results. Based on obtained results, it has been concluded that higher values of inlet water temperature and (L/G) provided the higher performance of the forced cooling tower.

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INTRODUCTION

A cooling tower is an apparatus used in industrial applications, icing, air conditioning implants, and chemical and petrochemical manufacture. The cooling tower is considered a unique heat exchanger, in which water and air in direct contact reduced the water temperature. The basic working phenomena of a cooling tower is based on when some evaporated water reduces the water temperature circulating in the cooling tower [1]. This phenomenon occurs due to direct contact of hot water with the air through the packing fill, increase heat transfer rate and moisture, and exit in a saturated or supersaturated state [2]. Further by this, the water stream can be cooled to certain degrees; however, most heat removal is dependent on the evaporation of water into the air [3]. Based on this working mechanism, it seemed that the heat transfer of the water is the essential criterion of the cooling towers [4].

Further, the heat transfer removal rate mainly depends on numerous factors such as water equipment design, condition, and adjustment [5]. Additionally, this heat transfer removal rate plays an essential role in the overall capacity of the cooling tower [6]. The calculation of the heat transfer rate is considered as the analysis of the cooling tower. The first idea of analysis of cooling tower was initiated in the 19th century by Lewis [7], and such idea was used by Robinson [8,9].

Robinson [8] developed general principles to apply for the design of cooling towers and revealed several basic concepts for the cooling tower mechanism to transfer heat between liquid, gases, and the liquid's vaporization. Markel [10] applied enthalpy force as a driving force to transfer heat from water to air. Further, to transfer heat from water to air, Lewis number (Le) was assumed to have a similarity between heat and mass convective transfer. This Lewis number was assumed as one and is still used for the convection phenomenon occurring in cooling towers. Lewis number is a dimensionless number, and it is the ratio of thermal spread to mass spread [11]. Moreover, the Lewis number (Le) and Lewis number factor (Lef) are two different items. The Lewis number is the ratio of α to D, as shown in equation 1, and processes convective heat and mass transfer. Whereas the Lewis factor (Le_f) is the relative rates of heat and mass transfer in an evaporative process, as shown in equation 2. Lewis's number is not constant and is tied to the nature of the vapor–gas mixture. It also depends on the nature of the boundary layer near the exchange surfaces and the thermodynamic state of the mixture [12]. At the same time, Lewis factors range from to 1.3 [11]. Baker and Shrylock [13] used assumptions and explanations made by Merkel [10] to develop detailed explanations of the cooling tower. Merkle number (Me) is a parameter used to calculate the cooling tower's performance. Me aims to find pressure drop to improve the transfer and increase proportionally with the increase in the surface area [3]. Further, Braun et al. [14] developed the effectiveness number of transfer units (NTU) relationships method based on Merkel's theory. In their model, the saturated air specific heat used for sensible heat exchanger was taking into account. Further, two parameters such as air-side and water-side heat transfer coefficients, were introduced in their model. The performance of the cooling tower is mainly dependent on Le, Me, and NTU parameters. Moreover, the cooling tower's performance can be considered the air efficiency, and it is the difference between the actual inlet and the outlet water temperature divided by this difference's maximum value b [15]. The flow rate of water has a direct relation with the cooling range. Increasing the flow rate of water, the cooling zone also increases. Also, the water inlet temperature has a direct relationship with the cooling range. When the inlet water temperature increases, the cooling range also increases [16]. Ghumran, [17] investigated the effect of water flow rate and temperature on the performance of the induced draft cooling tower. Cooling load, efficiency, and tower characteristics were calculated using experiments (DOE) by water temperature and flow rate as variable parameters. The results showed that the cooling load and efficiency were high at a high water temperature, low at a lower water temperature. Ataei et al., [18] developed a mathematical model to evaluate cooling tower performance through energetic analysis. The developed model was validated against experimental data and obtained an error of 0.14% between the predicted and experimental values. Further, this developed model allowed the energetic analysis of water and air and the cooling tower through the fundamental balance law. The cooling tower modeling results revealed that the amount of exergy supplied by water is more significant than that absorbed by the air. This is because the system generates entropy. Moreover, the results revealed that water exergy decreases continuously from top to bottom. On the other hand, air exergy has been expressed in terms of convective and evaporative heat transfer. Spray zone, packing, and rain zones consisted of a significant portion of the total heat rejected of the cooling towers. The heat rejected may occur in the spray and rain zones. Also, to analyze the performance of the cooling tower, spray and rainy zones are more significant to calculate the volume of the cooling tower. The error of about 6.5% for calculating the tower volume was observed when the spray and rain zones were neglected, and it was reduced to 3.15% when the spray and rain zones were considered [12] and [19]. So, it is significant to involve the spray and rain zones in analysis for a greater validity in determining and performance analysis. Therefore, in this research work, this three spray, packing, and rain zones were considered for calculating the performance of the cooling tower.

Moreover, as discussed earlier, the water inlet temperature and Lewis factor are also essential to analyze the performance of the cooling tower. Therefore, these two parameters were used to investigate the performance of the cooling tower. For the cooling tower performance, Le, Me, NTU, and efficiency were calculated using mathematical modeling equations. The mathematical model equations were solved by using an engineering equation solver (EES). Finally, the results obtained through mathematical modeling were validated with the experimental results.

