EXPERIMENTAL INVESTIGATION OF THE THERMAL PERFORMANCE OF WET COOLING TOWER WITH SPLASH FILLS PACKING

by

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With the increasing intensity of the ecological and environmental problems and the scarcity of fresh water, this paper was introduced to investigate the ability to use treated wastewater as a cooling media via studying its behavior throughout a cooling tower. The simultaneous transfer of heat and mass from the treated wastewater to air over splash-fill packing arranged in a zigzag manner was studied. The characteristic of the cooling tower, the outlet water temperature, and the rejected heat were investigated as the water-to-air ratio and inlet water temperature were varied. The core results show that the cooling tower of the tower decreases with increasing water-to-air ratio, and increases with the raise of inlet water temperature. Moreover, relationships between cooling tower and water-to-air ratio were obtained for each. It was also observed that the outlet water temperature increases gradually with increasing water-to-air ratio and temperature, and the difference between the inlet and outlet temperature becomes larger by increasing the inlet temperature. The heat rejected value increases with increasing the air-flow rate, water flow rate, and temperature. This study revealed that cooling tower of splash fills arranged in a zigzag manner was higher compared to other types of packing. In the same time, the results for the treated wastewater and fresh water were very close that gives approximate behavior, and this can save a huge amount of fresh water for other humanistic utilization, along with taking benefit from the treatment process of wastewater instead of through it into the aquatic systems.

Key words: *cooling tower, splash fills, characteristic of cooling tower, treated wastewater*

Introduction

A tremendous quantity of heat is generated by many industrial processes and continuous dissipation of it that should be done in parallel with such operations to continue operating efficiently, this is taken place with the use of cooling systems [1, 2]. Water is a non-toxic media that have a high specific heat capacity. It can be applied as a cooling media in cooling systems [3]. Consequently, this used water may discharge to the main resources and causes thermal pollution. Since a huge amount of water is used for cooling, or it may have been

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treated, *i.e.*, re-cooled, *via* the use of air as a medium that carries the rejected heat to the atmosphere, and this is done inside reliable equipment in the industry called the cooling tower.

The principle of the work of cooling tower is based on heat and mass transfer that take place between the hot water (where its enthalpy is decreasing during its cooling) and the air (in which its enthalpy is increased) that both flow throughout the tower. The wet cooling tower is better than a dry cooling tower or heat exchanger (where only heat transfer takes place through a surface that separates both fluids from direct contact) due to the direct contact and exchange of heat and mass. This leads to a stable exchange rate with no defeat due to fouling or scaling. The transfer is enhanced in the wet cooling tower by using fills that work to enlarge the area of transfer for both heat and mass. These fills are called packing, which has an effective advantage on the operation of the cooling tower. As a result, packed cooling towers performed a more efficient transfer coefficient (heat and mass) that prompt a close temperature approach between the fluids and results in a reasonable reduction in operation cost.

Packing can be considered to be one of the main parts of the cooling tower. Its effectiveness has a remarkable effect on the tower efficiency due to the large surface provided for the heat and mass transfer between water and air. The packing shapes, material, and arrangement all affect the efficiency of the cooling tower. Many researchers have studied the effect of using many types of packing and investigated their impact on the thermal performance, the hydraulic characteristic, energy demand, and the cost of operation [4-7].

One of the used fills in cooling towers is the splash fills, this type of fill breaks the comedown water drops into smaller ones and this leads to an increase in the transfer area between water and air beside the wetted film around the packing itself. Besides, the generation of smaller droplets will result in the separation of dirt from the water. This type of fills was made from wood, but recently, the designs had been modified using new materials like Plexiglas and PVC. Also, this type of fills provides a low-pressure drop through the tower [8, 9].

