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# Performance improvement of vapor compression cooling systems using evaporative condenser: An overview

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Reduction of energy consumption is a major concern in vapor compression cooling systems, especially in areas with very hot weather conditions. In hot weather conditions, performance of these systems decrease sharply and electrical power consumption increases considerably. Evaporative condensers enhance the heat rejection process by using the cooling effect of evaporation and therefore improve energy-usage efficiency. This paper presents an extensive review of the state of the art of evaporative condensers used in residential cooling systems: refrigeration, air-conditioning, and heat pump systems. The paper primarily concentrates on the energy consumption of residential cooling systems worldwide and its related problems. In addition, the paper covers the operation principles of evaporative-condensers, theory of heat rejection, and water evaporation rate. Finally, comparison between different types of condensers is presented. It is found that by using evaporative-cooled condenser instead of air-cooled condenser, the power consumption can be reduced up to 58% and the coefficient of performance can be improved by about 113.4% with systems of different cooling capacities ranging from 3 to 3000 kW.

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**Contents**



## 1. Introduction

Energy is a very important factor in driving strong economic development and growth of any country. With the increasing demand on energy, the research on conservation of energy and its efficient use is turning out to be one of the important topics. Reduction of energy consumption through efficient energy use or by reducing the consumption of energy services is a goal in all engineering fields [1–3]. Saving energy will decrease the dependence on fossil fuel, and this is an essential contributor in the measure and gross of the economy in any country due to the high

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**Nomenclature**

| | |
|---|---|
| $A$ | coil surface area, $m^2$ |
| $C$ | specific heat capacity, kJ/(kg K) |
| $G$ | rate of water spray, kg/s |
| $H$ | Enthalpy, kJ/kg |
| $H$ | condenser water basin height, m |
| $L$ | air flow rate, kg/s |
| $M$ | Working fluid charge mass, kg |
| COP | Coefficient of Performance |
| EACC | Evaporative Air Cooled Condenser |
| $h_{fg}$ | latent heat of vaporization, kJ/kg |
| $m$ | mass flow rate, kg/s |
| $P$ | power consumption, kW |
| $Q$ | heat transferred, kJ/s |
| $Q$ | volumetric flow rate, $m^3$/s |
| $T$ | temperature, °C |
| $U$ | overall heat transfer coefficient, kW/$m^2$ K |
| $V$ | velocity, m/s |
| PLRs | part load ratios |
| RH | relative humidity, % |
| SCT | saturated condensing temperature, °C |

*Greek symbols*

| | |
|---|---|
| $\rho$ | density, kg/$m^3$ |

*Subscripts*

| | |
|---|---|
| $a$ | air |
| $c$ | condensing |
| cond | condenser |
| comp | compressor |
| ch | chiller |
| $d$ | discharge |
| $d_b$ | dry bulb |
| in | inlet |
| out | outlet |
| $r$ | refrigerant |
| $s$ | suction |
| $w$ | water |
| $w_b$ | wet bulb |
| $w_{eva}$ | evaporated water |
| $w_s$ | water film surface |

prices of fossil fuel [4–6]. This saving and reduction in energy consumption, in addition, helps in decreasing global warming.

Increasing living standards and demand for human comfort has caused an increase in energy consumption. The amount of energy consumed by air conditioners, refrigerators, and water heaters is increasing rapidly, and occupies about 30% of the total power consumption [7]. Electricity consumption for air conditioning systems has been estimated around 45% for residential and commercial buildings [8]. Because of the rapid growth in world population and economy, the total world energy consumption is projected to increase by about 71% from 2003 to 2030 [9]. Therefore, any attempt to decrease the energy consumption of cooling systems as a whole will contribute to large-scale energy savings at the international level. Reduction of energy consumption of cooling units can be achieved by improving the performance. This can be done by lowering the compressor power consumption, increasing the condenser heat rejection capacity, or reducing the difference between condenser and evaporator pressures.

Higher condensing temperature causes an increase in the pressure ratio across the compressor, thus increasing compressor work and thereby decreasing the compressor lifetime and coefficient of performance. High outdoor air temperatures above 35 °C in summer is one of the reasons, leading to a drop in coefficient of performance of most air cooled units to the range of 2.2–2.4 [10]. In addition, if this temperature remained above 45 °C for an extended period, the air conditioner would trip because of the excessive condenser working pressure. Chow and Cengel [11,12] mentioned that the coefficient of performance of an air conditioner decreases about 2–4% for each 1 °C increase in the condenser temperature.

In many Middle East countries, the atmospheric temperature during summer approaches 40–45 °C or sometimes higher. During these prevailing conditions, the air conditioner compressor continuously works and consumes more electrical power and the COP deteriorates [13]. Therefore, it is required to decrease the ambient air temperature before it passes over the condenser coil, in order to decrease the temperature and pressure of the condenser. This can be achieved by using evaporative condensers, which reduces the temperature of the condensing environment from the outdoor dry bulb temperature to close to the outdoor wet bulb temperature [14]. Efficiency of evaporative condensers is essentially unaffected by high ambient temperatures in dry climates. The merit of evaporative condensers is most significant during utility peak periods when the difference between dry and wet bulb temperatures is often greatest [15].

Evaporative cooled condensers can have a smaller heat transfer area and lower airflow rate for the same overall heat transfer coefficient as compared with air-cooled counterpart [16]. This could result in overall significant savings in energy and demand since any small reduction in power consumption in the residential sector could save huge amount of energy [17,18]. The problem of evaporative cooled condenser has activated the research programs in order to improve the performance of the cooling systems by enhancing heat transfer rate in the condenser [19].

In this paper, a comprehensive review and subsequent analysis into the evaporative condenser technology is carried out. In addition, the paper addresses the energy consumption by residential cooling systems and covers the basic concept, operational principles, and theory of heat rejection by evaporative condensers.

## 2. Condensers used in cooling systems

Condensers in all cooling systems are used to reject the heat gained during evaporation and gas compression processes of the refrigerant to the ambient air. A change in the refrigerant state from superheated vapor to liquid occurs as energy is removed from the hot refrigerant to the ambient. Depending on the type of the cooling medium, there are three main types of condensers used named air-cooled, water-cooled, and a combination of the both types known as the evaporative cooled condenser.

Condensers used in conventional small and medium-sized refrigeration cooling systems (up to 20 TR) are mainly; air-cooled [20–22], and it represent the first type. The air-cooled condensers depend on the heat transfer between the condenser coils and the ambient airflow. Their energy performances are governed by the thermodynamic properties and heat transfer with air. Therefore, the thermodynamic performances of the cooling systems coupled with an air-cooled condenser will depend on climatic conditions, which prevent it from giving a constant performance. However, air-cooled condensers are the most widespread category and are simple, as it does not need water system, but only need a high airflow rate to improve its performance and thus sometimes results in noise problem. The air-cooled condensers have low capital and running cost as compared to water-cooled and evaporative condenser, in one hand. On the other hand, the power requirement for a system with an air-cooled condenser is greater than that required for other types of condensers. This can be attributed to the fact that the air-cooled condenser requires condensing temperatures of about 15–20 °C above the temperature of the ambient air [23].

Water-cooled condensers are the second type of condensers, where heat is rejected to the surrounding cooling water, which in turn rejects heat to the hot air through a cooling tower [24–26]. This type of condensers are more compact and have a higher heat transfer coefficient than air-cooled condensers, but it higher initial costs and needs water [27–30]. Therefore, they require a water pump to circulate the water, chemical treatment of the water to reduce fouling of the coils, and continuous supervising. The water-cooled condenser is the only type utilized when the distance between the compressor and the heat rejection site is too long to pump the refrigerant vapor with an acceptable pressure drop. In practice, water-cooled condensers are built in sizes from 0.5 to 10,000 TR capacities [31]. These condensers are used mainly used in heat pumps and for special applications.

The third type is the evaporative condensers. They have been used extensively to enhance heat transfer and improve performance of air-cooled condensers using evaporative cooling specially for the non-residential larger tonnage market. The evaporative condenser is a compact heat exchanger combining the functions of both air-cooled and water-cooled condensers. They utilize both sensible and latent heat transfers between the air and water, and the cooling is accomplished by the evaporation of the water into the air stream. Therefore, the airflow rate required for this type of condensers is less than that of an air-cooled condenser, so that a smaller fan and motor can be used. In addition, the water pumping and chemical treatment requirements of the water-cooled condensers are reduced.

