Prediction of outlet water temperature from cooling towers

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Abstract: This paper presents a very accurate method for water temperature prediction of outlet water from counter flow of cooling tower. This method was derived from the method of \[\frac{h_c A}{C_{pm}}\] which is called NTU (Number of Transfer Units). The effect of the water and air mass flow rate, wet bulb temperature of the inlet air, outlet water temperature, tower range, and temperature approach have been studied. The results of comparison between the presented and the NTU methods show a very good match when the outlet water temperature is between 29 and 45°C and a difference reaches to 7.23% between 26 and 28°C. Another very good match has been noticed when the air mass flow rate is between 15.6 and 16.5 kg/s with difference reaches to 2.5% when the air mass flow rate is between 10 and 15 kg/s. The last very good match has been noticed when the water mass flow rate is between 17.5 and 19 kg/s with the difference reaches to 1.2% when the water mass flow rate is (10 - 17 kg/s).

Keywords: Cooling Tower; Number of Transfer Units; Mass Flow Rate; Comparison; Temperature; Prediction; Inlet; Outlet.

Table 1: Nomenclature

| A  | Cross sectional area | m² |
|----|----------------------|----|
| C_{pm} | Specific heat of moist air | J/kg.K |
| G  | Air mass flow rate  | kg/s |
| H  | Enthalpy             | J/kg |
| h_a | Enthalpy of air      | J/kg |
| h_{ad} | Enthalpy of air entering the bottom increment | J/kg |
| h_{al} | Enthalpy of air leaving the bottom increment | J/kg |
| h_{aw} | Enthalpy of air at the inlet wet bulb temperature | J/kg |
| h_c | Convection heat transfer coefficient | W/m².K |
| h_i | Enthalpy of water   | J/kg |
| L  | Water mass flow rate | kg/s |
| N  | Number of tower increments-1 | ...... |
| NTU | Number of transfer units | ...... |
1. Introduction

Cooling towers are commonly used to dissipate heat from heat sources to heat sink (ambient environment). Their applications are typically in heat ventilation and air conditioning systems and power generators, etc. Heat rejection of cooling towers is accomplished by heat and mass transfer between hot water droplets and ambient air, figure (1-a).

Although cooling towers are relatively inexpensive and normally consume around ten percent of the whole system energy, their operation has significant effect on the energy consumption of other related subsystems, Ref.[1]. Therefore, optimizing cooling towers performance will not only increase the tower efficiencies but also has direct to other subsystems. Accordingly, there has been some research interest in this area.

In [2] stated that the heat removal from the water in a cooling tower is accomplished by a transfer of sensible heat due to the temperature difference of the air and water, and by latent heat which is equivalent to the mass transfer resulting from the evaporation of water. The work in [3] was concerned with the performance of table tennis spheres used as a packing for an air-water cooling tower operating as a fixed bed. In addition, [4] reviewed the heat and mass transfer process in cooling towers at water droplet level and analyzed an idealized spray-type tower in one dimension, which is useful for cooling tower designers.

The cooling tower performance prediction used today is directly related to Merkel’s deduction[3]. Merkel assumed that the ratio of the overall sensible heat unit conductance is equal to one [3]. This
assumption allows the overall driving force of the process to be based on the enthalpy difference. The deduction considers each water droplet to be surrounded by a film of saturated air from which the sensible heat and mass is transmitted from the bulk hot water to the air stream.

A universal engineering model, found in [5] can be used to formulate both counter flow and crossflow cooling towers. Using fundamental laws of mass and energy balance, the effectiveness of heat exchange is approximated by a second order polynomial equation. Finally,[6] presented a computational model for the thermal performance for closed wet cooling towers intended for use in conjunction with chilled ceilings in the cooling of buildings. A variable spray water temperature inside the tower was assumed. Moreover, optimization of the tower geometry and flow rates for specified design conditions was carried out in order to achieve a high value of the coefficient of performance (COP).

