Experimental evaluation of coupled heat and mass transfer in geothermal water cooling tower

**Abstract.** This research aims to study for the first time the thermal behavior of counter flow cooling tower using low temperature groundwater source for air cooling in domestic and agriculture fields under Kerbala climate. The thermal behavior of both water and air was analyzed experimentally in term of their temperatures for different mass flow rates with one type of packing. The experiments were conducted between 27 April and 12 June 2017. During these five weeks, the outdoor temperature and the average borehole water temperature at depth of 9 m ranges were 28 °C to 42°C and 22 °C to 26°C respectively. The analyses have shown that the evaporative cooling tower used in the present study provides conditioned air in or very close to the comfortable levels. Also, the study has shown that the effectiveness of the evaporative cooling tower is basically affected by airstream velocity.

**Keywords:** Evaporative cooler, geothermal energy, cooling tower, Holy Kerbala

**Nomenclatures**

| Letters | Subscripts | Greek Symbols |
|---------|------------|---------------|
| cp      | a          | η Effectiveness, (%) |
| m       | w          |               |
| h       | i          |               |
| Q       | wa         |               |
| T       | o          |               |
| V̇       | ev         |               |
| RH      | con        |               |
| W       | s          |               |
|         | d          |               |

**1. Introduction**

Iraqi climate is hot and arid during summer season which starts from May until October. The peak ambient temperature in recent years hits 55°C in July and August. Therefore, residential, commercial and industrial buildings require conditioning of air to establish thermal comfort conditions. Vapor compression systems (VCs) are widespread used. VCs are non-economic in energy
consumption, harmful to the environment and costly. To this end, an alternative cooling system should be used. The evaporative cooling systems (ECs) is very suitable to be applied in hot and dry weather. At the same time, ECs are efficient cooling devices, environmentally friend, and relatively cheap. Usually water is used in ECs as a coolant fluid, so the water temperature has an important impact on the ECs’ performance. Thus, ground water is an efficient source to be employed in this kind of devices due to its stable temperature around year which is cool in the summer and hot in the winter compared to the ambient temperature respectively. The temperature stability accrues at particular depth depending on a location. The present study was done under Holy Kerbala City located about in the middle of Iraq, (Latitude: 32°36’ and Longitude: 44°01’).

Heidarinejad et al. [1] studied direct evaporative cooling process which combined with geothermal passive cooling. The result showed that the effectiveness of the direct evaporative cooler (DEC) boosts the unity unlike the DEC that stands alone. Ambient air is passed through a pre-cooling coil in which ground water circulates inside; then, it is passed to the DEC. Momin [2] investigated the coefficient of performance (COP) of a cooling coil system that uses the ground water with/without an evaporative cooling as a pre-stage. The results showed that COP of the system alone reached 2.28, but it was enhanced to be doubled when an evaporative cooling pre-stage process was employed. Karamallah et al. [3] and Krommweh et al. [4] used the ground water for heating purpose. They reported that the usage of geothermal energy for air conditioning could save energy consumption, reduce harmful emissions and minimize the cost compared with a traditional air conditioning one.

Regarding to the thermal performance of ECs, many studies have done to address the main parameters that affect cooling efficiency. Amer et al. [5] reviewed the evaporative cooling technology. The review mentioned studies that dealt with direct, indirect and combined evaporative cooling systems. Direct evaporative cooler could reduce the air temperature, but the air moisture increases. On the other hand, in indirect evaporative cooler (IEC), the humidity remains constant, but the effectiveness is relatively low compared with DEC. however, the combined evaporative cooling system could provide indoor air with thermal comfort along with high effectiveness. Aziz et al. [6] investigated experimentally the effect of sprayed fluid temperature and airstream velocity on the thermal behavior of DEC. In the study, five water temperatures in range (10-50) °C were conducted with three air velocity gradient from low to high. The results showed that relative humidity increases with water temperature increases while it is not affected by the air velocity. Unlike the effectiveness which is enhanced when the velocity of air was speeded up. Also, Alkhedhairy et al. [7] investigated experimentally the effect of the air velocity and water droplet size of the cooling performance in direct mass and heat transfer evaporative cooler. Their study found that water drops’ size has a significant
impact on the evaporative cooling efficiency. In the other words, the finer size of droplet leads to increase the efficiency of the cooling process.

