Performance of a Cooling Tower with the Use of a New Kind of High-density Polyethylene (HDPE) Packing

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ABSTRACT

This research work deals with the performance of high-density polyethylene sheets arranged in splash used as a fill for a cooling tower. “A forced-draught counter flow cooling tower” of 400 mm × 400 mm cross-sectional area and 1.7m in height was built. The fill has been studied theoretically and experimentally. Air rates of 0.6, 1.2, and 1.8 kg/s.m2 were utilized with water flow rates within the range of 1 to 1.6 kg/s.m^2. The overall volumetric heat transfer coefficient, volumetric mass transfer coefficient (*Mt*), and the tower characteristics (*Mt/L*) are shown to be functions of the air and water flow rates concurrently. Four available input parameters were inlet water temperature, airflow rate, water flow rate, and full height. A computer program was prepared to perform numerical analysis for reducing data sets obtained from the plant. In addition, analysis was carried out for evaluating the volumetric heat and mass transfer coefficients along with the performance coefficient.

Keywords: Cooling Tower; polyethylene; mass transfer coefficient; heat transfer; Screw HDPE packing.

INTRODUCTION

A cooling tower is a machine that eliminates waste heat to the environment by acting as a heat rejection device. Heat elimination is achieved by cooling a stream of water at lower temperatures. A cooling tower is a machine in which water and air are in direct contact. The function of this machine is to reduce the temperature of the water (Li et al., 1997; Murtadah et al., 2020; Al-Moameri et al., 2021)). Such cooling towers can work in two ways. Firstly, in cases of closed-circuit, these dry towers depend merely on the air for cooling the operational fluid to approximate to the “dry-bulb air temperature.” Otherwise, some cooling towers may use the water evaporated for removing the heat accumulated in the process and for cooling the operational fluid to approximate the “wet-bulb air temperature” (Shah, 2016, Ma et al., 2018).

Mostly, cooling towers are used in the heating, ventilation, and air conditioning (HVAC) systems where pipes supply warm water to the cooling tower (García, 2017, Al-Moameri et al., 2019). In cooling towers, water is splashed by nozzles. The filling material inside the tower increases the surface area, and the air comes in contact with water. The air exchange heat and the water is cooled. The laboratory cooling tower is usually set with an air conditioning system. In this system, the water heater is set, and the cooling tower is used to cool water. A fan is used to provide air to the hot water, and the pump is installed to supply cooled water to the water heater (Tomberlin et al., 2018, Afshari and Dehghanpour, 2019). Water from the heater moves towards the cooling tower and is collected in the reservoir. Next, the water is sprayed over the area of the tower. The function of the reservoir is to provide extra water lost in the process of evaporation, and in this way, the level of water is maintained.

In recent years authors concluded that the efficiency of the cooling tower depends on many factors such as the packing (Al-Sharify et al, 2009; Abidzaid, 2010; Latif, 2012). In the Ragupathy study, the researchers investigated the thermal performance of a “forced-draught counter flows wet cooling tower” experimentally. The tower had a packing of expanded wire mesh kind. Such a kind had horizontal as well as vertical orientations. The experiments determined that the cooling tower performance was enhanced with the vertical orientation of the packing.

Lavasani et al.(Lavasani et al., 2014, Al-Moameri et al., 2020) applied a numerical integration method for calculating the thermal characteristics of the tower. Kelly and Swenson(Kelly, 1956, Al-Moameri et al., 2020) showed that the tower characteristic or temperature increases. They made a series of runs in which the hot water temperature varied from 100°F to 150°F, at constant *L*, packed height, and wet bulb temperature. In their study, they also found that the overall tower characteristics (*Mt/L*) can be expressed as the sum of the values of the (*Mt/L*) for the end effects and the packed section, as follows:

$$(Mt/L)_{total} = (Mt/L)_{ends} \quad + \quad (Mt/L)_{fill} \ldots.. \qquad \ldots(1)$$

For their investigation, they found that;

$$(Mt/L) = 0.007 + A + N * (L/G) \qquad \ldots\ldots.(2)$$

Where *A* and *N* are constants depending on the type of deck.