In this work, a temperature prediction method, which can be used to predict temperature of outlet water from counter flow cooling tower, is proposed. This method, based upon the $h_c A/C_{pm}$ equation, prediction of seawater shower cooling towers describes the experimental data with an accuracy of about 5%. [7] This study also conducted a comparative prediction of the outlet water temperature between freshwater and seawater in a shower cooling tower; results showed that cooling performance decreases as inlet water temperature increases. [7]. The prediction of outlet water temperature is a very big challenge to do because there is no direct equation to predict the temperature of the outlet water from cooling towers. In this work, the prediction approach is built on the assumption that the arithmetic mean enthalpy difference of the tower mid increment is equal to the arithmetic mean enthalpy difference of other tower increments.

### 2. Theoretical prediction of NTU

To determine the NTU of a forced draught counter flow cooling tower is shown in figure (1-b), Ref. [1] presented direct equation which can be expressed as,

$$h_c A/C_{pm} = 4.19 \Delta t \sum \frac{1}{(h_i-h_a)_m} \ldots \ldots \ldots (1)$$

Where $h_c A/C_{pm}$ = NTU and $(h_i-h_a)_m$ is arithmetic mean enthalpy difference for an increment of volume. In this case of determination, the cooling tower should be divided into many increases and calculating $h_i$, $h_a$, $(h_i-h_a)_m$ and $\frac{1}{(h_i-h_a)_m}$ for each increment.

Then, the summation of $\frac{1}{(h_i-h_a)_m}$ for all the tower increments can be used to find the NTU of that tower, equation (1).
2.1 Outlet Water Temperature Prediction:

This assumption can be expressed as,
\[
\sum \frac{1}{(h_i-h_a)_m} \biggm|_{\text{all tower increments}} = N \times \frac{1}{(h_i-h_a)_m} \biggm|_{\text{mid tower increment}} \ldots \ldots \ldots (2)
\]
where N is the number of tower increments.

The substitution of equation (2) in equation (1) gives,
\[
NTU = 4.19 L \Delta t \biggm|_{(h_i-h_a)_m}^{\text{mid increment}} \ldots \ldots \ldots (3)
\]
Ref. [1] gives straight equation from which the enthalpy can be determined. This equation is:
\[
h = 4.7926 + 2.568 t - 0.029834 t^2 + 0.0016657 t^3 \ldots \ldots \ldots (4)
\]
From equation (4), the enthalpy of water at the mid increment \( h_i \) can be determined, as,
\[
h_i = 4.7926 + 2.568 t_{mi} - 0.029834 t^2_{mi} + 0.0016657 t^3_{mi} \ldots \ldots \ldots (5)
\]
Where \( t_{mi} \) is the water temperature at the mid increment which can be determined from the next equation, \( t_{mi} \)?
\[
t_{mi} = t_{in} + 0.5 \left( \frac{1}{N} + 1 \right) \Delta t \ldots \ldots \ldots (6)
\]
\[
t_{mi} = 0.55 t_{in} + 0.45 t_{out} \ldots \ldots \ldots (6)
\]
Then, substituting equation (6) into equation (5) gives,
\[
h_i = 4.7926 + 2.568 (0.55 t_{in} + 0.45 t_{out}) - 0.029834 (0.55 t_{in} + 0.45 t_{out})^2 + 0.0016657 (0.55 t_{in} + 0.45 t_{out})^3 \ldots \ldots \ldots (7)
\]
The simplification of equation (7) yields,
\[
h_i = 0.000151786 t^3_{out} + (0.000556552 t_{in} - 0.006041385) t^2_{out} + (1.1556 - 0.01476783 t_{in} + 0.00068023) t_{out} + 0.0027713 t^3_{in} - 0.009024785 t^2_{in} + 1.4124 t_{in} + 4.7926 \ldots \ldots \ldots (8)
\]
The enthalpy of air at the mid increment can be determined from the following equation, Ref. [1],
\[
h_a = \frac{2 h_{aw} + (N+1)(h_{a1}-h_{a0})}{2} \ldots \ldots \ldots (9)
\]
Where \( h_{aw} \) is the enthalpy of air at the inlet wet bulb temperature which can be found by using equation (4)?
\[
h_{aw} = 4.7926 + 2.568 T_{wb} - 0.029834 T^2_{wb} + 0.0016657 T^3_{wb} \ldots \ldots \ldots (10)
\]
and \( h_{a1} - h_{a0} \) is the energy balance at the bottom section of the cooling tower, which can be expressed as,
\[
h_{a1} - h_{a0} = 4.19 \frac{L}{G} \Delta t \ldots \ldots \ldots (11)
\]
Now, substituting equations (10) and (11) into equation (9) yields,
The NTU of a counter flow cooling tower in different Outlet water temperatures.