THERMAL ANALYSIS AND GOVERNING EQUATIONS

Figure 1 shows the control volume of the counter flow cooling tower, and to drive the basic modelling equation, some assumptions must be considered:

1- Divide the counter flow of the wet cooling tower into 100 CV for mass and thermal analysis.
2- Neglect the heat transfer from the cooling tower wall to the surrounding.
3- Ignoring the heat transfer from the fun and pump.
4- Stable the specific heat of the dry air water and water. 5- Neglect the changes in kinetic and potential energies.
6- Stable and local regular(regular at each cross-sectional area) flow.
7- Fix the cross-sectional area of the tower.
8- Temperature change in one dimension (vertical direction).

Equation 3 represents the mass balance in counter flow wet cooling tower control volume [1]:

$$dL = G * d\omega \tag{1}$$

Equation 4 represents the energy balance in counter flow wet cooling tower:

$$G * dha = L * C_w * T_w + dL * C_w * T_w \tag{2}$$

Substitute Equation 3 into Equation 4

$$G * dh_a = L * C_w * T_w + G * d\omega * C_w * T_w \tag{3}$$

The difference in enthalpy of air in the wet cooling tower

$$dh_a = \frac{L}{G} * C_w * T_w + d\omega * C_w * T_w \tag{4}$$

The total heat transfer between water, air written [1]

$$dq_t = dq_l + dq_s \tag{5}$$

The ql calculated from [1]:

$$dq_l = h_{diff} * h_g * d_A * (\omega_s - \omega) \tag{6}$$

The qs heat calculated from [1]

$$dq_s = h_c * dA * (T_w - T_a) \tag{7}$$

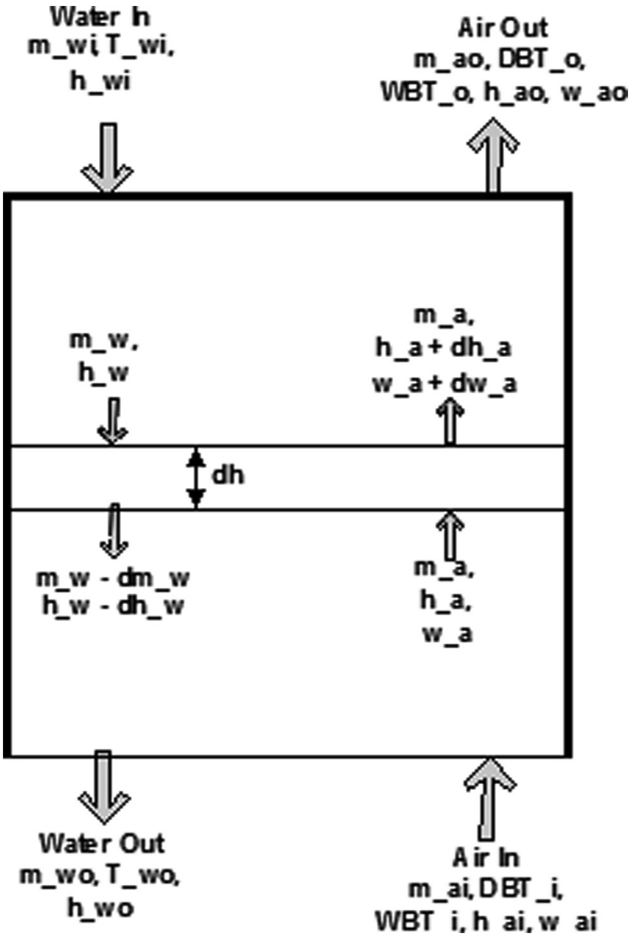

Figure 1. Cooling tower control volume.

By substituting the equations (8), (9) in equation (7) and facilitating this equations, the dq_t written as

$$dq_t = \frac{h_c * dA}{C_{pm}} * (h_{asat} - h_a) \tag{8}$$

Furthermore, the total heat can be written as

$$dq_t = L * C_w * dT_w \tag{9}$$

Substitute equation (11) in equation (10) [20,21]

$$\frac{h_c A}{C_{pm}} = \frac{L * C_w * dT_w}{(h_{as} - h_a)_m} \tag{10}$$

$$NTU = \frac{h_c A}{C_{pm}} = \frac{h_c AV}{\dot{m}_n} = c\left(\frac{m_{w,in}}{\dot{m}_a}\right)^n \tag{11}$$

$$NTU = \frac{L * C_w * dT_w}{(h_{as} - h_a)_m} \tag{12}$$

Where $(h_{as} - h_a)_m$ is the difference in arithmetic-mean of enthalpy in the control volume Lewis number for air-water vapor systems can be written as:

$$\mathrm{Len} = 0.8650.667\,\frac{\left(\frac{\omega_s + 0.662}{\omega+0.662} - 1\right)}{\left(\frac{\omega_s + 0.662}{\omega+0.662}\right)} \tag{13}$$

