Experimental study of cooling tower performance using ceramic tile packing

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Abstract

Deterioration of the packing material is a major problem in cooling towers. In this experimental study ceramic tiles were used as a packing material. The packing material is a long life burnt clay, which is normally used as a roofing material. It prevents a common problem of the cooling tower resulting from corrosion and water quality of the tower. In this study, we investigate the use of three different types of ceramic packings and evaluate their heat and mass transfer coefficients. A simple comparison of packing behaviour is performed with all three types of packing materials. The experimental study was conducted in a forced draft cooling tower. The variations in many variables, which affect the tower efficiency, are described.

Keywords: cooling tower, ceramic packing, efficiency

I. Introduction

Cooling towers are used for cooling large amounts of water in chemical industry, thermal power plants, nuclear power plants and petroleum industry. These heat and mass transfer devices are based on the evaporative cooling of water in contact with ambient air. The working volume of the tower is filled with packing material to increase contact between the two phases.

The theory of cooling towers has been studied in some depth since the first work of Merkel in 1925 [1]. It is a reasonably accurate and relatively simple mathematical description of the heat and mass transfer phenomena in a counter current tower. Jaber and Webb [2] presented an effectiveness-number of transfer units (e-NTU) method of analysis which is particularly useful for cross flow cooling towers. Simpson and Sherwood [3] studied the performances of forced draft cooling towers with a 1.05 m packing height consisted of wood slats. Kelly and Swenson [4] studied the heat transfer and pressure drop characteristics of splash grid type cooling tower packing. The authors correlated the tower characteristic with the water/air mass flow ratio and mentioned that the

factors affecting the value of the tower characteristic were found to be the water-to-air ratio, the packed height, the deck geometry and, to a very small extent, the hot water temperature. They also mentioned that the tower characteristic at a given water-to-air ratio was found to be independent of wet bulb temperature and air loading , within the limits of air loading used in commercial cooling towers. Barile *et al*. [5] studied the performances of a turbulent bed cooling tower. They correlated the tower characteristic with the water/air mass flow ratio.

El-Dessouky [6] studied the thermal and hydraulic performances of a three-phase fluidized bed cooling tower. He used spongy rubber balls 12.7 mm in diameter and with a density of 375 kg/m³ as a packing, and developed a correlation between the tower characteristic, hot water inlet temperature, static bed height, and the water/air mass flux ratio. Bedekar *et al*. [7] studied experimentally the performance of a counter flow packed bed mechanical cooling tower, using a film type packing. Their results were presented in terms of tower characteristics, water outlet temperature and effciency as functions of the water to air flow rate ratio, *L/G*. They concluded that the tower performance decrease with an increase in the *L/G* ratio, however they did not suggest any correlation in their work. Goshayshi and Missenden [8] also stud-

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ied experimentally the mass transfer and the pressure drop characteristics of many types of corrugated packing, including smooth and rough surface corrugated packing in atmospheric cooling towers. Their experiments were conducted in a 0.15 m × 0.15 m counter flow sectional test area with 1.60 m packing height. From their experimental data, a correlation between the packing mass transfer coefficient and the pressure drop was proposed. Milosavljevic and Heikkila [9] carried out experimental measurements on two pilot-scale cooling towers in order to analyse the performance of different cooling tower filling materials. They tested seven types of counter flow film type fills and correlated their pressure drop data as well as the volumetric heat transfer coefficient with the water and air flow rates.

More recently, Kloppers and Kroger [10] studied the loss coefficient for wet cooling tower fills. They tested trickle, splash and film type fills in a counter flow wet cooling tower with a cross sectional test area of 1.5 m × 1.5 m. They proposed a new form of empirical equation that correlates fill loss coefficient as a function of the air and water mass flow rates. There are several other mathematical models which can correlate heat and mass transfer processes occurring in wet cooling towers, such as the models proposed and discussed by Khan *et al*. [11] and Kloppers and Kroger [12], "V.G.A." type packing. This type of packing was first proposed for the mass transfer processes between gas and liquid [13] and has not been used in cooling water systems using direct contact between water and air. Lemouari [14] and Lemouari and Boumaza [15,16] used this packing in an evaporative cooling system to study its thermal and hydraulic performances. Therefore, this study presents an experimental investigation of the thermal performances of cooling towers filled with the "V.G.A." type packing. This packing consists of vertical grids disposed between walls in the form of zig-zag. The principle of its performance is as follows: the gas (air) enters at the bottom of the tower and goes to the top of that while crossing several times the vertical grids, whereas the liquid (water) is introduced at the top of the tower and flows along the vertical grids.