\[ h_{aw} = 4.7926 + 2.568 T_{wb} - 0.029834 T_{wb}^2 + 0.0016657 T_{wb}^3 + 2.095 (N + 1) \frac{L}{G} (t_{in} - t_{out}) \] 

(12)

The substitution of equations (8) and (12) into equation (3) gives,

\[
0.000151786 t_{out}^2 + (0.000556552 t_{in} - 0.006041385) t_{out}^2 + (1.1556 - 0.01476783 t_{in} + 0.00068023 t_{in}^2) t_{out} + 0.00027713 t_{in}^3 - 0.009024785 t_{in}^2 + 1.4124 t_{in} + 4.7926 - 4.7926 - 2.568 T_{wb} + 0.029834 T_{wb}^2 - 0.0016657 T_{wb}^3 - 2.095 (N + 1) \frac{L}{G} (t_{in} - t_{out}) =
\]

4.19 \[ \frac{N}{NTU} L(t_{in} - t_{out}) \] .......... (13)

The simplification of equation (13), gives,

\[
0.000151786 t_{out}^2 + (0.000556552 t_{in} - 0.006041385) t_{out}^2 + (1.1556 - 0.01476783 t_{in} + 0.00068023 t_{in}^2) t_{out} + 0.00027713 t_{in}^3 - 0.009024785 t_{in}^2 + (1.4124 - 2.095 (N + 1) \frac{L}{G} + 4.19 \frac{N}{NTU} L) t_{in} - 2.568 T_{wb} + 0.029834 T_{wb}^2 - 0.0016657 T_{wb}^3 = 0 \] .......... (14)

All parameters in equation (14) are known except the outlet water temperature \( t_{out} \), which can be found by solving this equation. The solution of equation (14) gives three roots, two of them are imaginary roots and the third one is real. The real root represents the outlet water temperature of cooling towers. The solution of equation (14) is very complicated; this led to the use of MATLAB package to find the roots of this equation for each case of cooling towers situations.

3. Results and Discussion

Table (2) and figure (2) present a comparison between the results of the presented work and Ref.[1] by showing the behavior of the relationship between the NTU and the outlet water temperature with a constant temperature range (\( \Delta t = 5^\circ C \)). For the presented work, the NTU was determined from equation (13) by substituting the outlet water temperature just to make sure of the results that this equation can give, It can be seen from figure (2) that the results of the presented work and Ref. [1] are normally closed when the outlet water temperature is between 29 and 45\(^\circ\)C. This comparison also shows a difference between them which reaches to 7.32 % when the outlet water temperature is between 26 and 28\(^\circ\)C. Moreover, it can be seen that the NTU decreases to 19.34 % when the outlet water temperature increases 1\(^\circ\)C keeping the other parameters constant. This means that, if the temperature approach increases, it needs smaller transfer area.

Table 2: The NTU of a counter flow cooling tower in different Outlet water temperatures.

