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Evaporative Cooling: A Review of its Types and Modeling

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Abstract

Evaporative cooling is a widely used energy-saving and environmentally friendly cooling technology. Evaporative cooling can be defined as a mass and heat transfer process in which the air is cooled by the evaporation of water and as a result a large amount of heat is transferred from the air to the water and thus the air temperature decreases. Evaporative cooling is mainly used in many cooling technologies used in buildings, factories, agricultural in addition to it is used industrially in cooling towers, evaporative condensers, humidification, and humidity control applications. Evaporative cooling is divided into direct evaporative cooling and indirect evaporative cooling, as well as water evaporative cooling and air evaporative cooling. This paper reviews the most important developments and technologies in evaporative cooling that lead to lower energy consumption and provide suitable cooling comfort.

Keywords: Direct evaporative cooling, Designs, Evaporative cooling, Effectiveness, Indirect evaporative cooling.

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1. Introduction

In the past few decades, the demand for energy in various parts of the world for cooling buildings has increased, raising concerns about depleting energy resources and contributing to global warming. For hot climate regions, energy demand ranges from 40 to 50 % of the total energy consumed, with the largest proportion of energy consumed in buildings going to heating and cooling systems [1], in addition to population growth and technological progress in the world in recent times. In addition to the higher life requirements and longer lifespan of occupants inside buildings, all this has led to an increased need to remove heat loads, especially in higher temperatures and tropical climates. This requires finding ways to improve cooling system performance and reduce energy consumption [2], [3]. One of the techniques used for cooling is evaporative cooling technology, as this technology is considered one of the most environmentally friendly methods because it consumes less energy and its performance increases as the temperature increases and the humidity decreases. Evaporative cooling is used in many applications such as residential buildings, as well as in industrial, commercial and agricultural buildings [1]. Evaporative cooling systems are classified into direct evaporative cooling, in this type the working fluids consisting of water and air are in direct contact. The second type is the indirect evaporative cooling system. In this type, the working fluids are separated by plates. While the third type is a combined evaporative cooling system between direct and indirect. Evaporative coolers are used in many domestic, industrial and commercial applications. They are also used to cool the air inside buildings, factories, and greenhouses. They work either as individual coolers or as complementary units to other cooling systems. They are also used in evaporative condensers and cooling towers [4]. In general, evaporative cooling consists of a porous material that is fed with water, where dry and hot air is drawn over the porous material and as a result the water evaporates in the air and its moisture increases and at the same time the air temperature decreases. The basic principle of controlling the evaporative cooling process is the transfer of heat and mass through the evaporation of water, as this process depends on the transformation of sensible heat into latent heat by means of a change in temperature. Sensible heat is heat associated with a change in temperature. While changes in sensible heat affect temperature, it does not change the physical state of water. Conversely, latent heat transfer only changes the physical state of a substance by evaporation or condensation. As water evaporates, it changes from liquid to vapor. This change of phase requires latent heat to be absorbed from the surrounding air and the remaining liquid water. As a result, the air temperature decreases and the relative humidity increases. The maximum cooling that can be achieved is a reduction in air temperature to the wet-bulb temperature at which point the air would be completely saturated [5], [6].

In the normal evaporative cooling system, the surrounding air is used directly, and therefore its ability to retain moisture is dependent on the external conditions (temperature and moisture content), and therefore the cooling efficiency is low at high humidity, and in order to improve the performance of the evaporative cooling system and increase its efficiency, the air is dried pre. The evaporative cooling process in which the air is dried before it is used is called enhanced evaporative cooling [4].

Table 1. shows the main advantages and limitations of the evaporative cooling system in general by comparing it with mechanical vapor compression cooling systems [1].

Table 1. Advantages and disadvantages of the evaporative cooling.

Advantages	Disadvantages
High COP in the range of 5-20, Its COP increase as the ambient temperature rises, which is opposite of MVC cycle.	Accumulated indoor humidity issues (only for DECs) which cause corrosion and condensation risks inside buildings.
Environmentally friendly system uses water as refrigerant.	Discomfort and health issues associated with highly humid environment.
Less initial and operation costs.	High humidity decreases the system efficiency.
Much less electricity demand, only for fan and pump. So, reduce energy usage by around 70 %.	Poor water quality could reduce the performance because of related deposits and scales problems (only for DECs).
Easy maintenance and repair comparing to MVC system.	Constant supply of water is needed.
Water consumption is partially offset by the reduction of electricity usage. EC systems consume as much water as conventional electricity-based air conditioners do.	Cooling capacity is limited by the ambient wet-bulb temperature.

This research aims at a general review of the evaporative cooling system and the latest technologies that have been reached in this field, which provide sufficient cooling comfort and reduce energy consumption in buildings. The most important advantages and disadvantages of the evaporative cooling system are reviewed, and practical and theoretical studies and research dealing with the subject of evaporative cooling and its types are reviewed.

2. Evaporative cooling technology

Evaporative cooling is based on the principle that water absorbs heat so that the liquid state turns into steam, and thus the sensible heat is transformed into latent heat. One of the most important benefits of evaporative cooling is its low cost, good energy savings, improve indoor air quality and also reduces carbon dioxide emissions from power plants [1]. Many researchers have been conducted to study evaporative cooling systems. Velasco et al. [7] developed a ceramic evaporative cooling system, which works as a semi-indirect cooler, where the water to be cooled is passed into a cooling tower made of ceramic tubes. This type of system allows the indoor air to be recalculated as a temperature drop ranging from 5-12 °C was obtained. Jain [8] developed a two-stage evaporative cooling system to improve the efficiency of the evaporative cooling system at high humidity and reduce air temperature. The results showed an increase in cooling efficiency by (100 to 110) %. El-Dessouky et al. [9] improved performance of a two-stage evaporative cooling system Where the operating system was considered a function of the thickness of the package and the rate of water flow as a function of the direct and indirect evaporative cooling unit. Shaheen and Hmmadi [10] conducted a theoretical and experimental study for a hybrid system consisting of a conventional refrigeration unit and an evaporative air cooler. This research aims to improve the performance of the evaporative air cooler, reduce the moisture content of the air leaving the system, and produce fresh water. The effect of several parameters such as inlet temperature, evaporator temperature, relative humidity and wetted pad thickness was studied. The results showed that the outlet temperature decreased by 1-3, and the amount of fresh water also increased when the relative humidity increased, the coil temperature decreased, and the front air velocity decreased. The results also showed that the effectiveness increases with the increase in the thickness of the pad.

2.1. Classification of Evaporative Cooling Systems

Depending on the type of heat and mass transfer process between water and air. Evaporative coolers could be classified into:

(a) Direct evaporative coolers, in which the working fluids (water and air) are in direct contact.

(b) Indirect evaporative coolers, where a surface/plate separates between the working fluids.

(c) Combined system of direct and indirect evaporative coolers and/or with other cooling cycles [4]. Fig. 1 shows a general classification of main types of evaporative cooling systems for building cooling.

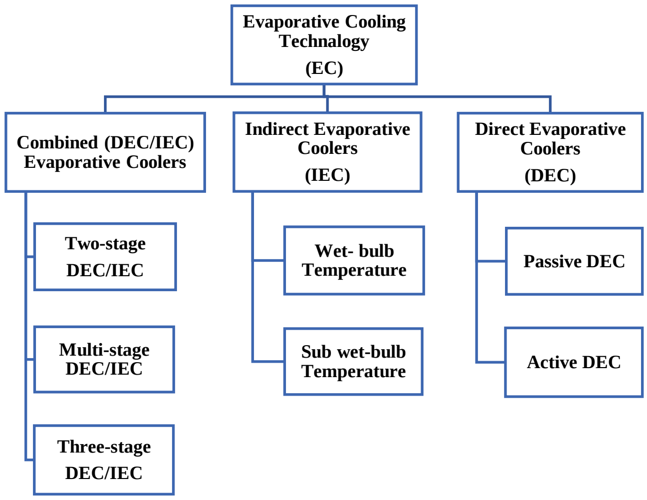

Fig 1. A classification of evaporative cooling systems in building cooling [1].