Jorge [17] studied the thermal performance of the cooling tower in chilled ceiling conditions. A mass transfer coefficient correlation is developed, and new variables are defined. Naphon [18] performed a study on the heat transfer characteristics of an evaporative cooling tower. The tower had 0.15 m × 0.15 m internal cross section and 0.48 m in height packed with eight layers of the laminated plastic plates. He presented theoretical and experimental results of the heat transfer characteristics of the cooling tower by making a comparison between them. However, the author did not suggest any empirical correlation for the heat transfer characteristics of the tower. Elsarrag [19] presented an

experimental study and predictions of an induced draft ceramic tile packing cooling tower. He used a tower of 0.64 m² cross section area and 2 m height with a filling portion of 0.8 m. Burned clay bricks were used as the packing material in his work. The author pointed out that the factors affecting the heat and mass transfer coefficients are the water to air flow rate ratio, the inlet water temperature and the inlet air enthalpy. Gharagheizi *et al*. [20] presented an experimental and comparative study on the performance of mechanical cooling tower with two types of film packing. They used vertical corrugated packing (VCP) and horizontal corrugated packing (HCP) having 0.64 m in high and 0.25 m² cross section area. These authors reported that the performance of the cooling tower is affected by the water/air mass flow ratio, the type and the arrangement of the packing. Besides the early experimental investigations, there exist several other mathematical models that correlate heat and mass transport phenomena and performance characteristics relative to direct-contact counter flow wet cooling towers, such as the models described in Benton and Waldrop [21], Kloppers [22], Fisenko *et al*. [23], Fisenko and Petruchik [24], Khan *et al*. [25], Qureshi and Zubair [26] and more recently Heidarinejad *et al*. [27].

The main purpose of this paper is to carry out an experimental investigation of the performance characteristics of a direct-contact counter flow wet cooling tower filled with the ceramic type packing in order to determine the parameters affecting the thermal effectiveness of the cooling tower as well as the heat rejected by this tower.

II. Experimental

The tested cooling tower is a forced draft counter flow type. A schematic illustration and photo of the used experimental apparatus are shown in Fig. 1. The main part of the installation is the cooling tower, having 1.5 m in height and 0.3 m × 0.3 m in cross section. Water is transported by pump through flow regulated valve. The water flow rate is measured by flow meter and distributed through spray nozzles. Water is distributed in the form of falling films over the expanded wire mesh fill. The water distribution system consists of six nozzles having diameter of 2 mm. By using this system water is directly distributed over the ceramic packing, and the films of falling water were uniform across the whole surface of the packing. The pressure drop at fill zone is measured by U-tube manometer. Chromel-alumel thermocouples were used to measure water inlet and outlet temperature and measure the water temperature in fill zone area. All thermocouples were connected to a 24 point digital temperature recorder. A forced draught fan was used to provide air flow to the tower. The air enters into tower, passes the rain zone, fill zone, spray zone and leaves the tower.

Table 1. Cooling tower operating parameters and measuring device specification

Parameter	Instrument Type	Range	Accuracy
Water temperature [°C]	Chromel-alumel thermocouples	0–70	0.1
Air temperature(DB & WB) [°C]	Sling psychrometer	0–60	0.1
Flow rat of water [lts/hr]	Flow meter	0–1000	0.01
Air velocity [m/s]	Vane type anemometer	0–50	0.1
Air pressure drop [mm]	U-tube manometer	0–100	1
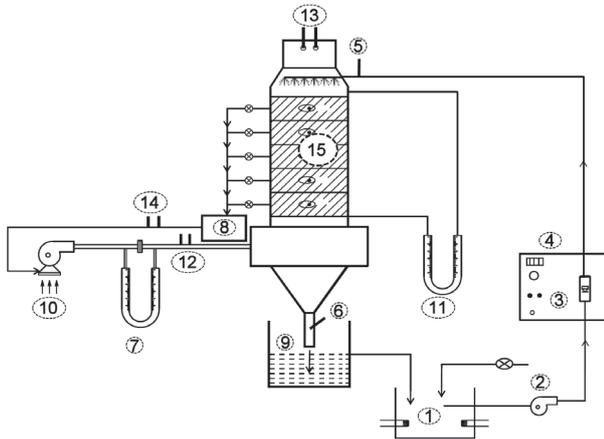
a)   b)

