Experimental study on performance improvement of air cooler incorporating two-stages

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Abstract. An experimental study was conducted using two compact heat exchangers (air-cooled) to improve indoor air conditions in Iraq summer weather. The layout of the rig is constructed in such a way that the air flows through a two-stage direct/indirect cooling system to minimize the high air temperature. The water in the basin of the unit was then unitized to the second stage as a working fluid. The findings showed that the temperature could be changed to a point 13% lower than that achieved by the standard design at an affordable cost and in an environmentally appropriate manner. The difference in the humidity ratio was also comparatively reduced with respect to the original discharge from the evaporative cooler alone, as the new system eliminates only sensible heat. This new design, is well-suited to hot and dry conditions where the cost of the air conditioning system based on refrigerants is high, the percentage increase in the overall effectiveness is about 25%.

Keywords: Modified evaporative cooler, indirect heat exchanger, inlet air temperature, indoor humidity ratio, evaporative cooling effectiveness

1. Introduction

The most eco-friendly and energy-saving type of air cooling is evaporative cooling, which uses water as a working fluid to cool the air temperature via evaporation process [1]. Evaporative cooling systems operating in hot and dry climates have recently attracted greater attention in several studies due to its average price, including maintenance costs, being more reasonable than that of other options [2]. It also demonstrates additional efficacy in terms of helping to clean air from dust and other harmful contaminants, such as bacteria by washing the air through the pads or other wetted materials. Thus, alongside from domestic applications, such systems are often used in manufacturing facilities[3].

In many environments, however, direct evaporative air cooling may not be preferred, so that such improvements can be made to boost indoor air quality [4]. One strategy is to focus on pad material, while another is to have several cooling stages. For instance, the experimental investigation of [5] took place in very hot weather with high humidity in Kuwait (adjacent to the Persian Gulf). The findings
revealed that for the indirect/direct type of evaporative cooling (IEC/DEC), the energy effectiveness ratio (EE\textsubscript{R}) was higher than that of the other arrangements. Following the same approach, [6] recorded an increase in cooling effectiveness of more than 90% if the output of each type was considered individually. Similar effects were noted in [7] based on experiments on different configurations of evaporative systems. Note that this type of arrangement (IEC/DEC type) is relevant to some applications, such as those for cold storages, where moisture is often desired.

In terms of design considerations, if an indirect heat exchanger is installed on the final stage of a cooling system, or simply as a direct / indirect (DEC/IEC) form of cooling, other benefits in addition to the comfortable indoor environment will accrue. When used as a coolant, cooled water collected from the direct evaporative device can be delivered to the second stage. Such a two-stage evaporative cooler system was modified and evaluated by [8] using a plate-type heat exchanger as an indirect cooling system and humidifier; this was filled with wooden shavings for use as a direct evaporative cooler unit. Tests showed that the relative humidity of the air in the room was then 50 to 75% as compared with 15 to 40% outdoors.

Increases in humidity will cause health issues if direct evaporative cooling is considered alone [9]. However, comfort air conditioning using evaporative cooling systems relies on environmental conditions and implementation characters [11]. Such methods of cooling may thus be effective for Iraq’s buildings and factories, as the proposed solutions are applicable to its environment, and the calculations of two-stages cooling systems are reflected to its special case. The decision to use evaporative cooling units in houses and buildings is likely to be largely based on the evaluation of the energy saved versus the capital investment [12], however, especially, where the refrigeration system involve high installation and maintenance costs as well as harm to the environment.

The aim of this work is to create a device that decreases the supply temperature as much as possible without altering the humidity ratio of hot and dry air. In other words, the current design seeks to hold air at low wet-bulb temperature (high relative humidity ratio), while simultaneously reducing the air-supplied temperature. Most of the regions in Iraq are hot and dry during summer (except those along the Persian Gulf and rivers), so that the new arrangement layout can be applied with humidity-constant air at low overall cost and environmentally friendly design.

2. Experimental setup

Air-cooled compact heat exchange was chosen for its high performance and convenient design for this analysis. As the heat transfer coefficient of air is comparatively low compared with that of water, this type of heat exchanger consists of plate thin-walled fins to maximise the heat transfer area and minimise losses of air pressure gradients. In experimental research, [10] examined the applicability of this type of heat exchangers to improve the inlet air conditions of a unit in a hot desert climate. In that study, the air temperature was reduced from 30°C to 15°C, using one heat exchanger, with ice added as a phase change material (PCM) in the water treatment system tank.
Figure 1. Schematic of the experimental setup describes the introduction of heat exchanges into an evaporative cooler compartment for the current study.

