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Experimental Investigation of Cross-Flow Geothermal Water Cooling Tower Used for Agriculture Purposes in the South Tunisia

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ABSTRACT

In Tunisia, geothermal water constitutes the main water resources potential for agriculture use in the south. However, vulnerability of crops to damage by high temperatures has driven the use of cooling towers for dropping temperature to an appropriate level for crop irrigation. Cross flow mechanical cooling towers widely spreads all over the south region of the country. These towers are sized empirically and present several problems in regard to operation and electrical energy consumption.

This paper presents experimental results of tests performed on geothermal water cross-flow cooling tower in the south of Tunisia. The aim of the work has been to determine experimentally the governing parameters, their effects on cooling performances and the cooling tower characteristics. The obtained results are very important since they will contribute to design cooling towers with high efficiency, energy saving and adapted to the climate conditions of the south of Tunisia.

1. INTRODUCTION

Cooling towers are important systems for cooling geothermal water before its utilization for irrigation, drinking water, or other purposes (Bourouni et al., 2005). In fact, in some contexts the geothermal water is the only water resources available in a region. This is the case of many remote areas in the south of Tunisia where medium temperature geothermal water sources (60°C to 80°C) are available. Therefor, better understanding of their performance is the goal of many engineers and researchers at the field of heat and mass transfer, Fisenko and Brin (2007), Fisenko et al. (2002).

In these cooling towers the working fluids are geothermal water and moist air. The cooling tower utilizes the mode of evaporative heat and mass transfer and convective heat transfer to cool warm water to approach the inlet air wet bulb temperature, by mean of direct contact between water droplets falling from top and the cross flow moist air stream. Packing materials are often used to increase the heat transfer area between hot water and air. In the south of Tunisia palm trees are used for this purpose.

Evaporative cooling of water in the cooling towers depends on atmospheric conditions (temperature, humidity and wind conditions), design and geometric parameters of the tower, and total mass flow rates of water and air, Petruchick et al. (2000). The Experimental investigations of cooling tower performance can help correctly to choose many parameters of the cooling tower.

Bernier (1999) presented an analysis of the basic heat and mass transfer processes occurring around a droplet in transient cooling of a spray counter flow tower. The influence of fill height, water retention time and water-air flow ratio on the tower performance was represented.

Several researchers have measured the heat and mass transfer coefficient in cooling towers. Thomas and Houston (1959) developed heat and mass transfer correlations using a tower of 2 m height and 0.3 m^2 cross section. Lowe and Christie (1962) measured the heat and mass transfer coefficients using 1.3 m^2 experimental column fitted with a number of different types of packing. They showed a close agreement with the results of Thomas and Houston (1959).

Jorge and Armando (2000) tested a new closed wet cooling tower. They obtained experimental correlations for the heat and mass transfer coefficients. They concluded that the existing thermal models where found to predict reliably the thermal performance of cooling towers.

Leburn and Silva (2002) generated a correlation between the global heat transfer coefficient UA from experimental analysis as a function of water and air flow rated entering the tower.

El Dessouky et al. (2004) carried an experimental investigation on two-stage evaporative cooling unit constructed and tested in the Kuwait environment. The system was operated during the summer season of Kuwait with dry bulb temperatures higher than 45°C. The system was operated as a function of the packing thickness and water flow rate. Results showed that the efficiency of the evaporative cooling tower varies over a range of 63-93%. The Nusselt Number varies over a range of 150-450, which corresponds to a heat transfer coefficient of 0.1-0.4 kW/m^2K.

The great part of these investigations concern the application of cooling towers in air conditioning; only few works have been interested to geothermal applications. Moreover, they concerns counter-flow cooling towers.

If counter flow coolers are widely studied and investigated in the literature, knowledge on the performance of cross-flow cooling towers is to date incomplete (governing parameters, influence of atmospheric conditions, etc.). For example, the majority of the elaborated correlations for heat and mass transfer coefficients are not established for this configuration, and hence can not be used for the design of such exchangers.

The present investigation is a contribution for a better comprehension of the heat and mass transfer behaviour of evaporative cross-flow cooling towers used in geothermal water cooling applications. Such study will help designers to propose more efficient cooling towers adapted to contexts similar to the south of Tunisia.