In the same field of direct mass and heat transfer regarding to cooling tower in which this term is used when air used as coolant fluid while hot water is the target fluid. Khan et el. [8] experimentally analyzed the thermal operations of counter flow cooling tower. Their study found that the mass flowrate of water to air has a noticeable effect on the heat transfer. If the water amount increase, the heat transfer rates decreases. Also, in cooling tower when air is the coolant fluid, the evaporation phenomenon is dominant on the convention one especially at the top of a counter flow cooling tower. Bourouni et al. [9] studied numerically the thermal behavior of cross flow cooling tower used to cool ground water temperature down to a desire limit for irrigation or home usages. The results showed that the change in water temperature between entering and leaving the cooling device is greater high than changing in air temperature because of the dominant evaporative process over the heat transfer by convection.

In brief, [1-4] studied the coupled ground water cooling systems, and focused on the main parameters that affect the cooling efficiency. While studies [5-7] interested in evaporative coolers regardless the water source. The rest mentioned studies [8 and 11] cared about the counter and cross flow cooling towers that used to reduce the water temperature.

This paper aims to analyze the thermal performance of the coupled geothermal counter flow cooling tower. It could be considered the first attempt to evaluate experimentally the thermal performance of mechanical draft cooling tower for cooling purpose in Iraq. This research is interested in achieving the thermal comfort conditions. The study was carried out in the University of Kerbala in Holy Kerbala City.

2. Experimental Setup and Apparatus

2.1. Experimental Apparatus

The main components of the experimental apparatus is shown in figure 1: (1) frame body of the base and tower, (2) cellulose pads, (3) air pump, (4) borehole and water pump, not appearing in the picture, (5) temperature data logger, (6) water flow meter and (7) digital thermo-anemometer.

Figure 2 shows the schematic diagram of experimental apparatus. The frame body consisted of the base and the packed tower. The base is dimensioned of $0.5 \times 0.5 \times 0.4$ m length, width and height respectively. It is used to fix the backed tower, distribute air and hold the water sump located at the bottom of the backed tower. The backed tower is squared cross section area with a side long 0.3 m and
its height is 2 m. The tested length is 1.5 m backed with eight cellulose pads, with 0.1 m in thickness. The cellulose pad is good packing for DEC due to high effectiveness ranged 75-95%, long life and clean air [5]. Ambient air is pumped upward through the backed tower by a centrifugal air pump. The amount of the air velocity is adjusted manually by choking and measured by the digital thermo-anemometer, Extech AN100: CFM/CMM Mini Thermo-Anemometer.

On the other hand, water is pulled from the water well, 9m depth located at garden of the Engineering College of the University of Kerbala, and pumped into the top of the backed tower by a water pump. A manual control valve is used to set water volume flowrate which was measured by a rotameter. Water is distributed into fine droplets by a bank of nozzles (shower) to soak the cellulose pads uniformly; then, it is accumulated in a water sump located at the bottom of the backed tower to be rejected into ground again (open cycle). Required pipe connections are conducted. Six thermocouples, type K, were installed to measure temperature at desire positions, and data logger, 12 Channels Temperature Recorder Model: BTM-4208SD, was used to record temperature measurements.
2.2 Experimental Procedures

Pre-tests were executed to make sure that all components of the experimental apparatus work properly. First, water transmission pipes were tested starting from the borehole through the water pump passing the water flow meter to the shower ending to exit. Next, the performance air pump was examined. Temperature measurements were performed for the inlet/outlet of both water and air. Also, the measurements of water rate and air velocity were recorded.

The experiential procedures are outlined as follow:
1. The air velocity was set to 1.8, 4.2 and 6.1 m/s.
2. The water volume flow rate set to (5, 10, 13 and 16) LPM.
3. Six experiments were conducted:
   a. Air velocity of 6.1 m/s was carried out with all water volume flow rates mentioned in (2)
   b. Velocities (1.8 and 4.2) m/s were conducted only with 16 LPM.
4. Record all temperature measurements (wet/dry bulb for inlet/outlet air and the temperature of water at the inlet/outlet, also).