Overall, HDPE is used to construct a cooling tower in terms of the fills as it is an optimum material. The sheets are produced, and there is no requirement for joints and bolts. Thus, the chances of a leak are reduced to zero levels. Also, the chances of rust and crack are reduced. Comparison of different types of cooling tower portrays the following noticeable points:

- Galvanized towers are corrosion-free.
- Zinc galvanized towers have an advantage that delays the corrosion further.
- HDPE towers are energy efficient, and minimum maintenance is required. Water conservation and sustainability also make them unique from others. HDPE is strong, dense, and stiff and has a crystalline structure. It is easy to clean, is the corrosion-resistant, and eco-friendly.

The construction of a typical cooling tower involves several steps ranging from the casing, fill to the flow type.

For the casing, selecting an appropriate material in the construction of the cooling tower is very important. The main purpose of the casing is to reduce maintenance needs and ensure the longevity of the tower with reliability. Galvanized steel, stainless steel, concrete, and fiberglass are the most common material used for casing. However, casings are usually made of glass fiber as it protects the tower from chemicals.

As discussed previously, the use of PVC, polymers, and polypropylene is common for the fill material in the tower. In some countries, the fill is made of wood. However, the wood is still in use; it was found that the plastic fill has a greater heat transfer capacity. Also, the fill may result in either crossflow or counterflow (Gharagheizi et al., 2007; Kariem et al., 2020). In crossflows, the air and water meet crossly. The air is allowed to enter from both sides while the warm water enters from the top. The cold-water leaves from the bottom. For the counterflow, there is a counterflow between air and water. The water is scattered over the fill, and the cold water leaves from the bottom(Mohiuddin and Kant, 1996)

In terms of the calculations, there are many small instruments used to calculate cooling towers' performance. The required parameters are water flow rate, air flow rate, inlet and outlet water temperatures, and dry bulb and wet bulb temperatures of air. In evaluating performance, the approach adopted, the range, and corresponding efficiencies of the system are very important. To be able to calculate the above parameters, the following correlations can be used.

$$Approach = Cold\ water\ temperature - wet\ bulb\ temperature$$

$$Range = Hot\ water\ temperature - Hot\ water\ temperature$$

$$Efficiency = \left(\frac{Range}{Range + Approach}\right) \times 100$$

The Liquid/gas ratio is a ratio between the water and air mass flow rates. Some changes are usually required to improve results, so adjustments are done in water loading and fan blade angle. In thermodynamics, it is a fundamental rule that the heat absorbed by air must be equal to the heat rejected by the water. Usually, the notations involve L being referred to as the water flowrate and G as the gas flowrate(Mohiuddin and Kant, 1996, Rzaij et al., 2020)

APPARATUS AND EXPERIMENTAL PROCEDURE:

As illustrated in Figure 1, a mechanical forced-draught counterflow cooling tower was constructed. A certain way was chosen for the arrangement of the tower to provide maximum possible access to the section of the tower. The maximum access of heat exchange is solely done for smoothing the process of maintenance and observation without impeding operations. The instruments and the equipment were systematically assembled to ensure that the energy and material balances could be accomplished readily.

In a closed system, water circulation was preserved during a run. With a centrifugal pump, the water from the 2x 2 x 1.65 ft tower basin is pumped. Next, the water passed through the constant vessel tank. The water flow circulation results in the provision of a steady-state head. The water then passes to the water heating tank made of stainless steel, with 6 * 2.5 KJ /s (240 volts) immersion elements. Then, the water passed towards the main area of the tower distribution.

Distribution of water on the fills 'upper edge was made possible using 14 P.V.C tubes with a 10-mm diameter. Each tube had 14 holes, was 2.5 mm in diameter, and ensured the film flow of the water. Next, the water flow rates were assessed using a rotameter, which was independently calibrated. Overall, the tower was 400 mm by 400 mm in cross-section. The difference between the inlet air distributor and water distributor was 1.4 m. Also, the front side of the tower was made of a moving plastic sheet.

From the bottom of the tower, the air entered and traveled thru the packing from slot entry. It must be noted that such an assembly results in a counter-current flow between the upward air and the falling water inside the tower. Furthermore, to control evaporation, a porous plastic pad, mist eliminator was positioned above the water distribution system in the tower. The air supply to the system was provided using a fan. The air volume flow rates were measured by using a U-manometer.