2. MATERIALS AND METHODS

2.1 Experimental Plant

The tested geothermal cooling tower is an induced draft cross flow type installed in the village of "El Menchia" localized in Kebili at the Southern part of Tunisia (latitude N33° 42' 7'', longitude E 8° 58' 25'' and altitude 34 m). The schematic diagram of the tower is shown in Figure 1. The Tower cross sectional area is 23 m^2, the total height of the tower is 10.20 m and the filling portion is 20%. Palms trees are used as the packing material (1) installed at the same level as the air intake (2). The packing is used to increase the contact surface between the geothermal water and the air. Atmospheric air is drawn by the fan (3) from side louvers and moves horizontally through the fill. The axial fan (3) is fixed on the top of the tower. The geothermal water comes from a geothermal source with an average temperature of 64°C. Water distributors (4) are used to distribute the geothermal water uniformly over the packing (1) and falls down into the water basin (5). One pump is used to circulate the geothermal water over the packing in a cross flow manner to the air. Evenly water vapor is absorbed by the air stream. Large droplets entrained in the air stream are collected by drift eliminators. Finally, the air stream is discharged at the top exit. The evaporative cooled water falls into the water basin and flows to canals (6) for irrigation purposes. The cooled geothermal water is used for the irrigation of a palm oasis close to the cooling tower.

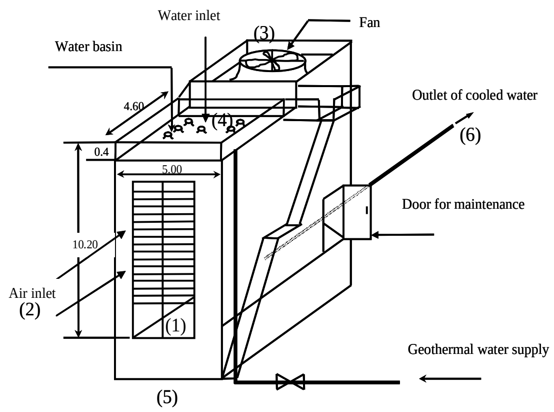

Figure 1: Schematic of the pilot geothermal water cooling tower.

2.2 Experimental Measurement

The cross flow mechanical cooling tower was instrumented with thermocouples, hygrometers and flowmeters to measure all the air and geothermal water parameters at the inlet, outlet and inside the cooling tower. Atmospheric parameters (wind velocity and direction, ambient air humidity and temperature and global solar radiation) are also measured.

The measurements were conducted throughout a year (from September 2005 to August 2006) in order to analyze the influence of the climatic conditions on the performance of the tower.

The temperature measurements inside the cooling tower were taken after allowing enough time for steady state readings. The inlet air and water temperatures were measured before and during the experiment.

The inlet water temperature is fixed by the geothermal source (around 64°C); air temperature and humidity correspond to the ambient conditions of "El Menchia".

The following measurements were implemented in the plant test arrangement:

2.2.1 Air Parameters

The temperature profile of air extracted by the fan is determined by using temperatures probes (type PRT 100 Ohms) at three levels across the cooling tower aspiration room: at the bottom, middle and top exit of the fun (Figure 2). The humidity of the extracted air is also measured at 1.5 m above the fun (RH_2).

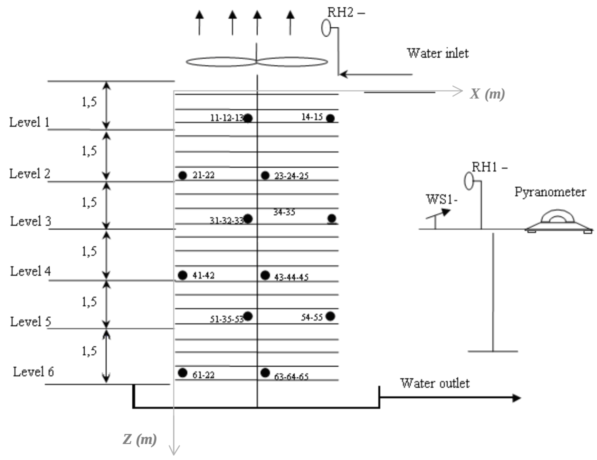

Figure 2: Vertical cross section of the experimental cooling tower, to scale (width 4.60 m, length 5.00 m, height 10.20 m): sensors location.

2.2.2 Water Parameters

The temperature profile of geothermal water is determined at six equidistant levels along the height of the tower by using probes (type PRT 100 Ohms) placed in thirty points (Figure 2). Five probes are fixed at each level; three of them in the middle and the other two probes are mounted alternatively on the extreme left or right side of the tower, as shown in Figure 3. This probes disposition will help in drawing the general air and water temperature profile all over the inside volume of the tower.