2.1.1. Direct Evaporative Cooling (DEC)

The direct evaporative cooling system is one of the simplest and oldest evaporative cooling systems. This technique has been used for thousands of years by ancient civilizations such as the use of porous earthenware containing water and wet pads located in the passages of supply air. In direct evaporative cooling the hot outside air is in direct contact with water, and thus cools the air as a result of the converting the sensible heat into latent heat. Although the direct evaporative cooling system is characterized by its high efficiency, low cost and energy savings, as it saves 70 % of energy, it consumes large amounts of water that contains a high percentage of minerals that are deposited on the pillows, and is only suitable for hot and dry climates direct [11]. evaporative cooling is divided into two parts, the first section is active evaporative cooling and this type requires electrical energy to operate, while the second section is passive evaporative cooling and this type works normally without the need for electrical energy. The direct evaporative cooling system works very efficiently in hot and dry climates as opposed to humid ones [1]. Fig. 2 represent basic structure and main components of DEC system and Table 2 shows the main types of active evaporative cooling.

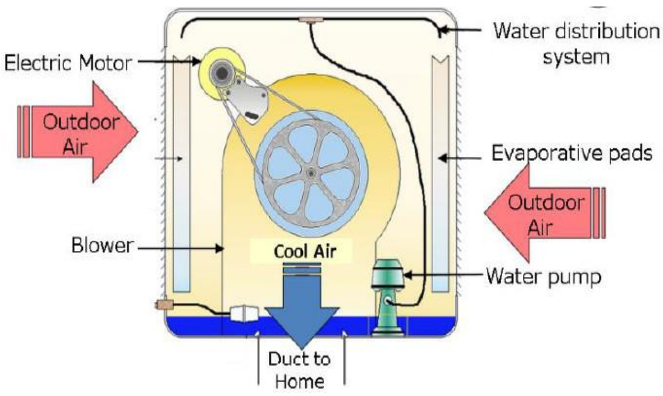

Fig 2. Basic structure and main components of DEC system.

Table 2. main type of active DEC.

System type	Evaporative media	Effectiveness	Features
Random media	Excelsior or plastic fiber/foam supported by plastic frame.	> 80 %	Low effectiveness. Short life-time. Hard to clean.
Rigid media	Blocks of corrugated materials: Cellulose, Plastic, Fiberglass.	75-95 %	High initial cost. Longer life-time. Cleaner air.
Remote pad	Random or rigid pads mounted on wall or roof of building.	75-95 %	Higher power consumption. Bacteria growth.

The main parameter considered when evaluating the performance of direct evaporative coolers is the effectiveness and cooling capacity which can be defined as:

$$\epsilon = \frac{T_1 - T_2}{T_1 - T_{wb}} \quad (1)$$

$$Q_C = m_a \, Cp_a (T_1 - T_2) \quad (2)$$

Where:

Cp_a = Specific heat of air, J/kg K.

m_a = Air mass flow rate, kg/sec.

T_1 = Evaporative outdoor dry bulb temperature °C.

T_2 = Evaporative indoor dry bulb temperature °C.

T_{wb} = Evaporative indoor wet bulb temperature °C.

ϵ = Evaporative saturation efficiency, %.

Q_C = Cooling capacity, kW.

The experimental and theoretical analysis of the types of evaporative cooling is important in order to know the laws related to the transfer of mass and heat that occur in the evaporative cooling processes, in addition to predicting the outputs of the client in different working conditions. A number of these studies and research. Zhang and Chen [12] analyzed the heat transfer process in a direct evaporative cooling system, where they developed a simplified physical model of the process DEC in which air was forced to flow over a wet plate to coincide with the mass and heat transfer process. Zhang [13] studied the characteristics of the heat and mass transfer process of a wet pad cooling device, assuming that the entire sprayed water evaporated, where a mathematical model was created for the process of DEC and calculation of speed and humidity. Qiang et al. [14] constructed a model to predict the performance of air treatment for a system in different working conditions. Direct evaporative cooling technology, which uses water evaporation in a wide range, was used for environmental control in agricultural buildings. Lee and Lee [15] created and tested regenerative evaporative cooler in order to improve the performance of the cooling system where the water flow rate was reduced by a certain amount in order to obtain an even distribution of evaporation water. The outlet temperature was measured, which was 22 °C, which is much lower than the entry temperature, which was 32 °C. Hammadi and Fadhil [16] designed and connected an evaporative cooling unit with the condenser of split-type air conditioner in order to reduce energy consumption and improve the performance of the cooling system. The evaporative cooling unit used was made of aluminum and covered with glass wool, a cellulose pad was used and placed in the face of the cooling unit evaporative, one of the most important results that have been reached is energy savings is 23 %. The coefficient of performance increase with decreasing the ambient temperature and reducing the maximum load of the power network in the hot weather region. Eidan et al. [17] presented an experimental study to improve the performance of a small-sized air conditioning system by direct evaporative cooling. It was designed to simulate a very hot climate where the dry bulb temperature reaches 55 °C, the highest temperature it reaches in the summer. The principle of operation of the system is that air flows over wet platforms before passing through the condenser. Four different basic parameters were studied, namely, energy saving, performance factor, automatic shutdown of compressor at very high temperature, and cooling capacity. The results showed a significant improvement in the system's performance, as the cooling capacity was increased and the electric power consumption decreased. In addition, the compressor continued to work despite the voltage drop, which is a major problem that most Middle Eastern countries, including Iraq, suffer from when the air temperature rises. Freon gas R22 was used as a refrigerant and an evaporative cooling system was added to complement the air conditioning system. Three gears were used in the experimental work while keeping the pads saturated with water through the water distribution system through a pump and tank, and the data was collected by a digital data recorder. Atmospheric conditions were simulated through the use of a heater and fan for air flow and the relative humidity was controlled through an electric heater and Taylor method was used for all data of all elements. The performance of the system was studied with and without evaporative cooling. Where the results showed that the air velocity when there is evaporative cooling positively affects energy saving as the pressure decreases at low air velocity and thus the efficiency of evaporative cooling increases and this fact has been proven mathematically and experimentally. Bishoyi and Sudhakar [18] studied experimental side of direct evaporative cooler that was tested in an apartment building with two different types of cooling pads. Whereas, a honeycomb cooling pad and an aspen cooling pad were used where the same rectangular cross-sectional area was taken into account for the analysis. Various performance parameters such as energy consumption, cooling capacity and energy efficiency ratio were studied, an analytical and experimental study. The results showed that the cooling capacity and energy efficiency ratio of air cooler with honeycomb cooling pad is better than

Aspen cooling pad in the same surface area. Coolers equipped with a honeycomb cooling pad reduce the outside air temperature by 8 °C, while a cooler that uses an aspen type cushion reduces the air temperature by 5 °C. Camargo et al. [19] have been explained the basic principles and operating principles of the direct evaporative cooling process. It also presents the mathematical development of heat exchange equations, which leads to determining the effectiveness of saturation. Experimental tests were conducted and the results were compared with the mathematical model. The results showed that evaporative cooling systems have great potential to achieve thermal comfort and can be used instead of traditional systems, which saves energy and protects the environment. Khobragade et al. [20] analyzed the empirical test of different materials on evaporative cooling pads based on weather data in India where the cooling capacity and saturation efficiency were calculated on a 4-inch-thick cooling pad. The effect of water and air flow rate on the cooling capacity and saturation efficiency of different cooling pad materials such as wood wool, cellulose and wicker grass was studied. It was found that cellulose gives the highest saturation efficiency and that the cooling capacity increases with the increase in the air flow rate, while the saturation efficiency remains almost constant. Abaranji et al. [21] discussed the problem of pillow material and stagnation of water in the tub is the same as the direct evaporative cooling method. In addition, the continuous operation of the pump increases the consumption of electrical energy. In this research, a porous material was used as a medium for storing water in order to eliminate the use of the sump and the pump. An experimental investigation was carried out under different relative humidity conditions (low, medium and high) in order to evaluate the porosity of the material. Worm fertilizer was used because of its good water-retaining properties, in addition to the fact that there is no need to change the materials every time. Where the results showed the possibility of using vermicompost in all operating conditions, however, the excellent performance of vermicompost was observed at low relative humidity where the temperature decreased by 9.5 °C. In addition, the worm fertilizer helped reduce energy by 21.7 %, by eliminating the pump. The difference in temperature, relative humidity and derived parameters such as evaporative cooling capacity and water evaporation rate are discussed. Ketwong et al. [22] studied the evaporative cooling technique for generating cool air in hot and dry climates, three factors affected the air temperature which are mass ratio, wet bulb temperature and feed water temperature. According to the simulation of ordinary air conditioner, the lower temperature of the feed water resulted in higher energy efficiency ratio, thus higher mass ratio was recommended in hot and humid climate area, while lower mass ratio was preferred in hot and dry climate area. The following hypotheses were used in his physical model, namely, that the properties of air and water are constant, the pillow is uniformly wet, and the heat loss in the surroundings is negligible. Direct evaporative cooling was used to generate cold air to cool the condenser and cool a larger area, thus improving the energy efficiency ratio. It was found that when the temperature of the nutrient water was higher than the temperature of the wet bulb, it decreased the mass ratio of the nutrient water to the circulating air and lowered the ambient air temperature. And vice versa to reduce the ambient air temperature when the feed water temperature is lower. Water in the air when the relative humidity is low. Among the most important equations that were used in this research are the equation for calculating the outside air temperature and the equation for calculating the effectiveness, which are mentioned later.