| NTU      | Outlet water temperature |
|----------|--------------------------|
| Presented work | Ref. [1] | \( t_{out}(^\circ C) \) |
| 119.8224       | 111.747      | 26         |
| 46.96925       | 45.87339     | 27         |
| 28.70365       | 28.41979     | 28         |
| 20.40158       | 20.33254     | 29         |
| 15.66244       | 15.66937     | 20         |
| 12.60117       | 12.63835     | 21         |
| 10.46317       | 10.51246     | 22         |
| X   | Y       | Z   |
|-----|---------|-----|
| 8.887365 | 8.940746 | 23  |
| 7.67926  | 7.732939 | 24  |
| 6.724792 | 6.776944 | 25  |
| 5.952646 | 6.002413 | 26  |
| 5.315944 | 5.362963 | 27  |
| 4.782599 | 4.82677  | 28  |
| 4.329907 | 4.371269 | 29  |
| 3.941349 | 3.980013 | 30  |
| 3.604618 | 3.640729 | 31  |
| 3.310356 | 3.344076 | 32  |
| 3.051323 | 3.082813 | 33  |
| 2.821826 | 2.851245 | 35  |
| 2.617328 | 2.644827 | 36  |
| 11.98224 | 11.747   | 37  |
| 16.96925 | 15.87339 | 38  |
| 28.70365 | 28.41979 | 39  |
| 20.40158 | 20.33254 | 40  |
| 15.66244 | 15.66937 | 41  |
| 12.60117 | 12.63835 | 42  |
| 10.46317 | 10.51246 | 43  |
| 8.887365 | 8.940746 | 44  |
| 7.67926  | 7.732939 | 45  |

Figure 2: Outlet water temperature variation with NTU for a constant tower range.
Table (3) and figure (3) show a comparison between the results of the presented work and [1] by showing the relationship between the NTU and the tower range $\Delta t$. Both the table and figure which show the presented work and [8] are very close when the temperatures range is between 1 and 11 °C. This comparison also shows a difference between them which reaches to 19% when the temperature range is between 12 and 22 °C. In addition, figure (3) shows that the NTU increases 30.6% if the tower range increases 2°C, which means that when the tower range increases, it needs larger transfer area.

Table 3: The NTU of a counter flow cooling tower in different tower range

| Tower range $\Delta t$ (°C) | NTU Ref. [1] | NTU Presented work |
|-----------------------------|----------------|-------------------|
| 1                           | 4.267168       | 4.268107          |
| 2                           | 8.482796       | 8.489622          |
| 3                           | 12.5951        | 12.61601          |
| 4                           | 16.55766       | 16.60084          |
| 5                           | 20.33254       | 20.40158          |
| 6                           | 23.8921        | 23.98126          |
| 7                           | 27.21894       | 27.30932          |
| 8                           | 30.30573       | 30.36269          |
| 9                           | 33.15281       | 33.1257           |
| 10                          | 35.76715       | 35.58998          |
| 11                          | 38.1601        | 37.75425          |
| 12                          | 40.34552       | 39.62304          |
| 13                          | 42.33909       | 41.20602          |
| 14                          | 44.15658       | 42.51707          |
| 15                          | 45.81388       | 43.57293          |
| 16                          | 47.32587       | 44.39236          |
| 17                          | 48.70651       | 44.99553          |
| 18                          | 89.96891       | 45.40276          |
| 19                          | 51.1246        | 45.63455          |
| 20                          | 52.18444       | 45.71053          |
| 21                          | 53.15787       | 45.64951          |
| 22                          | 54.05339       | 45.46913          |

Figure 3: Tower range variation with NTU for a constant inlet water temperature.

This presents a comparison between the results of the presented work and Ref. [1] by showing the behavior of the relationship between the NTU and the temperature approach with a constant temperature range ($\Delta t = 5°C$). Figure (4) shows that the results of the presented work and [9] are very close when the temperature approach is between 3 and 20°C. Moreover, this comparison shows a difference between the presented work and [10] which reaches to 7.32% when the outlet water temperature is between 1 and 2°C. It is clear that the NTU decreases 19.34% when the outlet water temperature increases 1°C. This means that, if the temperatures approach increases, it needs smaller transfer area.
Figure 4: Temperature approach variation with NTU for a constant tower condition[9]

Table (4) and figure (5) present a comparison between the presented work and Ref. [1] by showing the behavior of the relationship between the NTU and the wet bulb temperature of inlet air. Both the table and figure show that the results of the presented work and Ref. [1] are very close when the wet bulb temperature is between 15 and 27 °C. There is also a difference between them when the wet bulb temperature is more than 28 °C. From figure (5), it can be seen that the NTU increases 11.54% when the wet bulb temperature increases 1 °C. This means that it needs larger transfer area when the temperatures approach decreases.