3. Effectiveness of direct evaporative cooler

As mentioned before EC is an efficient device in hot and arid climate. Thus the purpose of using EC is to cool and humidify hot and dry air. All orientations of flow (e.g. parallel flow, cross flow and counter flow) provide the same correlation of cooling effectiveness. A schematic diagram of a counter-flow cooling tower shown in figure 3(a). Cooling and humidify process is shown on the psychometric map in figure 3(b).

![Schematic diagram of counter flow EC](image1)

![Cooling and humidifying of moist air](image2)

**Figure 3.** (a) Schematic diagram of counter flow EC, (b) Cooling and humidifying of moist air psychometric process.
The energy balance between water and air in an experimental insulated cooling tower follows the energy conservation principle. The amount of absorbed heat by water is equal to the heat rejection of air.

\[
Q_w = Q_a \\
Q_w = Q_{\text{Con}} + Q_{\text{Ev}} \\
Q_w = m_w c_p W (T_{a,o} - T_{w,i}) \\
(m_{w,i} T_{w,i} - m_{w,o} T_{w,o}) c_p w = m_a (h_{a,i} - h_{a,o})
\]

Which,

\[
m_{w,o} = m_{w,i} - m_{w,Ev}
\]

The evaporation mass flow rate of water into the air stream calculated as follows:

\[
m_{w,Ev} = m_a (W_o - W_i)
\]

Cooling effectiveness of EC is defined as the ratio of actual reducing in air dry bulb temperature to the maximum on, or it is the ratio of actual increasing in moisture to the maximum one.

\[
\eta = \frac{T_{a,i} - T_{a,o}}{T_{a,i} - T_{a,w}} = \frac{W_{a,o} - W_{a,i}}{W_o - W_{a,i}}
\]

4. Results and Discussions

4.1. Ground water temperature profile

The temperatures profile of outdoor and ground water in the well hole were measured at eight different measuring times and shown in figure 4 for the weeks in the investigation period from 27 April to 12 June, 2017. During that period, the outdoor temperature and the average well hole water temperature ranges were 28 °C to 42°C and 22 °C to 27°C respectively.

The relative stability of well water and significant chaining in ambient air temperature for specific period of time are shown in figure 4. The lower trend represents the well cold water temperature, and the upper refers to the ambient air temperature. The reason behind the slight change of well water temperature is that the earth temperature differs from season to season, rainfall, soil type, and depth of well. Changing in the temperature of the deep ground layers is less than changing in air temperature due to difference in heat capacity of both air and soil. Therefore, in Spring, the ground layers becomes warm less than air unlike in summer in which air acts as a sink of absorbed heat from warm buildings [10]. Likewise during autumn, the soil layers cools very slowly than the air, and in winter is warmer than the air and becomes a natural source of heat adding to a cold building. At soil depths greater than 9 m below the surface of the current study location, the soil temperature is relatively constant, and corresponds roughly to the temperature of water measured in groundwater well 9 m deep.
4.2. Variation of air and water temperatures along the tower.

The air temperature variation along the tower length is illustrated in figure 5 for the two levels with height 1.5 m. It is noticed that after the first level and along the up forward of the cooling tower, the temperature of air decreases with constant cold water flow rate. After direct contact between hot air and cold water, air temperature reduces due to the dominant convective heat transfer. On the other hands, well water temperature reduces slightly because of evaporative phenomenon. It was noticed that the outlet air temperature is very close to the inlet water temperature. The difference in air temperature between the inlet and outlet of cooling tower is about 22.7, 21.5 and 19.5°C for air velocity of 6.1, 4.2 and 1.8 m/s, respectively. That variation comes from the direct dominant convective heat transfer along with miner water evaporation. In contrast, when air acts as a coolant fluid in cooling tower [8].
Temperature of sprayed water changing in the direction counter to the hot air flow is explained in figure 6. This figure shows that the water temperature decreases along the tower height and with the increasing in air velocity. The decreasing in water happens because of the potential evaporation. The air, initially dry inducing, a heat and moves counter cold water. Along its way through the tower, the air temperature decreases and the moisture increases, generating a continuous increase in the evaporative potential that lead to the decrease in water temperature between the outlet and inlet of the air flow. Between entering and leaving sections, the difference in water temperature is about 0.5 °C for air velocity of 1.8 m/s. The water temperature reduced further more when the air velocity goes up due to the increase in evaporation.