$$T_{db,o} = T_{db,i} - \left[\frac{w_{a,i}\left(h_{f,w,o} - h_{g,w,i}\right) + MR\left(h_{f,w,o} - h_{f,w,i}\right) + w_{a,o}\left(h_{g,w,o} - h_{f,w,o}\right)}{Cp_{da}}\right] \quad (3)$$

$$E = \frac{T_{db,i} - T_{db,o}}{T_{db,i} - T^{*}_{db,o}} \times 100\ \% \quad (4)$$

Camargo et al. [23] presented the basic principles and operating principles of direct evaporative cooling system. He also developed a mathematical model for the direct evaporative cooling system through the energy conservation equation for an initial control volume and analysis of mass and heat transfer between moist air and water. On the practical side, performance tests were conducted on the air conditioner by evaporative cooling model ECOBRISA20, where an evaporator device was installed with dimensions (6.5 m length 5.3 m width 2.9 m height) and the following parameters were determined: Outside air temperature and humidity, evaporative cooler inlet air temperature, evaporative cooler temperature, water temperature inside supply piping, evaporative cooler leaving air velocity and evaporative pad surface temperature. The mathematical model was compared with the experimental results. Wua et al. [24] analyzed the transfer of mass and heat between water and air in direct evaporative cooling based on the energy balance analysis of air. A simplified cooling efficiency correlation proposal has been developed, whereby strong wet sheets with different wave angles are formed for the air duct. In this paper, the effect of the thickness of the pillow unit and the front air speed on the cooling efficiency of the direct evaporative cooler was discussed, as it was found that the best forward speed is 2.5 m/s to determine the frontal area of the pillow unit in the specified air flow. The fact that the thickness of the pillow and the air speed of the front inlet are two main factors affecting the cooling efficiency, while the inlet air conditions (dry and wet bulb temperature) do not affect the cooling efficiency. Where the cooling efficiency decreases by increasing the air speed at a certain thickness, due to the decrease in the contact time between water and air, while the cooling efficiency increases with the increase in thickness and at a certain speed, due to the increase in the contact surface between air and water. Fouda and Melikyan [25] simplified mathematical model was developed to describe the transfer of heat and mass between water and air in a direct evaporative cooler. The mathematical model consists of the governing equations and their boundary conditions and a number of associated algebraic equations. Where the latent heat of evaporation of water was taken as a source of heat in the energy equation and the mass of evaporated water was considered as a collective source in the mass equation. In this paper, the effect of dry bulb temperature of incoming air, pad thickness and inlet air velocity on the cooling efficiency of evaporative cooler was studied. The results of the mathematical model were compared with experimental data, where the comparison showed that the theoretical results are very close to the results obtained from the experiments. Hammadi and Japer [26] developed a mathematical model for a direct evaporative cooling system based on the equations of heat and mass transfer, where a number of hypotheses were put in order to simplify the proposed mathematical model, as a fully wet pillow was taken into account, and the thermal properties of water and air are fixed, as well as the heat transfer coefficient and mass is constant. One of the most important results obtained is that the effectiveness decreases as the air flow rate increases, and the best thickness of the wet pad is 30 cm and when hybrid system is used, the time steady state decreases for the temperature of air. Laknizia et al. [27] simulated a direct evaporative cooling system by using a wet pad as the model was used in poultry houses in special climatic conditions. The goal is to improve the basic parameters that affect system performance. Through the open source, the thermodynamic properties of moist air are extracted, and a computer program was used to conduct a parametric study for the purpose of obtaining the effects of forward speed and thickness of the used pad on the performance of the system. Simulations were performed on cellulose pad cooling and the results showed that the system has the ability to reduce the external temperature during the maximum period of climate warming with a higher performance factor. The equations were solved and codes written by means of MATLAB program and to extract the thermodynamic properties of moist air, the MATLAB library was used. The parameters entered in the MATLAB program were the saturation efficiency and the input conditions, which are the atmospheric conditions of the outside environment at a dry outside temperature. The performance efficiency was calculated based on the front air velocity and the thickness of the cushion. A physical model was presented in order to study and evaluate the performance of a direct evaporative cooling system. The results showed that the cooling capacity and the rate of water consumption increase with the increase in the thickness of the pillow and the increase in the forward speed, while the operating rate increases with the increase in the thickness of the pillow and the decrease in the forward speed of the air. On the other hand, the coefficient of performance will decrease with the increase in the thickness of the pillow and the increase in the forward speed of the air. Haruna et al. [28] analyzed the performance of direct evaporative cooler theoretically at different air speeds and specific saturation efficiency in hot and dry climates. The parameters studied are relative humidity, cooling capacity, outlet air temperature and water consumption rate. It was concluded that the cooling capacity and water consumption rates change linearly with the saturation efficiency. It was concluded that direct evaporative cooling is beneficial in hot and dry climates when the used cooling pad has high saturation efficiency and moderate air velocity. Heidarinejad et al. [29] discussed the results of the performance analysis of the ground-assisted hybrid evaporative cooling system. The combined ground circuit provides the pre-cooling effect which is necessary for the conditioning process. It allows direct evaporative cooling to cool the air until it has challenged the temperature of the wet bulb. Four vertical geothermal heat exchangers are used in the form of a chain. In order to obtain an accurate prediction of the performance, a fluid dynamic computational simulation was carried out. The results revealed that the simulations showed that the GCC system and the DEC system could provide comfortable conditions, while the latter system alone could not do that. Where the cooling efficiency of a hybrid system is more than doubled, thus this hybrid system can reduce the air temperature below the ambient wet bulb temperature. This system can be considered as environmentally clean and energy saving alternative to mechanical vapor pressure systems. In the above study, the capital, Tehran, was chosen, as it is densely populated, has a high demand for air conditioning systems, and its geographical location is good for examining the thermal performance of the hybrid system. The study showed that air conditioners with the DEC system alone cannot provide comfort, but with the use of the hybrid system, the performance of the cooling system increased. Al-Badri and Al-Waaly [30] developed a prediction model for the performance of direct evaporative cooling with chilled water. This model is based on the mass-temperature balance between water and air in a steady state. The cooling process status line has been divided into segments in order to determine the air condition at the pad outlet. This procedure facilitated determining the performance factor that was used to determine the DEC efficiency rather than the saturation efficiency. The effect of air temperature at entry, relative humidity, sub-cooling of water and the ratio of water and air mass flow rate on the performance factor was studied. The experiments that were conducted showed that the mass flow rate ratio is one of the most influential parameters on the performance of direct evaporative cooling, where the performance of DEC can be greatly increased by cooling water and reducing the mass flow rate ratio. The performance factor can be improved by increasing the sub-cooling of the water. The effect of humidity on the performance factor disappears as the mass flow rate increases and the sub-cooling decreases.

2.1.2. Indirect Evaporative Cooling (IEC)

The objective of the indirect evaporative cooling method is to reduce the sensible heat of the air without causing any change in the moisture content, this is done by using a heat exchanger. Several types and configurations of the heat and mass exchanger are used for IECs, such as plate-fin HMX, plate-type HMX, tube-fin HMX, tubular-type HMX, and HPHX. The indirect evaporative cooling system consists of a heat exchanger, fan, pump, water tank and water distribution system. The working fluids are separated by a highly conductive plate. Evaporative cooling systems are classified according to the extent to which they cool the supply air into Wet-bulb temperature IEC systems and sub wet-bulb temperature ICE systems [3]. There are many factors that affect the performance of indirect evaporation cooling systems, the most important of which are: cooling power (CP), wet bulb efficiency (WBE), dew point efficiency (DPE), coefficient of performance (COP), and power consumption (PC). Fig. 3 represent the basic structure of IEC system.