Figure 1. Schematic illustration (a) and experimental setup (b) of forced draft cooling tower: 1. water heater, 2. pump, 3. flow meter, 4. display and control unit, 5. hot water thermometer, 6. cold water thermometer, 7. U-tube manometer - air flow, 8. psychometric gun, 9. receiving tank, 10. forced draft fan, 11. U-tube manometer– ΔP of pakcing, 12. air inlet temperature. (T_{DB1} T_{WB1}), 13. air outlet temperature (T_{DB2} T_{WB2}), 14. psychrometric gun temperature 15. expanded wire mesh fill

In the present experimental work many parameters affecting the performance of counter flow wet cooling towers were investigated. These parameters and their corresponding range are given in Table 1.

III. Ceramic tile packing

In the experimental study, ceramic tile packing was used as tower packing material. This type of packing is considered as unique for film packing. The forming of ceramic packing is made in such a way that each little aperture acts as directing vane for air, moving bulk of air alternately from one side to the other. This ac-

Figure 2. Picture of the ceramic packing

tion results in air travelling a distance of about 1.25 m through the total depth of packing. Compared with different standard cooling packings, ceramic packing provides the minimum restriction to the passage of air. The pictures of the used packings with dimensions are shown in Fig. 2.

IV. Cooling tower theory

When air flow passes a wetted surface there is a transfer of sensible and latent heat. If there is a difference in temperature between the air and the wetted surface, heat will be transferred. If there is a difference in the partial pressure of water vapour in the air and that of the water, there will be a mass transfer. This transfer of mass causes a thermal energy transfer because if some water is evaporated from the water layer, the latent heat of this vaporized water will be supplied to the air. The concept of enthalpy potential is a very useful one in quantifying the transfer of heat (sensible and latent) in those processes and components where there is a direct contact between the air and water.

Heat transfer rate in the cooling tower is represented by the difference between the enthalpy of moist air at bulk water temperature and the enthalpy of the moist air. Total heat transfer rate per unit volume of packing (dV) from the interface to the air is the sum of sensible heat (dq_S) and latent heat (dq_L).The following equation
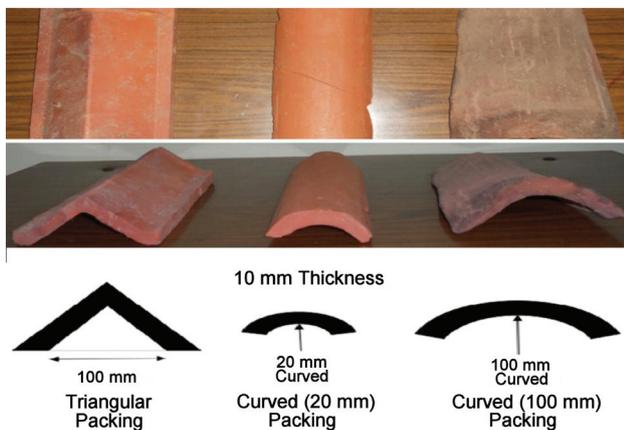
can be obtained by applying energy and mass balance to the water, interface and air:

$$dq_S = L \cdot c_{pw} \cdot dt = U_g \cdot a \cdot dV(T_i - T_a) \qquad (1)$$

$$dq_L = h_{fg} \cdot dm = h_{fg} \cdot K \cdot a \cdot dV(\omega_i - \omega) \qquad (2)$$

Energy conservation demands that heat lost by water must be equal to heat gained by air.

$$L \cdot c_{pw} \cdot dt = G \cdot dh = K \cdot a \cdot (h_i - h_a) \cdot dV \qquad (3)$$