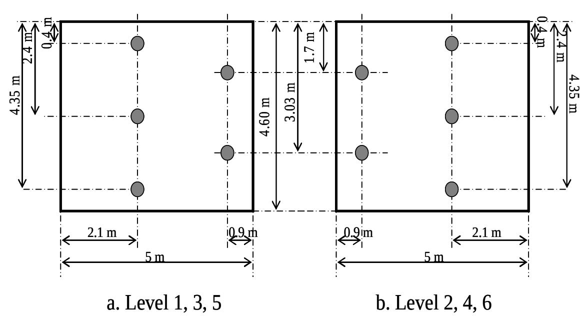

Figure 3: Location of thermocouples in the different levels of the cooling tower (Upper view).

The temperatures of the inlet, outlet geothermal water and the collected condensate water vapor are also measured using the same type of temperature probe.

Two flowmeters are placed upstream and downstream the cooling tower to measure the inlet and outlet geothermal flow rate. This permits to deduce the quantity of the evaporated water.

2.2.3 Climate Parameters

The different weather parameters are measured close to the cooling tower by using a meteo station. The table 1 summarizes the different probes used for measuring the climate conditions.

Table 1: Probes for climate conditions measurement.

Measured parameter	Probe
Ambient air temperature	AM100A temperature sensor by Rotronic
Ambient air humidity	AM100A humidity sensor by Rotronic
Wind velocity	Wing Anemometer (type A100R)
Wind direction	Potentiometer Windvane (type W200P)
Global solar irradiation in the horizontal plane	Pyranometers (type Kipp and Zonen thermopile pyranometers CM11)

All sensors, individually calibrated, are connected to a computer controlled data acquisition system. Data have been collected with a 15 minute interval during one year excepted March, April and May when water parameters were not collected due to the breakdown of the data logger machine. All data has been transferred monthly to a PC for further evaluation.

3. COOLING TOWER THEORY

3.1 Heat and Mass Transfer in Cooling Towers

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 evaporates from the water layer, the latent heat of this vaporized water will be supplied to the air and subtracted from the water. 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.

The expression for transfer of the total heat dq_t through a differential area dA is expressed by Stoecker and Jones (1985):

$$dq_t = \frac{h_c.dA}{C_{pm}}(h_i - h_a) \quad (1)$$

The name of enthalpy potential originates from the above equation because the potential for the transfer of the sum of the sensible ad latent heat is the difference between the enthalpy of the saturated air at the wetted surface temperature h_i and the enthalpy of the air stream h_a.

The rate of heat removed from the water is equal to the rate gained by the air, so the following expression can be written:

$$dq_t = m_a.dh_{a=}4.19.m_w.dT \quad (2)$$

3.2 Heat and Mass Transfer Coefficients Calculation

The heat transfer coefficient can be calculated by equalizing equations (1) and (2) and rearranging:

$$\frac{h_c.a.L}{C_{pm}m_w} = 4.19.\int_{in}^{out} \frac{dT}{h_i - h_a} \quad (3)$$

The relation between the heat and mass transfer coefficients is expressed by Reynold's analogy (Treybal (1981)).

$$\frac{h_c}{K_x.C_{pm}} = Le^{2/3} \quad (4)$$

It is found that in most cases of air-water contact, the Lewis number Le can be considered to be unity as a good approximation (Kern (1997)):

$$\frac{h_c}{C_{pm}} = K_x \quad (5)$$

By substituting equation (5) in equation (3), the mass transfer coefficient can be expressed as:

$$\frac{K_x.a.L}{m_w} = 4.19\int_{in}^{out} \frac{dT}{h_i - h_a} \quad (6)$$

The integration of equation (6) is solved numerically by dividing the packed height into small segments starting from the bottom to the top of the tower.

3.3 Thermal Efficiency of Cooling Towers

The efficiency of a cooling tower is defined as the actual difference in water temperature between the inlet and the outlet of the tower divided by the maximum value that this difference could reach. Since water temperature cannot be lower than the wet bulb temperature of air, the maximum difference is therefore equal to the difference between the water temperature at the inlet of the tower and the wet bulb temperature of air. The efficiency of the cooling tower can be calculated by the following equation:

$$\eta = \frac{T_{w,in} - T_{w,out}}{T_{w,in} - T_{w,b}} \quad (7)$$

Where η is the cooling efficiency, $T_{w,in}$ and $T_{ow,out}$ are respectively the inlet and outlet temperatures of the geothermal water, and $T_{w,b}$ the inlet wet bulb temperature of the air stream.