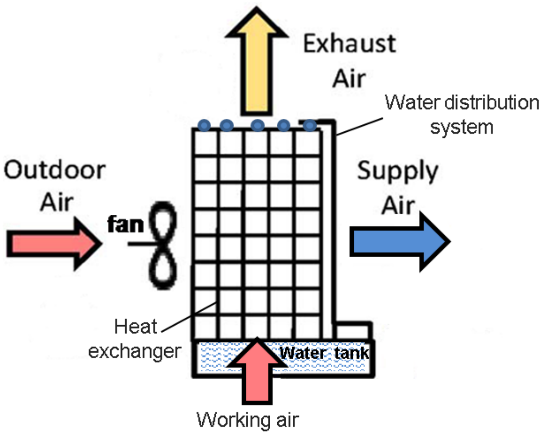

Fig. 3 Basic structure of IEC system.

2.1.2.1. Experimental Studies

Huanga et al. [31] presented an experimental analysis of a respirator that uses a heat exchanger with indirect evaporative cooling technology. Two models were made with a horizontal exchanger and a vertical exchanger. In the horizontal exchanger the water was distributed in the return air duct only on the lower surface while the upper surface was dry. In the vertical exchanger, both the lower and upper surfaces are wet. The results showed that both horizontal and vertical exchangers produce low air temperatures and provide comfortable conditions. At different operating conditions, the results showed that the thermal performance of the horizontal exchanger is lower than the thermal performance of the vertical exchanger. The results also showed the possibility of using indirect evaporative cooling in wet and dry places, but it is preferable not to use the horizontal exchanger in dry areas.

Antonellis et al. [32] conducted on an indirect evaporative cooling system based on cross-flow heat in order to evaluate the performance of the coolant in different operating conditions. The effect of many factors has been investigated, the most important of which is the difference in air flow rate, secondary air temperature, nozzle numbers, and humidity. The results showed that the performance of the evaporative cooler does not depend significantly on the number of nozzles and their size, while it is greatly affected by the water flow rate. The taken readings also showed that the nozzles placed in reverse order provide greater efficiency for the wet bulb.

Shahzad et al. [33] improved indirect evaporative cooling proposal is presented for reasonable cooling, which can be combined with dehumidification processes to obtain sustainable cooling. The improvement was made by adding three major modifications to the traditional systems in order to overcome their limitations. A generic cell was designed and tested under various weather conditions to verify performance. Where the test showed several results, the most important of which is first: multiple injection of working air in wet channels improves the use factor compared to traditional injection. Second: the vertical heat exchanger is considered the best for the diffusion and collection of water. It also helps to overcome the problems of sagging membranes. Third: the use of aluminum foil instead of poor heat transfer and hydrophilic membranes enhances heat transfer and prevents any vital growth that may occur on the membranes. The simple schematic of a generic cell is shown in Fig. 4 (a) and improved cell is shown in Fig. 4 (b).

Antonellis et al. [34] modeled an indirect evaporative cooler based on a cross-flow heat exchanger, where many experiments have been conducted under typical data center operating conditions. In this paper, the indoor air conditions, water flow rate and wet ability of the heat exchanger surface were changed. The results show that the model can predict the performance of the system in a wide range of operating conditions and that it can give a significant decrease in the initial air temperature. Goswami et al. [35] presented an experimental study in order to increase the performance of the cooling system by compressing air vapor to air, using the indirect evaporative cooling process. A 2.5-ton air conditioning system condenser without a media cushion was used in a University of Florida lawn. The experimental results showed that by using evaporative cooling, the supply air was cooled to a lower temperature. There is also a reduction in energy consumption due to the use of an evaporative cooled condenser. Gomez et al. [36] explained the experimental study that was developed to describe the indirect evaporative cooling system made of polycarbonate. The prototype, made of polycarbonate sheets, acts as a heat exchanger that is used to exploit the cooling potential of exhaust air from an air-conditioned space. Thus, recovering the remaining energy. One of the most important reasons for using polycarbonate in the heat exchanger is the possibility of providing water on one side without doing special treatments to avoid corrosion of the material. It is also characterized by being light in weight and at a low price. Ahmad et al. [37] evaluated the performance of an indirect evaporative cooler with a capacity of 5 tons under specific environmental conditions (43.9 bulb dry temperature and 19.9 % relative humidity) and a variable fan speed. The distilled water recovery system is designed to recover water from the dryer and from evaporative cooled indirect air in the form of distilled water. The results indicated that the energy efficiency of the incoming air is directly proportional to the decrease in the temperature of the wet bulb. The results also showed that the indirect evaporative cooler provides low-cost evaporative cooling without adding moisture to the air, and it is suitable for use in dry and hot climates. The experimental results also showed the energy efficiency of the incoming air.

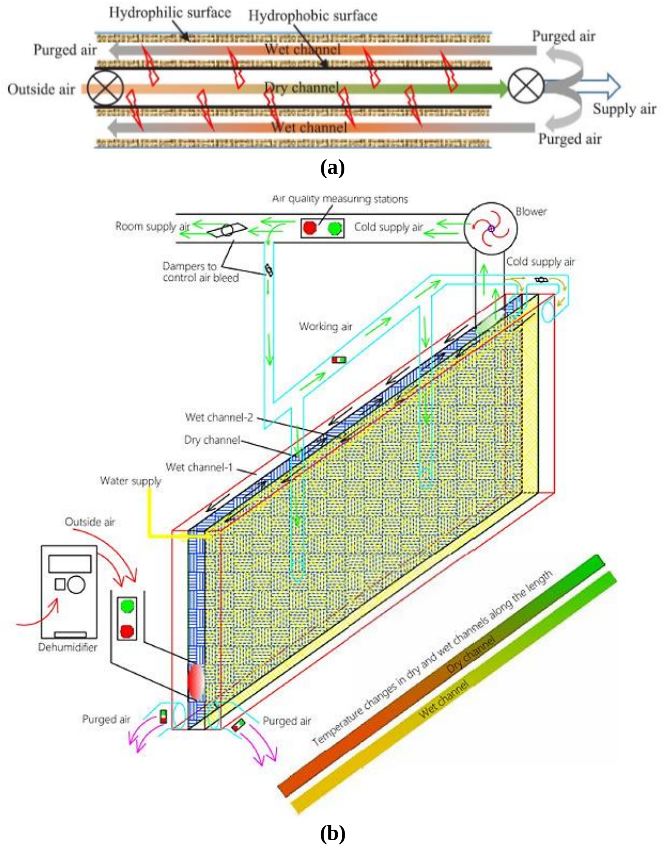

Fig. 4 Evaporative cooler generic cell process schematic, **(a)** Indirect, **(b)** Improved indirect.

2.1.2.2. Theoretical Studies

Rajski et al. [38] conducted a theoretical study was, the aim of which is to accurately evaluate the cooling performance indicators such as the cooling capacity, wet lamp effectiveness and performance factor under different conditions. The effect of different operating parameters on the performance of an indirect evaporative cooler based on gravity-supported heat pipes (ICE based on GAHP) was studied. A mathematical model was developed to numerically simulate mass and heat transfers, and the mathematical model was validated by using empirical data. Relying on the numerical simulation that was conducted, it was concluded that the cooling efficiency strongly depends on the conditions of the incoming air. The inlet air velocity must be 1.5 m/s or less due to the increased pressure loss. The theoretical results were compared with the experimental data and a good fit was obtained. Hasan [39] presented a way to achieve the temperature of the sub-humid air resulting from indirect evaporative cooling. Where an analytical model was developed based on the effectiveness method (e-NTU), which is a well-known method used to solve heat transfer problems in heat exchangers. The main research idea is to obtain semi-humid bulb temperature by indirect evaporative cooling of the air and by pre-cooling and indirect working air before entering the wet passage. It is clear from the research that the modified analytical model for indirect evaporative coolers can be based on the e-NTU method for reasonable heat exchangers after making the appropriate modifications by assuming linear and redefining the possible gradients and parameters of the heat capacity rate and transfer coefficient. The model was used in order to find the performance of the indirect regenerative evaporative cooler. The results obtained were compared with the results of the numerical model, as well as the results obtained from the experimental data, where the results of the model showed good agreement. Hasan [40] founded a method to obtain air at sub wet bulb temperature by indirect evaporative cooling without using a vapor pressure device. The main idea of the research is to treat the air flow inside the cooler by separating the working air from the product air that was previously indirectly cooled. A model was developed describing the mass and heat transfer process, where four types of coolers were studied: a single-stage counter-flow regenerative cooler and three two-stage coolers (reverse flow, parallel flow, and combined parallel regenerative flow). The performance comparison of the four types of evaporative cooler was carried out. The results showed a good agreement between the model and the experimental data. This method increases the possibility of using evaporative coolers in buildings and in other industrial applications, as this method is able to cool the air to temperatures below the temperature of the surrounding wet bulb. Boxem et al. [41] designed a model of a small volume evaporative cooler (400 m^3/h) to predict exit temperature and cooling capacity under different environmental conditions. The model uses the Chilton and Colburn approximation for evaporation and is based on the estimated engineering characteristics. The model predicts the outlet temperature at given inlet conditions and air flow rates.

