Basrah Journal for Engineering Sciences, Vol. 24, No. 1, (2024), 69-80

Review Article

Journal homepage: www.bjes.edu.iq
ISSN (Online): 23118385, ISSN (Print): 18146120

An Overview of Enhancing the Efficiency of Vapor Compression Cooling Systems by the Implementation of Evaporative Condensers

Haider Mumtaz Hussain [1, *], Salman Hashim Hammdi [2]

[1,2] *Department of Mechanical Engineering, College of Engineering, University of Basrah, Basrah, Iraq*
E-mail addresses: haideralbayati200487@yahoo.com , salman.hammadi@uobasrah.edu.iq
Received: 24 October 2023; Revised: 18 November 2023; Accepted: 23 November 2023; Published: 15 February 2024

Abstract

This paper explores the significance of energy conservation in the context of rising energy consumption and its impact on economic growth. With a focus on cooling systems, particularly evaporative condenser technology, the study aims to investigate its fundamentals, operating principles, and theoretical aspects. The paper delves into the various types of condensers used in cooling systems, emphasizing the role of evaporative condensers in enhancing heat transfer efficiency. The operating principles of evaporative condensers are detailed, considering factors such as air and water flow rates, wet bulb temperatures, and heat transfer coefficients. Theoretical models and mathematical approaches for evaluating evaporative condenser performance are also reviewed.

The research includes an extensive review of existing literature on evaporative condenser technology, covering refrigeration models, HVAC systems, and various experimental studies. Theoretical models are discussed, highlighting the challenges in accurately modeling evaporative condenser behavior. The paper also presents achievements and advancements in research, including experiments that demonstrate the positive impact of evaporative cooling on air-cooled condenser systems. Various case studies and experimental validations showcase the potential energy savings and improved performance achieved through the incorporation of evaporative condensers in cooling systems. By switching from an air-cooled to an evaporatively-cooled condenser, one can reduce electricity consumption by 58%, according to research. This alternate condenser type improves performance by 113.4% at from 3 to 3000 kW of cooling power.

Keywords: Energy saving, Energy, Evaporative condenser, COP, Cooling.

https://doi.org/10.33971/bjes.24.1.8

1. Introduction

Energy is crucial to national economic growth. Due to rising energy consumption, energy conservation and use are becoming more important. Various engineering disciplines strive to reduce energy consumption by implementing efficient or decreasing energy service use [1–3]. Reduced energy use will reduce dependency on fossil fuels, which is vital to a nation's economic growth and stability due to their high costs [4–6]. Energy conservation reduces global warming.

Energy consumption is rising due to rising living standards and comfort. AC, refrigerator, and water heater energy use is increasing, accounting for 30% of total power demand [7]. Commercial and residential air conditioning systems use 45% of electricity [8]. Global energy consumption is anticipated to expand by 71% between 2003 and 2030 due to population and economic expansion [9]. Thus, every effort to reduce cooling system energy use will help save energy globally. Energy use can be reduced by improving cooling unit performance. To attain this goal, reduce compressor power utilization, increase condenser heat rejection, or lower the condenser-evaporator pressure differential.

An elevated condensing temperature raises the compressor's pressure ratio, increasing compressor effort and diminishing compressor lifespan and performance coefficient. Summer ambient temperatures above 35 °C drop most air-cooled device performance coefficients to 2.2–2.4 [10]. Due to the massive pressure on the condenser, the air conditioning unit may trip if the temperature stays above 45 °C for a long time.

The coefficient of performance of an air conditioner indicates a reduction of approximately 2-4% for every 1 °C rise in the condenser temperature [11, 12]. Summer temperatures in several Middle Eastern countries exceed 40–45 °C, sometimes higher. Under current conditions, the air conditioner compressor runs continuously, increasing electricity consumption and decreasing COP [13]. Thus, the air must be cooled before passing over the coil to lower the condenser's temperature and pressure. Condensing environments can be cooled evaporative condensers convert outside dry bulb temperatures to outdoor wet bulb temperatures [14]. In dry regions, high ambient temperatures rarely affect evaporative condenser efficiency. Evaporative condensers are crucial when dry and wet bulb temperatures vary substantially during peak utility demand [15]. Evaporative-cooled condensers have the same heat transfer coefficient but less airflow and heat transfer area. [16]. This phenomenon could result in huge energy and demand savings, as even small home power usage reductions can save a lot [17], [18]. Research on evaporative-cooled condensers aims to increase heat transfer rates to increase the cooling system's efficiency [19].

Evaporative condenser technology is thoroughly examined and evaluated in this paper. The present study also investigates residential cooling system energy consumption, concentrating on evaporative condenser heat dissipation fundamentals, operating principles, and theory.

2. Cooling system condensers

Cooling systems need condensers to transfer heat from refrigerant evaporation and gas compression to ambient air. Heat from the hot refrigerant to the environment converts it into liquid. Air, water, or evaporative-cooled condensers exist.