Figure 1 shows a schematic diagram applicable to the current work in which the configuration of direct and indirect evaporative cooling system (DEC/IEC) is considered. There are two water pumps in the system tank to circulate the water, and thus, the water sprays via gravity only through two layers of wood pads, which act as heat sinks to the air. Before it is drawn into the room, the cold air passes through the second stage represented by two heat exchangers. The construction details of the test rig are listed in Table 1, which thus highlights the key features under consideration. The size of the air cooler is based on a typical commercial design, which may, however, not provide the two additional devices with sufficient room. Within the air main passages to the centrifugal fan, heat exchangers (HEX) made of aluminium are equipped. The electric motor has two speeds to allow for more nuance in controlling air flow rate.

Table 1. Design specifications of the air cooler, DKH-350 model, with a flow rate of 350 cfm.

| Equipment name                  | Characterization | Features                                | Number |
|---------------------------------|------------------|-----------------------------------------|--------|
| Compartment box of the whole unit| 74 x 74 x 85 cm³ | cast iron                               | 1      |
| Heat exchanger (HEX)            | 15 x 0.5 x 20 cm³ | Aluminum pipes and fins                  | 2      |
| Wetted pads                     | 60 x 0.5 x 65 cm³ | wood                                    | 6      |
| Water pump                      | 35 max. Watt     | UN 1300 model                            | 2      |
| Electrical motor                | 2 x RPMs         | Electrogen type CL12b120B2               | 1      |
| Centrifugal fan                 |                  |                                         | 1      |
| Flexible connection hoses       |                  | insulating materials                     | 5      |

Figure. 2 depicts the main components of the apparatus at different points of view. Before these were installed to main rig the heat exchangers were calibrated externally. Figure. 2 (a) also displays the additional pump which operates and works works in the same manner as the original pump. The hot
A wire anemometer used to measure the air flow was calibrated at both motor speeds. The temperature and relative humidity sensors (Humidistat: Fluke form 971 and Elitch DT-3) used for the different time periods are shown in Figure 2 (b).

![Figure 2. Experimental apparatus: (a) two heat exchangers mounted on the inlet duct and (b) the main test panel displaying the measuring instruments.](image)

Values were recorded at various times during the day and month, with additional data collected at peak periods, when temperature gradient between indoor and outdoor conditions is the highest, in order to determine the influence of the severe hot weather on the performance of the cooling device. Vibration of the apparatus was prevented by applying extra fasteners and joints to protect the instruments from any interruptions. Temperature and relative humidity (RH) sensors were placed in different positions to determine the thermal effectiveness of the evaporative cooler before and after the installation of the
indirect heat exchangers. The first four sensors were attached around the evaporative cooler device in order to assess the average properties of outdoor air. While one temperature and RH sensor (which offered the same reading of air properties through each HEX) were installed at each of the following locations: after each HEX and at the round duct of the supply air. A hot wire anemometer (5% accuracy) was used during the experimental process to measure the air velocity of the supply air streams, the reading terminal was positioned at the center of the supply duct.

The operation process was established by turning on the electric motor and the water pumps, and readings were recorded throughout the system after the completion of a transient start-up period. For the other data collocations under various outdoor conditions, the method was repeated. The intermediate temperature and humidity between the two stages were also reported for each test.

3. Experimental calculations

The following basic calculations were implemented in order to evaluate the effectiveness of the evaporative cooler after the improvements were added:

3.1. Air mass flow rate

Air flow rate plays a major role in the design of evaporative cooling systems, particularly when specific ducts or branches might add costs to the overall price. The heat exchangers were connected herein to the main centrifugal fan for convenience, and these can cause additional losses to the design-point specifications. In this analysis, however, this secondary factor was ignored as the air flow speeds were both variable and controllable by means of an actuator mounted on the main remote according to the following equation:

$$m_{air} = \rho_a u_a A,$$

where the air discharges from a circular area, $A = \pi r^2$, and $r$ represents its radius. Thus, the air velocity, $u_a$, varies from 3 to 6.5 (m/s).