This equation considers the heat transfer from interface to the air stream, but interfacial conditions are intermediate. By neglecting the film resistance and by postulating the mass transfer coefficients, based on the driving force of enthalpy h_i at the bulk water temperature T_w, integration of the above equation gives:

$$\int_0^V \frac{K \cdot a \cdot dV}{L} = \int_{T_{w1}}^{T_{w2}} \frac{c_{pw}}{h_i - h_a} dt = \frac{K \cdot a \cdot V}{L}$$

$$NTU = \frac{K \cdot a \cdot V}{L} = \int_{T_{w1}}^{T_{w2}} \frac{c_{pw}}{h_i - h_a} dt \qquad (4)$$

$$\frac{K \cdot a \cdot V}{L} = Tower \ \ Characteristics$$

Tower characteristics can also be referred to as the number of transfer units (*NTU*) of the system. This is a dimensionless parameter which is the characteristic value of the packing. The cooling tower effectiveness is the ratio of range to the ideal range:

$$Effectiveness(\varepsilon) = \frac{Range(R)}{Range(R) - Approach(A)}$$

$$\varepsilon = \frac{T_{w1} - T_{w2}}{T_{w1} - T_{wb1}} \qquad (5)$$

$$Range(R) = T_{w1} - T_{w2} \qquad (6)$$

$$Approach(A) = T_{w2} - T_{wb1} \qquad (7)$$

A tower characteristic is determined numerically by integrating Eq. (4) between inlet and outlet water temperatures.

Liquid/gas (*L/G*) ratio of a cooling tower is the ratio between water and the air mass flow rate. Against the designed values, seasonal variations require adjustment and tuning of water and air flow rates to get the best cooling tower effectiveness. The heat removal from water must be equal to the heat absorbed by the surrounding air.

$$L(T_{w1} - T_{w2}) = G(h_{a2} - h_{a1}) \qquad (8)$$

$$\frac{L}{G} = \frac{h_{a2} - h_{a1}}{T_{w1} - T_{w2}} \qquad (9)$$

V. Results and discussion

In this experimental study the operating parameters, cold water temperature (t_{w1}), L/G ratio, dry bulb temperature (t_{db1}) are maintained as 45 °C, 0.5 and 32 °C,
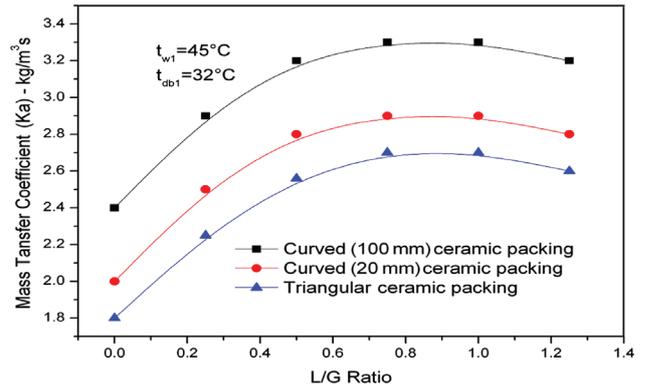

Figure 3. Vitiation of mass transfer coefficient with *L/G* ratios
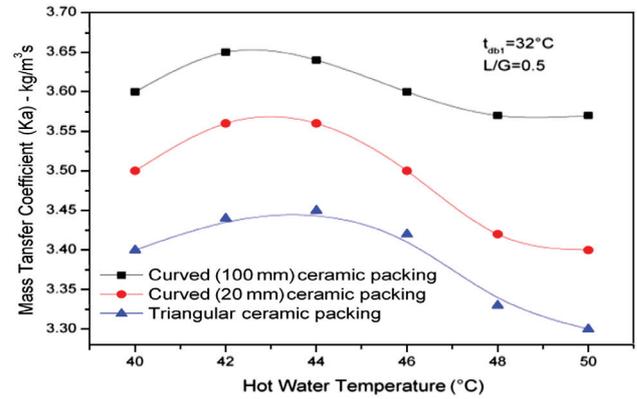

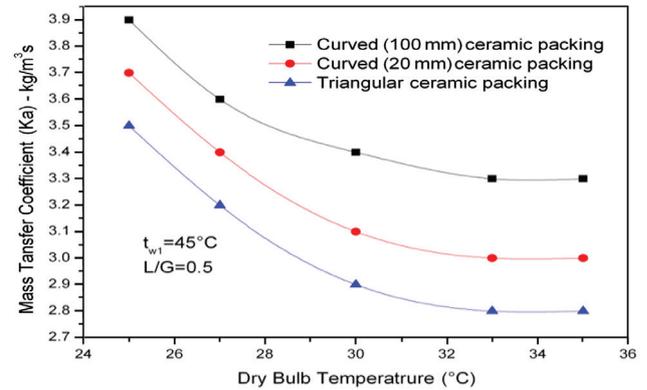**Figure 4. Variation of mass transfer coefficient with hot water temperature**