Water-cooled and evaporative condensers offer condensing temperatures limited by ambient wet bulb temperature, which is lower than ambient dry bulb temperature. Therefore, refrigeration systems with these types of condensers can work with lower condensing temperatures, thus using energy more efficiently. Consequently, systems with these types of condensers have higher coefficient of performance and refrigeration capacity than systems with air-cooled condenser.

Although the evaporative and water-cooled condensers consume about the same amount of water per unit refrigeration, yet the evaporative condenser contains much less water than a water-cooled condenser cooling-tower combination. This is because the whole part of the water circulation system of the evaporative condenser is contained within the condenser casing. Moreover, initial cost of the evaporative condenser is lower than that of the water-cooled condenser due to the reduced space and number of the components. Although water and air-cooled condensers are relatively simple to model accurately, evaporative condenser present some difficulties because of water evaporation into the air stream involved.

## 3. Operating principles of evaporative condensers

A popular design and basic components for an evaporative condenser is shown in Fig. 1. An evaporative condenser consists of a condensing coil, a water spray, a fan, a circulating water pump, a water eliminator, a water basin, an outer casing, and controls.

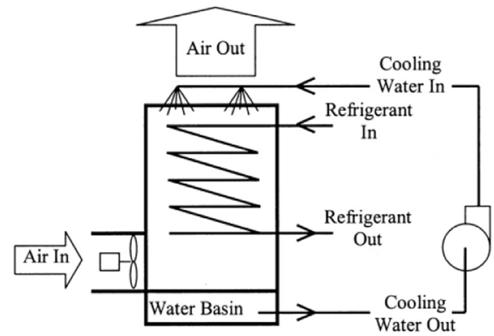


**Fig. 1.** Schematic representation of a typical evaporative condenser.

In evaporative condensers, the hot refrigerant pumped by the compressor flows through condenser tubes. Water from the basin, is pumped and sprayed over the condensing coil from above to keep it wet by a thin layer covering the coil-tubes. At the same time, air is drawn and simultaneously blown up through the condenser tubes by a fan. Thus, small part of water on the condenser tubes evaporates into the air absorbing latent heat of evaporation both from the refrigerant through the tube walls and from the remaining water, thereby cooling and condensing the gas itself. The un-evaporated water is drained to the bottom of the condenser unit, and then pumped back up to the sprayers using a water pump. Hosoz and Kilicarslan [23] showed that the evaporation rate of the water is about 5%, and an equal amount of makeup water is provided to the system by means of a float valve located in a water tank.

It should be mentioned that the refrigerant temperatures in the condensing unit more closely follow the outdoor wet bulb temperature than the outdoor dry bulb temperature. This allows for higher operating COP than their air-cooled counterparts because wet bulb temperatures can be as much as 4.4 °C lower than peak summer dry bulb temperatures, especially in dry climates.

## 4. Theory of heat rejection by evaporative condensers

An evaporative condenser rejects energy by both heat and mass transfer on the outside surface of the condenser tubes. The main component of energy rejected by the condenser comes from evaporating the water, so an evaporative condenser is mainly a wet-bulb sensitive device [19]. The rate of sensible heat transfer based on the dry bulb temperature difference between the inlet and outlet air is defined by:

$$Q_{\text{sensible}} = \dot{m}_a Cp_a (T_{a,o} - T_{a,i}) \tag{1}$$

The rate of latent heat transfer based on the specific humidity ratio difference between the inlet and outlet air can be calculated by:

$$Q_{\text{latent}} = \dot{m}_a h_{fg} (\omega_{a,o} - \omega_{a,i}) \tag{2}$$

The heat transfer in evaporative condensers takes place in two phases. The first phase is between condensing refrigerant and the water film covering the coil ($Q_{c\to w}$) and is expressed by Eq. (3),

$$Q_{c\to w} = U_{c\to w} A_c (T_{c,s} - T_w) \tag{3}$$

The increase in air velocity affects the overall coefficient of heat transfer of the condenser. At higher air velocities, the Reynolds number along the coil surface increases which improves the Nusselt number and hence the heat transfer coefficient. The improvement in heat transfer rate lowers the saturated condensing temperature (SCT), and hence the work of compression. In actual applications, minimizing the condenser-fan power and achieving the lowest SCT is the goal.

The second phase of heat transfer takes place between the water film on the coil surface and the air passing through the coil. This heat flow is dependent on the enthalpy of the air entering the condenser and the enthalpy of the saturated air (adjacent to the water film) at the refrigerant condensing temperature. This phase of heat removal is expressed by Eqs. (4) and (5),

$$Q_{w\rightarrow a} = h_w A_{w\rightarrow a}(T_a - T_w) \tag{4}$$

$$Q_{w\rightarrow a} = k_m A_{w\rightarrow a}(\omega_{ws} - \omega_a)h_{fg} \tag{5}$$

The evaporation of sprayed water into the air provides the predominant phase of heat rejection in evaporative-condensers. Hence, the ambient wet-bulb temperature becomes one of the main driving forces affecting the performance of these condensers. Apart from the physical characteristics of the condenser (surface area and coil material) and the ambient conditions, the performance of the evaporative-condenser is largely influenced by the airflow and spray-water rate. Eq. (6) correlates the overall heat transfer ability of an evaporative-condenser as a function of airflow and water-spray rates,

$$H = K.G^{0.48}L^{0.22} \tag{6}$$

where $H$ is condenser capacity indicator, $k$ is constant, $G$ is rate of water spray, and $L$ is the rate of airflow.

This expression suggests that the water spray rate has greater influence on the condenser capacity than does the airflow rate. In actual applications; however, water flow rate is rarely controlled. On the other hand, airflow rate is widely controlled to achieve optimum condensing temperatures and condenser-fan power and use.

## 5. Researches and achievements related to evaporative-condensers

### 5.1. Theoretical studies

The modeling of an evaporative condenser is complicated by the fact that three different fluids normally flow in different directions, interact with each other through heat and mass transfer processes. Many modeling procedures, each with a varying degree of approximation, can be found in the literature [32,33]. Early evaporative-condenser models [34,35] assumed that the temperature of water stream would stay constant. Then, it was found that this assumption gave incorrect results for the heat performance of the system. Accepting that the water temperature would change, investigators presented a simple model requiring only analytical solution, Parker [36]. Based on the work of Parker, another analytical model by Peterson et al. [37] was developed and tested on an evaporative condenser. It was found that this model under predicted the heat load by 30%. Ettouney et al. [16] developed correlations for the external heat transfer coefficient and the effectiveness of an evaporative-condenser used for condensing superheated water vapor. Dreyer [38] presented various mathematical models for thermal evaluation of evaporative-coolers and condensers. These models ranged from the exact model based on the work of Poppe and Gener [39] to the simplified models of Mizushina et al. [40,41]. However, there are many devoted to the analytical determination of heat performance of evaporative-condensers based on refrigerator, air conditioning, and heat pump systems.

#### 5.1.1. Refrigerating systems

Bykov et al. [42] investigated the heat and mass transfer and fluid flow characteristics in an evaporative-condenser of a refrigerator system. They found a complex pattern of water temperature and air enthalpy changes. Their research facilitated optimizing the heat and mass transfer spaces as well as the effect of extended surfaces.

Yu and Chan [43] described a method of using direct evaporative coolers to improve the energy efficiency of air-cooled chillers under various operating conditions and with different strategies for staging condenser fans. These coolers are installed in front of air-cooled condensers to precool outdoor air before entering the condensers. In these systems, compressor power dropped following the decrease in the condensing temperature under most operating conditions. On the other hand, the pressure drop across the cooler imposed the use of additional condenser-fan power. The overall saving of chiller power varied from 1.4 to 14.4%.

Bilal and Syed [44] investigated mathematical models of evaporative fluid coolers and evaporative condensers in conjunction with the fouling model. The results are validated with experimental ones and numerical data reported in the literature. Schematic diagram of the evaporative-condenser is shown in Fig. 2. An asymptotic fouling model similar to the one developed for cooling towers in conjunction with the numerical model of the counter flow evaporative cooler and condenser have been used to study the risk based performance characteristics of evaporative coolers and condensers, including the effect of fouling on the performance index. It was demonstrated that there is over 50% decrease in effectiveness for both the evaporative-cooler and -condenser. Furthermore, it was found that there is about 5% increase in the outlet temperature of the process fluid for the given fouling model.