Table 4: Comparison between the presented work and Ref. [1]

| Wet bulb temperature (Twb °C) | NTU |
|-------------------------------|-----|
| Ref. [1]                      |     |
| Presented work                |     |
| Linear (Presented work)       |     |

Figure 5: Wet bulb temperature of inlet air variation with NTU for a constant inlet water temperature
Table 4: The NTU of a counter flow cooling tower in different wet bulb temperature

| Wet bulb temperature $T_{wb}$ (°C) | NTU          | Ref. [1]   | Presented work |
|------------------------------------|---------------|------------|----------------|
| 15                                 | 7.355327      | 7.367846   |
| 16                                 | 7.768036      | 7.781875   |
| 17                                 | 8.247109      | 8.262544   |
| 18                                 | 8.810865      | 8.828262   |
| 19                                 | 9.484781      | 9.504636   |
| 20                                 | 10.3054       | 10.3284    |
| 21                                 | 11.32709      | 11.35422   |
| 22                                 | 12.63445      | 12.66717   |
| 23                                 | 14.36689      | 14.40742   |
| 24                                 | 16.77152      | 16.82341   |
| 25                                 | 20.33254      | 20.40158   |
| 26                                 | 26.14647      | 26.24136   |
| 27                                 | 37.34549      | 37.46516   |
| 28                                 | 68.06718      | 67.83559   |

Table (5) and figure (6) present a comparison between the presented work and Ref. [1] by showing the relationship between the NTU and the air mass flow rate. Both of the table and figure show that the presented work and Ref. [1] match when the air mass flow rate is between 15.6 and 16.5 kg/s. In addition, it can be seen that there is a difference between them which reaches to 2.5% when the air mass flow rate is between 10.5 and 15 kg/s. Furthermore, figure (6) shows that the NTU decreases 6.13% if the air mass flow rate increases 1 kg/s. This means that it needs smaller transfer area when the air mass flow rate increases.

Table 5: The NTU of a counter flow cooling tower in different air mass flow rates.

| Air mass flow rate $L$ (kg/s) | NTU          | Ref. [1]   | Presented work |
|-------------------------------|---------------|------------|----------------|
| 10                            | 34.22311      | 34.16208   |
| 10.5                          | 30.88453      | 31.35652   |
| 11                            | 28.53083      | 29.17813   |
| 11.5                          | 26.76618      | 27.43774   |
| 12                            | 25.38638      | 26.01532   |
| 12.5                          | 24.27379      | 24.83101   |
| 13                            | 23.35534      | 23.82967   |
| 13.5                          | 22.58283      | 22.97188   |
| 14                            | 21.92318      | 22.2289    |
| 14.5                          | 21.35275      | 21.5791    |
| 15                            | 20.85415      | 21.00595   |
| 15.5                          | 20.33254      | 20.40158   |
| 16                            | 20.02338      | 20.0412    |
| 16.5                          | 19.67333      | 19.63138   |
| NTU | Air mass flow rate L(kg/s) |
|-----|---------------------------|
| 17  | 19.35802                  |
| 17.5| 19.07241                  |
| 18  | 18.81247                  |
| 18.5| 18.57483                  |
| 19  | 18.35667                  |
| 19.5| 18.15572                  |
| 20  | 17.96993                  |
| 20.5| 17.79766                  |

**Figure 6:** Air mass flow rate variation with NTU for a constant water mass flow rate
Figure 7: Water mass flow rate variation with NTU for a constant air mass flow rate.

Table (6) and figure (7) present a comparison between the presented work and Ref. [1] through showing the behavior of the relationship between the NTU and the water mass flow rate. The comparison shows that both results match when the water mass flow rate is between 17.5 and 19 kg/s, and it also shows that there is a difference between them which reaches to 4.66% when the water mass flow rate is between 10 and 17 kg/s. Moreover, figure (7) shows that the NTU increases 10% if the water mass flow rate increases 1 kg/s, which means that, when the amount of the inlet water increases, the transfer area should be larger.