The wet bulb temperature T_{wb} can be determined by using the Mollier Diagram or by solving the following equation (Devers 1994):

$$p_v = p_s(T_{w,b}) - \frac{C_{p,a}(T - T_{w,b})[p - p_s(T_{w,b})]}{0.622L_{T_{w,b}}} \quad (8)$$

Where p_v is the partial pressure of vapor in the air, $p_s(T_{w,b})$ is the saturation pressure of vapor at the wet bulb temperature,

$C_{p,a}$ the specific heat of the air and $L_{T_{w,b}}$ the latent heat of evaporation of water at the wet bulb temperature.

The equation (8) gives more accurate results than using diagrams, for this reason a C++ program was performed for its resolution.

4. EXPERIMENTAL RESULTS AND DISCUSSION

In the following, experimental results related to the effect of the governing parameters on the cooling tower performances are presented. The performances of the cooling tower can be expressed by its efficiency η (equation 7) or the geothermal water difference ΔT_W between the inlet and the outlet:

$$\Delta T_W = T_{W,in} - T_{W,out} \quad (9)$$

A particular attention is carried in the experimental data treatment for the selection of results corresponding to the same input parameters.

4.1 Water Distribution Inside the Cooling Tower

The variation of water temperature inside the cooling tower in the direction of the geothermal water flow (OZ) for the various vertical sections is illustrated in Figure 4. These sections corresponding respectively to the positions X = 0.9 m, 2.1 m, 2.9 m and 4.1 m coincide with the thermocouple locations (see Figures 2 and 3). These results are obtained during one typical day of the summer season. A typical day of a given month is the one presenting the nearest average temperature and humidity values of the ambient air to those provided by the national weather report spreading on a period of ten years.

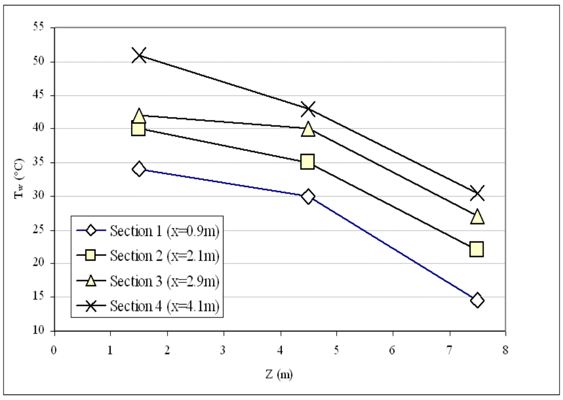

Figure 4: Variation of the water temperature in the cooling tower during one typical day of the summer season, (T_a=38°C, T_w=64°C, φ=15.44%, m_a=110 kg/s, m_w=224 kg/s).

The curves in Figure 4 show that the water temperature decreases in passing through the tower (so depending on the direction of the geothermal water flow (OZ)). This variation in temperature is due to heat and mass transfer that occurs between geothermal water and air by convection and evaporation. On the other hand, the same curves give the change in water temperature in different sections (abscissa X of 0.9 m, 2.1 m, 2.9 m and 4.1 m) for the same altitude Z. We notice that the water temperature increases in the direction of the air flow (OX). This can be explained by the variation of air temperature and humidity. The flow of water near the entrance of air cools better than the water flow at the air outlet because at its entrance, the air is cooler and less humid than at the outlet; so it could cool better the water by both evaporative and convective effects.

4.2 Effect of Air Temperature on the Performance of the Cooling Tower

Figure 5 illustrates the influence of the ambient air temperature on the cooling capacity of the tower. This figure shows that the ambient air temperature has a considerable effect on the operation of the cooling tower. Indeed, the geothermal water temperature gap ΔT_w varies from 29.2°C, for an ambient temperature of 32°C, to 39.5°C for an ambient temperature of 42°C. Note that the relative humidity is kept constant and equal to 15.44%. This result is inconsistent with the convective cooling principle, but can be explained by the evaporative cooling. In fact, when the air temperature is increased and its relative humidity is maintained constant, the difference between the saturation pressure and the partial pressure of vapor is increased. This will induce to increase the air ability to evaporate the water.