3.2. Cooling capacity

This is a measure of the system’s ability to remove heat from the inlet air, which can be described as[13]:

$$Q = m_{air} C_p a \Delta T,$$

where, $\Delta T$ is the temperature difference between the outdoor and supply air such that, $\Delta T = T_{out} - T_s$. Employing this simple formula for the problem under consideration, the total heat capacity for the air side is

$$Q_{tot.} = Q_{evap. cooler} + Q_{HEX}$$

$$Q_{tot.} = m_{air} C_p a [(T_0 - T_2) + (T_2 - T_s)],$$

where $T_2$ is the air DBT before the HEX

and thus;
\[ Q_{\text{tot.}} = m_{\text{air}}C_p(T_o - T_s), \]  

where \( T_2 \) is the intermediate temperature of the two devices connected. The thermal effectiveness of heat exchanger is not taken into consideration, nor the quality of the wetted surfaces. It is also possible to measure the heat capacity \( (Q_{\text{HEX}}) \) based on the water flowing through the heat exchanger tubes.

### 3.3. Saturation effectiveness

The effectiveness of an evaporative cooler system is defined as the ratio of the actual dry-bulb temperature (DBT) difference between the air to the greatest temperature difference [5]. Based on this, the following equation provides the cooling effectiveness (\( \varepsilon \)) of the modified evaporative cooler:

\[ \varepsilon_{\text{sat.}} = \frac{\text{DBT}_o - \text{DBT}_s}{\text{DBT}_o - \text{WBT}_o} \times 100 \]  

where \( \varepsilon \) is the cooling effectiveness (%), \( \text{DBT}_o \), and \( \text{DBT}_s \) are the outdoor and supply DBTs of the air stream (°C), and \( \text{WBT} \) is the outdoor wet-bulb temperature of the air stream (°C).

### 3.4. Energy Effectiveness Ratio

The energy effectiveness ratio, also known as the coefficient of performance (COP), is the ratio of the cooling capacity of the classical evaporative cooler to the power consumption of the system [2]. This term can be extended to express the performance of the modified evaporative cooler, being mathematically written as

\[ EER = \frac{Q_c}{W} \]

where \( Q_c \) is cooling capacity and \( W \) is the power consumed by the motor and water pumps, based on motor revolutions per minute and the operation of one or both pumps.

### 4. Results and Discussions

The major focus of this study is on reducing the temperature output of the cooling unit and maintaining minimal variation in the moisture content. Figure. 3 demonstrates the air-conditioning mechanism effects on psychometric chart by comparing the traditional evaporative cooler and the modified system under the same outdoor weather conditions. It was observed that the cooling process in the first case is adiabatic with almost constant enthalpy, while in the second case, after the addition of the heat exchangers, the cooling process is primarily at constant enthalpy through the pads and purely sensible through the heat exchangers. The temperature and humidity ratio of the supply air is thus reduced considerably, which explains the function of the installed indirect heat exchangers.
Variations in the supply air conditions are given in the left corner of Fig. 3. The dry-bulb temperature for the standard cooler was 26.6 °C at the same air flow rate, which was lowered to 24.8 °C through the HEXs. This reduction in temperature provides some hint that the temperature change before and after the HEX could be much greater if the device was built on a larger scale with optimised heat transfer area. While reduction in the supply temperature is important, another quantity that affects the comfort design conditions is the decrease in the humidity ratio (W). Figure 3 reveals that the maximum value of this parameter is 0.01496 ($k_{\text{moisture}}/k_{\text{air}}$), which is reduced to 0.01351 ($k_{\text{moisture}}/k_{\text{air}}$) by the HEXs. The supply point thus has a lower enthalpy and dew point temperature, which are favorable from a design point of view. Additionally, at these test conditions, there was only a small increase in the humidity ratio (RH) from 68.0 to 68.5, on utilising the DEC/IEC system. Many data were collected, and a few are provided below to illustrate certain important points in this study.

In Figure 4, the

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**Figure 3.** Psychometric charts of major test results obtained in this study for weather conditions in Iraq before and after applying the second cooling stage (modified cooling system).
differences in the temperature gradient ($\Delta T$) between the outside and inside flow conditions, as in Equation (4) are plotted. At different points of daytime operation, the magnitude of $\Delta T$ is clearly higher over the modified unit than that on the standard one, indicating that more heat has been lost; for all other flow conditions, the same behaviour was observed, though this is not shown here. At constant air speed, $\Delta T$ increases as long as the outdoor temperature exceeds its maximum, and using the heat exchangers makes a clear difference regarding $\Delta T$ (with and without the HEX), which was offering about a 13% decrease rate.