Xiaoli [45] studied combining air-cooled chiller with a direct evaporative-cooler to reduce the entering air temperature of condenser to improve the performance of air-cooled chiller, as shown in Fig. 3. He developed a mathematical model for the energy performance of evaporative air-cooled condenser (EACC) to evaluate the energy saving potential more accurately. The impacts of various factors on the energy saving potential were analyzed and it was found that there exists an optimal pad thickness which maximizes the energy saving. Optimization results of the pad thickness in 31 main cities in China were presented. The maximum energy saving potential of EACC in China was between 2.4% and 14.0% depending on the climatic condition. Greater degree than other models took into account the influence of water–air

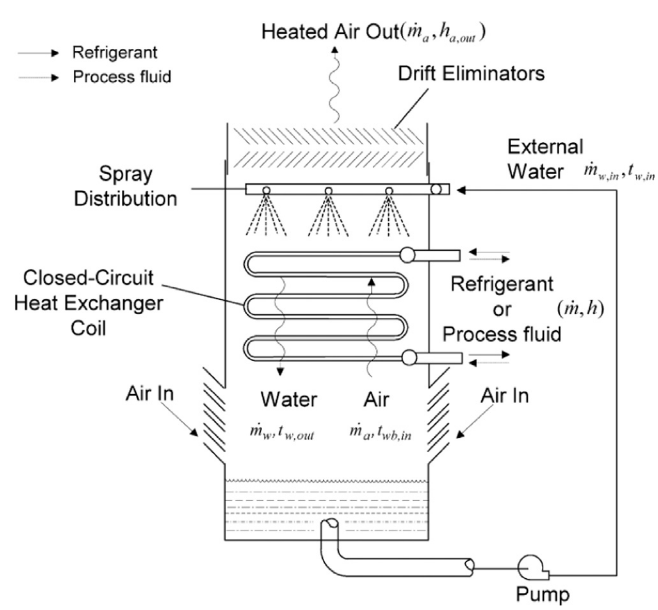


**Fig. 2.** Combined schematic of a counter-flow evaporative fluid cooler and evaporative condenser.

interface area on heat performance of the cooler in dependence of spraying density and geometrical configuration of the tubes.

Wojciech [46] investigated new mathematical model of evaporative-cooler with counter current airflow. Fig. 4 shows the schematic diagram of evaporative-cooler. They proposed a method of adjusting the model to geometrical arrangement used in bare-tube heat exchangers. They compared the mathematical results with the experimental results of the evaporative-water cooler test. The mathematical model gives a satisfactory agreement with the experimental result. Greater degree than other models took into account the influence of water–air interface area on heat performance of the cooler in dependence of spraying density and geometrical configuration of the tubes.

Ettouney et al. [16] analyzed an evaporative condensers based on the water/air mass flow rate ratio. They compared the performance of an evaporative condenser with the performance of the same system operated dry. They showed that thermal performance of the evaporative condenser is up to 60% higher than an air-cooled system.

Salah and Youssef [47] proposed a theoretical model for a rotating disk evaporative condenser to predict the performance characteristics in a refrigeration system over a wide range of investigated parameters. They compared the results with the experimental data of Hwang et al. [36], Fig. 5. It was found that the COP of a system using evaporative-condensers is nearly the same as that of a system using water-cooled condensers utilizing a cooling tower. The optimum air-inlet velocity was 3 m/s for a range of inlet relative humidity from 20 to 80% and an optimum disk speed of 35 rpm.

Youbi et al. [48] proposed a water spraying system in front of the air-cooled condenser to reduce air temperature, Fig. 6. They developed a semi-local numerical model for a sprayed air-cooled condenser coupled with a refrigeration system. They predicted the COP of the refrigeration system and found it could be improved up to 55%. Many modeling procedures, each with a varying degree of approximation, can be found in the literature [32–34].

A numerical model to investigate the heat transfer coefficients for an evaporative-cooled condenser of an air-conditioning system

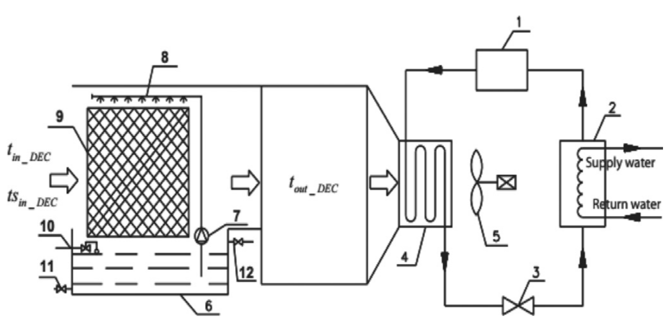


**Fig. 3.** Schematic diagram of (EACC).

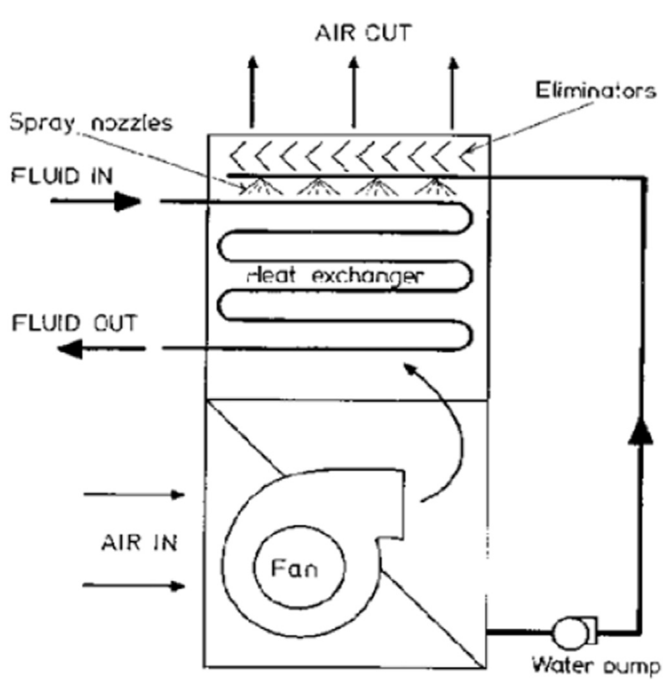


**Fig. 4.** Sechmatic diagram of evaporative fluid cooler.

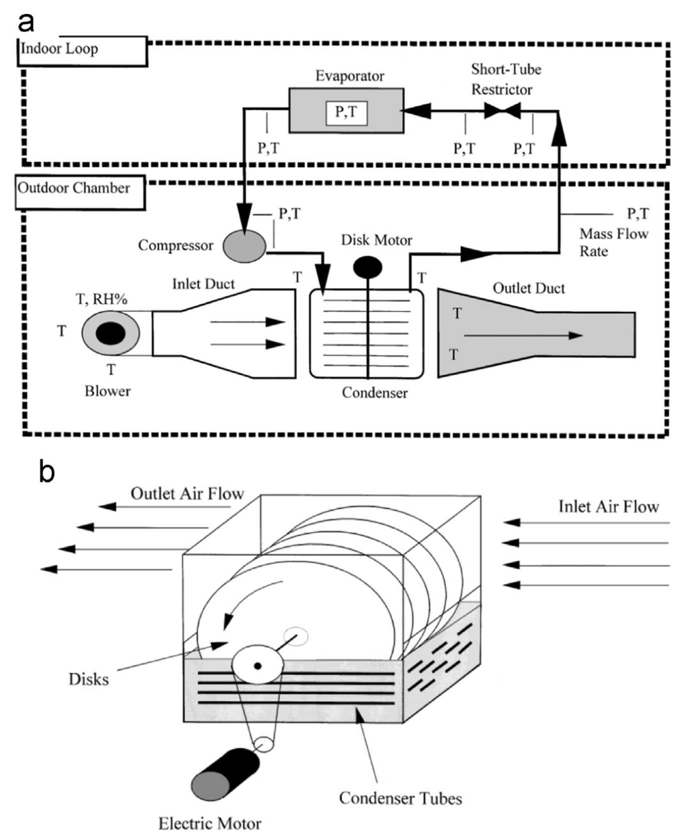


**Fig. 5.** Evaporative condenser system layout (a) and condenser system (b).

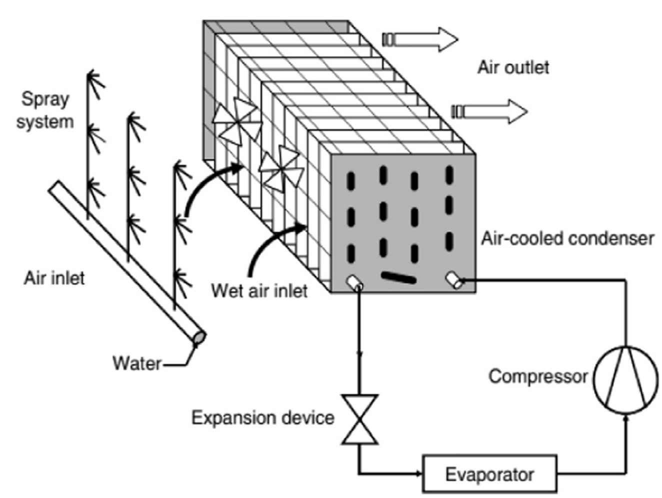


**Fig. 6.** Schematic representation of the simulated system.

was developed by Jahangeer et al. [4]. The simulation was performed for a single un-finned tube of the condenser with the air flowing across the tube. Fig. 7 shows the condenser surface with the water film. The numerical simulation was carried out using finite difference techniques. Water was sprayed on top of the tube in the form of fine sprays and the flow rate was set to achieve film thicknesses of 0.075, 0.1, and 0.15 mm, respectively. The tube wall temperature was assumed constant because for most of the tube length, condensation of the refrigerant occurs at the saturation temperature of the refrigerant. Results were compared with the available experimental and numerical data from the literature. They found that the wall to air overall heat transfer coefficient was as high as 2000 W/m$^2$ K with the incorporation of the evaporative cooling.