4.3. Cooling and humidity process through the cooling tower

The psychrometric evaporative cooling processes are shown in figure 7. Arid and hot air at condition 1, 2 and 3 enters and contacts directly the sprayed well water in present of wetted cellulose pads. Partial amount of water was vaporized due to the heat gaining from the hot air. In addition to heat transfer by evaporation, heat also rejects from hot air to the cold water by convection. Thus, the temperature of moist air decreases and its moister increases at conditions 1′, 2′ and 3′ at the outlet of the cooling tower. Based on the figure 7 and comfortable zone [1], the evaporative cooling system with water flow rate of 16 LPM could provide comfort condition for air velocity 6.1 m/s, while for the (1.8 and 4.2) m/s are very close. The values of the absolute humidity in the air direction flow, for the
three air velocities of 1.8, 4.2, and 6.1 m/s are 60 %, 70 % and 78 %, respectively as it is declared in the figure 7. Unsurprisingly, dried air gains moisture after direct contacting with water.

![Psychrometric chart](image)

**Figure 7.** Cooling and humidifying processes on psychrometric chart.

### 4.4. Effect of air and water flow rates

The water and air temperatures versus air velocity and water flow rate are plotted in figure 8 and figure 9, respectively. It is interesting to see that the well cold water enters the cooling tower with temperature ($T_{wi}$) and sprayed downward the cooling tower decreases continuously along the length the tower due to the increasing in air velocity. This is usually predicted when hot water to be cooled. However, in spite of $T_{wi}$ is less than ambient air temperature ($T_{ai}$) in the present study, water temperature still decreases, also. That means the evaporation amount coming up with increasing the mass flow rate of air. The evaporation makes temperature of water goes down. On the other hand, airstream enters the tower from the bottom with $T_{ai}$ and then decreases before approaching the top of the tower. In this region, $T_{wi}$ is much lower than $T_{ai}$, and $T_{w}$ is always below $T_{a}$. This results in heat rejected by air to the water conventionally. The difference between them is reduced when the air
velocity increases. As predicted, the air wet-bulb temperature \( T_{wa} \) reduces along with increasing of air flow rate in the tower, but it is still higher than \( T_w \).

**Figure 8.** Changing of air (dry and wet bulb) and water temperature with air velocity at \( V_w = 16 \) LPM.

![Figure 8](image-url)

**Figure 9.** Changing of air (dry and wet bulb) and water temperature with water flow rate at air velocity=6.1 m/s.

![Figure 9](image-url)

The inlet water temperature was 26 °C for all conducted experiments due to the stability of the ground temperature. Figure 9 shows that the decreasing in temperature of leaving water from the cooling tower becomes less with increasing of \( V_w \). The reason behind that, that the evaporative surfaces were wetted more than required, so the amount of water evaporation decreases. In the other words, an increase in water flow rate leads decrease the evaporation rates. Therefore, as it expected that the wetted surfaces for convective heat transfer will be increased. Regarding to the air stream dry bulb temperature goes down while wet bulb goes up. Both different behaviors are affected slightly with the increasing of \( V_w \).

4.5. Cooling Effectiveness

Effectiveness is the most important term that should be considered to measure an evaporative cooler’s (EC) performance. Based on the analyses in part 3 of the current paper, the cooling effectiveness for ECs alone is always less than 100 %. However, when ECs are combined with the additional enhancement systems, the effectiveness could be more than 100 % as reported in [1]. In the present study, cellulose pads were used as packing media which leaded to effectiveness in range (77-89) %. That range is in good agreement with what was mentioned in [5]. From figure 10 the maximum effectiveness achieved in the current research is 89 %, and it was relatively as function of air velocity. The trend of EC effectiveness obtained presently is in consistent with a previous study [6].
5. Conclusions

The behavior of an evaporative cooling tower combined with the ground cold water has been investigated under the conditions of Kerbala city climate. Usually forced counter flow cooling tower employed to cool water. Therefore, the present work could be considered the first attempt for using mechanical draft counter flow cooling tower as air cooler in Iraq. The effectiveness of ECs is the most important indicator to evaluate its performance. The results show that the effectiveness is mainly affected by the air velocity. Moreover, the present work proved that evaporative coolers or air washers are efficient in dry and hot regions by providing air with in or very close to the comfortable thermal air conditions. Also, this type of cooling systems has no emissions, efficient in electrical power consumption and cheap.
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