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Analysis of Performance of Cooling Towers with Different Fill Characteristics at Different Weather Conditions in Bangladesh

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ABSTRACT

The design and operation of cooling towers are needed to be studied and optimized before the installation because of their tremendous importance, especially in industrial applications. As both heat and mass transfer takes place in a functional cooling tower it becomes quite complex to derive the design calculation for a specific requirement and to do performance analysis of existing ones. The present study focuses on the critical performance analysis of different types of cooling towers found in the industries of Bangladesh. . A full and step-by-step procedure of characteristic curve for specific type of cooling tower has been discussed. From the collected data, the tower characteristics curve for different types of cooling tower is generated. Tower characteristic equation from the linear relation of $\frac{KaV}{L}$ vs L/G on log log demand curve has been deduced for a cooling tower to understand the fill characteristics of a specific type. In order to assess the performance of the cooling towers, Merkel's theory has been adopted. Merkel's theory is based on the enthalpy analysis of the surrounding air under tower operating conditions. Volumetric heat and mass transfer coefficient for the modern cooling towers are investigated. The proper fill volume can be easily determined from the deduced volumetric heat and mass transfer co efficient prior to the design. The effect of wet bulb temperature, considering the monthly local variation throughout the year, on NTU and L/G of cooling towers is examined. In addition, the effect of the fill type is analyzed based on the cooling capacity and flow rate. The methodology and analysis presented in this work will aid in proper designing and predicting the performance of a cooling tower for a given condition in the industries of the region.

Key Words Cooling tower; Heat transfer coefficient; Merkel's theory; Performance analysis; ε-NTU.

1. Introduction

Cooling towers are mechanical devices whose main purpose is to reject heat from the coolant into the ambient air. . This rejection of heat can be done by both sensible heat transfer and latent heat transfer. Both methods of heat transfer are obtained in cooling towers. In Bangladesh, various large and small industries like oil refineries, pharmaceuticals, textile mills as well as commercial buildings use cooling towers to serve their purpose. In quite a lot of them the cooling towers are not giving desired performance as they are not running in optimum conditions which hampers their production. Following literature shows the investigation on the important performance parameters of cooling towers in Bangladesh which will help the industries to get optimum results. The authors here have given a general method for cooling tower analysis for all these towers. The collected data are from wet mechanical induced draft cooling towers as these are mostly used in industries of Bangladesh. These induced draft cooling towers may have been counter or cross flow.

To get sufficient performance from a cooling tower, proper designing is a must. Cooling tower theory was first introduced by Merkel in 1925 [1]. It is the earliest and simplest model. That's why the most of the studies in the literature follows the method. Snyder [2] developed a cross – flow cooling tower model by applying the theory for the design of heat exchangers to calculate the heat and mass transfer characteristics. Another method called the Poppe and Roneger Method [3] requires iterative calculations. Jaber and Webb [4] developed several equations for applying the ε-NTU method directly to a cross – flow cooling tower. This simplifies the complicated calculations in Merkel and Poppe method and reduces computational time. Klopper and Kroger [5] gave the critical analysis between Merkel and Poppe method. From their analysis to determine the outlet water temperature of cooling tower either the Merkel or ε-NTU method should be used, but for the estimation of the heat transfer rate, the prediction through the Poppe approach was found more accurate.

In the presented study, a generalized method for cooling tower analysis for different types of existing and operational cooling towers has been provided. Field data have been collected from a total of fifteen (15) operational cooling towers from different installations in Bangladesh, where cooling towers serve the purpose of cooling water for chiller, generators, and other refinery activities. In these applications both the film and splash type fills are used. The effect of fill characteristics on these cooling towers is examined. The tower characteristics curve for different types of cooling towers is generated. The volumetric mass transfer coefficient for the modern cooling towers are investigated using the method used by Leeper [6]. The effectiveness of a cooling tower largely depends on the surrounding wet bulb temperature. In this work, the

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authors have studied the effect of wet bulb temperature on NTU and L/G of cooling towers. According to the annual weather condition, monthly average wet bulb temperature throughout the year is considered to calculate the change of the tower performance.