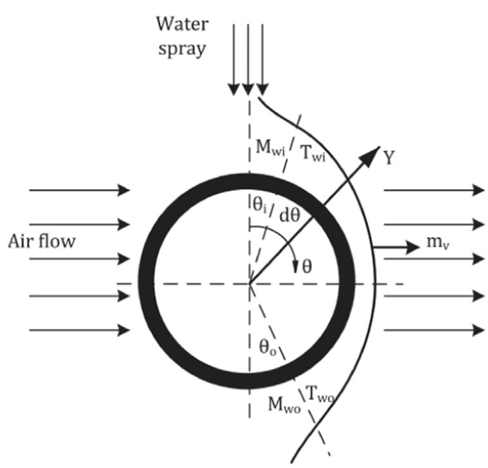


**Fig. 7.** Condenser surface with the film.

*5.1.2. Air conditioning and heat pump systems*

Yu and Chan [49] attempted to improve the COP of air-cooled screw chillers, when their condensers are designed with evaporative pre-coolers and variable-speed fans. They developed a thermodynamic model for an air-cooled screw chiller. The model considers empirical equations to describe condenser component. In addition, condenser components contain an algorithm to determine the number and speed of staged condenser fans. They validated the model using chiller specifications and a wide range of operating data in the steady state mode. It was found that the optimum set-point condensing temperature is a function of chiller load and the wet bulb temperature of the outdoor air. They reported that using the new condenser design and condenser fan operation result in a 5.6–113.4% increase in the chillers COP, depending on the chiller load and weather condition. In addition, the cooling capacity can be enhanced by 3.8–28.2%, which enables the chillers to operate at higher loads.

*5.2. Experimental work and model validation*

There have been several experimental studies on improving the performance of air-cooled condensers taking advantage of evaporative cooling.

*5.2.1. Refrigerating systems*

Nasr and Salah [50] carried an experimental and theoretical investigation of an innovative evaporative condenser utilizing sheets of cloth wrapped around tubes of a residential-refrigerator condenser. Sheets were allowed to suck the water from a water basin by capillary suction effect as shown in Fig. 8. As air flows through the condenser, water evaporates resulting in cooling both the water in the basin and the sheets rapped around the condenser tubes. The experimental results showed that the condenser temperature decreases 0.45 °C for each degree decrease in

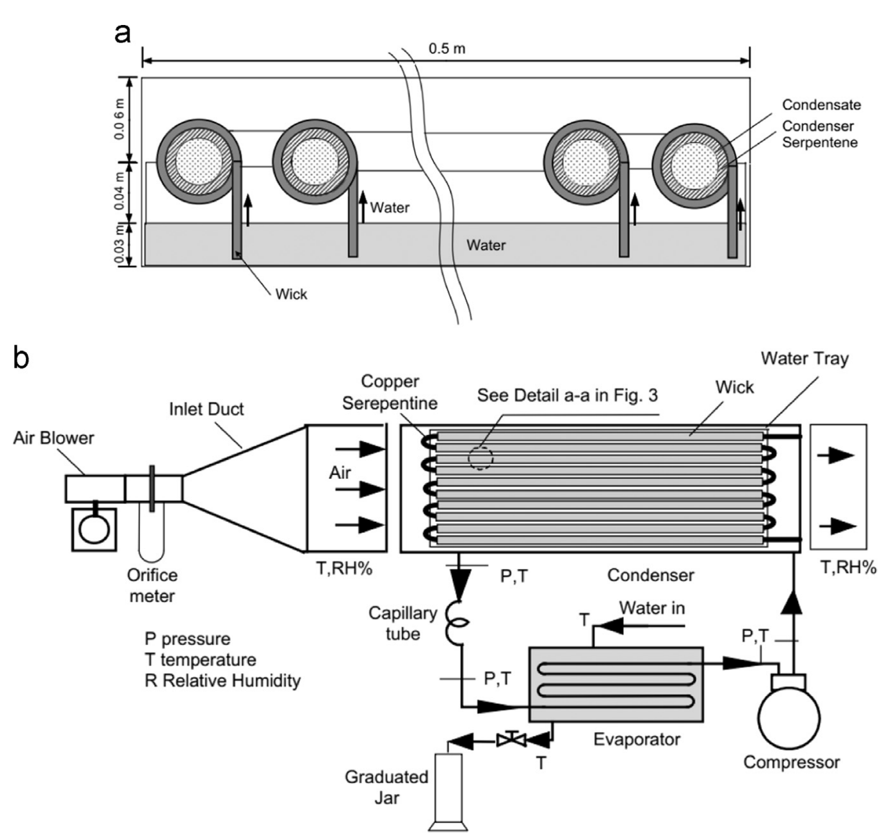


**Fig. 8.** Layout of the expermental apparatuse (a) and schematic of evaporative condenser design (b).

evaporator temperature when the air velocity was 2.5 m/s, and the ambient condition were 29 °C and 37.5% relative humidity. Meanwhile this decrease was 0.88 °C in the case of air velocity 1.1 m/s, ambient condition of 31 °C, and relative humidity of 47.1%. The theoretical results showed that the proposed evaporative-condenser can operate at a condensing temperature of 20 °C lower than that of air-cooled condenser for heat flux of 150 W/m$^2$, and air velocity of 3 m/s. They concluded that, the proposed evaporative-condenser has the ability to reject heat 13 times higher than the air-cooled condenser.

Michalis et al. [51] developed an incorporated evaporative-condenser comprised of fins, basin of water condensates and system of drop cloud via spraying, as shown in Fig. 9. The work aimed to improve the performance of the cooling provision by creating dew point conditions. It has been concluded that the incorporated evaporative-condenser improved the COP of provisions up to 110%. It also maximizes the life duration of the cooling unit and saves up to 58% energy because of the reduction in the temperature difference. However, since the air filled with water droplets was directly induced to the condensing unit, corrosion problem would possibly occur on equipment.

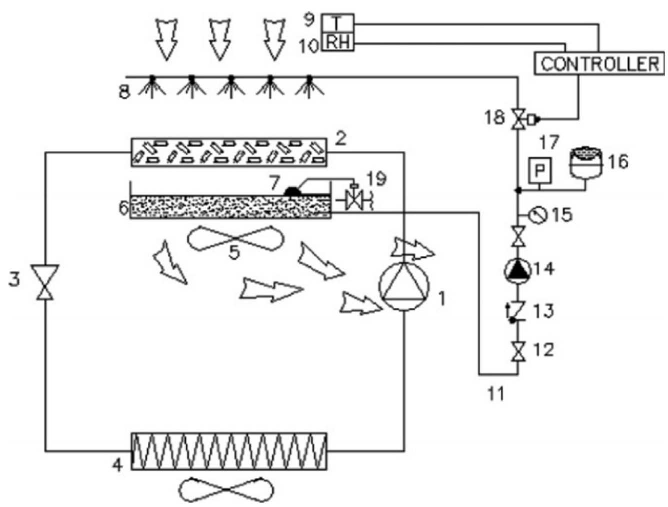


**Fig. 9.** Schematic of incorporated evaporative condenser.

Ertunc and Osoz [52] described an application of artificial neural networks (ANNs) to predict the performance of a refrigeration system with an evaporative condenser. An experimental refrigeration system with an evaporative condenser was set up. The ANN predictions were found to agree well with the experimental values with mean relative errors in the range of 1.90–4.18%. Manske et al. [53] investigated the influence of evaporative condenser operating strategies on the refrigeration system's overall performance. The methods, analysis, and results presented in this paper focused on evaporative condenser sizing and head pressure control. Simulation results for the annual performance of the investigated refrigeration system showed a reduction in annual energy consumption by 11% as a result of the recommended design and control changes.