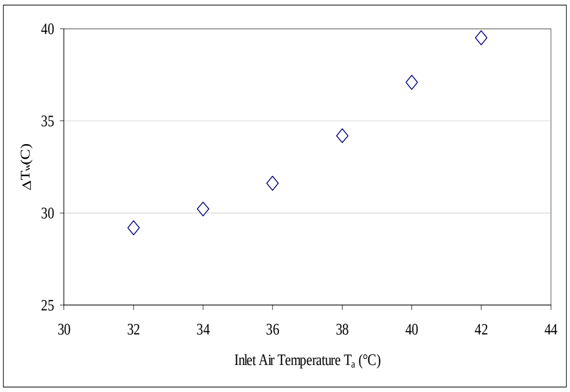

Figure 5: Effect of the inlet air temperature on the geothermal water temperature cooling, (T_w=64°C, φ=15.44%, m_a=110 kg/s, m_w=224 kg/s).

Figure 6 shows the variation of the cooling tower efficiency versus the inlet air temperature in the same conditions. The same tendency as the figure 5 is observed; the cooling tower efficiency increases from 61% at T_a=32°C to 93% at T_a=42°C. These results are consistent with literature review data (El-Desouky et al. 2004).

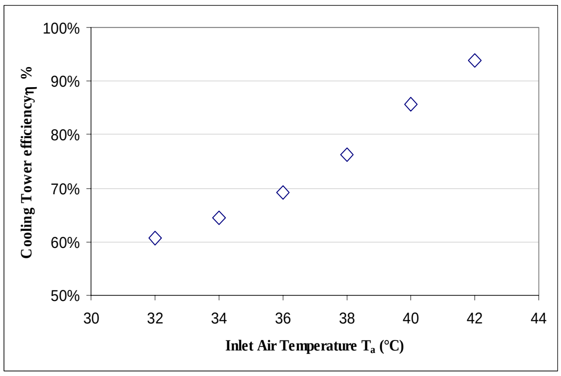

Figure 6: Effect of the inlet air temperature on the cooling tower efficiency, (T_w=64°C, φ=15.44%, m_a=110 kg/s, m_w=224 kg/s).

Based on these results we can conclude that increasing air temperature has two opposite effects. From one side it reduces the heat transfer by convection (convective effect) and from the other side increases the evaporation. The global balance shows that the cooling capacity of the tower is improved. The present result is pertinent because it emphasizes that in the direct contact cross-flow cooling tower, the evaporative effect is more important than the convective effect. This result was also observed by El-Dessouky et al. (2004).

4.3 Effect of Air Humidity on the Performance of the Cooling Tower

Figure 7 shows the variation of the geothermal water temperature gap ΔT_W versus the relative humidity of the air.

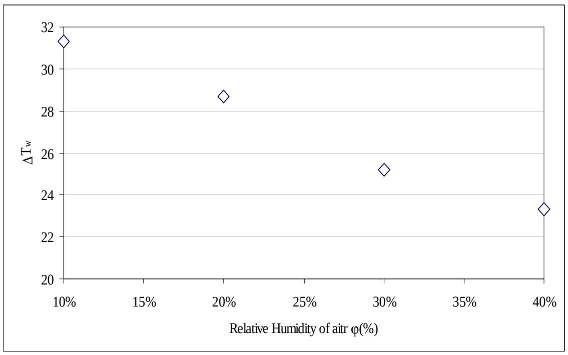

Figure 7: Effect of the inlet air humidity on the cooling performances of the tower, (T_a=38°C, T_w=64°C, m_a=110 kg/s, m_w=224 kg/s).

This figure shows that if the relative humidity of the air increases, the cooling performance of the cooling tower decreases deeply. Indeed, for a relative humidity of 10%, the temperature difference ΔT_w is 31.3°C. This value decreases to 23.3°C for a relative humidity of 40 %. These results were obtained for a constant temperature of ambient air (38°C). Increasing relative/absolute air humidity at a constant temperature induces to the decrease of mass transfer from the water to the air (evaporation effect) which explains the tendency observed in the figure 7.