To calculate the Merkel number, find three equations depended on the assumption to each one [11,21], the first equation

$$\mathrm{Mep} = \frac{h_{diff}A}{m_w} = \int \frac{m_a\, d\omega/dT_w}{m_w\, \omega_{sw} - \omega_{sa}}\, dT_W \tag{14}$$

The second equation depended on the Merkel method by assuming the evaporative loss is negligible.

$$\mathrm{MeM} = \frac{h_{diff}A}{m_w} = \frac{h_{diff}a_{fi}A_{fr}L_s}{m_w} = \frac{h_d a_{fi} L_s}{G_w} \tag{15}$$

$$= \int \frac{T_{wi}}{T_{wo}} = \frac{c_{pw}dT_w}{(h_{masw} - h_{ma})} \tag{16}$$

The third method developed equations to two cases: One when ma is greater than mwcpw/(dhmasw/dTw)

$$\mathrm{Mee} = \frac{c_{pw}}{\frac{d_{h\ masw}}{dT_w}}\, NTU \tag{17}$$

And if ma is less than mwcpw/(dhmasw/dTw)

$$\mathrm{Mee} = \frac{m_a}{m_w}\, NTU \tag{18}$$

Cooling tower efficiency

$$(\varepsilon) = \frac{T_{w,in} - T_{w,out}}{T_{w,in} - T_{a,b})} \tag{19}$$

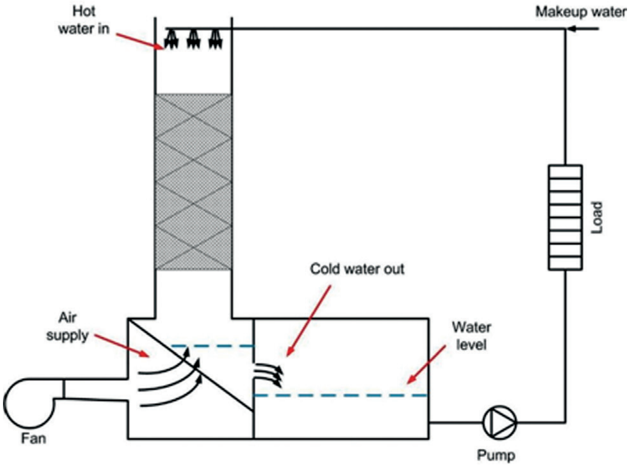

Figure 2. Test rig.

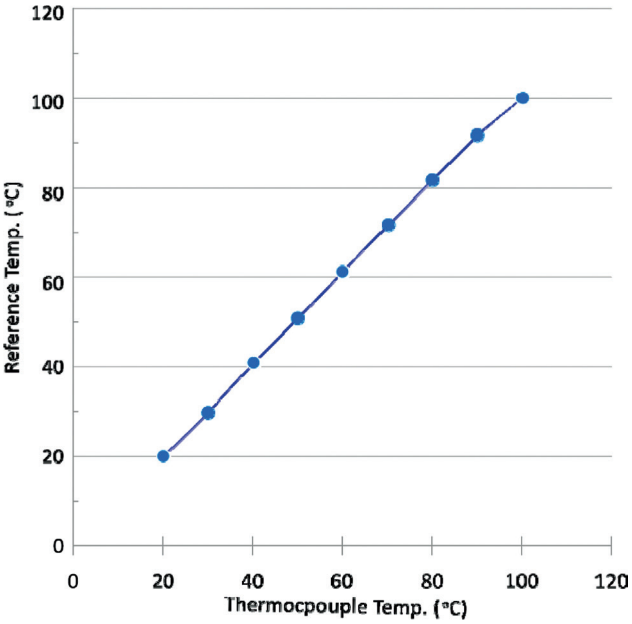

Figure 3. Thermocouples Calibration.

TEST RIG

Figure 2 shows the apparatus used for experimental investigation. The length, width, and height of a rectangular box were measured as 0.2, 0.2, and 0.8 m^2 respectively. The rectangular box is filled with 12 packing layers, each consisting of 5 cm of carton. Further, a spray nozzle (2mm diameter) was used to distribute water on the packing layer regularly. The tube has four holes to take a reading; a centrifugal pump was used for pumping water from the tank to the cooling pipe. A blower was put in to control airflow through the pipe; a manometer was used to measure the flow rate of air. This manometer was placed on an orifice of damper fixed at a certain distance from the blower, and the manometer was calibrated with a digital reference manometer. The temperature was measured using six thermocouple type k, two of them used to know the inlet and outlet temperature of the water, and the rest were used to measure DBT, WBT of the inlet, and outlet air. Figure 3 illustrates the calibration of thermocouples and clarifies a tiny error in the thermocouples reading because the curve is linear related to the reference temperature.

RESULT AND DISCUSSION

The cooling tower characteristics NTU, Le, and Me were calculated through mathematical modeling. In addition to it, experimental results were also found through the experimental test rig. Different (L/G) from 0.5 to 1.5 and water inlet temperature from 28°C to 42°C were chosen for calculating NTU, Le, Me, and efficiency of the cooling tower. Figure 4 shows the NTU results at different (L/G) and different temperatures. The results revealed a direct relationship of NTU with the air mass flow rate. The gradual increase in the NTU of the cooling tower increases the air mass flow rate. This is mainly because of the mass of airflow rate. [22] depicted that the performance of the cooling tower is mainly dependent on the quantity of air mass flow rate through the fill.