It is worth mentioning that in the cooling tower, the heat transfer factor was the fill, made from HDPE, as shown in Figure 2. Different heights of packing used were: 25, 50, 75, and 100cm, according to the tests carried out. These heights were chosen to assess the end effects specifically. Moreover, the distance between the top of the fill and the tubes for water distribution was maintained at4 cm to avoid splashing. Eleven calibrated thermocouples were used for measuring water and air temperatures. These were situated systematically and allowed for determining the air or water’s weighted average temperature at all points. Also, a single thermocouple was used for measuring the inlet water temperature.

Table 1 details the measured variables and the corresponding thermocouple codes.

Table 1 The measured variables.

Temperature	Thermocouple code	
Intel water temperature	1	
Outlet air dry bulb temperature	2	3
Outlet air wet bulb temperature	4	5
Outlet water temperature	6	7
Inlet air dry bulb temperature	8	9
Inlet air wet bulb temperature	10	11

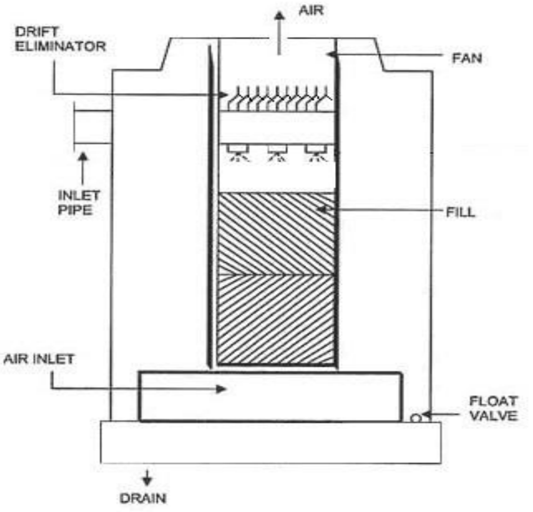

Figure 1 Schematic diagram of the cooling tower.

Figure 2 Screw HDPE packing.

RESULTS AND DISCUSSION

The tower characteristics (*Mt/L*) are shown in Figure 3 to Figure 6. These figures show plots of the tower's characteristics; the water to air ratio values (*L/G*), for HDPE, fill at the height of 25,50,75 and 100 cm respectively, and nominal inlet water temperature (t_{12})at 45°C.

The results show that nearly parallel and straight lines are enough to fit the data mentioned above. The above result was also addressed and reported by other authors.

The results showed that at constant air flux *G*, an increase in the water to air ratio leads to a decrease in the characteristics of the tower. The point can explain such behavior that increases in water flux, *L*, at a constant *G*, result in increases in heat load, which sequentially decreases the filling ability for the excess heat load dissipation.