Hwang et al. [54] compared the experimental performance of a new design for the evaporative-condenser where tubes were immersed in a water bath as shown in Fig. 5, with that of an air-cooled condenser for a split heat pump. The system was tested in an environmentally controlled chamber that was able to simulate test conditions as specified by ASHRAE Standard [55]. A motor rotates disks, which are partially submerged in the water-bath, while air is blown across them. The disks carry a thin water film from the bath to the air system. The water-film is consequently evaporated into the air stream. The tubes of the condenser reject heat to the water bath and the evaporation from the film rejects heat to the air stream. It was found that this evaporative-condenser had a higher capacity than the original air-cooled condenser up to 8.1% and a higher coefficient of performance up to 21.6%.

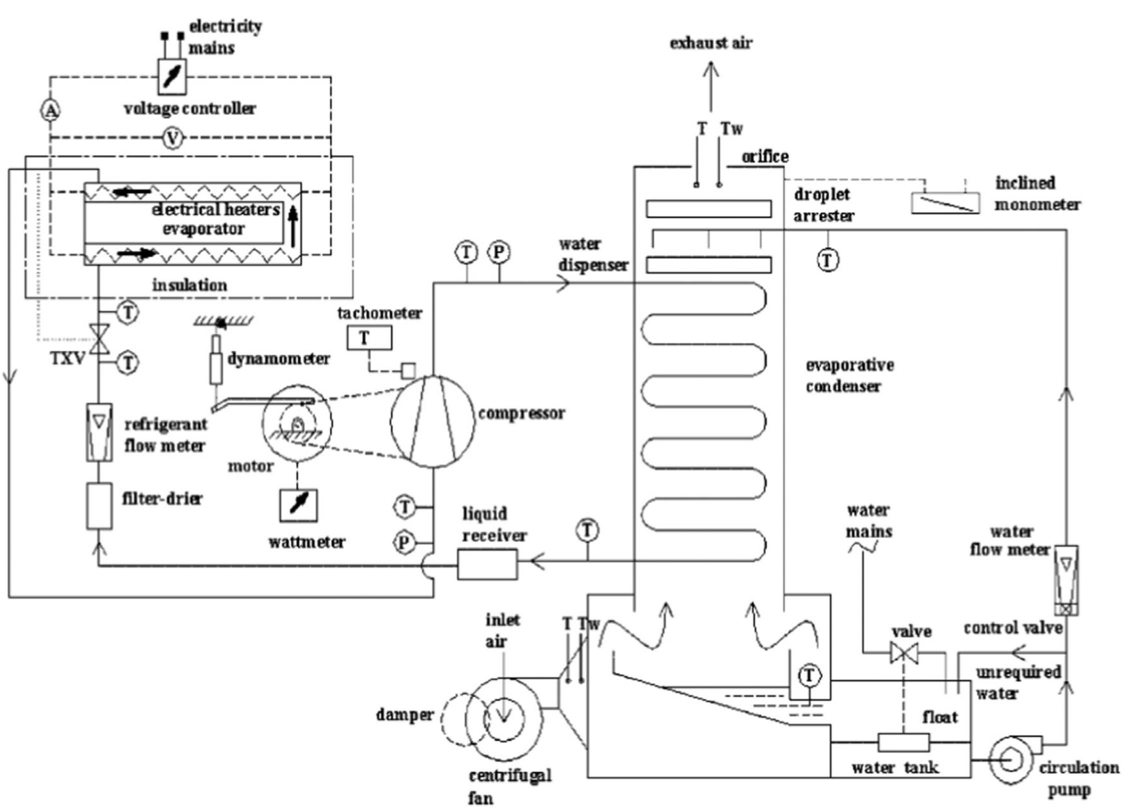


**Fig. 10.** Schematic of the experimental unit with evaporative condenser.

Hosoz and Kilicarslan [23] compared the performance characteristics of refrigeration systems employing three types of condensers, namely the air-cooled, the water-cooled, and the evaporative-condensers. Each system was operated under the same condensing and evaporating temperatures, and environmental conditions. The layout of the experimental set-up with an air-cooled and evaporative-condenser is shown in Fig. 10. Experimental results showed that, evaporative-condenser system showed a 14.3% gain in COP and a decrease in compressor power by 31% over the air-cooled condenser operating at the same conditions. In addition, the system with water-cooled condenser had a higher refrigeration capacity by 2.9–14.4%, and a higher COP by 1.5–10.2% more than the one with evaporative-condenser.

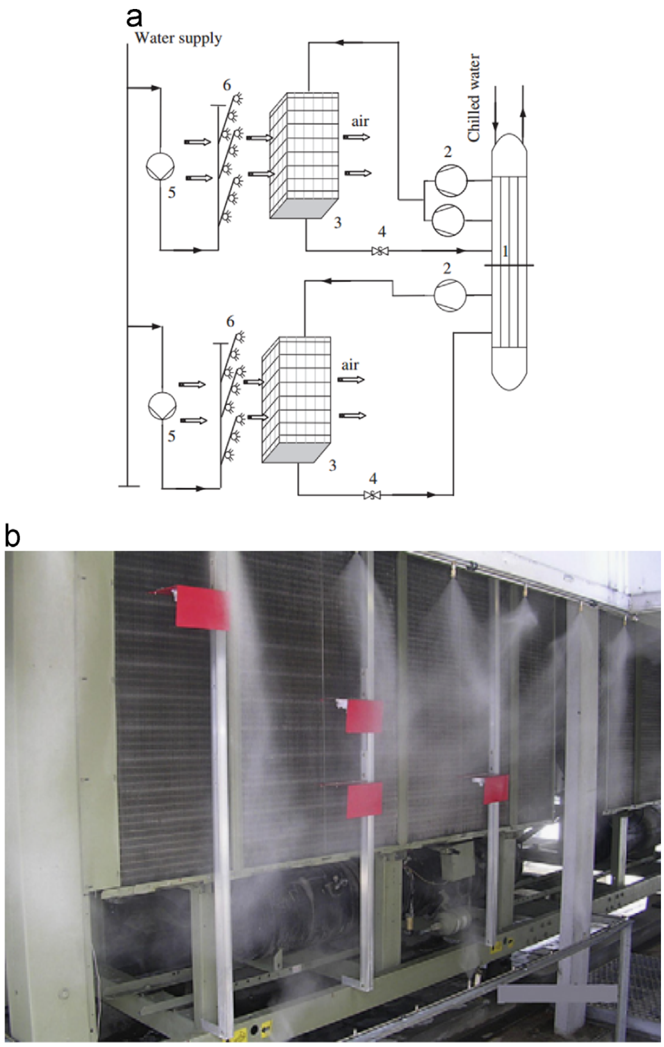


**Fig. 11.** Schematic of the water mist system (a) and photograph of the water mist system with data (b).

Yang et al. [56] investigated the effect of water mist evaporative pre-cooling on air-cooled chillers by on-site experimental studies in a subtropical climate to improve the chiller efficiency. Fig. 11 shows a schematic of the water mist system and a photograph of the water mist system. Experimental results showed that, the dry bulb temperature of air entering condenser with water mist pre-cooling drops by up to 9.4 °C from the ambient air temperature. The chiller COP could be improved by up to 18.6%. The study showed that the water mist system coupled to air-cooled chillers is an energy efficient and environment friendly technique. They added that the application of water mist pre-cooling associated with a chiller system is uncommon. They expected that the water mist system to be widely applied due to its remarkable advantage. In another study Yu and Chan [57], they simulated the application of water mist system.