Further, the quantity of evaporation depends on the airflow rate, the humidity of the inlet air, and the cooling tower outlet air [1]. Additionally, increasing the mass airflow rate cause to increase in the heat rejected rate and improves the cooling tower's performance. The performance of the cooling tower also depends on the inlet water temperature [16]. The NTU increased with increasing the inlet water temperature, as depicted in the results shown in Figure 4. Also, it can be concluded that NTU has a direct relationship with the inlet water temperature. The results obtained for this section are also confirmed with the results obtained by [15], [6] and [1].

The NTU was also calculated by using equation (13). Based on the experimental data obtained for $\dot{m}_w$ and $\dot{m}_a$, the empirical constants c and n were estimated. Finally, the correlation between mathematical modeling and experimental data for NTU was also calculated. The correlation for NTU was calculated for all temperature range values used in this research work as presented in Table 1.

The correlation for results obtained through mathematical modeling and experimental data for NTU showed R^2 in the better and acceptable range. This indicated that the results obtained through mathematical modeling and experimental data are in good relation.

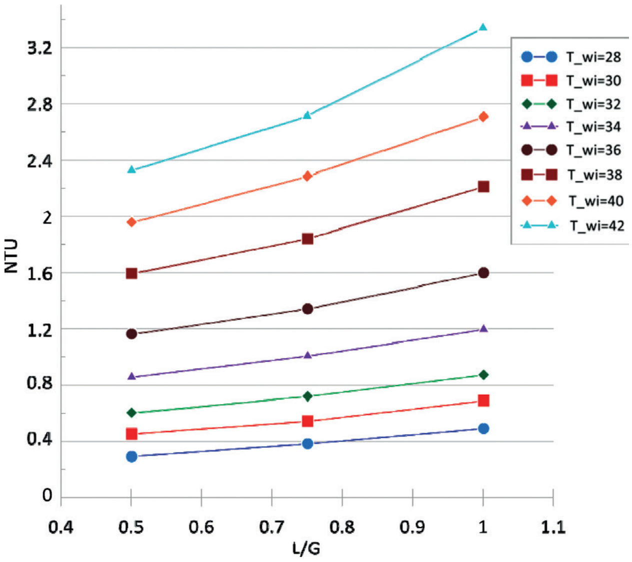

Figure 4. Relationship of NTU with L/G relation at Tw (28-42)°C.

Figure 5 shows the NTU results with inlet water temperature and water variation to the air mass flow rate ratio. These results revealed that the NTU increased with increasing the inlet water temperature and is proportional toinlet water temperature. NTU is a parameter that measures the heat transfer size of the cooling tower, and the results revealed that inlet water temperature increased the heat removal rate from the cooling tower. This is mainly because the higher temperature can increase the entropy generation caused by evaporation [1]. Further, the higher values of water variation to the air mass flow rate ratio provided better results for NTU.

Moreover, equation 14 was used to calculate NTU for the different temperatures ranged from 28°C to 42°C. The NTU increased from 0.49 to 2.88, 0.381 to 2.717, and 0.296 to 2.326 for the inlet water temperature from 28°C to 42°C for the water flow rate of 0.075, 0.05, and 0.03 kg/sec respectively. These values indicated that the higher NTU was obtained at higher inlet water temperature and higher water flow rate. Also, the results obtained for this section are confirmed with the results obtained by [16] and [1].

Figure 6 shows the Merkel number results with the inlet water temperature for different water flow rates. The results showed that the Markel number and inlet water temperature have a direct relationship with each other. The Merkel

Table 1. Correlation of NTU for all temperature range values

Inlet water temperature °C	Correlation	R^2
28	$NTU = 0.4891 * \left(\frac{\dot{m}_w}{\dot{m}_a}\right)^{0.7364}$	0.9936
30	$NTU = 0.6778 * \left(\frac{\dot{m}_w}{\dot{m}_a}\right)^{0.5936}$	0.9698
32	$NTU = 0.8628 * \left(\frac{\dot{m}_w}{\dot{m}_a}\right)^{0.5185}$	0.9844
34	$NTU = 1.1835 * \left(\frac{\dot{m}_w}{\dot{m}_a}\right)^{0.4725}$	0.988
36	$NTU = 1.5747 * \left(\frac{\dot{m}_w}{\dot{m}_a}\right)^{0.4516}$	0.9775
38	$NTU = 2.1754 * \left(\frac{\dot{m}_w}{\dot{m}_a}\right)^{0.4661}$	0.9743
40	$NTU = 2.675 * \left(\frac{\dot{m}_w}{\dot{m}_a}\right)^{0.4636}$	0.9852
42	$NTU = 3.2704 * \left(\frac{\dot{m}_w}{\dot{m}_a}\right)^{0.5136}$	0.9677