Table 6: The NTU of a counter flow cooling tower in different water mass flow rates.

| Water mass flow rate L (kg/s) | NTU Ref. [1] | NTU Presented work |
|------------------------------|--------------|--------------------|
| 10                           | 8.515385     | 8.11851            |
| 10.5                         | 9.044104     | 8.648201           |
| 11                           | 9.585826     | 9.193499           |
| 11.5                         | 10.14116     | 9.755108           |
| 12                           | 10.71075     | 10.33379           |
| 12.5                         | 11.29528     | 10.93028           |
| 13                           | 11.89548     | 11.54546           |
| 13.5                         | 12.51217     | 12.18021           |
| 14                           | 13.14618     | 12.83546           |
| 14.5                         | 13.79845     | 13.51225           |
| 15                           | 14.46997     | 14.21165           |
| 15.5                         | 15.16183     | 14.93483           |
| 16                           | 15.87516     | 15.68298           |
| 16.5                         | 16.61124     | 16.45743           |
| 17                           | 17.37144     | 17.25961           |
| 17.5                         | 18.15726     | 18.09102           |
| 18                           | 18.97034     | 18.95329           |
| 18.5                         | 19.81249     | 19.8482            |
| 19                           | 20.68569     | 20.77763           |
Table (7) and figure (8) show the predicted outlet water temperature from the cooling tower with different water mass flow rates keeping other parameters constant. Figure (8) shows three facts. Firstly, when the water mass flow rate increases, the NTU also increases. This means that it needs larger transfer area. Secondly the NTU decreases when the outlet water temperature increases because of the increase in the temperature approach. Thirdly when the outlet water temperature increases the three curves become close to each other which means that the effect of water mass flow rate has been limited when the temperature approach increased.

Table 7: The predicted outlet water temperatures from counter flow cooling tower with different water mass flow rates.

| L (m) | Water mass flow rate (kg/s) | \( t_{\text{out}} \) (°C) |
|-------|-----------------------------|-----------------------------|
| L = 16 |                             |                             |
| 19.5  | 21.59206                    | 21.74356                    |
| 20    | 22.53403                    | 22.74823                    |
| 20.5  | 23.51427                    | 23.79402                    |
| L = 18.8 |                           |                             |
| 19.5  | 27.04927418368127           | 27.06978862001806           |
| 20    | 28.0262193947271            | 28.0463565850353            |
| 20.5  | 29.01017690182144           | 29.02783062954643           |
| L = 20 |                             |                             |
| 19.5  | 29.99856154097001           | 30.01386251771270           |
| 20    | 30.98983061792152           | 31.00316464725122           |
| 20.5  | 31.98307373199926           | 31.99477613148814           |

Table 7: The predicted outlet water temperatures from counter flow cooling tower with different water mass flow rates.
Table (8) and figures (9-a)&(9-b) show the behavior of the relationship between the predicted outlet water temperature and the NTU with different air mass flow rates. Figure (9-a) shows that the increase of air mass flow rate causes the NTU to decrease. This means that it needs smaller transfer area. The NTU decreases when the outlet water temperature increases because of the increase in the temperature approach. The three curves are close to each other when the outlet water temperature increases. This means that the effect of air mass flow rate has been limited when the temperature approach increased.

Table 8: The predicted outlet water temperatures from counter flow cooling tower with different air mass flow rates.

| Air mass flow rate (kg/s) | G = 13 | G = 15.6 | G = 17 |
|---------------------------|--------|----------|--------|
| 27.05571644525663        | 27.04927418368127 | 27.01008313977778 |
| 28.07037909512880        | 28.02621939474271 | 27.99486001513698 |
| 29.05647444331491        | 29.01017690182144 | 28.98451475711881 |
| 30.04138111551974        | 29.99856154097001 | 29.97705500761211 |
| 31.02834077247204        | 30.98983061792152 | 30.97148419565744 |
| 32.01753708726621        | 31.98307373199926 | 31.96717614435426 |
| 33.00860148837541        | 32.9777380838655  | 32.96377106319648 |
| 34.00117705389895        | 33.97340843103291 | 33.96105476634101 |
| 34.99497446176385        | 34.96989994175317 | 34.95884868043804 |
| 35.98973195954115        | 35.96698782716793 | 35.95706718909009 |
| 36.98527524829089        | 36.96454672315768 | 36.95558286954283 |
| 37.98148684288675        | 37.96253923428828 | 37.95437596975309 |
| 38.97821124819170        | 38.96082093461332 | 38.95338000791725 |
| 39.97539984610151        | 39.95939291269287 | 39.95256667285889 |
| 40.97295747992029        | 40.95820215405314 | 40.95188518148153 |
| 41.97084529939215        | 41.95717520972825 | 41.9513767313355 |
| 42.96900633361959        | 42.95630907072199 | 42.95096688147918 |
| 43.96739940423626        | 43.95561951347262 | 43.95060585550317 |
| 44.96602069100311        | 44.95500497409979 | 44.95037026432629 |