Singla *et al.* [10] have used an expanded wire meshed packing to investigate its effect on the performance of the cooling tower by changing the controlling factors, *i.e.* air and water flow-rate. They developed a regression for the Merkel number. They found that many feasible sets of controlling factors be in content with a specific value of the Merkel number, which makes it useful to work with many desired conditions. Kong *et al.* [11] investigated the impact of using new fills, which made of foamed ceramic and they called it FCP-08, on the thermal performance of the cooling tower. They found that the cooling tower filled with their newly formed packing was having a great performance and excellent water-cooling capacity. Singh and Das [12] studied the influence of several types of fills on the thermal behavior of the cooling tower. They proved that the trickle fills are more efficient compared to others in the same conditions. Amini *et al.* [13] conducted the effect of nano-fluid on the thermal performance in rotational type splash fills cooling tower. They studied many variables and they found that the water to air flow has a major effect on thermal performance.

Nowadays, the growth in manufacturing, energy production, and the scarcity of fresh water has necessitated the development of systems that use new sources of water or reuse water from other systems, like taking benefit from the use of wastewater from other industrial processes [14-16]. The reuse of water protects the precious restricted feeding of fresh water since less is required for the premeditated use and also reduces the eco-system thermal pollution [17]. Treated municipal wastewater (TMWW) is an optional choice of water sources as a result of its wide geographic allocation and significant amount. In many studies concerning cooling towers, the use of TMWW was limited by mixing it with fresh water before the addition to the cooling towers. It has been also used as the only source of makeup water for cooling towers after effective treatment to avoid the usual problems of bio-fouling [18]. By this, the use of treated wastewater has a double advantage, the reduction of wastewater discharged to the plant and the reduction of the amount of fresh water as a makeup source.

So far, the majority of the previous studies had foxed on the use of fresh water. In this study, the thermal performance feature of a cooling tower filled with splash packing arranged in a zigzag manner was conducted to investigate its variation with some important working parameters with the employment of treated wastewater as the working media. The amount of rejected heat from water with air flow and inlet temperature variation was also investigated carefully because it can co deduce the relation between the variables and the thermal performance and their effect on consuming energy during operation. The use of mathematical expression had been introduced to assist in the evaluation of the thermal performance of the cooling tower fills.

Mathematical model

The characteristics of the cooling tower fills and the thermal boundary layer

The cooling tower is an essential unit and is the core unit in the heat dissipation system. The majority of mass and heat transfer takes place in the cooling fills sections of this unit. For this, there is a considerable advantage from studying this transfer performance of the fills. By using the mathematical model, a quantitative evaluation of the thermal performance can be done for the cooling tower fills.

The heat transfer between the water and the air is taking place by both the sensible and the latent types of heat as explained in fig. 1. A small section of high d*z* of the tower fill is considered for analysis. As seen, the transfer mechanism between upward air and counter-current water occurs throughout the fills where the air absorbs water heat. In this system, the air enthalpy increases from $H_{a,i}$ to $H_{a,o}$ and at the same time, the water temperature is reduced from $T_{w,i}$ to $T_{w,o}$.

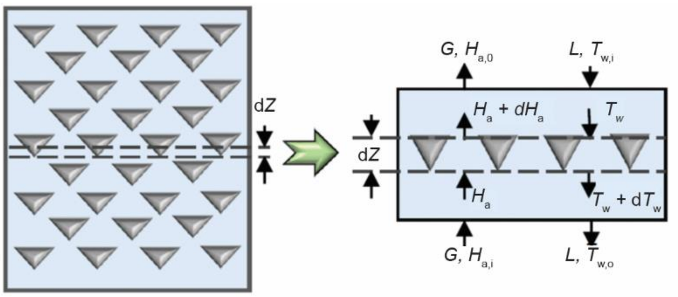

Figure 1. The process of transfer in the splash fills cooling tower

To simplify this situation, the transfer of both heat and mass will be assumed to take place along the direction of the fluids flow, throughout the fills in a steady-state process. Also, the system will be considered as adiabatic, so that the losses that affect the environment will be ignored. The temperature distribution inside the droplets formed due to breaking over splash fills will also be ignored because of its small diameter.