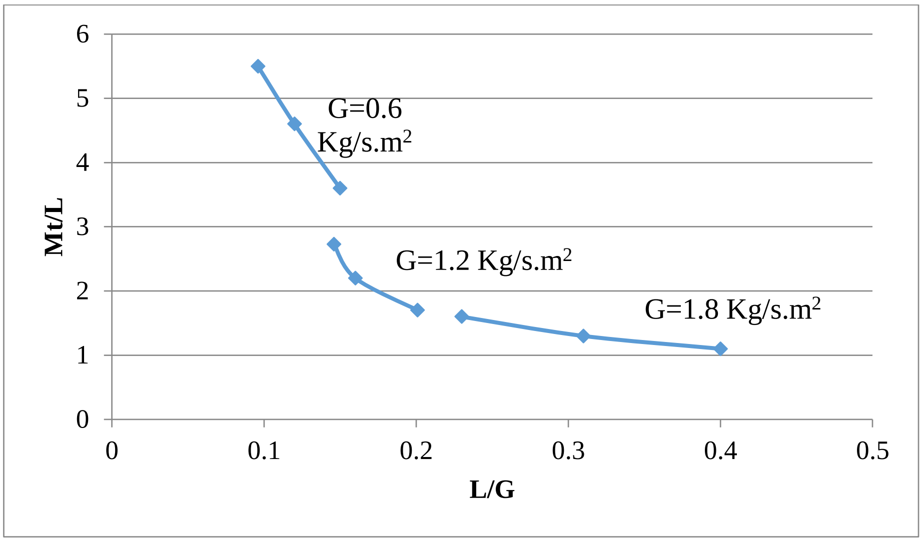

Figure 3 Uncorrected Mt/L vs. L/G for Screw packing at TL = 45°C, Z = 25 cm

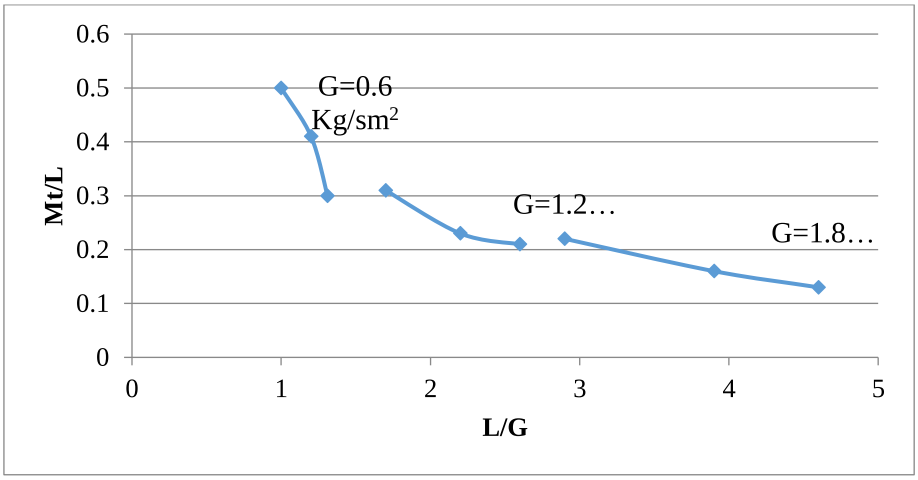

Figure 4 Uncorrected Mt/L vs. L/G for Screw packing at TL = 45°C, Z = 50 cm

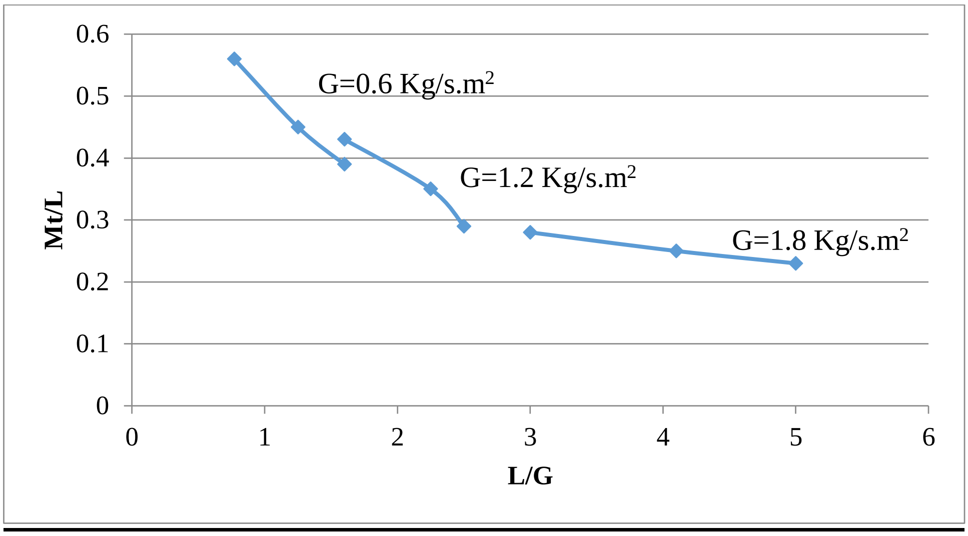

Figure 5 Uncorrected Mt/L vs. L/G for Screw packing at TL = 45°C, Z = 75 cm

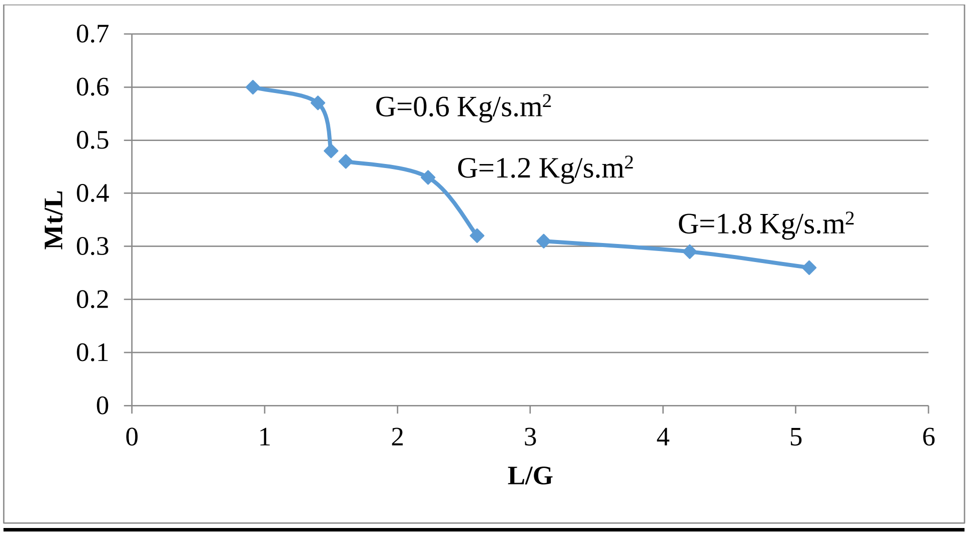

Figure 6 Uncorrected Mt/L vs. L/G for Screw packing at TL = 45°C, Z = 100 cm

The effect of the inlet water temperature is illustrated in Figure 7 on the tower characteristics. The figure indicates that tower characteristics decrease with increases in the inlet water temperature for the constant value of water: air ratio (*L/G*). Such a finding proves that increases in heat loads decrease the characteristics of the