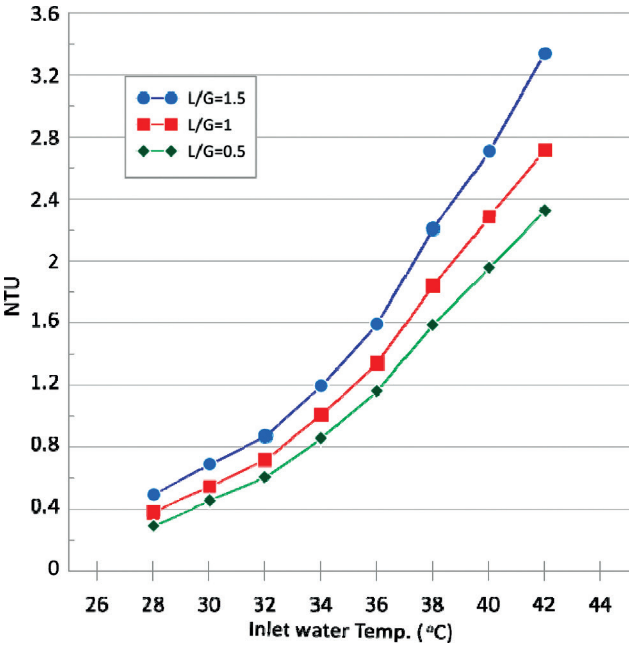

Figure 5. Experimental NTU of cooling tower.

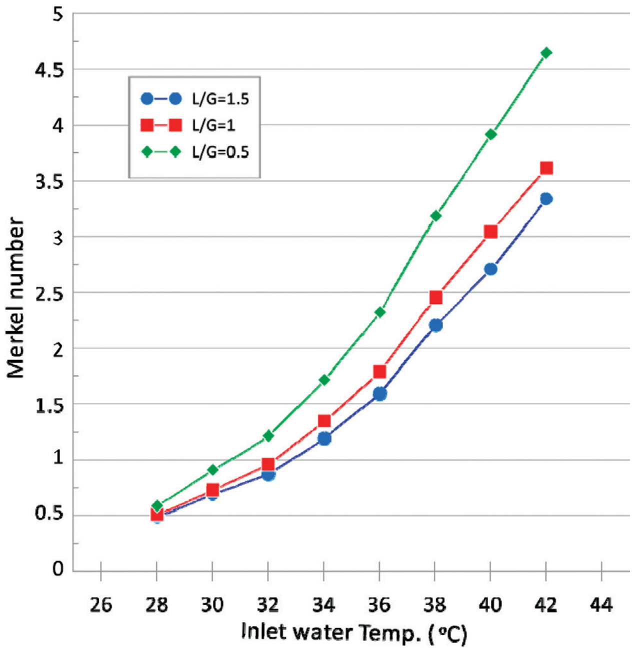

Figure 6. Experimental Me of cooling tower.

number gradually increased with increasing the inlet water temperature. However, the Merkel number has an inverse relationship with the air mass flow rate. Usually, the Merkel number depicts the heat transfer from air to water in the fill zone. The enthalpy of air mainly affects the heat removal from water [23] and [24]. This is the reason that the Merkel number is lower at a higher L/G ratio. The results obtained in this section for the Merkel number are confirmed with the results obtained by [1].

Further, as discussed earlier, the Merkel number increased with increasing inlet water temperature. Equation 16 was used to calculate the Merkel number, and the obtained results revealed that increasing the inlet water temperature, Merkel number increased from 0.49 to 3.06, 0.51 to 3.6, and 0.59 to 4.36 for water flow rate 0.075, 0.05, and 0.03 kg/sec, respectively.

Figure 7 shows the Lewis factor variation with the inlet water temperature for different water flow rates. It can be seen from graphical results that the Lewis factor approximately remained constant, where the change of inlet water temperature and the water flow rate was not affected by the Lewis factor because the enthalpy potential was increased. Further, equation 15 was used to calculate the Lewis factor for water inlet temperature. The results showed that the water inlet temperature increased from 28°C to 42°C caused to change of the Lewis factor from 0.9102 to 0.9218, 0.9107 to 0.9222, and 0.911 to 0.9226 for the water flow rate of 0.075, 0.05, and 0.03 kg/sec respectively.

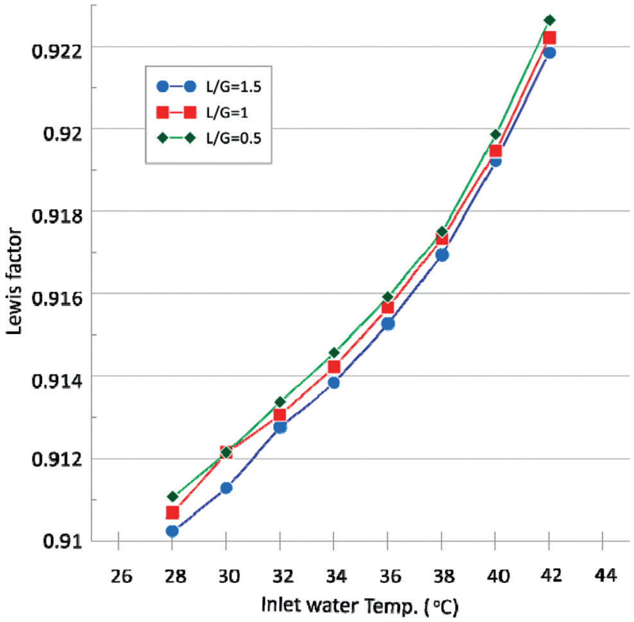

Figure 7. Experimental Le of cooling tower.