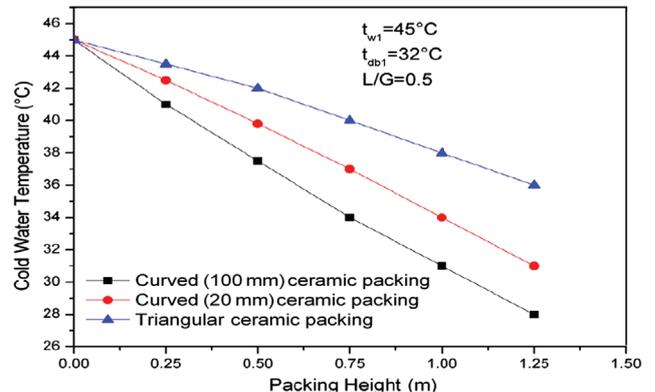**Figure 5. Variation of mass transfer coefficient with inlet air dry bulb temperature**

Figure 6. Variation of cold water temperature with packing height
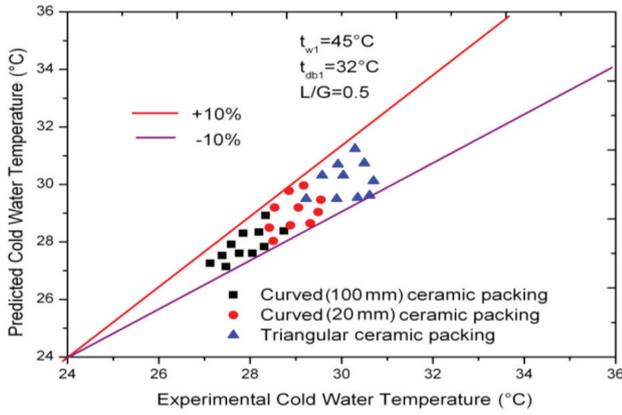
Figure 7. Relation between experimental and predicted cold water temperature
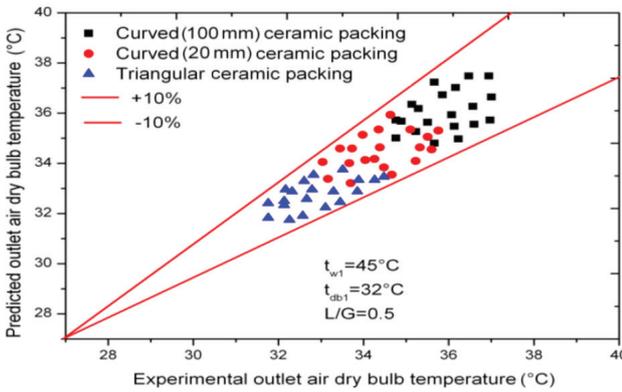

Figure 8. Relation between experimental and predicted outlet air dry bulb temperature

respectively, based on the literature review. The mass transfer coefficient was found from the experimental data. The heat and mass transfer coefficients are related by Reynolds's analogy [17], and the factors that influence the mass transfer coefficient also affect the heat transfer coefficient. As shown in Fig. 3, the mass transfer coefficient increased with the increases of the L/G ratio. However, it can be observed that there is some degree of difficulty in the mass transfer when a high L/G ratio was employed. The heat transfer coefficient has
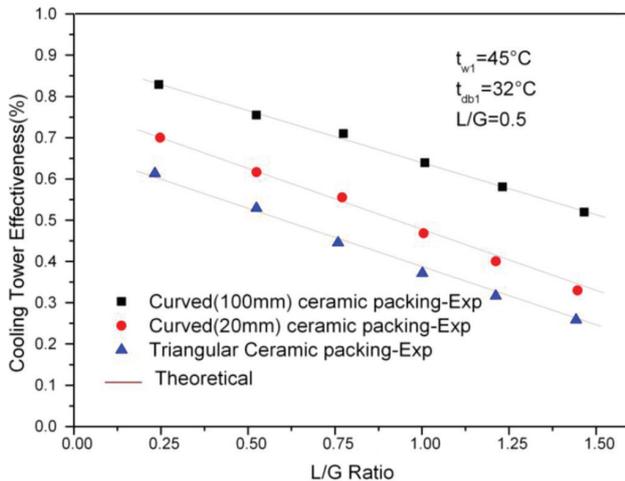

Figure 9. Variation of cooling tower effectiveness with L/G ratio

been increased up to $L/G = 1$ and then decreased. At $L/G < 1$, the contact area between air and water is large and better heat transfer rate is achieved. Similarly the heat transfer rate coefficient is higher in curved (100 mm) ceramic packing compared with other two. The contact area of water and air with the 100 mm ceramic packing is the largest, and the retention time is long. With other two packings the retention time is shorter and the contact of water to air is very short period.