tower. Moreover, the results from the experiments revealed that a decrease in *Mt/L* amounted to about 6% for each 5oC rise in the water temperature at the inlet.

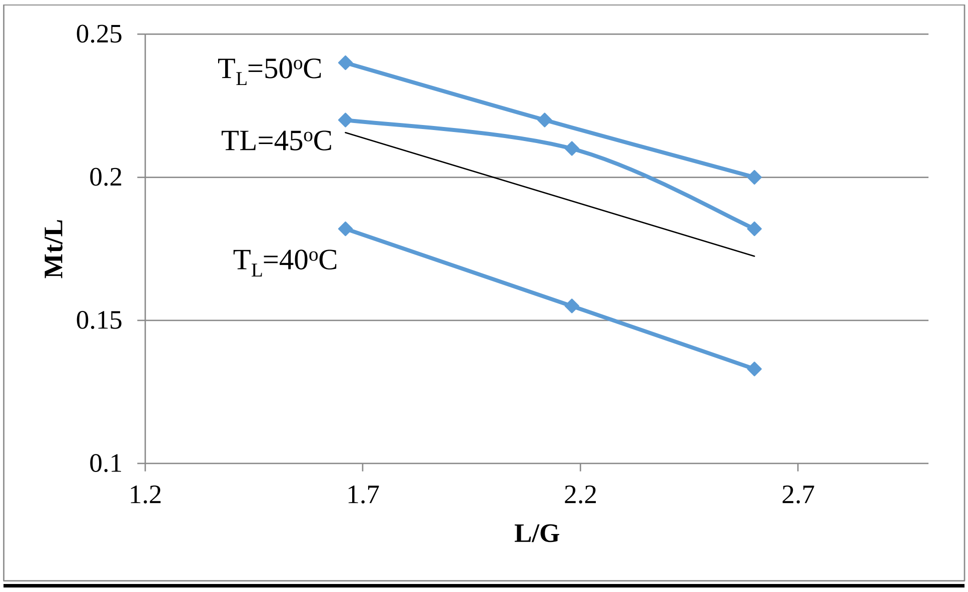

Figure 7 Uncorrected Mt/L vs. L/G for Screw packing at Z = 25 cm and G = 0.6 Kg/s.m^2

Figure 8 shows the effects of the water temperature at the inlet corresponding to the air flux, G, on the volumetric mass transfer coefficient (*Mt*). Based on these results, potential decreases in *Mt* occur due to an increase in the inlet water temperature. As demonstrated in Figures 5 and 6, this is mainly because of reducing the tower characteristics *Mt/L*. In contrast, increases in air flux from 1.2 to 1.8 Kg/s.m^2 increase *M* by about 16%. The increase in M is sole since the evaporation rate is directly related to the air rate.