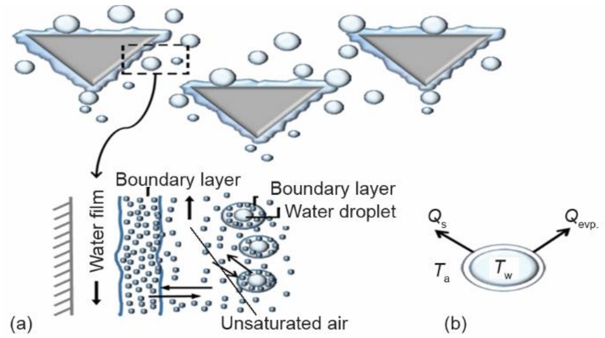

Figure 2. Microscopic transfer of heat; (a) in the film water and film water over the droplets and (b) the type of heat transfer

As explained, the cooling of water is taking place due to the flow of heat and mass from the water to the air. Besides, heat transferred will occur between water and air by gathering of convection process of both water and ai, fig. 2(a). The hot water to be cooled will exchange both heat and mass with the adjacent air through the water layer, a water layer, and near droplets beside also the water layer and water column. For each formed drop, there will be a loss of heat by both sensible Q_s, which depend on temperature difference, and latent Q_{evp} that depends on the moisture content and latent heat of evaporation, fig. 2(b).

Thus, by summing the sensible and latent heat transfer between the two fluids in the contact area of dC [m^2] between water and air:

$$\mathrm{d}Q = \left[h(T_\mathrm{w} - T_\mathrm{a}) + \lambda h_\mathrm{m}(x_\mathrm{w} - x_\mathrm{a})\right]\mathrm{d}C \tag{1}$$

and if we assume that the heat required for the evaporation of water is tantamount to heat lost by the air, then:

$$h(T_\mathrm{b} - T)\mathrm{d}C = \lambda h_\mathrm{m}(x_\mathrm{b} - x)\mathrm{d}C \tag{2}$$

where T and x are the temperature and the moist content in the main air stream. While T_b and x_b represent the temperature and the moist content in the boundary layer surface.

The heat balance on the air side yields:

$$G\lambda(x_\mathrm{b} - x) = GC_{p,\mathrm{a}}(T_\mathrm{b} - T) \tag{3}$$

by combining eqs. (2) and (3), the Lewis coefficient is defined [19]:

$$\mathrm{Le}_f = \frac{h}{C_{p,\mathrm{a}} h_\mathrm{m}} = 1 \tag{4}$$

then by using eqs. (1) and (4), the heat transfer equation in the very small element of dz is obtained:

$$\mathrm{d}Q = h_\mathrm{m}(H''_\mathrm{w} - H_\mathrm{a})\delta A\mathrm{d}z \tag{5}$$

Where the enthalpy of the moist air is [20]:

$$H = C_{p,\mathrm{a}}T_{\mathrm{a,wet}} + C_{p,\mathrm{v}}x + \lambda x \tag{6}$$

an element volume energy balance gives the following equation:

$$C_{p,\mathrm{w}}(L\mathrm{d}T_\mathrm{w} + T_\mathrm{w}\mathrm{d}L) = G\mathrm{d}H_\mathrm{a} = \mathrm{d}Q \tag{7}$$

Then:

$$\frac{1}{C}C_{p,\mathrm{w}}L\mathrm{d}T_{\mathrm{w}}=G\mathrm{d}H_{\mathrm{a}}=\mathrm{d}Q \tag{8}$$

where C is a correction coefficient that counts the losses of heat by water evaporation which is the function of $T_{\mathrm{w,o}}$ and is generally close to unity.

Now, by combining eqs. (8) and (5):

$$\frac{h_{\mathrm{m}}\delta A\mathrm{z}}{L}=\frac{C_{p,\mathrm{w}}}{C}\int_{T_{\mathrm{w,i}}}^{T_{\mathrm{w,o}}}\frac{\mathrm{d}T_{\mathrm{w}}}{H'_{\mathrm{w}}-H_{\mathrm{a}}} \tag{9}$$

The left side of eq. (9) represents the characteristic of the cooling tower (CCT) that is also known as the Merkel number while the right side of the equation represents the cooling load of the tower. To calculate the CCT value, the right side of eq. (9) could be estimated numerically by using the Chebyshev method as follows [21, 22]:

$$\frac{h_{\mathrm{m}}\delta A\mathrm{z}}{L}=CCT=\frac{\Delta T_{\mathrm{w}}\,C_{p,\mathrm{w}}}{4}\left[\frac{1}{\Delta H_1}+\frac{1}{\Delta H_2}+\frac{1}{\Delta H_3}+\frac{1}{\Delta H_4}\right] \tag{10}$$

where $\Delta H_{\mathrm{n}}=H'_{\mathrm{w,n}}-H_{\mathrm{a,n}}$ at any n region.