Figure 8: Predicted temperature of outlet water variation with NTU for different water mass flow rate

Table 8: The predicted outlet water temperatures from counter flow cooling tower with different air mass flow rates.
Table (9) and figures (10-a) & (10-b) show the behavior of the relationship between the predicted outlet water temperature and the NTU with different wet bulb temperatures. It can be seen from figure (9-a) that the NTU increases if the wet bulb temperature increases because when the wet bulb temperature increases, the temperature approach decreases which, in turn, make the NTU increases. The NTU increases when the outlet water temperature increases. This means that when the temperature approach increases, it needs smaller transfer area to cool the inlet water. Finally, figure (10-b) shows that, the three curves get closer when the outlet water temperature increases. This means that, when the temperature approach increases, the effect of the wet bulb temperature is limited.
Table 9: The predicted outlet water temperatures from counter flow cooling tower with different wet bulb temperatures.

| Wet bulb temperature $T_{wb}$ (°C) | T$_{wb} = 20$ | T$_{wb} = 23$ | T$_{wb} = 25$ |
|------------------------------------|---------------|---------------|---------------|
| 27.02627424098096                 | 27.03598931614876 | 27.04927418368127 |
| 28.01657753451342                 | 28.02117240149303 | 28.02621939474271 |
| 29.00833674887105                 | 29.00957198541680 | 29.01017690182144 |
| 30.0012999773841                  | 30.00039058050302 | 29.99856154097001 |
| 30.99528837148307                 | 30.99297491547818 | 30.98983061792152 |
| 31.99012317445875                 | 31.98691400631960 | 31.98307373199926 |
| 32.98565618241108                 | 32.98192085192543 | 32.97773808338655 |
| 33.98176976143140                 | 33.97771944091170 | 33.97340843103291 |
| 34.97839222288341                 | 34.97418478046276 | 34.96989994175317 |
| 35.97544994590311                 | 35.97119461589845 | 35.9669878216793 |
| 36.97285452353290                 | 36.96861733869510 | 36.96454672315768 |
| 37.97058512982251                 | 37.96643716404007 | 37.96253923428828 |
| 38.96860144737116                 | 38.96454604194793 | 38.96082093461332 |
| 39.96683953821648                 | 39.96293290786728 | 39.95939291269287 |
| 40.96532276809289                 | 40.96155717532213 | 40.95820215405314 |
| 41.96394883224593                 | 41.96034148296561 | 41.95717520972825 |
| 42.96277248134931                 | 42.95932141535314 | 42.95630907072199 |
| 43.961755225724725               | 43.95844929554882 | 43.95561951347262 |
| 44.96085288626242                 | 49.5769387029062 | 44.95500497409979 |

Figure 10-a (column chart): Predicted temperature of outlet water variation with NTU for different wet bulb temperature
Finally, Table (10) figure (11) shows the predicted outlet water temperature from a cooling tower with different L/G keeping another parameters constant. Figure (11) shows that when the value of L/G decreases, the NTU decreases also, which means that it needs larger transfer area. The NTU decrease when the outlet water temperature increases because of the increase in the temperature approach. Figure (11) also shows that, when the outlet water temperature increases, the three curves become close to each other which means that the effect of L/G has been limited when the temperature approach increased.