2. Methodology

To evaluate the approx. results of the cooling tower output widely used Merkel's Theory had been applied. Merkel's theory is based on the enthalpy analysis [7] of the surrounding air in operating condition. Typically To design a cooling tower for a specific application following parameters are known or required to meet:

- Hot water temperature;
- Cold water temperature;
- The atmospheric wet-bulb temperature;
- The atmospheric dry-bulb temperature.

Merkel's Equation enables both these calculations—for proposed and for existing towers—to be carried out. It is based on the assumption of uniform, one-dimensional counter-flow, but can be adapted to other conditions.

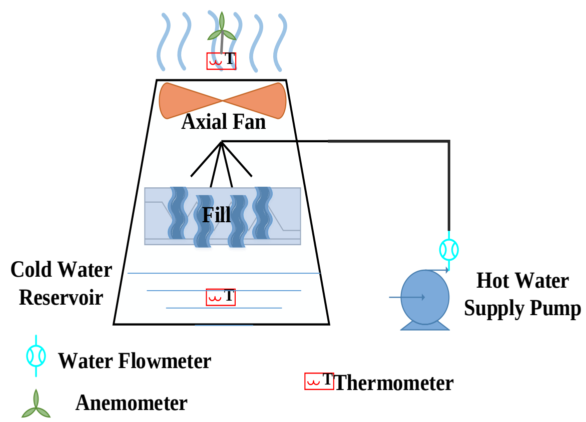

Fig.1 Experimental setup for data collection of an industrial grade operating cooling tower.

In these study to evaluate the results of the performance characteristics of cooling towers following data have been collected from the operational sites-

- **i.** Inlet water temperature in the supply (T_1)
- **ii.** Water flowrate from the supply line (L)
- **iii.** Outlet water temperature (T_2)
- **iv.** Outlet air velocity from the fan exit (v_G)
- **v.** Dry bulb and wet bulb temperature of the site.

3. Numerical Modeling:

I. Range of the operating cooling tower, $R= T_1-T_2$ (1)

II. Outlet Air Temperature Assumption, t_2: At first it is to assume that the outlet air temperature of the cooling tower to get the properties for further calculations. The outlet temperature is to be assumed form the correlation with the inlet and outlet water temperature: $t_2=\frac{T1+T2}{2}$ (2)

The approximated outlet temperature is very close to the actual design outlet air temperature [6].

III. Water-Air flowrate Ratio (L/G): From the energy balance between air and water yielding the following

$$L/G=\frac{h2-h1}{Cp*(T1-T2)} \quad (3)$$

IV. Tower Characteristic: The cooling characteristic, is represented by the Merkel equation:

$$\frac{kaV}{L}=\int_{T2}^{T1}\frac{dT}{hsa-ha} \quad (4)$$

Eq. (4) says that at any point in the tower, heat and water vapor are transferred into the air (approximately) due to the difference in the enthalpy of the air at the surface of the water and the main stream of the air. The $\frac{kaV}{L}$ represents the sum of NTUs defined for a cooling tower range.

Table 1 The following step is to help draw the tower characteristic by Simpson's rule.

Temperature, T (◦F)	Saturation Air enthalpy, h_{sa} (Btu/lb)	Air enthalpy at ambient condition, h_a (Btu/lb)	Difference between the enthalpy, h_{sa}-h_a (Btu/lb)	Inverse of enthalpy, $\frac{1}{hsa-ha}$ $(Btu/lb)^{-1}$
T_2	h_{sa1}	h_1	Δh_1	$1/\Delta h1$
T_2+0.2*R	h_{sa2}	h_1+ 0.2*Δh_a	Δh_2	$1/\Delta h2$
T_2+0.4*R	h_{sa3}	h_1+ 0.4*Δh_a	Δh_3	$1/\Delta h3$
T_2+0.6*R	h_{sa4}	h_1+ 0.6*Δh_a	Δh_4	$1/\Delta h4$
T_2+ 0.8*R	h_{sa5}	h_1+ 0.8*Δh_a	Δh_5	$1/\Delta h5$
T_1	h_{sa6}	h_2	Δh_6	$1/\Delta h6$
				Average = $\frac{\sum 1/\Delta h}{6}$

Here, $\Delta h_a=h_2-h_1$

Calculate, $NTU = \frac{kaV}{L} = R*(\frac{1}{hsa-ha})_{avg}$ (5)

The value of KaV/L becomes a measure of the order of difficulty for the liquid cooling requirements.