### 5.2.2. *Air conditioning and heat pump systems*

Islam et al. [58] studied experimentally and numerically the performance of a commercially air-conditioning system with evaporative-cooled condenser coil. The results showed that the COP of the evaporative-cooled air-conditioning unit increases by about 28% compared to the conventional air-cooled air-conditioning unit. Wang et al. [59] investigated experimentally the COP augmentation of an air-conditioning system utilizing an evaporative-cooling condenser. An evaporative-cooling unit was located upstream from the condenser as shown in Fig. 12. The results indicated an inverse relation between the condenser inlet dry bulb temperature and the COP. Using the evaporative-cooling condenser to pre-cool the air, the drop in the saturation temperature though the condenser increased from 2.4 to 6.6 °C. In addition, results showed an increase in the mass flow rate of refrigerant that went into the evaporator. This mass increase of liquid entering the evaporator consequently resulted in the increase of COP from 6.1% to 18%. A power reduction up to 14.3%

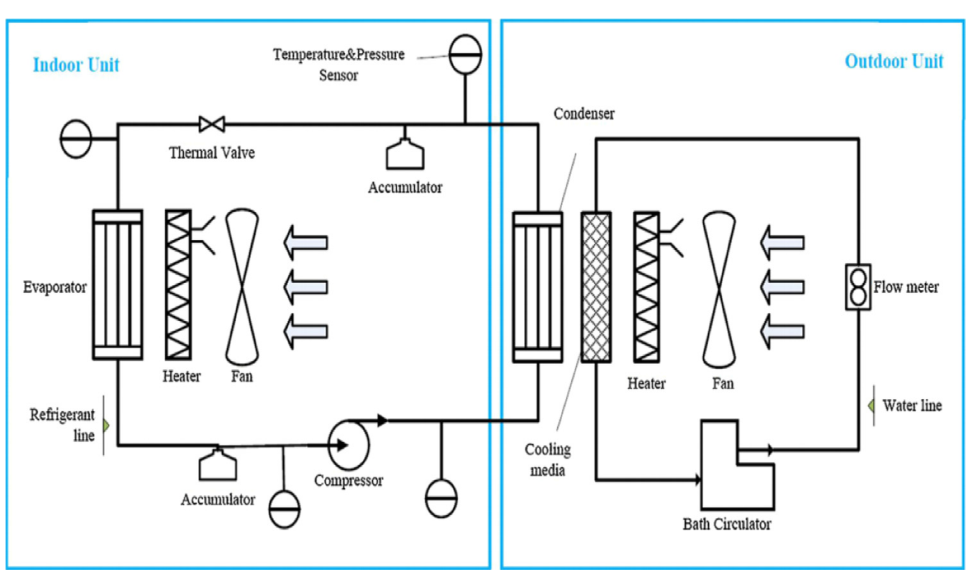


**Fig. 12.** Experimental setup of an air-conditioning system utilizing an evaporative-cooling condenser.

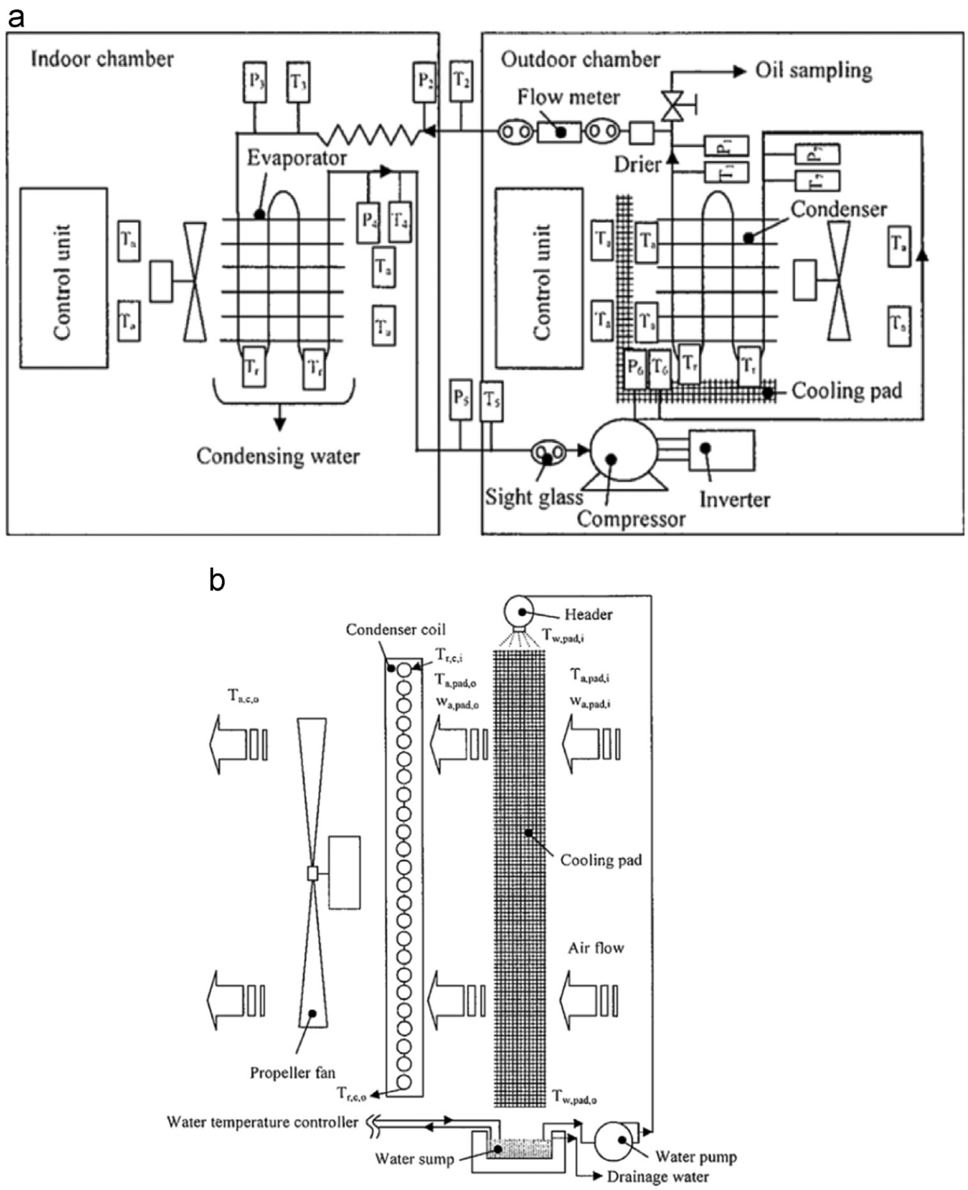


**Fig. 13.** Schematic diagram of the (a) experimental setup and (b) evaporative cooling system installed with a condensing unit.

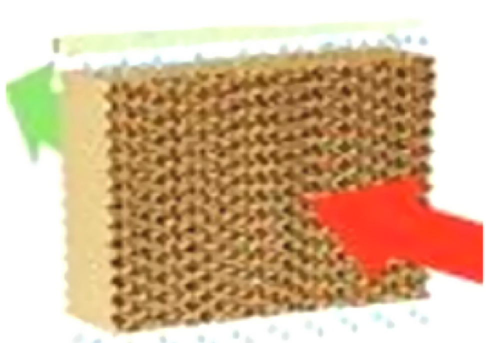

**Fig. 14.** Photograph of the cellulose pads.

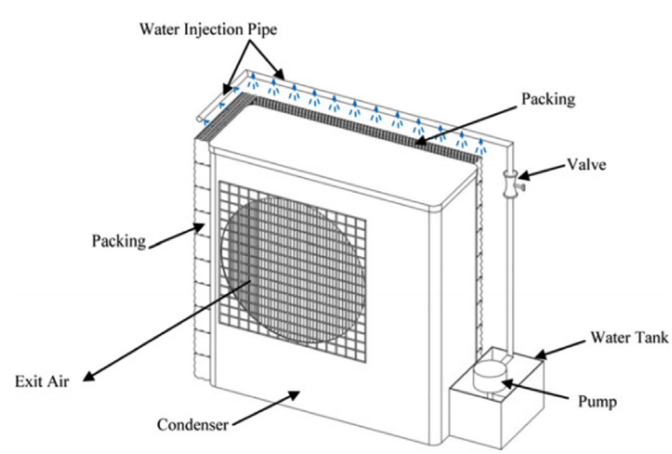


**Fig. 15.** Schematic view of the retrofitted condenser.

on the compressor was also achieved. Although greater power reductions were fulfilled at higher dry bulb temperatures, yet in this circumstance the cost-optimal applicable temperature is around 33.1 °C.

Pongsakorn and Thepa [60] in an experimental and numerical study investigated the proper operating strategies and the appropriate capillary tube length with optimal refrigerant charge of an inverter air conditioner system. Fig. 13a shows the schematic diagram of the experimental setup and Fig. 13b shows the evaporative cooling system installed with a condensing unit. The adapting system was tested by varying of frequency, water flow rate, and spraying temperature. A water injection rate of 200 l/h yields the best COP at a low frequency range while a flow rate of 100 l/h being at a high frequency range. They concluded that the proposed models gave a satisfactory agreement with test data.