As had been already mentioned, the CCT is affected by the flow rate of the fluids used. For that, the relation between the tower characteristic and the water to air flow rates is fitted in a power-relation form for each set of experiments for each level of water inlet temperature, and it will take the form of:

$$\frac{h_{\mathrm{m}}\,\delta A\mathrm{z}}{L}=\mathrm{CCT}=b(R)^{\mathrm{d}} \tag{11}$$

where b and d are constants and R – the ratio of water to air mass flow rates inside the tower.

Heat rejected

The rejected heat was calculated with the aid of an equation proposed by Klopper, which is an improved Merkel equation:

$$\text{Heat rejected [kW]}=L\,C_{p,\mathrm{w}}T_{\mathrm{w,i}}-(L-L_{\mathrm{evp}})C_{p,\mathrm{w}}T_{\mathrm{w,o}} \tag{12}$$

where L_{evp} refers to the flow rate of the evaporated water and can be calculated using the following relation:

$$L_{\mathrm{evp}}=G(x_{\mathrm{a,o}}-x_{\mathrm{a,i}}) \tag{13}$$

Experimental work

Specifications of treated wastewater

The water that has been used in the present work is treated wastewater collected from local stations in Baghdad, Iraq before through it to the Tigris River. The specifications of treated wastewater are shown clearly in tab. 1.

Apparatus

The detail of the experimental set-up used to perform in this study was provided in a previous publication dealing with the cooling tower study [8], fig. 3. The cooling system used in this study consist of the cooling tower (which is the main part), a basin, and an air inlet chamber located below the tower. There was also a water heating tank that was used to heat the circulated water to the desired temperature of operation, and this tank was connected to a make-up tank. The system also has a water pump to circulate water that flows through a rota-meter to control its flow, an air blower to boost air through the tower to the top. Sensors used to measure temperature and humidity were located in the desired location in the system.

Table 1. Analysis of treated wastewater used in this study

Parameters	Values	Limitation	Parameters	Values	Limitation
pH	7.1	6.5-9	PO_4	2.9	3
COD	34.2	< 100	NO_3	5.3	50
BOD	30	< 40	TDS	1200	---
Cl	276	600	TSS	14.6	60
SO_4	295	400	O&G	0.4	10

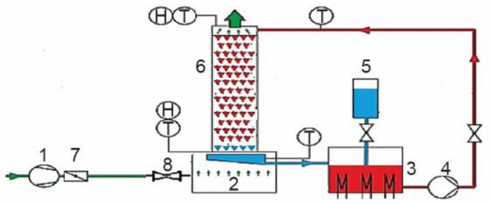

Figure 3. Schematic of the experimental set-up: *1 – air blower, 2 – air inlet-chamber, 3 – water heating tank, 4 – water pump, 5 – make-up tank, 6 – packed cooling tower, 7 – electronic controller unit, 8 – venture meter, H – Humidity sensors, and T – temperature sensors*

Three variables have been studied in this work to investigate their effects on CCT, the heat rejection, and the outlet water temperature. The liquidflow rate (4000-8000 kg/m^2 per hour), air-flow rate (5000-6300 kg/m^2 per hour), and water inlet temperature (40-50 °C). The splash fills were arranged in a zigzag manner to enhance the formation of more droplets. Each set of experiments have done at the desired values of the water and air-flow rates and the water inlet temperature. After then, the temperature and humidity values though out the tower were measured. Each experiment was repeated three times. In the first, the air-flow was modulated from low to high flow rates. In the second, the air-flow was modulated from high to low flow rates. While in the third, the air flow was regulated randomly. The water temperature at many locations and air humidity were recorded for each experiment, and the average of these tries was taken to use for subsequent calculations. The CCT was calculated *via* the use of eq. (10). Each run was repeated also using freshwater as a hot medium to be cooled in the tower.