V. Tower Characteristic Curve:

To plot the tower characteristic curve, at first different L/G ratio for a specific type cooling tower was taken and all calculations discussed above are repeated to generate the data for various NTU to the plot. The curve represents "Design NTU".

Calculation of the value of the constant C, m; related to cooling tower design using the equation:
An equation form to analyze the thermal performance capability of a specified cooling tower was required. The following equation is most accepted as is very useful, since K_aV/L vs. L/G relationship is a linear function on the log-log demand curve.

$$\frac{kaV}{L} = C \times (L/G)^{-m} \quad (6)$$

4. Results and Discussion:

Table 2 Collected Cooling Tower Operating Data from Different Industries of Bangladesh:

Cooling Tower Model	Cooling Tower Type	WBT (°C)	Range (◦C)	Approach (◦C)
ART 250 RT	Counter Flow	28	6	4
SPC 200 RT	Counter Flow	28	7	3
ART 250 RT	Counter Flow	28	6	3
ART 300 RT	Counter Flow	27.5	3.5	17
ART 400 RT	Counter Flow	27	5	3
SPC 200 RT	Counter Flow	28	4	4
SPC 350 RT	Counter Flow	28	6	3
SPC 350 RT	Counter Flow	26	12	3
ART 250 RT	Counter Flow	27	11	4
ARTH 250 RT	Counter Flow	30	8	6.5
ARTX SP 400 RT	Cross Flow	27	8	15
PET 370 FC2	Cross Flow	27	5	3
PET 371 FC2	Cross Flow	27	16.25	4
PET 371 FC2	Cross Flow	27	6	9
PET 372 FC2	Cross Flow	26	10	3

For the present analysis, the following relations and variations are discussed.

I. Theoretical Relation between $\frac{KaV}{L}$ and L/G:

Where, $\frac{kaV}{L}$= Tower Characteristic that represents design NTU by Merkel equation.
C=Constant related to the cooling tower design, or the intercept of the characteristic curve at L/G=1.
m= Exponent related to the cooling tower design (slope of the curve), determined from the test data.
Design procedures and these factors affecting cooling tower selection and performance are discussed
The characteristic curve is determined by field testing more than two characteristic points at different L/G ratios. The slope of this line should fall within the expected range and serves as a check on the accuracy of the measurement.

The NTU of **Fig.2** is calculated from Eq. (5) by the steps stated in the methodology. After calculating NTU from the expected range and the operating conditions, the optimum L/G ratio is also calculated from Eq. (3).
Fig.2 is showing an exponential decrease of NTU with an increasing L/G ratio. Increasing L/G ratio means that the volumetric water flow is higher than the volumetric airflow. As a result, water molecules get lesser time to evaporate due to which the number of transfer units is decreased. After the value of L/G of 3 to 3.5, the change of NTU with L/G becomes asymptotic which means that no further latent heat transfer takes place due to the lack of time for water to be evaporated.

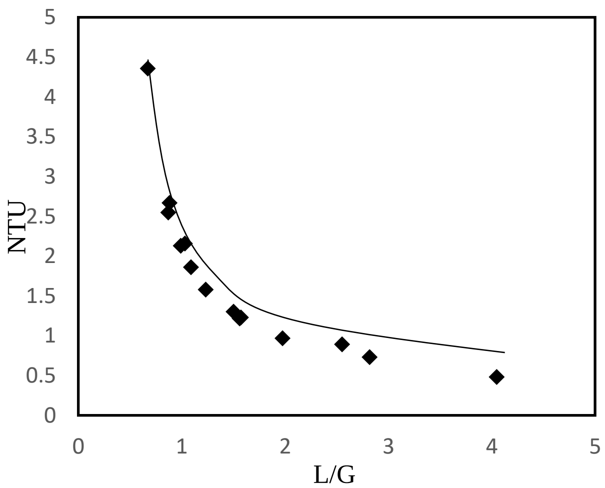

Fig.2 Relation between NTU and required L/G for different range

II. Tower characteristic equation from the linear relation of $\frac{KaV}{L}$ vs L/G on log-log demand curve:
Cooling tower with model names ART 250RT, SPC 200 and 350 RT have been selected for this analysis. The calculated demand curve parameters then are plotted in a log-log graph to get the characteristic curve in **Fig.3** and **Fig.4**. The negative value of the slope 'm' Eq. (6) of the equation indicates the inverse relation between NTU and L/G. A higher value of the slope means to get a