The model neglected the effect of brine deposition, as it was considered that the deposition does not affect the water transfer in the paint, and this could lead to the production of an additional thermal barrier. Jain and Hindoliya [42] evaluated the performance of the indirect evaporative cooler and its potential for energy saving in Indian climates in summer. Three climates suitable for moderately indirect evaporative cooling were selected, which are hot, dry and temperate. The analysis was carried out in two stages. In the first stage, an evaluation was conducted to ascertain whether the indirect evaporative cooler was able to build a comfortable indoor condition. In the second stage, the energy needed by the indirect evaporative cooler was calculated, and it was found that in order to obtain the same cooling effect under the same climatic conditions, the energy needed by the indirect evaporative cooler was about 55 % less than the energy needed by a conventional air conditioner. Wang et al. [43] presented a comparison between the performance of the HMX cross-flow heat exchanger and the regenerative heat exchanger through the cross-flow of indirect evaporative cooling using the numerical method. A numerical model was built and its validity was validated by the validity of the existing experimental data. In this paper, the difference in mass and heat transfer between two HMX devices was studied and the main parameters of performance were compared and analyzed. The results of the study of the effect of the main operating parameters on the cooling performance of each of the HMXs showed that the cooling capacity of the regenerative HMX is 20.1 % higher than the cooling capacity of the conventional HMX at a low air flow rate. The results also showed that when both HMXs are used alone, the cooling performance of the regenerative HMX is better than that of the conventional HMX in the case of low air flow rate. When used in multi-stage evaporative cooling systems with a high supply air flow rate, conventional HMX is more suitable as a first stage of the system for pre-cooling the supply air, while regenerative HMX is more suitable as a second stage for supply air re-cooling. Niassar and Gilani [44] developed two mathematical models were, the first model was used to simulate parallel, synchronous and countercurrent. While the second model was used in order to determine the thermal performance of the different types of heat exchangers. Total energy balance equations were taken into account in order to calculate the outlet air temperature and relative humidity. The effect of the direction of the air flow in the ducts of the indirect evaporative cooler on the system performance was also studied. The results showed that the system can create a good indoor condition at 50 °C and relative humidity less than 70 %. The results also showed that the evaporative cooling system can be successfully used in humid and hot climates to obtain good indoor thermal comfort. Riffat and Zhu [45] developed a mathematical model for mass and heat transfer in order to predict the performance and simulate the characteristics of the indirect evaporative cooler. Where the principle of indirect evaporative cooling was introduced using porous ceramic as a source of cooling and heat pipe as a heat transfer device. A computer program consisting of a basic model was developed in order to solve the theoretical equations and the mathematical model was compared with the experimental results and a good agreement was obtained between them. Several results have been reached, the most important of which is that in order to obtain high efficiency, the indoor air speed must be adjusted to a reasonable speed. Also, to improve the performance of the coolant, the thermal conductivity between the surface of the ceramic vessel and the heat pipe condenser must be increased. High cooling capacity can be obtained in dry and windy weather. Fakhrabadi and Kowsary [46] deals with the optimal design of the regenerative mass heat exchanger (RHMX) for indirect evaporative cooling. The closed space cooling capacity is the product of the supplied air mass flow rate, the specific heat of the supplied air and the difference between the supply air temperature and the comfort temperature as a criterion for evaluating the performance of the regenerative heat exchanger and mass heat exchanger (RHMX) cooling performance. To obtain an optimal performance and to adjust the design parameters, a simplified and improved conjugated gradient method was used. The effect of the parameters of the heat exchanger and the condition of the incoming air on the values of the design variables and on the performance of the improved RHMX was studied. One of the results obtained is that the inlet air temperature and the inlet relative humidity greatly affect the cooling capacity. The model was validated by comparing the results with experimental data. Chen et al. [47] simplified analytical model has been developed for an indirect evaporative cooling unit at three condensing states, based on the e-NTU method, as it is an easy-to-use method suitable for annual forecasting in engineering projects. The model was combined with TRNSYS construction simulation software and the simulation results were compared, which showed good agreement with the collected data. On the other hand, proposals were made about other cases such as non-occurrence of condensation, partial condensation and complete condensation. One of the measures taken is to redefine the heat transfer coefficient and specific heat capacity of the wet surface that can be applied under conditions of condensation and evaporation. One of the results that was reached is that the condensation of fresh air in the indirect evaporative cooling unit takes a large percentage of operating hours in hot and humid areas. Cui et al. [48] created a hybrid system that combines an indirect evaporative cooling system (IEHX) and a vapor compression system. This model was applied in a humid tropical climate.

The main objective of this system is to try to obtain a precooking of the incoming air of the vapor pressure system.

A computational model was developed to theoretically verify the performance of IEHX with product air condensation by using space exhaust air as working air under hot and humid conditions. The model was used to verify the performance of two types of IEHX in terms of temperature and humidity distribution process, efficiency and cooling capacity, and in terms of energy consumption. The simulation results showed that the resulting air can be cooled and dehumidified at the same time, and the results of the theoretical model were compared with the experimental results, where a good agreement was obtained. Kim et al. [49] established

an experimental dry coil unit for an indirect evaporative cooling system. This was done by connecting an indirect evaporative cooler with a reasonable heat exchanger by a chain. The performance data of the experimental unit was reached under different operating conditions. The results showed that it is possible to obtain an efficiency of more than 40 % by using Dry Coil IEC even in hot and humid areas. Dry Coil IEC reduces the size of the cooling coil by precooking the air as it can be used to recover reasonable heat from the exhaust air during winter operation. The experimental data obtained by running the experimental unit fit well with the values of the effectiveness of the dry coil predicted by the model. Al-Abbasi and Al-Alawi [50] developed a mathematical model based on the principles of mass, momentum and energy. The effect of five parameters on the performance of the indirect evaporative cooler was studied, and these parameters are the air velocity in the dry duct, the height of the dry duct, the air flow ratio in the wet to dry ducts, the length of the duct, and finally the height of the wet duct. Simulations of the indirect evaporative cooler were made with design criteria for two different climates, both of which are characterized by high temperatures in the summer, but one of these two climates has high relative humidity and the second climate has much lower relative humidity. The results showed that the temperature changes in the dry channel at a greater rate than in the wet channel, in addition to that the change in temperature is directly proportional to the evaporation flow rate. San Jo et al. [51] developed a model for calculating heat and mass transfer based on the basic principles of thermal calculations for the performance of an indirect evaporative cooler. Some safeguards have been made and incorporated in order to make the model more user-friendly. One of the results of this research is that the standard structure of the developed computer program greatly facilitates the application of the model in other operating conditions and on different geometric shapes, and this allows an improvement in the design of the indirect evaporative cooler in the future. Guo and Zhao [52] carried out a numerical analysis of the indirect evaporative air cooler in order to understand the process of heat and mass transfer in the narrow vertical channels of the indirect evaporative cooling and secondly to study the effect of a different set of parameters on the thermal performance of the evaporative air cooler. These parameters include the width of the duct, the speed of the primary and secondary air flow, the relative humidity of the inlet, in addition to the wet ability. It was concluded that the high ability to wet the plate, the low relative humidity of the secondary air stream upon entry, the width of the smaller channel, and the high speed of the secondary air relative to the primary air, all these parameters give a higher efficiency of the indirect evaporative cooler. These results are of great importance when designing an indirect evaporative air cooler.