Results and discussion

In this study, the main goal was to calculate and make a comparison of the CCT of the cooling tower filled with splash fills arranged in a zigzag manner and worked with treated wastewater. The performance of the cooling tower is dependent on the flow of the fluids in-side it and their inlet and outlet temperatures. All the obtained results were produced for four levels of both wastewater and airflow rate and three levels of the inlet water temperature.

Cooling characteristic of the tower

To investigate the effect of the working treated wastewater inlet temperature and the flow rate of both fluids, *i.e.*, water and air, on the cooling tower characteristic, the experiments have been done by keeping constant two of the variables and changing the third.

Figure 4(a) shows the surface response of the impact of the inlet treated wastewater temperature (40 °C, 45 °C, and 50 ºC) and the treated water to the air ratio on the CCT. It is clear from fig. 4 that increasing the inlet treated wastewater temperature will increase the CCT, and this increase was larger for the case of a small ratio of the working fluids. While at the higher ratio of L/G, the effect of temperature becomes less pronounced. The raise of the temperature will increase the temperature driving force responsible for the sensible heat transfer and the evaporation will be increased consequently. While the CCT has decreased with the increase of fluids ratio for all temperatures as revealed in fig. 4. This behavior is accounted for the decrease in the evaporation process of the water for each inlet water amount due to the time shortened of heat transfer that leads to its weakness.

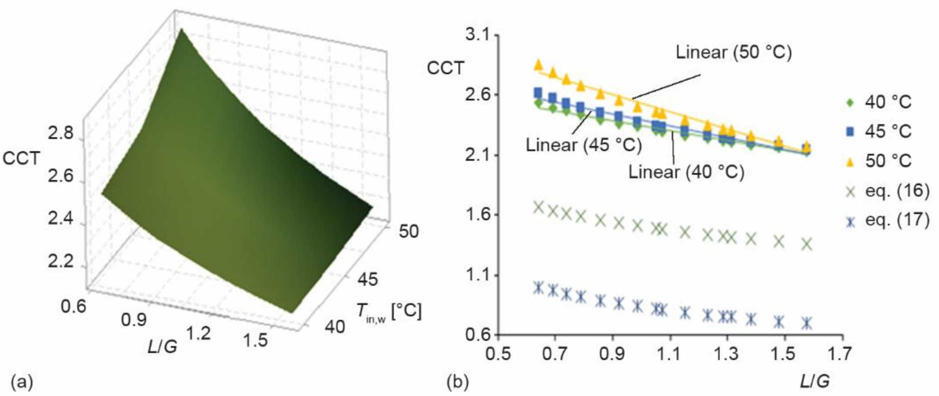

Figure 4. The CCT *vs.* flow ratio at different temperature; (a) surface plot and (b) compared to other researches (*for color image see journal web site*)

As had been mentioned earlier in the previous sections, CCT is greatly influenced by the fluid’s ratio. For this reason and to estimate an equation identifying the exchange of heat between the warm water and the colder air over the splash fills packing, mathematical correlations between the CCT and the water-to-air ratio are countered into the form of an individual power function for every inlet water temperature, which are:

$$\text{For } T_{\text{w,i}} = 40\ ^\circ\text{C} \quad \text{CCT} = 2.33\frac{L}{G}^{-0.19} \quad \text{with } R^2 = 91\% \tag{14}$$

$$\text{For } T_{\text{w,i}} = 45\ ^\circ\text{C} \quad \text{CCT} = 2.37\frac{L}{G}^{-0.22} \quad \text{with } R^2 = 94\% \tag{15}$$

$$\text{For } T_{\text{w,i}} = 50\ ^\circ\text{C} \quad \text{CCT} = 2.50\frac{L}{G}^{-0.3} \quad \text{with } R^2 = 95\% \tag{16}$$

where R^2 indicates how well the regression model fits the data.