smaller change in NTU, the L/G ratio is needed to be changed more and vice-versa. The coefficient C is the indicator of NTU at unit L/G ratio which helps to compare the performance among different cooling towers. As both sides of the Eq. (6) are dimensionless, the constants m and C varies with different fill types. The cooling towers used in this analysis use the same type of fill known as film fill. As long as they have the same intrinsic properties of the fill though they have different sizes and different operational conditions their characteristics are of same. As a result, each of the characteristics curve show a similar value of the constants resulting in a linear pattern on the log log graph. This is an important analogy to be made that concludes that for further design this logarithmic relation can be used for the initial guess.

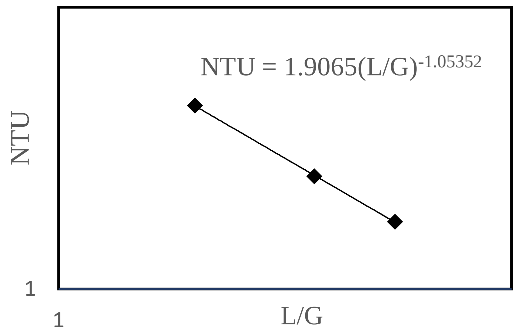

Fig.3 Tower Characteristic Curve of ART 250 RT

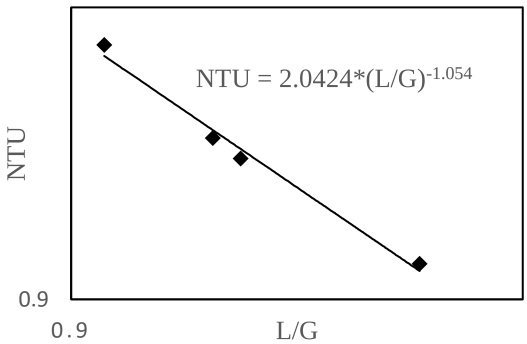

Fig.4 Tower Characteristic Curve of SPC 200 and SPC 350 RT

III. **For the same Range with the change of W. B. T, the relation with L/G, between Approach and NTU:**
For an evaporative heat exchanger operation in the climatic condition of Bangladesh, one of the major limitations of performance is the average relative humidity being high. On the above, the change of the relative humidity as well as the W.B.T is also significant. **Fig.6** show the effects of the change of W.B.T throughout the year on the change of flow rate ratio for maintaining a fixed range [8]. And **Fig.5** indicates that NTU has an exponential relation with the change of approach. For a fixed working range of cooling towers the increase of approach indicates the increase in driving force (h_{as} –h_a) [9,10], and the NTU is the inverse of the driving force Eq. (4).A higher value of approach means the exit air is getting less saturated. **Fig.6** shows a linear decrease of L/G ratio with increasing W.B.T. Lower L/G ratio indicates that the flowing air will get less amount of evaporated water to get saturated. On the other hand, higher L/G is very expensive to achieve. As a result, the users keep the L/G ratio within 1.2 to 2 for keeping a balance between cost and performance.