2.1.2.3. Experimental and Theoretical Studies

Li et al. [53] presented a comparative study of two types of heat exchangers for indirect evaporative cooling. The thermal performance of this exchanger in different positions (horizontal and vertical) was checked by numerical simulation and based on a numerical model based on the original mathematical methods. To validate the model, a vertical prototype and a horizontal prototype with the same exchanges were created and tested on the test bench. Based on the test, the results showed that the numerical model used has good accuracy, as the effect of the supply air inlet parameters (relative humidity and temperature) on the thermal performance of the two models at the constant inlet air flow rate and the variable inlet air flow rate was investigated. Where the results showed that when the air flow rate is constant, the temperature of the air leaving the vertical exchanger is lower than the temperature of the air leaving the horizontal exchanger, while a higher cooling capacity is obtained from the vertical exchanger compared to the horizontal. Also, from the results obtained, the thermal performance of the horizontal exchanger is lower than that of the vertical one, due to the presence of larger dry areas in the exhaust air channels in the horizontal exchanger, and this leads to a negative transfer of heat from the supply air to the exhaust air. Paolo et al. [54] deals with the study of the indirect evaporative cooling system at different operating conditions (humidity percentage, flow rate, air duct temperature). The work was divided into three sections. The first section dealt with the description of the test device adopted in the research and the description of its experimental setup. While the second section describes the developed model and its calibration with the experimental data collected in a specialized test facility. As for the third and final section, it showed the advantages of using an indirect evaporative cooling unit, through a parametric analysis based on the developed model. One of the most important results obtained is that the process of spraying water on the heat exchanger increases the cooling power of the system even if the water flow rate is very low. The results also showed that the indirect evaporative cooling system saves a large amount of energy in all operating conditions even when the water flow rate is low. Go´mez et al. [55] fabricated a ceramic evaporative cooling system fabricated as a semi-direct coolant because it depends on moisture. The air returning and coming from the air-conditioned room passes through ceramic tubes, where the sensible heat and latent heat are exchanged with the outside air stream. This system is used in climates characterized by high temperatures and humidity such as tropical environments. One of the results obtained is that the design of the recovery system eliminates the risks of external contamination, as no mixing occurs between the interfering flows during the exchange process, because the ceramic structure acts as a filter. Jiang and Xie [56] presented theoretical analysis and practical performance of an innovative indirect evaporative cooling cooler. After the design process, a simulation was carried out in order to analyze the output water temperature and the cop that the coolant can perform in addition to the cooling efficiency in relation to the input dew point temperature. The effect of internal parameters such as heat transfer area and water-to-air flow rate was studied and compared with the designed values. For the practical test the structure of the main components of the chiller is analyzed and an arrangement of cold-water flows of the system is proposed. It was concluded that the relationship between the water temperature and the dew point temperature is linear if it is less than the temperature of the wet bulb inside. Stoitchkov and Dimitrov [57] presents a brief method to calculate the efficiency of wet surface cross plate heat exchangers. A model with a down-flowing water film was developed that corresponds to the real conditions of the heat exchangers. The McLean-Cross and Banks method was used to correct the estimated efficacy.

2.1.3. Indirect/Direct Evaporative Cooling (IEC/DEC)

One of the advantages of the direct evaporative cooling system is its high effectiveness, but the internal humidity increases, while in the indirect evaporative cooling system the effectiveness is lower, but the humidity is constant. In order to obtain the good characteristics of the two systems (increasing the air coolness at low relative humidity), the combined system IEC/DEC was designed. This type of evaporative cooling system consists of basic components which are IEC unit heat exchanger, DEC unit evaporative pads, water tank and water recirculation system. The IEC/DEC system consists of two stages, the first stage is indirect evaporative cooling, in which the outside air is cooled, followed by the stage of direct evaporative cooling, and in this stage the air is cooled to a temperature lower than the temperature of the wet bulb with additional moisture. Fig. 5 represent basic structure of two stage IEC/DEC [7]

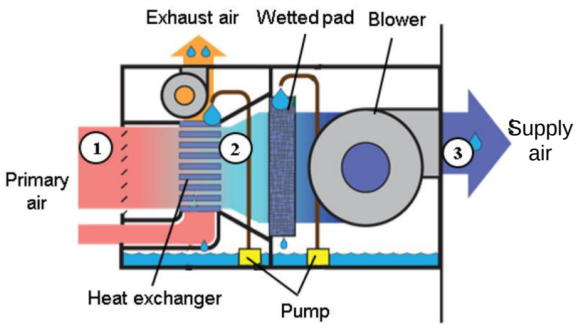

Fig. 5 basic structure of two stage IEC/DEC.

Heidarinejad et al. [58] conducted to examine the performance of two-stage indirect evaporative cooling in an experimental way and in different climatic conditions. The first stage of the system is the stage of indirect evaporative cooling, followed by the stage of direct evaporative cooling. A simulation of the external design was made. The results showed that this system has good capabilities to create and provide comfort conditions in areas where direct evaporative coolers cannot provide comfortable climatic conditions. The results also showed that the two-stage cooling system consumes more water compared to a direct evaporative cooling system. El-Dessouky et al. [59] constructed and tested an experimental platform for a two-stage evaporative cooling unit in Kuwait. The system consists of an indirect evaporative cooling unit followed by a direct evaporative cooling unit, where the system operates in the summer at temperatures above 45 °C. Among the parameters affecting the evaporative cooling system are the water flow rate, the placement of the heat exchangers and the thickness of the fill. Kim and Jeong [60] evaluated the energy performance of a direct and indirect evaporative cooler powered by a 100 % outdoor air system (IDECOAS), which operates in two modes of operation. The effectiveness of the direct evaporative cooler and the indirect evaporative cooler was verified by measuring the difference in relative humidity and air temperature at each measurement site. In addition, the power consumption of the cooling coil and fan was measured by placing counters on each device. The results showed that the system that operates in the two-stage mode gives better results in terms of energy savings compared to the traditional system in the warm seasons, but it consumes more energy in the cold seasons. Lebrun et al. [61] simplified method was used to analyze the phenomenon of mass and heat transfer in direct and indirect contact cooling towers and evaporative condensers. Merkel's theory was relied on to build the theoretical model, where the specific theoretical treatment was applied to all evaporative exchangers and the effect of water flow rate and incoming air for these exchanges was calculated. Simple relationships were found linking the equivalent thermal resistance with air flow rates and cooling mass. The model was validated by comparing the results with the manufacturer's catalog data. Aljubury and Ridha [62] designed small size evaporative cooling system consisting of two stages, the first stage consists of an indirect evaporative cooling heat exchanger. As for the second stage, it consists of three platforms for direct evaporative cooling. The groundwater was used as a coolant. The purpose of this study is to provide systematic experimental results regarding the micro-climate inside the greenhouse in the summer in order to solve the problem of cooling loads in protected agriculture in Iraq. The results showed that the use of groundwater improved the efficiency of the indirect evaporative cooling unit with a higher percentage than the direct evaporative cooling. And the designed system was good for ventilation, cooling and increasing the humidity to achieve the conditions required to protect agriculture.

3. Conclusions

In this paper, a review was made of direct and indirect evaporative cooling techniques, which can be applicable in high efficiency in heating and cooling systems used in many fields where water is used as a means to reduce air temperature by a large amount. Evaporative cooling systems are considered one of the most efficient and environmentally friendly systems. Evaporative cooling differs from common cooling systems in that it provides efficient cooling without the need for an external power source. It is recommended that more research and development be done regarding potential applications of evaporative cooling systems that enhance air conditioning systems.

4. Recommendations

Although the research that was discussed dealt with the subject of direct evaporative cooling and indirect evaporative cooling in order to improve the performance of the cooling system and reduce energy consumption, heat pipes can be used to improve the performance of the cooler. It was found that the specifications of heat pipes have an important role in the efficiency of the system, such as the inner diameter and the outer diameter, as well as working fluids, wick structure and other specifications.

Another technique used to improve system performance is the use of fins on the condenser, where the use of axial fins on the outside of the condenser facilitates the flow of water and increases the heat transfer area between the condenser and the surrounding water, thus increasing the efficiency of the cooler.

References

[1] V. Vakiloroaya, B. Samali, A. Fakhar, and K. Pishghadam, "A review of different strategies for HVAC energy saving", Energy Conversion and Management, Vol. 77, pp. 738-754, 2014. https://doi.org/10.1016/j.enconman.2013.10.023

[2] C. Buratti, P. Ricciardi, and M. Vergoni, "HVAC systems testing and check: a simplified model to predict simplified thermal comfort conditions in moderate environments", Applied Energy, Vol. 104, pp. 117-127, 2013. https://doi.org/10.1016/j.apenergy.2012.11.015

[3] X. Xu, P. J. Culligan, and J. E. Taylor, "Energy Saving Alignment Strategy: achieving energy efficiency in urban buildings thermal environment", Applied Energy, Vol. 123, pp. 209-219, 2014. https://doi.org/10.1016/j.apenergy.2014.02.039

[4] Y. M. Xuan, F. Xiao, X. F. Niu, X. Huang, and S. W. Wang, "Research and application of evaporative cooling in china: a review", Renewable and Sustainable Energy Reviews, Vol. 16, Issue 5, pp. 35-46, 2012. https://doi.org/10.1016/j.rser.2012.01.052

[5] J. T. Libertya, B. O. Ugwuishiwu, S. A. Pukuma, and C. E. Odo, "Principles and Application of Evaporative Cooling Systems for Fruits and Vegetables Preservation" International Journal of Current Engineering and Technology, Vol. 3, No. 3, pp. 1000-1006, 2013.