Cooling tower efficiency is the ratio of range to the ideal range of the output, and in other words, it can be calculated by using the difference between cooling water inlet temperature and ambient wet bulb temperature [25]. This relationship indicated that the water inlet temperature has a significant effect on cooling tower efficiency. The higher inlet temperature can produce higher cooling tower efficiency [26]. Figure 8 shows the efficiency of the cooling

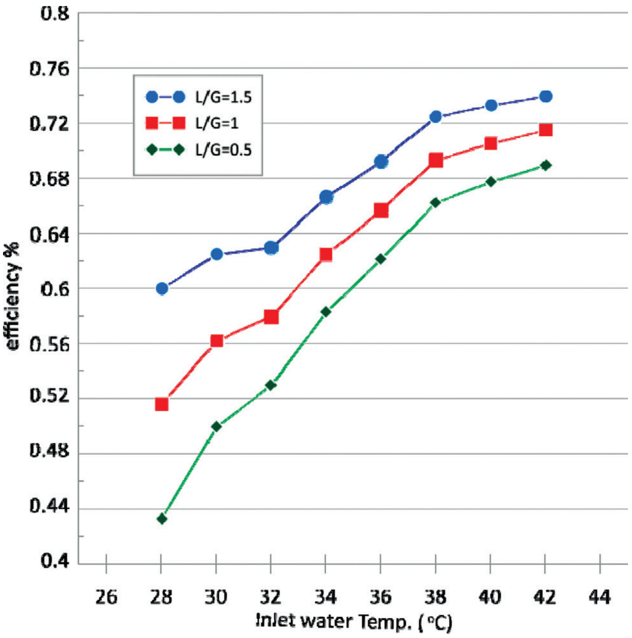

Figure 8. Efficiency of cooling tower.

tower with inlet water temperature and water variation to the air mass flow rate ratio. The graphical results depict that the cooling tower efficiency is in direct relationship with inlet water temperature, and it increased with increasing the inlet water temperature. Also, the inlet water temperature increases the range in which the range is proportional to the temperature difference.

Moreover, equation 21 was used to calculate cooling tower efficiency for different water inlet temperatures and different water flow rates. The results showed that cooling tower efficiency increased with increasing the water inlet temperature and water flow rate. When the water inlet temperature increased from 28°C to 42°C, it obtained as to 0.72, 0.5 to 0.7 and 0.46 to 0.67 for water flow rate 0.075, 0.05 and 0.03 kg/sec respectively.

Figures in Appendix – A depict the relation between experimental and theoretical NTU with inlet water temperature for three values of water to air mass flow rate ratios. The graphical results show a straight line between the experimental and theoretical NTU and inlet water temperature. This means that the experimental and theoretical results are in good agreement. However, the deviation between them is 17, 22, and 25% for three water-to-airflow rate ratio values (1.5, 1, 0.5).

Figures in Appendix – B, show the relation between experimental and theoretical Me with inlet water temperature for three values of water to air mass flow rate ratio, respectively. The results revealed a linear relationship between the experimental and theoretical Me and inlet water temperature for three different water flow rates. However, the deviation between them is 25, 29, and 23% for three water-to-airflow rate ratios 1.5, 1, and 0.5, respectively.

Figures in Appendix – C shows the experimental and theoretical relationship between Le with inlet water temperature for three values of water to air mass flow rate ratios as 1.5, 1, and 0.5, respectively. The theoretical results for the Lewis factor changed by increasing the water inlet temperature from 28°C to 42°C, mainly becausethe enthalpy potential was increased. The theoretical results remained constant for water to air mass flow rate ratios of 1.5, 1, and 0.5. Moreover, the graphical presentation of experimental and theoretical values of Le showed perfect agreement between the experimental and the theoretical and deviation between them is about 8.7, 8.6, 8.6 % for three water-to-air flow rate ratios as 1.5, 1, and 0.5 respectively.

CONCLUSION

Cooling towers are primarily used for large thermal applications to dissipate the absorbed heat into the atmosphere. The dissipation of heat occurred due to convection heat transfer between water and external and or through evaporation of water particles. Further, among other parameters, the inlet water, and mass airflow also significantly affect the dissipation of heat rejection in the cooling towers. The temperature of the inlet water and the amount of airflow rate has been used to investigate the performance of the cooling tower. There numerous characteristics to analyse the performance of cooling towers. In this research work, the performance characteristics such as NTU, Me, Le, and efficiency of the cooling tower were investigated with different inlet water temperatures and water-to-air flow rate ratios. The analysis was carried through mathematical modeling equations. The EES system was used to solve the mathematical equations.