Table 10: The results of water mass flow rate/Air mass flow rate (L/G) with NTU for different Outlet water temperature

| NTU       | Outlet water temperature | Water mass flow rate/Air mass flow rate |
|-----------|--------------------------|----------------------------------------|
| t<sub>out</sub> °C |                          | L/G 1.4 | L/G 1.2 | L/G 1 |
| Presented work | Ref. [1]           |          |          |          |
| 119.8224  | 111.747                 | 26       | 1.002210489 | 1       | 0.996893 |
| 46.96925  | 45.87339                | 27       | 1.001839501 | 1       | 0.996291 |
| 28.70365  | 28.41979                | 28       | 1.001494449 | 1       | 0.996745 |
| 20.40158  | 20.33254                | 29       | 1.001227856 | 1       | 0.997241 |
| 15.66244  | 15.66937                | 20       | 1.001022885 | 1       | 0.997663 |
| 12.60117  | 12.63835                | 21       | 1.000863385 | 1       | 0.998007 |
| 10.46317  | 10.51246                | 22       | 1.000737863 | 1       | 0.998287 |
| 8.887365  | 8.940746                | 23       | 1.000635945 | 1       | 0.998517 |
| 7.67926   | 7.732939                | 24       | 1.000552971 | 1       | 0.998706 |
| 6.724792  | 6.776944                | 25       | 1.000483989 | 1       | 0.998864 |
| 5.952646  | 6.002413                | 26       | 1.000426729 | 1       | 0.998997 |
| 5.315944  | 5.362963                | 27       | 1.000377756 | 1       | 0.999109 |
1. The uncertainty of Enthalpy of air at the inlet wet bulb temperature \( h_{aw} \)
   \[
   \frac{\partial h_{aw}}{h_{aw}} = \sqrt{\left(\frac{\partial T_w}{T_w}\right)^2} = \sqrt{\left(\frac{15}{28}\right)^2} = 0.535
   \]

2. The uncertainty of Enthalpy of air leaving the bottom increment \( h_{a1} \)
   \[
   \frac{\partial h_{a1}}{h_{a1}} = \sqrt{\left(\frac{\partial T_{out}}{T_{out}}\right)^2} = \sqrt{\left(\frac{20}{45}\right)^2} = 0.57
   \]

3. The uncertainty of Enthalpy of air entering the bottom increment
   \[
   \frac{\partial h_{a0}}{h_{a0}} = \sqrt{\left(\frac{\partial m_{ai}}{m_{ai}}\right)^2} = \sqrt{\left(\frac{10}{20.5}\right)^2} = 0.48
   \]

4. The uncertainty of Enthalpy of air \( h_a \)
   \[
   \frac{\partial h_a}{h_a} = \sqrt{\left(\frac{\partial h_{aw}}{h_{aw}}\right)^2 + \left(\frac{\partial h_{a1}}{h_{a1}}\right)^2 + \left(\frac{\partial h_{a0}}{h_{a0}}\right)^2} = \sqrt{(0.57)^2 + (0.48)^2 + (0.535)^2} / 2 = 0.46
   \]

**Figure 11**: Predicted temperature of outlet water variation with NTU for different \( L/G \) values.
Conclusions

From this work, several conclusions have been drawn and may be summarized as follows:

1- The proposed prediction method is a very powerful method which can be used to predict the temperature of the outlet water from counter flow cooling towers.

2- To get very accurate results from the proposed method, the parameters of water and air should be within limits, outlet water temperature is more than 29°C, tower range is less than 11°C, temperature approach is more than 4°C, wet bulb temperature is less than 27°C, air mass flow rate is more than 15.6 kg/s, and water mass flow rate is more than 17.5 kg/s.

3- The proposed method can be used when the water and air parameters are out of the specific limits. However, the drawn results will be slightly different from the actual results.

4- The number of transfer units NTU varies directly with the wet bulb temperature and inversely with the outlet water temperature for a given range.

5- The number of transfer units NTU varies directly with the water mass flow rate and inversely with the air mass flow rate at a given wet bulb temperature.

6- The number of transfer units NTU varies directly with the tower range and inversely with the temperature approach at a given wet bulb temperature.

7- Variation in water mass flow rates has a greater effect on tower transfer area than the variation on air mass flow rates at a given wet bulb temperature and tower range.

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