Adarsh et al. [61] assessed experimentally the effect of putting a cellulose pad between the fan and the condenser to humidify the incoming air in a 1.5 TR air conditioner, as shown in Fig. 14. The experimental results showed that, the COP reached 8.03, which is higher than the standard value (5.98) of the conventional residential split air conditioners. They concluded that, the coefficient of performance of the air conditioner increased and power consumption decreased by decreasing the air temperature into the condenser.

Hajidavalloo and Eghtedari [62] studied experimentally the effect of using an evaporative cooled air condenser on the performance of an air-cooled split-air conditioner. Variable ambient air conditions were examined to determine the effect of changing the system to an evaporative-cooled one on the COP and power consumption. Fig. 15 shows the proposed system. Experimental results showed that by using evaporative-cooled air condenser under hot weather conditions, the COP could be improved up to 50% and the rate of improvement increases as ambient air temperature increases. In addition, they found that the power consumption could be reduced up to 20%.

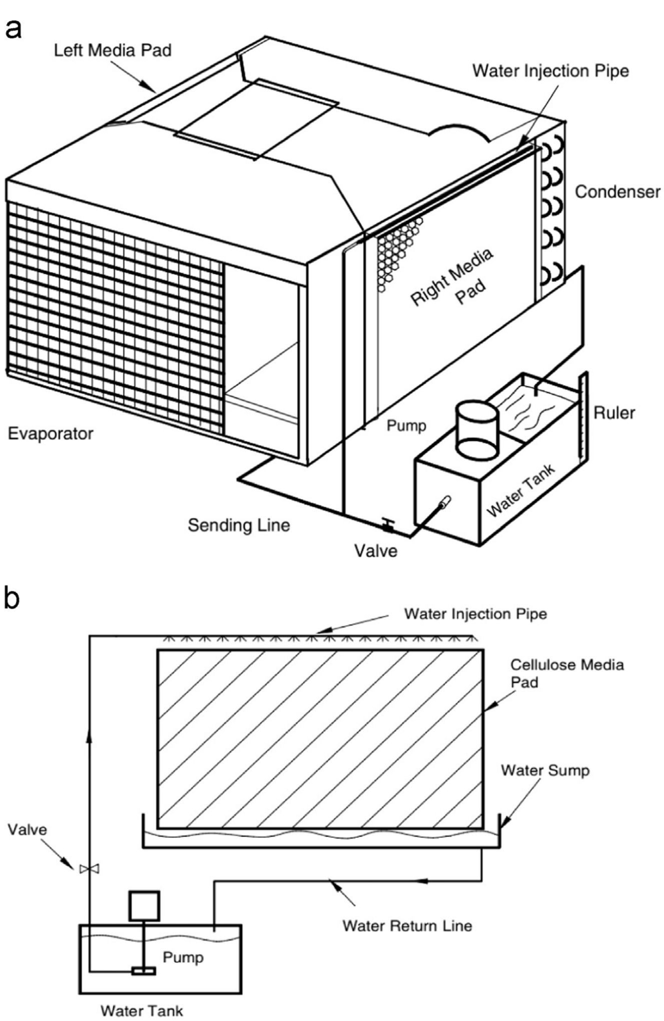


**Fig. 16.** Schematic diagram of the retofitted air conditioner (a) and water circulation diagram of evaporative media pad (b).

In order to reduce the condensing temperature in a window-type air conditioner, Hajidavalloo [17] proposed a new design for media-pad employing evaporative cooling in the condenser of a 1.5 TR under very hot weather condition. They put two cooling pads in both sides of the air conditioner and injected water on them in order to cool down the air before passing it over the condenser. The water droplets within the cooling pads, exchanging heat with hot-air flow, were trapped and dropped to the bottom. The retrofitted air conditioner used is shown in Fig. 16. The experimental results showed that thermodynamic characteristics of the new system were considerably improved achieving 16% decrease in power consumption and 55% increase in the coefficient of COP.

Chainarong and Doungsong [63] experimentally investigated the use of various indirect evaporative cooling types to reduce energy consumption in a domestic split-type air conditioner. The condensing unit is retrofitted with a corrugated media pad type evaporative cooler, water sprayers, a water source and a pump as shown in Fig. 17. Air-stream entering condensing unit is cooled down at two positions, i.e. in the front of and within cellulose-corrugated pad. Moreover, injecting water into the air is divided into two types: water curtain and water spray. Results showed that the electrical consumption and COP strongly depend on the ambient conditions. Due to the effects of condensing pressure, when the ambient temperature rises, the electrical consumption becomes higher, while the COP becomes lower. Utilizing the indirect evaporative cooling system decreases the temperature of air entering the condensing unit, and then it considerably

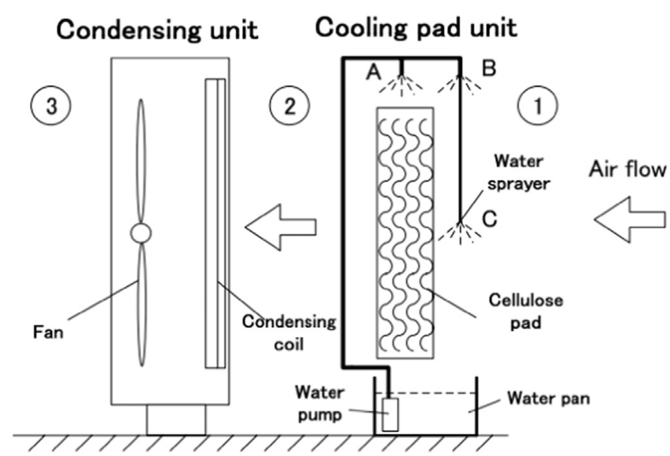


**Fig. 17.** Schmatic diagram of evapoative condenseing system.


**Fig. 18.** Photograph of outdoor unit of hybrid air conditioner including storage unit.

**Table 1**
Summary results of previous studies for experimental and theoretical studies for evaporative condenser.

| Ref. no | Testing set | Refrigerant | Testing method | Operating conditions | COP improvement ($\epsilon$) | Energy saving | Cooling capacity (kW) |
|---|---|---|---|---|---|---|---|
| **Research type: Experimental** | | | | | | | |
| [59] | Split air conditioner | HFC -410A | An evaporative cooling unit was located upstream from the condenser. | $T_a$=33.1 °C<br>$T_{cond}$=22–46 °C | 18% | 14.3% | 5.3:7 |
| [61] | | HFC -134a | Employing a cellulose pad between the fan and the condenser to humidify the incoming air | $m_r$=0.029 kg/s<br>$W_{comp}$ =0.93 kw | 34% | – | 5.27 |
| [62] | | HCFC-22 | Evaporative cooler coupled with air-cooled condenser | $T_a$=26 °C<br>RH=85%<br>$m_r$=0.03661 kg/s | 50% | 20% | 5.6 |
| [63] | | – | Condensing unit is retrofitted with various type of indirect evaporative coolers | $T_a$=27.01: 31.06 °C<br>RH=63.29: 85.38%<br>$V_a$=0.9 m/s | 48% | 15% | 8.84 |
| [64] | | – | A split air conditioner with a hybrid equipment of energy storage and water heater all year around. In summer, ice storage coils work as evaporator. In winter, energy storage tank absorbs the condenser heat to store heat during the heating process | $T_a$=7: 35 °C | 21.5% | – | 3 |
| [23] | Vapor compression system | HFC -134a | Compares the performance characteristics of refrigeration systems employing three types of condensers, air-cooled, water-cooled and evaporative condenser | $T_a$=19.5 °C<br>$T_{cond}$=40 °C | 14.3% | 31% | – |
| [65] | | | The condenser was retrofitted with a media pad type indirect evaporative cooler, a water source, and a pump | $T_a$=34 °C | – | 20% | 8.8 |
| [56] | Air-cooled chiller | | Studied the effect of operating water mist system on the performance of air-cooled chillers under various operating conditions in a subtropical climate. | $T_a$=23.8–33.5 °C<br>$T_{cond}$=35 °C<br>$T_{chin}$=12 °C<br>$T_{chout}$=7 °C<br>RH= 31.3–90.1% | 18.6%. | – | 705 |
| [54] | Split heat pump system | HCFC-22 | Condenser tubes are immersed in a water bath. Disks, which are partially submerged in the water bath | ASHERAE Standard 116 [38]<br>$T_a$=26.7 °C | 21.6% | – | 9 |
| **Research type: Theoretical** | | | | | | | |
| [49] | Air-cooled chiller | HFC -134a | Developed and validated a thermodynamic model for a new condenser design of air-cooled chillers using evaporative pre-coolers and variable speed fans. | $T_a$=35 °C<br>$T_{cond}$=50 °C<br>$T_{chin}$=5.5 °C<br>$T_{chout}$=7 °C | 113.4% | – | 1000 |
| [44] | | – | Presented a mathematical model integrated with the fouling model using the experimental data on tube fouling | $T_a$=10:25 °C | – | – | – |
| [46] | Vapor compression system | – | A new mathematical model of evaporative fluid cooling with countercurrent airflow is presented. A new mathematical model of evaporative fluid cooling with countercurrent air flow is presented | – | – | – | – |
| [48] | | – | Proposed a semi-local numerical model for a sprayed air-cooled condenser coupled with a refrigeration system | – | 55% | – | – |
| **Research type: Experimental and Theoretical** | | | | | | | |
| [17] | Window-air-conditioners | HCFC-22 | Investigated a new design with high commercialization potential for incorporating of evaporative cooling in the condenser of window-air-conditioner. Putting two cooling pads in both sides of the air conditioner and injecting water on them in order to cool down the air before it passing over the condenser. | $T_a$=45:46 °C<br>$T_{cond}$=41:45 °C | 55% | 16% | 5.27 |
| [64] | Vapor compression system | – | Proposed an innovative condenser by putting sheets of cloth wrapped around condenser tubes to suck the water from a water basin by capillary effect | $T_a$=29:31 °C<br>$V_a$=1.1:2.5 m/s | – | – | – |
| [51] | Air-cooled cooling system | HCFC-22 | Developed an incorporated evaporative condenser comprises of a system of fins, basin of water condensates, circuit pump and system of drop cloud via spraying | $T_a$=39:45 °C<br>$T_{cond}$=27:45 °C | 110% | 58% | 0.3–3000 |
| [60] | Inverter air conditioner | HCFC -410A | Investigated the proper operating strategies and the appropriate capillary tube length with optimal refrigerant charge of an inverter air conditioner system | $T_a$=18:27 °C | 18.32% | 35% | 3.5 |