These findings were compared, in fig. 4(b), to other results for other types of packing. Kong *et al.* [11], gave many relations for the foamed ceramic corrugated board with sine waves of 1 m high cooling tower for many temperatures, but the nearest one was that at temperature 38 ºC, which was:

$$\mathrm{CCT} = 1.5083 \frac{L}{G}^{-0.2269} \tag{17}$$

Lemouari *et al.* [23] relationship for a Vertical Grid packing at 50 ºC in the same range of L/G ratio for 0.42 m high was:

$$\mathrm{CCT} = 0.84 \frac{L}{G}^{-0.4} \tag{18}$$

The results found by Amini *et al.* [13], for rotating splash fills of 0.6 m high in a cooling tower working with water and many types of nanofluids were not correlated in a relationship, but their work showed that for pure water inlet temperature between 40 ºC and 42.5 ºC, CCT was about 1.3 for a flow ratio L/G = 0.5, and it decreased to about 0.3 for fluid flow ratio L/G = 3. The former comparison results show that the splash fills arranged in a zigzag manner improve the cooling performance due to the formation of many tiny droplets, fig. 2(a). This will cause the transfer of both heat and mass will be from three film boundaries, the water film surrounding the splash, the water film of the droplets, and the column film compared to two films in the other type. This improvement in heat and mass transfer coefficient can cause a remarkable energy saving.

Outlet water temperature

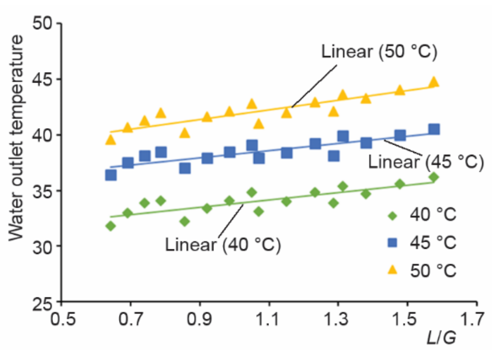

Figure 5. Variation of outlet water temperature with the variation inlet water temperature and flow ratio

It is clear from fig. 5 that the outlet water from the cooling tower is varied with the variation of both its inlet temperature and the water-to-air ratio. As can be seen, there is a gradual increase in the outlet temperature of the water with increasing the water-to-air flow rate. For example, the outlet water temperature was less than the inlet (of 40 ºC) by about 8 ºC at a low L/G ratio. While for that of 50 ºC, the outlet was less by about 11 ºC due to the increase in the difference between the water and the air temperatures. With increasing the L/G that all the mentioned previous outlet temperature increases gradually, and this gives a result that better cooling can be achieved at a lower flow ratio.

Heat rejection

Figures 6-8 show changes taken place in the rejected heat (which were calculated using eqs. (12) and (13) with the variation of air flux for different levels of water flow-rate for an inlet water temperature of 40 °C, 45 °C, and 50 ºC, respectively. As obvious in these figures, the rejected heat in a cooling tower filled with splash fills increases with increasing air flow rate when keeping the inlet water temperature constant for all water flow-rate. The cause of this behavior can be attributed in part to the enhancement of water evaporation for each inlet amount of air. As the water flow rate increases to a higher level at a low air flow rate, the heat rejected tends to be slower than that at a higher air flow rate due to the heavy-duty for the same air flow. Additionally, the rejected heat increases with increasing the inlet water temperature for the same air and water flow-rate. This positive change is due to the heat transfer from the higher temperature water toward the lower temperature air. From the heat and mass transfer point of view, the rate of diffusion of vapor augment with the augmentation of the inlet water temperature, and the evaporation process intensify and the transfer of both mass and heat becomes stronger, leading to the augmentation of the rejected heat.

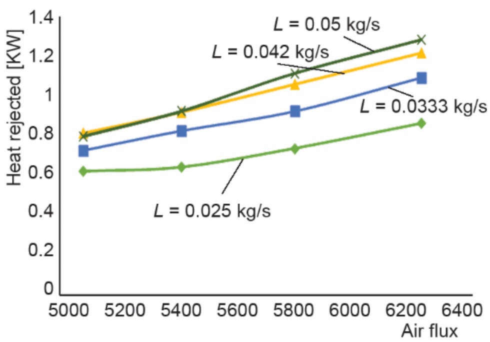

Figure 6. Heat rejected at the inlet water temperature of 40 °C

At the end of this section, it is very important to mention that the results obtained of using wastewater as a medium to be cooled in a cooling tower were very approximate to that of freshwater and by making the subsequent calculations, the results were the same and have given very approximate points. This observation indicates that using treated wastewater as a cooling medium is very economical and can save a huge amount of fresh water for other humanistic utilization. At the same time taking benefit from the treatment process of wastewater instead of discharging it to the aquatic systems and reducing the environmental impact of the industrial activities.