[6] P. M. La Roche, Passive Cooling Systems in Carbon Neutral Architectural Design, Boca Raton, FL: CRC Press, Ch. 7, Section 7.4, pp. 242- 258, 2012.

[7] E. V. Gómez, F. J. R. Martínez, F. V. Diez, M. J. M. Leyva, and R. H. Martín, "Description and experimental results of a semi-indirect ceramic evaporative cooler", International Journal of Refrigeration, Vol. 28, Issue 5, pp. 654-662, 2005. https://doi.org/10.1016/j.ijrefrig.2005.01.004

[8] D. Jain, "Development and testing of two-stage evaporative cooler", Building and Environment, Vol. 42, Issue 7, pp. 2549-2554, 2007. https://doi.org/10.1016/j.buildenv.2006.07.034

[9] H. El-Dessouky, H. Ettouney, and A. Al-Zeefari, "Performance analysis of two-stage evaporative coolers", Chemical Engineering Journal, Vol. 102, Issue 3, pp. 255-266, 2004. https://doi.org/10.1016/j.cej.2004.01.036

[10] M. Q. Shaheen and S. H. Hmmadi, "Combined evaporative air cooler and refrigeration unit for water purification and performance enhancement of air-cooling system", University of Thi-Qar Journal for Engineering Sciences, Vol. 10, No. 1, pp. 79-90, 2019. https://jeng.utq.edu.iq/index.php/main/article/view/223

[11] Y. M. Xuan, F. Xiao, X. F. Niu, and X. Huang, S. W. Wang, "Research and applications of evaporative cooling in China: A review (II) Systems and equipment", Renewable and Sustainable Energy Reviews, Vol. 16, Issue 5, pp. 3523-3534, 2012. https://doi.org/10.1016/j.rser.2012.02.030

[12] X. Zhang, and P. L. Chen, "Analysis of non-equilibrium thermodynamics on the transport processes in direct evaporative cooling", Journal of Tongji University, Vol. 23, No. 6, pp. 638-43, 1995.

[13] J. Y. Zhang, "Theoretical analysis of heat and mass transfer between water and vapor in wet pad", Transactions of the Chinese Society for Agricultural Machinery, Vol. 30, pp. 47-50, 1999.

[14] T. W. Qiang, H. G. Shen, and Y. M. Xuan, "Performance prediction of a direct evaporative cooling air conditioner using neural network method", HVAC, Vol. 35, No. 11, pp. 3-10, 2005.

[15] J. Lee, and D. Y. Lee, "Experimental study of a counter flow regenerative evaporative cooler with finned channels", Journal of Heat and Mass Transfer, Vol. 65, pp. 173-179, 2013. https://doi.org/10.1016/j.ijheatmasstransfer.2013.05.069

[16] S. H. Hammadi, and M. Fadhil, "Energy Saving in a Split-Type Air Conditioner with Evaporative Cooling System", Thi-Qar University Journal for Engineering Sciences, Vol. 8, No. 2, pp. 116-126, 2017.

[17] A. A. Eidan, K. J. Alwan, A. Al-Sahlani and M. Al-fahham, "Enhancement of the Performance Characteristics for Air-Conditioning System by using Direct Evaporative Cooling in Hot Climates", Energy Procedia, Vol. 142, pp. 3998-4003, 2017. https://doi.org/10.1016/j.egypro.2017.12.311

[18] D. Bishoyi and K. Sudhakar, "Experimental Performance of a Direct Evaporative Cooler in Composite Climate of India", Energy and Buildings, Vol. 153, pp 190-200, 2017. https://doi.org/10.1016/j.enbuild.2017.08.014

[19] J. R. Camargoa, C. D. Ebinumab and J. L. Silveira, "Experimental Performance of a Direct Evaporative Cooler operating during summer in Brazilian city", International Journal of Refrigeration, Vol. 28, Issue 7, pp. 1124-1132, 2005. https://doi.org/10.1016/j.ijrefrig.2004.12.011

[20] N. N. Khobragade and S. C. Kongre, "Experimental Performance of Different Evaporative Cooling Pad Material of Direct Evaporative Cooler in Hot and Dry Region", International Journal of Innovative Technology and Research, Vol. 4, No. 3, pp. 2920-2923, 2016. https://www.ijitr.com/index.php/ojs/article/view/838

[21] S. Abaranji, K. Panchabikesan, and V. Ramalingam, "Experimental Investigation of a Direct Evaporative Cooling System for Year-Round Thermal Management with Solar-Assisted Dryer", International Journal of Photoenergy, Vol. 2020, pp. 24, 2020. https://doi.org/10.1155/2020/6698904

[22] W. Ketwong, T. Deethayat and T. Kiatsiriroat "Performance Enhancement of Air Conditioner in Hot Climate by Condenser Cooling with Cool Air Generated by Direct Evaporative Cooling", Case Studies in Thermal Engineering, Vol. 26 2021. https://doi.org/10.1016/j.csite.2021.101127

[23] J. R. Camargo, C. D. Ebinuma, and S. Cardoso, "A Mathematical Model for Direct Evaporative Cooling Air-Conditioning System", Revista de Engenharia Térmica, Vol. 2, No. 2, pp. 30-34, 2003. http://dx.doi.org/10.5380/reterm.v2i2.3473.

[24] J. M. Wua, X. Huang, and H. Zhang, "Theoretical analysis on heat and mass transfer in a direct evaporative cooler", Applied Thermal Engineering, Vol. 29, Issue 5-6, pp. 980-984, 2009. https://doi.org/10.1016/j.applthermaleng.2008.05.016

[25] A. Fouda, and Z. Melikyan, "A simplified model for analysis of heat and mass transfer in a direct evaporative cooler", Applied Thermal Engineering, Vol. 31, Issue 5, pp. 932-936, 2011. https://doi.org/10.1016/j.applthermaleng.2010.11.016

[26] S. H. Hammadi and O. K. Japer, "Studying the performance of evaporative cooler using pre-cooling water system", Thi-Qar University Journal for Engineering Sciences, Vol. 9, No. 1, pp. 1-8, 2018. https://jeng.utq.edu.iq/index.php/main/article/view/1

[27] A. Laknizia, M. Mahdaouic, A. B. Abdellaha, K. Anounea, M. Bakhouya, and H. Ezbakhe, "Performance analysis and optimal parameters of a direct evaporative cooling system under the climate conditions of Morocco", Case Studies in Thermal Engineering, Vol. 13, 2019. https://doi.org/10.1016/j.csite.2018.11.013

[28] I. U. Haruna, L. L. Akintunji, B. S. Momoh, and M. I. Tikau, "Theoretical Performance Analysis of Direct Evaporative Cooler in Hot and Dry Climates", International Journal of scientific and Technology Research, Vol. 3, Issue 4, pp. 193-197, 2014.

[29] G. Heidarinejad, V. Khalajzadeh, and S. Delfani, "Performance analysis of a ground-assisted direct evaporative cooling air conditioner", Building and Environment, Vol. 45, Issue 11, pp. 2421-2429, 2010. https://doi.org/10.1016/j.buildenv.2010.05.009

[30] A. R. Al-Badri and A. A. Y. Al-Waaly, "The influence of chilled water on the performance of direct evaporative cooling", Energy and Buildings, Vol. 155, pp. 143-150, 2017. http://dx.doi.org/10.1016/j.enbuild.2017.09.021

[31] S. Huanga, W. Li, J. Lu, and Y. Li, "Experimental study on two type of indirect evaporative cooling heat recovery ventilator", Procedia Engineering, Vol. 205, pp. 4105-4110, 2017. http://dx.doi.org/10.1016/j.proeng.2017.09.910

[32] S. De Antonellis, C. M. Joppolo, P. Liberati, S. Milani, and L. Molinaroli, "Experimental analysis of a cross flow indirect evaporative cooling system", Energy and Buildings, Vol. 121, pp. 130-138, 2016. http://dx.doi.org/doi:10.1016/j.enbuild.2016.03.076

[33] M. W. Shahzad, M. Burhan, D. Ybyraiymkul, S. J. Oh, and K. C. Ng, "An improved indirect evaporative cooler experimental investigation", Applied Energy, Vol. 256, pp. 340-346, 2019. https://doi.org/10.1016/j.apenergy.2019.113934