enhances the system performance. The maximum energy saving occurs when the water spray works together with cellulose cooling pad. With the use of evaporative cooling systems, COP is improved by around 6–48%, and electrical consumption is approximately reduced by 4–15%.

Wang et al. [64] proposed a split air conditioner with a hybrid equipment of energy storage and water heater all year around. In summer, ice storage coils work as evaporator. In winter, energy storage tank absorbs the condenser heat to store heat during the heating process. Fig. 18 shows a photograph of the hybrid air conditioner including the storage units. Compared with the original air conditioner, they obtained around 28% increase in cooling capacity and 21.5% improvement in the COP.

Goswami and Mathur [65] investigated the increase in the performance of air conditioners with air-cooled condensers. The ambient air was evaporative-cooled before passing through the condenser. The condenser of an existing 2.5 TR (8.8 kW) air conditioning system was retrofitted with a media pad type evaporative cooler, a water source, and a pump. The system performance was monitored with and without the evaporative cooler on the condenser. It was noticed that the condenser utilizing evaporative-cooled air saved energy up to 20% compared with the same condenser utilizing air at ambient conditions. They mentioned that energy savings could pay for the cost associated with retrofitting the condenser in as little as two years.

Hajidavalloo [32] evaluated the application of media pad evaporative cooling system in a 1.5 TR window-air conditioning system under very hot weather condition. He injected water directly on the condenser and reported a 10% reduction in power consumption.

## 6. Water evaporation rate in evaporative-condenser

In evaporative condensers, make up water is supplied to the unit to compensate the water loss due to water evaporation and the physical escape of water molecules that become entrained in the air stream. However, a large percent of the entrained molecules are recaptured by the condenser's drift eliminators. Hence, this loss is typically minimal. Therefore, the greatest amount of water consumption is lost through the evaporative cooling process and is directly related to climate zone conditions. Water consumption increases in hotter/dryer climate zones. Assuming 100% efficient drift eliminators, the rate of water loss solely due to the evaporation can be estimated using the following equation

$$M_{weva} = Q_{latent}/h_{fg} \tag{7}$$

Evaporative condensers require treated water because the contaminants will lead to scaling which reduces the overall heat transfer of the condenser. In addition, cooling water must be changed periodically to avoid excessive mineral build-up in the sump water. This can be accomplished either by periodically purging the sump or through a bleed line where water is continually bled off the high-pressure side of the circulating pump during operation.

## 7. Summary

The review work indicates that evaporative-cooled condenser is one of the immediate solutions to save electric power consumption and increase the coefficient of performance of cooling systems. Most of the previous reviewed studies made modifications in the already available air-cooled condenser to work as evaporative-cooled condenser. Some innovative designs for employing evaporative-condenser have been presented. In the present study, the overall energetic performance of the cooling system with air-cooled condenser ($COP_{ACC}$) and evaporative-cooled condenser ($COP_{EC}$) has been defined as the ratio between the cooling capacity ($Q_{evap}$) and total power supplied (consumed):

$$COP_{ACC} = \frac{Q_{evap}}{W_{com} + W_{fan}} \tag{8}$$

$$COP_{EC} = \frac{Q_{evap}}{W_{com} + W_{fan} + W_{pump}} \tag{9}$$

The $COP_{ACC}$ and $COP_{EC}$ were computed and the results are presented in Table 1. The percentage enhancement in the COP using the evaporative-cooled condenser is defined as,

$$\epsilon = \frac{COP_{EC} - COP_{ACC}}{COP_{EC}} \tag{10}$$

A summary of the pervious theoretical and experimental studies on evaporative-condensers for cooling systems has been presented in Table 1. A comparison between results of different studies based on the percentage enhancement in the COP using the evaporative cooled condenser ($\epsilon$) and energy saving with cooling capacity are shown in Fig. 19 and Fig. 20, respectively. It was found that by using evaporative-cooled condensers instead of air-condensers, the COP can be improved from 14.3 to 113.4% and the power consumption can be reduced from 15 to 58% when using systems with cooling capacities ranging from 0.7 to 3000 kW.

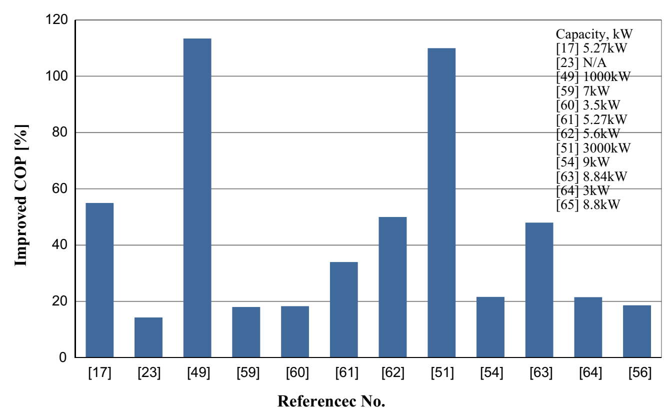


**Fig. 19.** Comparison between results of different studies of COP improvement and cooling capacity.

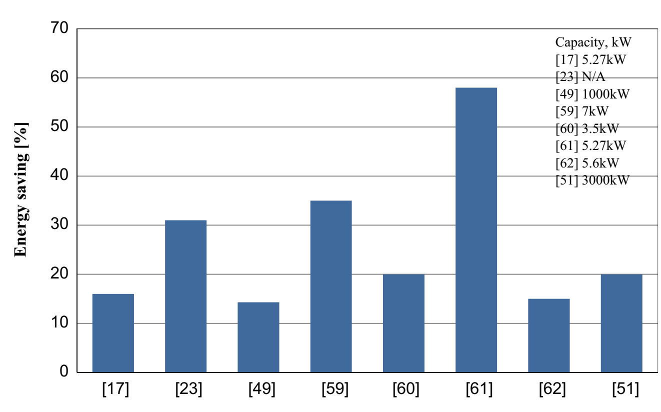


**Fig. 20.** Comparison between results of different studies of energy saving and cooling capacity.

## 8. Conclusion remarks

There is an urgent need to develop cost-effective technologies and to improve the cooling system efficiency. Evaporative-cooled condenser is one of the immediate solutions to the quest for efficient use of millions of residential cooling systems around the world. Thus, reducing energy use and peak demand in hot-dry climates including Middle East, East Asia, as well as countries near the Equator. Researchers presented many simple and innovative designs and it could easily be applied on existing refrigerator and air-conditioning systems. Major results are summarized in figure and tabular form at the end of this paper. It was also found that by using evaporative condenser instead of air-cooled condenser, the power consumption can be reduced up to 58% and the COP can be improved by about 113.4%. Finally, this paper aims to promote wider application of evaporative-condensers in different cooling systems.

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