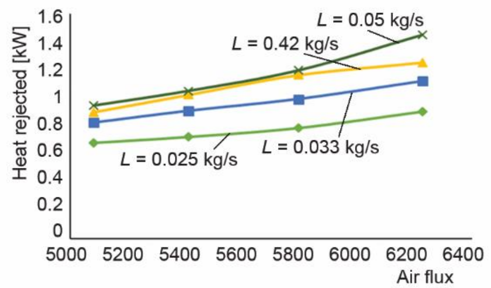

Figure 7. Heat rejected at the inlet water temperature of 45 °C

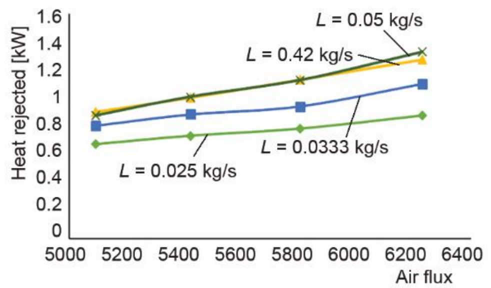

Figure 8. Heat rejected at the inlet water temperature of 50 °C

Conclusions

In this study, the thermal performance of a cooling tower was studied under the effect of the characteristic of the CCT, heat rejected, and the outlet water temperature. The packing used is splash fills have arranged in a zigzag manner to increase the breaking of the falling droplet to a smaller one. The core results are the following.

- A simplified model of the cooling tower containing the thermal performance combined with the Merkel and thermal resistance models is proposed. The thermal performance model of cooling towers that use splash fills arranged in a zigzag manner proposed has only two empirical parameters.

- The CCT has related in a function with the water-to-air ratio for each temperature investigated. Three relationships have been estimated with the high fitting of the data to the regressions. The results for the treated wastewater and the freshwater are very approached. Therefore, they give very close results in the calculations and this is a super benefit for the use of treated wastewater instead of through resulting in saving a huge amount of freshwater for humanistic uses.
- The CCT was decreasing with the increase of water-to-air ratio, and at the same time increased with the augmentation of the inlet temperature. At the same time, it has been found that the CCT in the studied splash packing is higher than other investigated packing due to the duplication of the formed film for the heat and mass transfer.
- The outlet temperature increases gradually with increasing the water-to-air ratio for all inlet temperatures. The difference between the inlet and the outlet water temperature increase with increasing both L/G and inlet temperature.
- The heat rejected increases with increasing air flow rate when keeping the inlet water temperature constant for all water flow rates and the rejected heat tends to increase with increasing the inlet water temperature for the same air and water flow rate.

Nomenclature

A – cross sectional area of the tower, [m^2]
C_p – specific heat, [kJkg^{-1}K^{-1}]
G – air flow rate, [kgs^{-1}]
H_w – enthalpy of saturated air at corresponding temperature, [kJkg^{-1}]
H_a – enthalpy of air at the desired position in the tower, [kJkg^{-1}]
h – convective heat exchange coefficient, [Wm^{-2}K^{-1}]
h_m – mass transfer coefficient, [kgm^{-2}s^{-1}]
L – water flow rate, [kgs^{-1}]
Q – heat transfer, [kW]
T – temperature, [K]
z – high, [m]
x_a – H_2O content of air at temperature T_a, [kgkg^{-1}]
x_w – H_2O content of saturated air at temperature T_w, [kgkg^{-1}]

Greek symbols

δ – specific surface area of packing in the element, [m^2]
λ – latent heat, [kJkg^{-1}]

Subscripts

a – air
i – inlet
o – outlet
w – water
v – water vapor

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