**Figure 4.** Overall difference between outdoor and supply air temperatures with and without heat exchangers at outdoor thermal conditions of DBT = 40 °C, RH = 20% and (a) air velocity = 3.5 (m/s) and (b) air velocity = 3.6 (m/s).

Regardless of the outside magnitudes of the relative humidity ratio, the supply air $\Delta T$s were measured separately at various times a day using the two approaches (DEC/IEC and DEC alone); these are plotted for clarity in Figure 5. By using the heat exchanger, the temperature drop is doubled for hot outdoor temperatures. This may indicate that the water temperature in the basin is greatly lowered as the evaporation level rises, suggesting that heat exchangers offer efficient cooling operation at high outdoor temperatures. For both techniques, there is a slight increase in $\Delta T$ of the air supply temperatures between about 31 °C and 33 °C with respect to the outdoor air temperature, which seems to hold steady at one degree.
Figure 5. Temperature difference between supply air conditions with and without heat exchangers at an outdoor air velocity of 3.6 m/s.

The influence of wind velocity on evaporative cooler performance, as expressed by the heat power (KW), is explored and plotted in Figure 6. The air velocity was measured at constant DBT at various values such as $u_{\text{air}} = 3.5$ and $6.5$ m/s. The cooling process was more effective, particularly when adding additional equipment in front of the air passage, at higher air velocities. The figure also demonstrates how the modified unit increased the heat power; at high air speeds, this increase was even bigger.

Figure 6. Heat capacity per Equation (4) to show the effect of increasing the air mass flow rate with and without the heat exchangers.

The difference in effectiveness of the evaporative cooler with and without HEX operation is clarified in Fig. 7. Cooler effectiveness is obviously improved at a rate varying from 3.5 to 25 percent by the addition of indirect HEX at the same outdoor conditions as compared to the traditional evaporative cooler.
Figure 7. The saturation effectiveness appearing in Eqn. (8) employed with and without the heat exchangers at two air speeds.

Another important point that can be inferred from Figure 8 are the outcomes of using the modified unit with respect to the atmosphere and the economy. Unlike other refrigeration systems, where the compressor takes more electrical energy to regulate heat flow at a set supply temperature, as the outside temperature rises, the improved evaporative cooling system takes less electrical consumption, as the water in the basin drives the cooling behaviours in this arrangement. It is also possible to boost the cooling properties of the water in the basin and/or substitute more suitable fabrics into the pads, thus making the evaporative cooler even more environmentally friendly. Further work on this is proposed for the future.
Figure 8. Energy effectiveness ratios using the heat exchangers at varying outdoor temperatures.

5. Conclusions

An experimental investigation was carried out to study the effects of design modifications on the cooling capacity and energy effectiveness ratio of an evaporative cooler. The influences of the ambient temperature and air velocity on the conventional and modified evaporative cooler systems were also tested. Measurements were taken at different outdoor air temperatures ranging from 30°C to 42°C for two air speeds, 3.5 and 6.5 m/s. The results indicated that a significant improvement in cooling effectiveness can be achieved using indirect heat exchanger-based air coolers, with a percentage increase of about 25%. The new arrangements thus made it possible to reduce the indoor temperature by about 13% more than the standard air cooler. It was also noted that the variation in the humidity ratio between the inlet and outlet conditions was decreased compared with that produced by the original design due to the introduction of the indirect heat exchanger. A further benefit of having the direct evaporative cooling system in the first stage was the ability to use the relatively cold water in the reservoir as a coolant for the heat exchanger. This innovative design is well adapted to hot and dry conditions such as those in the most regions of Iraq, particularly where the electrical power associated with refrigerant-based air conditioning systems has become very expensive.

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Nomenclature

**Acronyms**

| Acronym | Description |
|---------|-------------|
| EER     | Energy Effectiveness Ratio |
| DBT     | Dry-bulb temperature |
| WET     | Wet-bulb temperature |
| DEC/IEC | Direct/Indirect evaporative cooling system |
| HEX     | Heat exchanger |
| RH      | Relative humidity |

**Symbols**

| Symbol | Description |
|--------|-------------|
| °C     | The degree Celsius |
| Q      | Heat gain or cooling capacity |
| W      | Cooling power |
| a      | Air |

**Subscripts**

| Subscript | Description |
|-----------|-------------|
| s         | Supply air conditions |
| sat.      | Saturation point |
| o         | Outdoor air conditions |

**Greek symbols**

| Symbol | Description |
|--------|-------------|
| ε      | Effectiveness |
| ρ      | Density |

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