[34] S. De Antonellis, C. M. Joppolo, P. Liberati, S. Milani, and F. Romanoa, "Modeling and experimental study of an indirect evaporative cooler", Energy and Buildings, Vol. 142, pp. 147-157, 2017. http://dx.doi.org/doi:10.1016/j.enbuild.2017.02.057

[35] D. Y. Goswami, G. D. Mathur, and S. M. Kulkarni, "Experimental Investigation of Performance of a Residential Air Conditioning System with an Evaporatively Cooled Condenser", Solar Energy and Energy Conversion Laboratory, Vol. 115, No. 4, pp. 206-211, 1993. https://doi.org/10.1115/1.2930051

[36] E. V. Gómez, A. T. González, and F. J. R. Martínez, "Experimental characterization of an indirect evaporative cooling prototype in two operating modes", Applied Energy, Vol. 97, pp. 340-346, 2012. https://doi.org/10.1016/j.apenergy.2011.12.065

[37] A. Ahmad, S. Rehman, and L. M. Al-Hadhrami, "Performance evaluation of an indirect evaporative cooler under controlled environmental conditions", Energy and Buildings, Vol. 62, pp. 278-285, 2013. http://dx.doi.org/10.1016/j.enbuild.2013.03.013

[38] K. Rajski, J. Danielewicz, and E. Brychcy, "Performance Evaluation of a Gravity-Assisted Heat Pipe-Based Indirect Evaporative Cooler", Energies, Vol. 13, Issue 1, pp. 1-20, 2020. https://doi.org/10.3390/en13010200

[39] A. Hasan, "Going below the wet-bulb temperature by indirect evaporative cooling: Analysis using a modified e-NTU method", Applied Energy, Vol. 89, Issue 1, pp. 237-245, 2012. https://doi.org/10.1016/j.apenergy.2011.07.005

[40] A. Hasan, "Indirect Evaporative Cooling of Air to a Sub-Wet Bulb Temperature", Applied Thermal Engineering, Vol. 30, Issue 16, pp. 2460-2468, 2010. https://doi.org/10.1016/j.applthermaleng.2010.06.017

[41] G. Boxem, S. Boink, and W. Zeiler, "Performance model for small scale indirect evaporative cooler", Proceedings of Clima 2007 WellBeing Indoors, 2007.

[42] J. K. Jain and D. A. Hindoliya, "Energy saving potential of indirect evaporative cooler under Indian climates", International Journal of Low-Carbon Technologies, Vol. 11, Issue 2, pp. 193-198, 2016. https://doi.org/10.1093/ijlct/ctt076

[43] Y. Wang, X. Huang, and Li Li, "Comparative Study of the Cross-Flow Heat and Mass Exchangers for Indirect Evaporative Cooling Using Numerical Methods", Energies, Vol. 11, Issue 12, 2018. https://doi.org/10.3390/en11123374

[44] M. Sh. Niassar, and N. Gilani, "An Investigation of Indirect Evaporative Coolers, IEC With Respect to Thermal Comfort Criteria", Iranian Journal of Chemical Engineering, Vol. 6, No. 2, pp. 14-28, 2009.

[45] S. B. Riffat, and J. Zhu, "Mathematical model of indirect evaporative cooler using porous ceramic and heat pipe", Applied Thermal Engineering, Vol. 24, Issue 4, pp. 457-470, 2004. https://doi.org/10.1016/j.applthermaleng.2003.09.011

[46] F. Fakhrabadi, and F. Kowsary, “Optimal design of a regenerative heat and mass exchanger for indirect evaporative cooling”, Applied Thermal Engineering, Vol. 102, pp. 1384-1394, 2016. http://dx.doi.org/10.1016/j.applthermaleng.2016.03.115

[47] Y. Chen, Y. Luo, and H. Yang, “A simplified analytical model for indirect evaporative cooling considering condensation from fresh air: Development and application”, Energy and Buildings, Vol. 108, pp. 387-400, 2015. http://dx.doi.org/doi:10.1016/j.enbuild.2015.09.054

[48] X. Cui, K. J. Chua, M. R. Islam, and K. C. Ng, “Performance evaluation of an indirect pre-cooling evaporative heat”, Energy Conversion and Management, Vol. 102, pp. 140-150, 2015. http://dx.doi.org/10.1016/j.enconman.2015.02.025

[49] M. H. Kim, J. H. Kim, A. S. Choi, and J. W. Jeong, “Experimental study on the heat exchange effectiveness of a dry coil indirect evaporation cooler under various operating conditions”, Energy, Vol. 36, Issue 11, pp. 6479-6489, 2011. https://doi.org/10.1016/j.energy.2011.09.018

[50] O. Al-Abbasi, and Y. Al-Alawi, “Modeling of indirect evaporative cooling and its performance analysis in harsh environments”, Heat and Mass Transfer, Vol. 55, pp. 3165-3178, 2019. https://doi.org/10.1007/s00231-019-02650-w

[51] J. F. S. J. Alonso, F. J. R. Martínez, E. V. Gómez, and M. A. A. G. Plasencia, “Simulation model of an indirect evaporative cooler”, Energy and Buildings, Vol. 29, Issue 1, pp. 23-27, 1998. https://doi.org/10.1016/S0378-7788(98)00014-0

[52] X. C. Guo, and T. S. Zhao, “A parametric study of an indirect evaporative air cooler”, International Communications in Heat and Mass Transfer, Vol. 25, Issue 2, pp. 217-226, 1998. https://doi.org/10.1016/S0735-1933(98)00008-6

[53] W. Y. Li, Y. C. Li, L. Zeng, and J. Lu, “Comparative study of vertical and horizontal indirect evaporative cooling heat recovery exchangers”, International Journal of Heat and Mass Transfer, Vol. 124, pp. 1245-1261, 2018. https://doi.org/10.1016/j.ijheatmasstransfer.2018.04.041

[54] P. Liberati, S. De Antonellis, C. Leone, C. M. Joppolo, and Y. Bawa, “Indirect Evaporative cooling systems: modeling and performance analysis”, Energy Procedia, Vol. 140, pp. 475-485, 2017. https://doi.org/10.1016/j.egypro.2017.11.159

[55] E. V. Gómez, F. J. R. Martínez, F. V. Diez, M. J. M. Leyva, and R. H. Martín, “Description and experimental results of a semi-indirect ceramic evaporative cooler”, International Journal of Refrigeration, Vol. 28, Issue 5, pp. 654-662, 2005. https://doi.org/10.1016/j.ijrefrig.2005.01.004

[56] Y. Jiang, and X. Xie, “Theoretical and testing performance of an innovative indirect evaporative chiller”, Solar Energy, Vol. 84, Issue 12, pp. 2041-2055, 2010. https://doi.org/10.1016/j.solener.2010.09.012

[57] N. J. Stoitchkov, and G. I. Dimitrov, “Effectiveness of cross flow plate heat exchanger for indirect evaporative cooling”, International Journal of Refrigeration, Vol. 21, Issue 6, pp. 463-471, 1998. https://doi.org/10.1016/S0140-7007(98)00004-8

[58] G. Heidarinejad, M. Bozorgmehr, Sh. Delfani, and J. Esmaeelian, “Experimental investigation of two-stage indirect/direct evaporative cooling system in various climatic conditions”, Building and Environment, Vol. 44, Issue 10, pp. 2073-2079, 2009. https://doi.org/10.1016/j.buildenv.2009.02.017

[59] H. El-Dessouky, H. Ettouney, and A. Al-Zeefari, “Performance analysis of two-stage evaporative cooler”, Chemical Engineering Journal, Vol. 102, Issue 3, pp. 255-266, 2004. https://doi.org/10.1016/j.cej.2004.01.036

[60] M. H. Kim, and J. W. Jeong, “Cooling performance of a 100 % outdoor air system integrated with indirect and direct evaporative coolers”, Energy, Vol. 52, pp. 245-257, 2013. http://dx.doi.org/10.1016/j.energy.2013.02.008

[61] J. Lebrun, C. A. Silva, F. Trebilcock and E. Winandy, “Simplified models for direct and indirect cooling towers and evaporative condensers”, Building Services Engineering Research and Technology, Vol. 25, Issue 1, pp. 25-31, 2004. https://doi.org/10.1191/0143624404bt088oa

[62] I. M. A. Aljubury, and H. D. Ridha, “Enhancement of evaporative cooling system a greenhouse using geothermal energy”, Renewable Energy, Vol. 111, pp. 321-331, 2017. https://doi.org/10.1016/j.renene.2017.03.080