Further, experimental analysis through the test rig was also carried by using the same inlet water temperature values and water-to-air flow rate ratios. Both experimental and theoretical results of the performance characteristics were compared. Based on the obtained theoretical and experimental results, the following conclusions have been drawn:

1- The inlet water temperature and water-to-air flow rate ratios significantly changed the cooling tower performance characteristics.
2- NTU gradually increased with increasing the inlet water temperature and water-to-air flow rate ratios.
3- Me also continuously increased with increasing inlet water temperature. However, it achieved lower values at higher values of water-to-air flow rate ratio.
4- The Lewis factor also increased with increasing inlet water temperature, whereas it decreased by increasing the water-to-air flow rate ratio.
5- The efficiency of the cooling tower showed a direct relationship with inlet water temperature and

water-to- air flow rate ratios. It continuously increased with increasing both inlet water temperature and water-to-air flow rate ratios.

6- The experimental and theoretical results for NTU, Me, and Le showed good agreement with each other. The theoretical results depicted that NTU and Me increased with increasing inlet water temperature and water- to-air flow rate ratios and were in good relationship with experimental results. However, Le did not show any change (theoretical result) for changing water-to-air flow rate ratios but has a slight deviation for all the three water-to-air flow rate ratios.

NOMENCLATURE

A	Area (m^2)
cpa	Specific heat of air (kJ/kg.k)
Cw	Specific heat of water (kJ/kg.k)
DBT	Dry bulb temperature (°C)
G	Air flow rate (kg/s)
ha	Enthalpy of the air (kJ/kg)
h as	Saturated enthalpy of air (kJ/kg)
hdiff	mass transfer coefficient (kg/m2s)
h f,w	Saturated liquid enthalpy of water (kJ/kg)
L	Water flow rate (kg/s)
Le	Lewis factor
L/G	water to air mass flow rate
Me	Merkel number
NTU	number of transfer units
qt	Total heat transfer (kW)
qs	Sensible heat transfer (kW)
ql	Latent heat transfer (kW)
Ta	Air temperature (°C)
Ta,b	wet-bulb temperature of the ambient air stream
Tw	Water temperature (°C)
WBT	Wet bulb temperature (°C)
Greek letters	
ε	efficiency%
Subscripts	
a	Air
i	in
n	Number of section
o	out
sat	Saturated of air