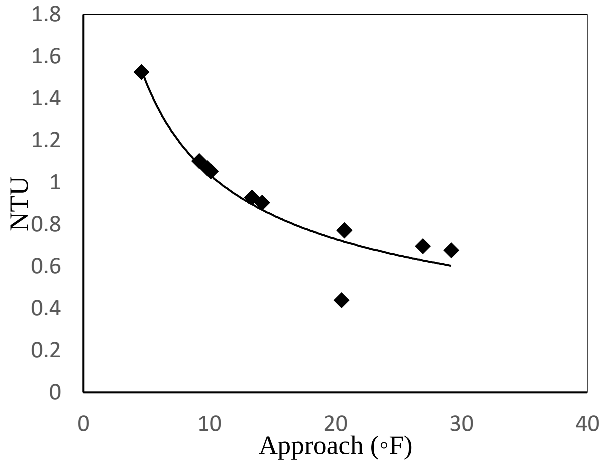

Fig.5 Change of NTU with Approach for a fixed Range

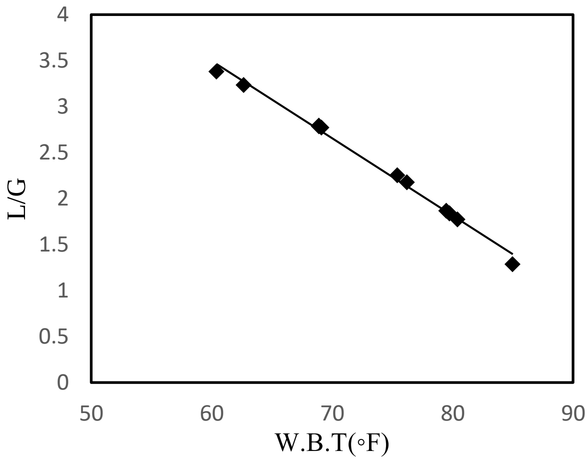

Fig.6 Change of L/G with W.B.T

IV. Variation of fill volume with heat load and water flow rate
To increase the cooling effect, more heat transfer surface is required. Larger fill volume provides a larger surface area for the water droplet to be evaporated. In places where the volumetric flow rate of water is higher, the water requires more evaporation to maintain a fixed range. The higher surface area serves the purpose of more evaporation of water [11]. **Fig.7** shows a linear increase of required fill volume with increasing cooling capacity and water flow rate. Both of the curves have a similar gradient as they are proportionally related.

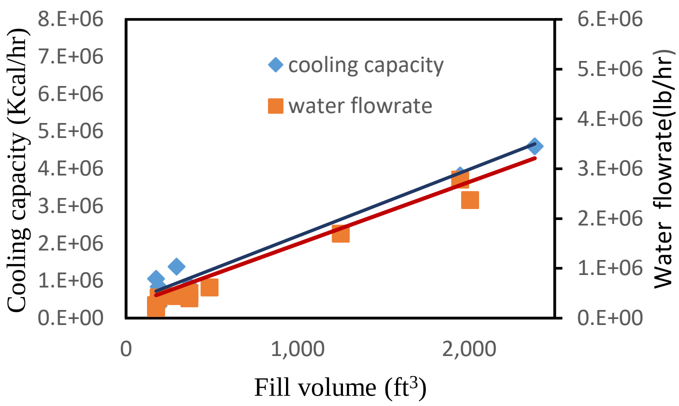

Fig.7 Cooling Capacity and Water Flowrate with Fill Volume

V. Calculated volumetric heat and mass transfer co-efficient for different model cooling tower

Table 3 Calculated volumetric heat and mass transfer co-efficient.

Tower Name	Heat and Mass Transfer Coefficient (K_a)
ART 250 RT	1844.36
ART 250 RT	1975.67
ART 250 RT	2119.80
SPC 200 RT	1701.77
SPC 200 RT	2261.53
SPC 350 RT	2031.83
SPC 350 RT	2356.86
PET 371 FC2	2324.10
PET 371 FC2	1891.16

From the calculated NTU value, water mass flow rate and the fill volume of the respective model in **Table 3** shows the calculated value of the volumetric heat and mass transfer coefficient k_a from the Eq.(4) which varies within a certain range an average value of around 2000 lbs air/hrft^3_{fill} [12]. For the modern design problem solution, this co-efficient can be taken into account as the first-hand value.\

VI. Variation of experimental and predicted water outlet temperature

From Eq. (3), the iterative method is used to predict the water outlet temperature for the obtained L/G collected from the field inspection in **Table 4** [13]. However, from **Table 4** it is also observed that in some cases the predicted water outlet temperature is very close to the WBT, even lower than WBT which is practically impossible because the air becomes saturated before the water reaches to the WBT and the only remaining way to decrease the water temperature more is by sensible heat transfer between air and water. Achieving same temperature of flowing air and water through sensible heat transfer will require a long time, very large surface area and the tower size will become infinite. Here in **Table 4** the predicted temperature is determined from existing L/G ratio value collected from field data. The theoretical L/G is assumed to be the most optimum operational condition. So more the deviation of the present L/G form the theoretical one indicates that the system has been running in either overdesign or under design condition and it can be determined by deriving the predicted outlet water temperature. Modern towers commonly have the value of approach temperatures as low as 5°F. If the predicted temperature gives a value of approach which is higher than that limit of ideal value it indicates the system is running in under design condition. On the contrary lower the approach limit or the predicted temperature exceeding the limit of WBT indicates the cooling system is being running in over design condition.