Figure 9 shows the impact of the inlet water temperature and air flux, *G*, on the volumetric heat transfer coefficient (*Ht*). The impact is similar to the impact on *Mt*. This is whole since the subsequent calculations were made using the Lewis relationship (equation 4):-

$$Ht = Mt \, . \, C_s \qquad \ldots\ldots. (4)$$

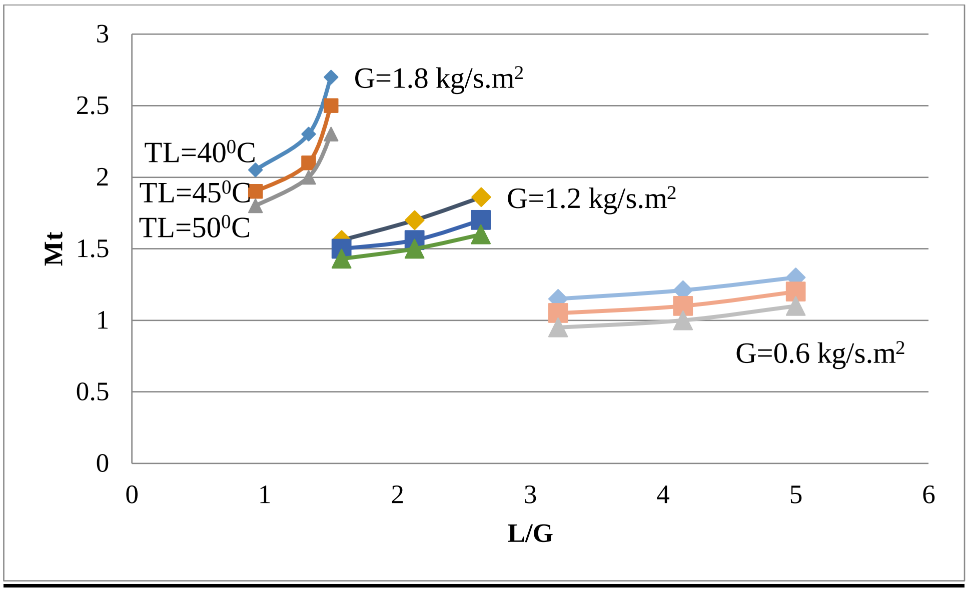

Figure 8 Volumetric mass transfer coefficient vs. L/G for screw packing and Z=60 cm

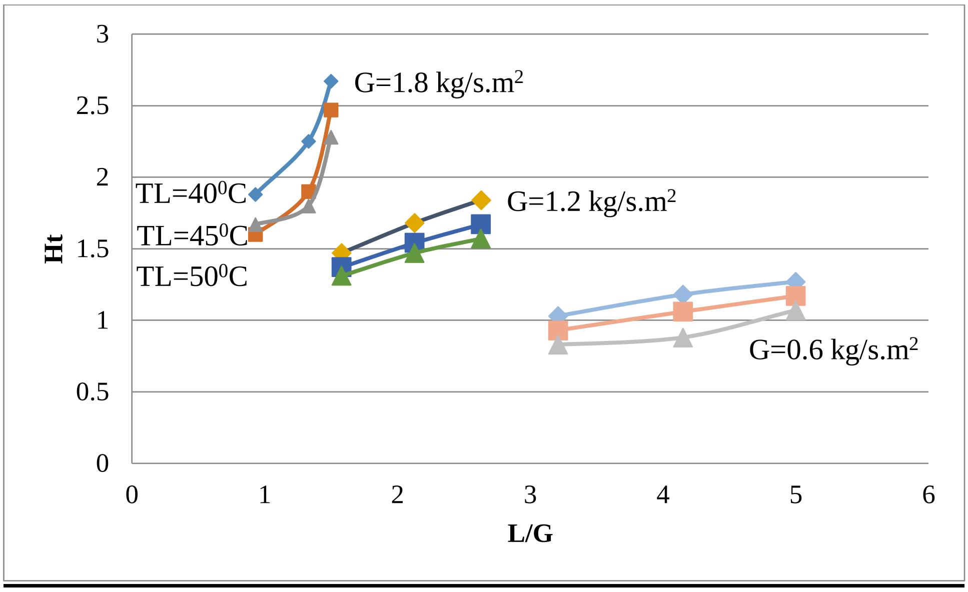

Figure 9 Volumetric heat transfer coefficient vs. L/G for screw packing and Z=60 cm