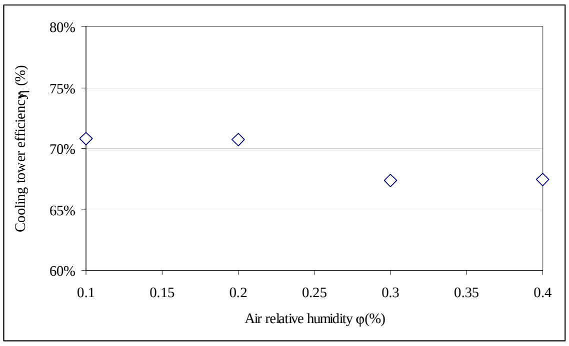

Figure 8: Effect of the inlet air humidity on the cooling tower efficiency, (Ta=38°C, Tw=64°C, ma=110 kg/s, mw=224 kg/s).

Figure 8 presents the variation of cooling tower efficiency η versus the relative humidity of air. This figure shows that the efficiency η decreases slightly with relative humidity. In fact when the air humidity increases from 10% to 40%, η decreases from 71% to 67%. This slight dependency can be explained by the variation of the wet bulb temperature of the air with the relative humidity. In fact for the climate conditions of "El Menchia" region and for (T_a=38°C, φ=10%) the wet bulb temperature of the air is 19.8°C. In theses conditions the outlet temperature of the geothermal water is 32.7°C (ΔT_w = 31.3°C) giving an efficiency of 71%. When the inlet air parameter become (T_a = 38°C, φ = 40%), the corresponding wet bulb temperature is 29.4°C. The geothermal water is cooled only to 40.7°C (ΔT_w=23.3°C). This gives an efficiency η of 67%. So we can conclude that decreasing air humidity improve the cooling performance of the tower but has not a significant influence on the cooling tower efficiency.

4.4 Mass and Heat Transfer coefficients

Basing on the equations (3 to 6), the heat and mass transfer coefficients of the cooling tower was calculated. We obtain: h_c=2.18 kW/m^2.C and K_x=2.15 kW/m^2°C. The results are higher than those obtained by El-Dessouky et al. (2004) but lower than the data of Lowe and Christie (1962). The closest values given by correlations found in the literature are those obtained by Thomas and Houston (1959):

$$h_c a = 3.0 m'^{0.26}_w \, m'^{0.72}_a \quad (10)$$

$$K_x a = 2.95 m'^{0.26}_w \, m'^{0.72}_a \quad (11)$$

Using the equation (10), we obtain a value of the 2.50 kW/m^2°C for the heat transfer coefficient; regarding the mass transfer coefficient a value of 2.59 kW/m^2°C is obtained by applying the equation (11). Comparing to our experimental results this correspond to a gap of more than 15%. These results highlight that no reliable correlations are available up to now for heat and mass transfer coefficients in cross flow evaporative cooling towers. More effort should be done in future investigations to elaborate new correlations for this kind of configuration.

5. CONCLUSION

In this paper, a cross-flow geothermal cooling tower is investigated experimentally in the south of Tunisia. The water temperature profile inside the cooling tower is analyzed and the effect of inlet air temperature and humidity are studied.

The experimental results show a dominance of the evaporative effect comparing to the convective effect. In fact, it was highlighted that the influence of air humidity on the cooling tower performances is more important than that of air temperature.

The results of this investigation will give designers and researchers more informations on the governing parameters for the cooling tower performance and the optimal operation conditions, which allows to reduce the energy consumption of these heat exchangers.

It is highly recommended to continue research investigations in this area in search for low energy consumption geothermal cooling units as these would contribute to a cleaner environment and would conserve the limited resources of fossil fuel.

NOMENCLATURE

a	area of heat and mass transfer (m^2/m^3)
A	area of heat and mass transfer (m^2)
C_p	Specific heat (kJ/kg K)
h	enthalpy (kJ)
h_c	heat transfer coefficient (kW/m^2.K)
K	mass transfer coefficient (kg/m²s)
L	tower length (m)
L_0	latent heat of evaporation of water at 0 °C (kJ/kg)

$L_{T_{w,b}}$	latent heat of evaporation of water at the wet bulb temperature
Le	Lewis factor
m	mass flow rate (kg/s)
m’	superficial flow rate (mass velocity) ($kg/m^2.s$)
P	pressure (Pa)
q	heat flux (kJ/kg)
Q	heat (J)
T	temperature (°C)
V	volume (m^3)
X, Z	Spatial coordinates (m)

Greeks:

φ	relative humidity of ambient air (%)
η	cooling tower efficiency (%)

Subscripts:

a	air stream
as	dry air
db	dry bulb
ev	evaporated
i	wetted surface
in	inlet
m	average
out	outlet
s	saturation
v	vapor
w	water
w, b	wet bulb

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