Table 4 Predicted water Temperature of Tower Outlet

Model	Experimental Temperature (◦F)	Predicted Temperature (◦F)	WBT (◦F)
ART 250 RT	89.6	82.97	82.4
ART 250 RT	87.8	75.62	80.6
SPC 200 RT	87.8	89.72	82.4
SPC 200 RT	89.6	84.53	82.4
SPC 350 RT	87.8	83.06	82.4
SPC 350 RT	84.2	89.87	78.6
ARTH 250 RT	97.7	81.25	86
ARTX 400 RT	107.6	67.09	80.6
PET 370	86	82.58	80.6
PET 371	87.8	73.63	80.6
PET 371	96.8	74.98	80.6
PET 372	84.2	81.06	78.8

Fig.8 clearly gives the indication that more the variation in L/G from the ideal value gives more variation in the predicted water temperature for cooling towers. For a cooling tower if outlet temperature needs to be acquired as close as the calculated predicted temperature, the theoretical L/G has to be maintained.

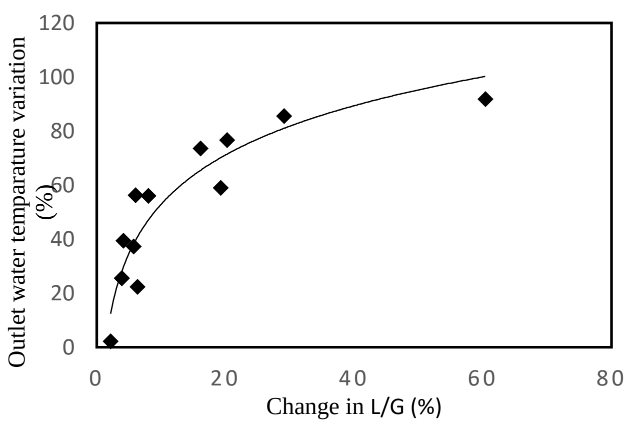

Fig.8: Percentage of change of theoretical and experimental water outlet temperature with L/G.

5. Conclusion:

For a certain model of cooling tower working in a specific weather condition, operating it in the optimum condition requires a certain combination of air and water flow rate. However, the experimental water and air mass flow rate ratio might not be the same as the theoretical L/G ratio because it is calculated from the one-dimensional heat balance equation which ignores all the other complexity of the practical operation. The tower characteristics curve helps to find the optimum L/G ratio. Developing the tower characteristic curve is an effective way to find the optimum running condition graphically for considering the design conditions and after the installation of the effective running condition. The calculations presented in this study show that the cooling capacity can be increased by a combination of changing the air and water mass flow rate which can be obtained cost-effectively by variable speed motors. Moreover, by considering the monthly change of weather over the year the change of W.B.T results in a different optimum condition. If this can be taken into account and be operated by the adjustment of fan motor speed and pump discharge, it will result in better power efficiency and better constant performance throughout the year. The methodology and analysis presented in this work will aid in predicting the performance of a cooling tower for a given condition in the industries of Bangladesh. By considering the proper fill volume beforehand, omits the chance of overdesign or under-design of the towers.

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NOMENCLATURE

t_{db} : Dry Bulb Temperature, ◦F
t_{wb} : Wet Bulb Temperature, ◦F
RH: Relative Humidity, %
R: Range, ºF
T_1: Hot Water Temperature, ◦F
T_2: Cold Water Temperature, ◦F
t_1 : Inlet Air Temperature, ◦F
t_2 : Outlet Air Temperature, ◦F
L: Water Mass Flow rate, lb/h
G: Air Mass Flow Rate, lb/h
h_{as}: Saturation Air enthalpy, Btu/lb
h_a :Air enthalpy at ambient condition, Btu/lb
h_1 : Inlet Air Enthalpy, Btu/lb
h_2 : Outlet Air Enthalpy, Btu/lb
C_p: Specific Heat of Water, Btu/ lb.◦F
k_a= Volumetric Air Mass Transfer Constant, lbs air/hr.ft^3_{fill}
V = Effective Tower Volume, ft^3