Figures 4 and 5 show the variation of the mass transfer coefficient with inlet hot water and dry bulb temperature. The mass transfer coefficient has been increased when the inlet water temperature was raised from 40 °C to 45 °C as shown in Fig. 4, but it has been decreased when the water temperature was above 45 °C. This is mainly because the driving force increases with the increase of the inlet water temperature and a better heat and mass transfer occurs, but a higher outlet water temperature was obtained by continued increasing of the inlet water temperature. Above 45 °C the heat transfer rate decreased and water evaporation rate increased. From the Fig. 4 it is evident that heat transfer rate is higher in the 100 mm ceramic packing. The mass transfer coefficient has been decreased with the increase of the inlet air dry bulb temperature as shown in Fig. 5. This is due to the decrease in the driving force, which is reflected as a decrease in the mass transfer coefficient. Figure 5 shows that at low inlet dry bulb temperature the heat transfer rate is higher and that is decreased drastically from 25 °C to 30 °C. After that there are no major changes in the heat transfer because the driving force is higher at the lower dry bulb temperature.

Figure 6 shows the variation of the cold water temperature at different packing height. In the experimental study, the total packing height is 1.25 m and the water temperature has been measured at 0 m, 0.25 m, 0.5 m, 0.75 m, 1 m and 1.25 m level. In this experimental study, minimum cold water temperature was achieved with 100 mm ceramic packing. It is due to the larger packing contact area.

The deviation between the predicted values and experimental data is shown in Figs. 8 and 9. The cold water temperature and dry bulb temperature can be predicted within an error of ±10%. The cold water temperature was predicted using cooling tower software (CTS). This correlation was used to estimate the difference in packings' performance. In this study 100 mm curved packing achieved better performance. Cooling tower effectiveness was calculated with experimental results. From the experimental study effectiveness is higher in the lower L/G ratio and it was decreased drastically with increasing the L/G ratio. In lower L/G ratio, larger quantity of air was in contact with less quantity of water. But in higher L/G ratio, the quantities air and water are reverse. So the better cooling tower effectiveness was achieved at lower L/G ratio and with 100 mm curved ceramic packing.

IV. Conclusions

Numbers of experimental runs were conducted in the forced draft cooling tower with different types of burnt clay as packing materials. Different variables were considered for the experimental run. It was found that the heat and mass transfer coefficients are influenced by the L/G ratio, inlet water temperature and inlet dry bulb air temperature. Better heat transfer rate was achieved in the 100 mm curved ceramic packing compared with other two types of packing. The correlations between the experimental and predicted values were within 10% for the cold water temperature and outlet dry bulb temperature. Higher cooling tower effectiveness was achieved in the low L/G. Theoretical and experimental cooling tower effectiveness was within 5% error. From the experimental study, it was determined that 100 mm curved ceramic packing showed the best performance. It is due to the shape of the packing, contact area and retention time of water and air in the packing zone.

NOMENCLATURE

a : Area of water interface per unit volume [m²/m³]
c_p : Specific heat [kJ/kg·°C]
L : Mass flow rate of water [kg/s]
G : Mass flow rate of air [kg/s]
h : Enthalpy [kJ/kg]
m : Mass [kg]
K_a : Combined heat and mass transfer coefficient [kJ/m²·s]
A_v : Surface area of water droplet per unit volume of the tower [m²/m³]
K : Overall mass transfer coefficient [kg/s.m²]
q : Heat transfer rate [kJ/s]
U : Overall heat transfer coefficient [kJ/m²·s·°C]
V : Cooling tower volume [m³]
t : Water temperature [°C]
W : Absolute humidity

SUPERSCRIPTS AND SUBSCRIPTS

’   : Air bulk water temperature
”   : Interface between water and air
a : Air
s : Sensible heat
L : Latent heat
w : Water
wb: Wet bulb temperature
1,2: Inlet and outlet of cooling tower

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