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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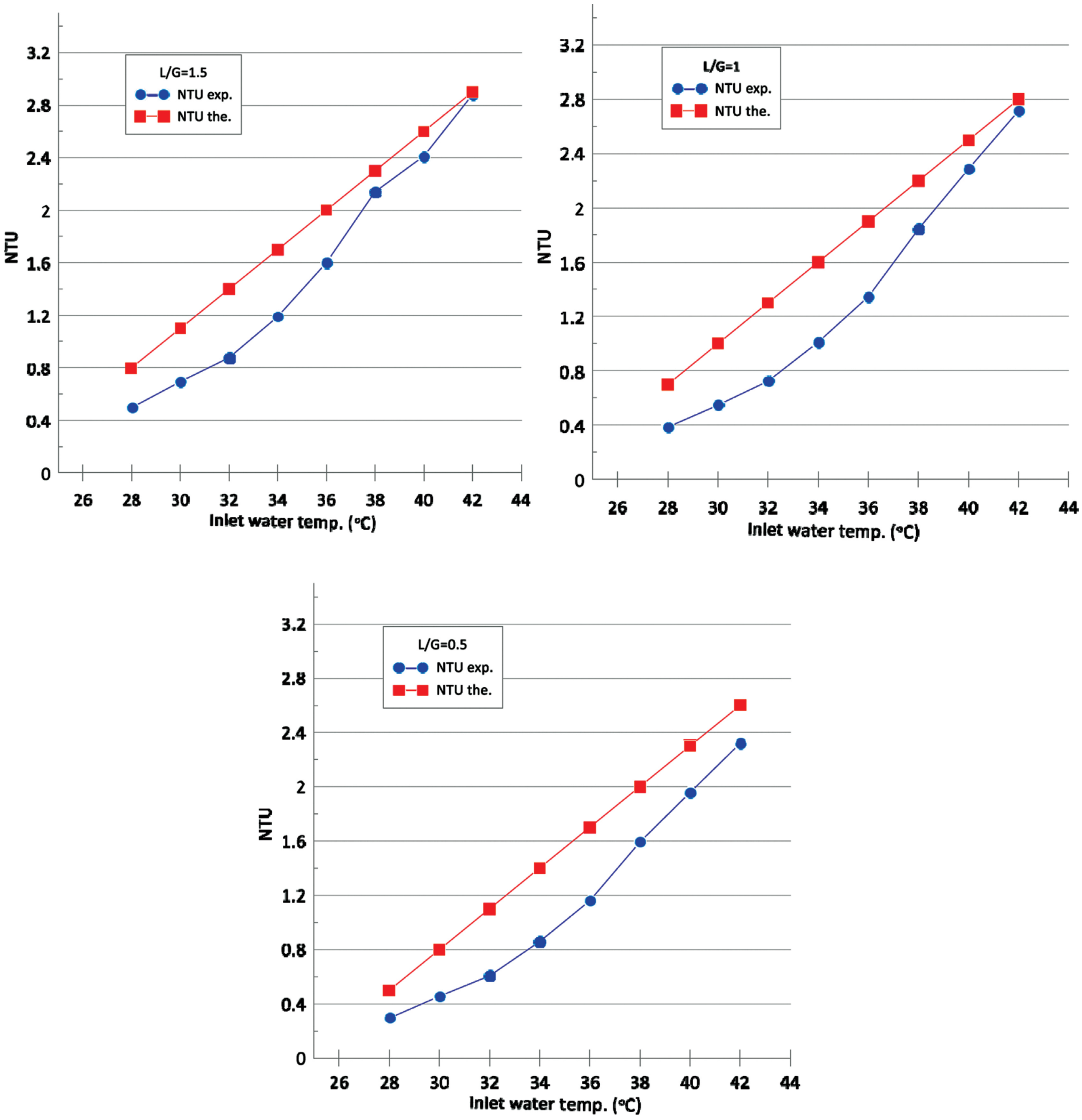
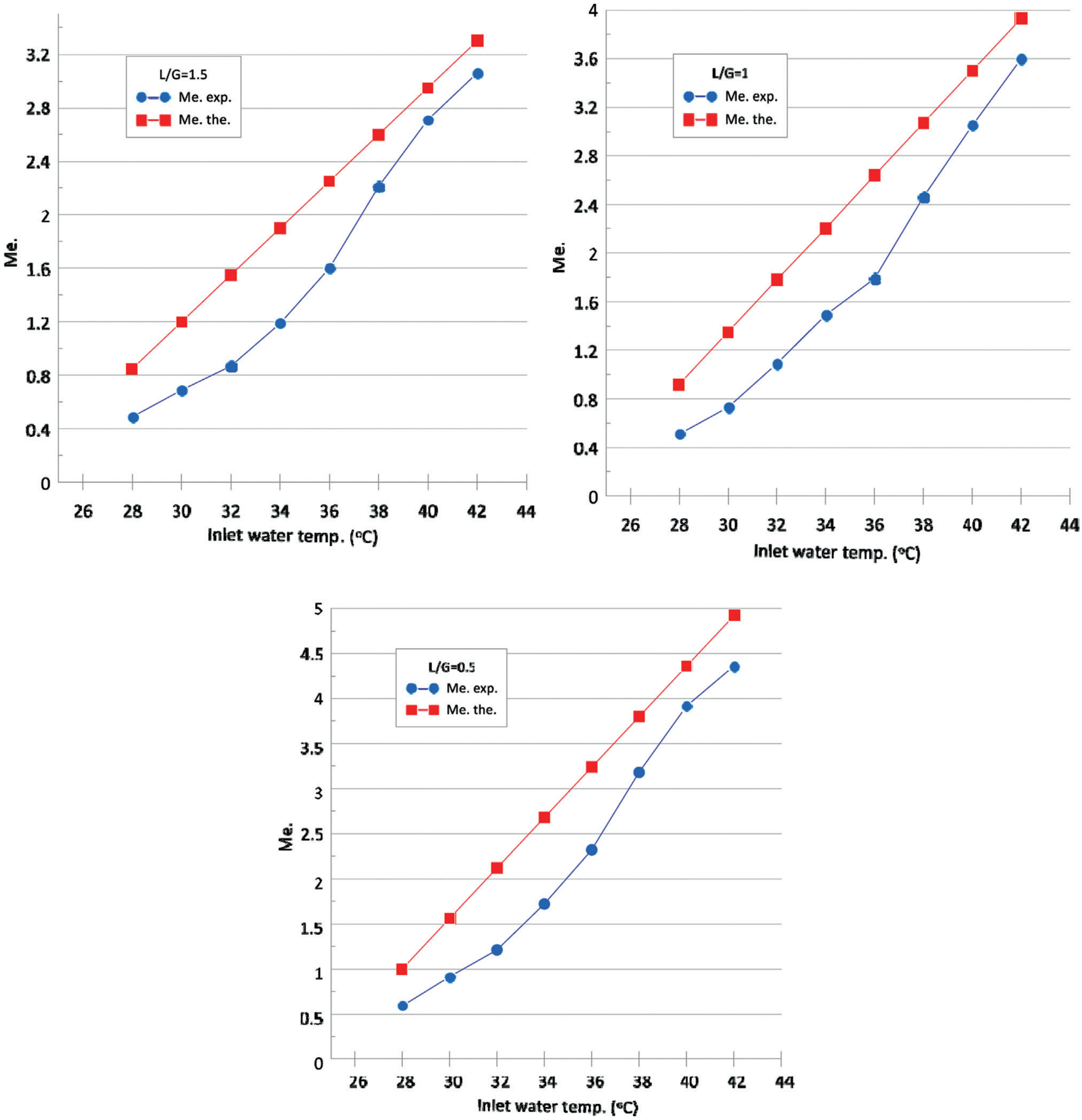
Appendix – A: Experimental and Theoretical NTU for the cooling tower



Appendix – B: Experimental and Theoretical Me for the cooling tower



Appendix – C: Experimental and Theoretical Le for the cooling tower