Comparisons between the tower characteristics (*Mt/L*) in different packed heights for HDPE fill (tL2 = 313 k (40 0C)) for uncorrected height due to the endpoint are shown in Table 2. Also, the literature reports that several researchers in the same fields have attempted to correlate L/G with tower characteristics. The formulae of type in equation (5) are widely utilized to estimate the air and constants cm tower characteristics. Table 2 shows the comparisons between the tower characteristics (Mt/L) in different packed heights for HDPE fill for uncorrected height

$$Mt = c\ (L/G)^{m} \quad ....(5)$$

With a constant air flux, G, the magnitude of end effects is tested and determined at numerous heights. Upon extrapolation to 0-height, the characteristic tower value for end effects is achieved. Thus, the value of the *Mt/L* equation can be achieved by intercepting the vertical axis. Also, corresponding to the end effects, the number of transfer units can also be attained. These can be subtracted from the uncorrected tower characteristics (*Mt/L*). On the contrary, the horizontal axis intercept corresponds to the (-) value of *Zeq*, which is the end effects' equivalent height.

Again, the tower characteristics *Mt/L* at various packed elevations are compared, following the exclusion of the end effects' values. The correlations are listed in Table 3.

The tested data correlation comprises of understanding the fundamental curve, which agrees with all other curves while considering *L* as well as *G* independently for accounting the air flux variation as:

A 1.1 % probability is associated with the expected error. Also, with each correlation, a similar

$$Mt = 0.671(L)^{-0.76}\ (G)^{0.55} ....(6)$$

term will be associated (see eq. 6)

Table 2 Comparisons between the tower characteristics (Mt/L) in different packed heights for HDPE fill for uncorrected height

Height (cm)	Uncorrected Correlations
100	Mt = 0.633 (L/G)-0.553
75	Mt = 0.547 (L/G)-0.513
50	Mt= 0.461 (L/G)-0..456
25	Mt= 0.376 (L/G)-0.366
100	Mt= 0.633 (L/G)-0.824
75	Mt= 0.563 (L/G)-0.808
50	Mt= 0.713 (L/G)-0.825
25	Mt= 0.416 (L/G)-0.727
100	Mt= 0.686 (L/G)-0.447
75	Mt= 0.711 (L/G)-0.807
50	Mt= 0.512 (L/G)-0.561
25	Mt= 0.417 (L/G)-0.617

Table 3 Corrected Correlations

Height (cm)	Corrected Correlation
100	Mt = 0.422 (L/G)-0. 766
75	Mt = 0.347 (L/G)-0. 698
50	Mt= 0.285 (L/G)-0.622
25	Mt = 0.135 (L/G)-0.751
100	Mt = 0.551 (L/G)-0.801
75	Mt= 0.561 (L/G)-0. 917
50	Mt = 0.322 (L/G)-0.89
25	Mt= 0.317 (L/G)-0. 77
100	Mt= 0.505(L/G)-0. 635
75	Mt= 0.377 (L/G)-0.592
50	Mt= 0.295 (L/G)-0.501
25	Mt= 0.263 (L/G)-0.631

CONCLUSIONS

It is apparent from the research work that using minimum water and airflow ratio, *L/G*, allows for achieving the maximum performance in a given volume of tower fill. The "Least square method" was employed for correlating the experimental results, where the dependent variable (*Mt/L*) correlated with water and airflow ratio (*L/G*) by fitted log-log data. Also, the exponents of the equation lied in the range between -0.40 and -0.81. Finally, the end effects involve (open space on top of the fill and the open space beneath the fill), where a certain amount of cooling took place in these zones. Thus, a parametric study for HDPE fills material was conducted, which assisted in the estimation of the tower characteristics in terms of such effects regarding the corrected value. The results "correlation equation per unit depth of fill height" are provided as the individual volumetric coefficient of heat and mass transfer (*Ht*, and *Mt*), which were observed to be influenced merely by the variables in the system, for instance, the inlet water temperature and the air and water fluxes. The following equation can be utilized in this context. in future works, it is recommended to develop a computer simulation for the performance of the cooling tower.

$$Mt = 0.671\, L^{-0.7}\, G^{0.53}$$

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NOMENCLATURE:

A	Cross - sectional area, m^2
B	Dimensional constant
G	Airflow rate, kg/s. m^2
Ht	Heat transfer coefficient, kW/m^2. k
L	Water flow rate, Kg/s. m^2
Mt	Mass transfer coefficient, kg/s. m^2
Hg1	Enthalpy of air at the tower outlet, kJ/kg dry air
Hg2	Enthalpy of air at the tower inlet, kJ/kg dry air
Z	Fill height m

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