Up to twenty TR, the majority of medium-sized and small refrigerated chillers employ cooled air condensers [20-22]. Heat is transferred between coils and ambient airflow in air-cooled condensers. These devices' energy efficiency relies on thermodynamics and air-based heat transport. Climate influences cooling systems and air-cooled condensers' thermodynamic efficiency, preventing consistency. Due to their waterlessness, air-cooled condensers are the most frequent and simple. Instead, they use high airflow to enhance efficiency, which might produce noise. Air-cooled condensers cost less to build and operate. Other condensers use less power than air-cooled ones. Air-cooled condensers must maintain 15-20 °C higher condensing temperatures than ambient air [23].

The second condenser uses adjacent cooling water to dissipate heat. A cooling tower converts cooling water to hot air [24–26]. This condenser is smaller and has better heat transmission than air-cooled ones. This requires water and more initial investment [27–30]. Thus, water circulation requires a pump. To reduce coil dirt, chemically treat water. Operations must be monitored and managed. Only the water-cooled condenser is employed when the compressor-to-heat rejection point distance exceeds the pressure drop for pumping refrigerant vapor. According to [31], water-cooled condensers can hold half to ten thousand TR. These condensers are used in heat pumps and other specialized equipment.

Evaporative condensers third. In large-tonnage non-residential applications, evaporative cooling improves heat transfer and air-cooled condenser performance. Micro-heat exchangers called evaporative condensers combine air- and water-cooled operations. Air and water exchange sensible and latent heat, while water evaporation cools the air. This condenser requires less airflow than an air-cooled one, allowing a smaller fan and motor. Fewer chemicals and water pumps are needed for water-cooled condensers.

Water-cooled and evaporative condensers have restricted the condensation process temperatures to the external wet bulb temperature, usually lower than the dry bulb temperature. These condensers reduce the temperature of the refrigeration system, saving electricity. These condensers have a greater performance coefficient and refrigeration capacity than air-cooled ones. Despite consuming the same amount per refrigeration unit, evaporative condensers use less water than water-cooled condenser cooling-tower combinations. All of the evaporative condenser's water circulation system is inside the casing. Evaporative condensers cost less than water-cooled ones because they are smaller and have fewer parts. Evaporative condensers are tougher to model than water and air-cooled ones because water evaporates into the air stream.

3. Evaporative condenser operating principles

Figure 1 depicts a typical evaporative condenser design and components. Evaporative condensers have a coil, spray, fan, pump, eliminator, basin, casing, and controls.

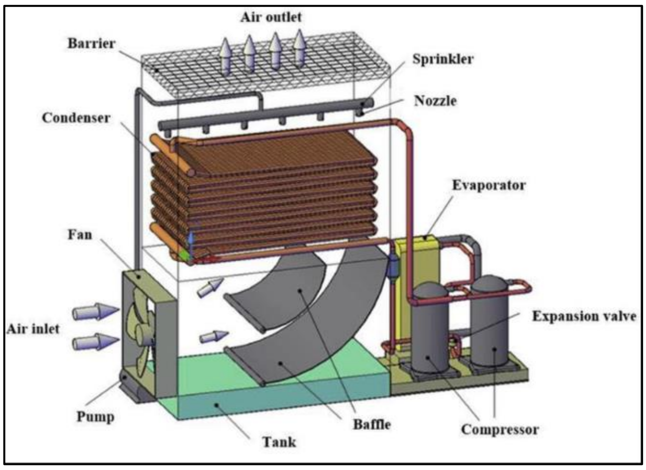


Fig. 1 Standard evaporative condenser schematic.

Tube-based evaporative condensers circulate compressor-pumped hot refrigerant. Basin water is pumped and sprayed from above to keep coil tubes wet. Fans blow air through condenser tubes. Thus, as a part of the water in the condenser tubes releases into the air, latent heat from the refrigerant accumulates through the exterior of the tube, causing the gas to cool and condense. Pumps deliver un-evaporated condenser unit bottom water to sprayers. Evaporative condensers were analyzed utilizing the water/air mass flow rate ratio by Ettouney et al. [16]. Evaporative condenser and dry system performance were compared. Evaporative condensers beat air-cooled systems 60% thermally. Hosoz and Kilicarslan [23] found that a water tank float valve supplies makeup water to compensate for 5% water evaporation.

More than exterior dry bulb temperatures, refrigerator condensing unit temperatures resemble external wet bulb temperatures. Wet bulb temperatures in arid regions can be 4.4 °C lower than peak summer dry bulb temperatures, giving better COP than air-cooled devices.

4. Heat rejection theory for evaporative condensers

Evaporative condensers Employ heat and mass transfer on the tubes to remove energy. Evaporative condenser units are sensitive to wet bulbs [19] because they refuse energy primarily through water evaporation. Sensible heat transfer occurs due to a variation in dry bulb temperature between the entering and exiting air:

$$Q_{latent} = \dot{m_a}.cp_a\left(T_{a,o} - T_{a,i}\right) \tag{1}$$

Latent heat transfer rate is the difference in specific humidity ratio between incoming and departing air, calculated using the following equation:

$$Q_{latent} = \dot{m_a}.h_{fg}\left(\omega_{a,o} - \omega_{a,i}\right) \tag{2}$$

Evaporative condensers transfer heat twice. Equation (3) describes the first stage between the condensing refrigerant and the coil's water layer (Qc-w):

$$Q_{c\rightarrow W} = \dot{U_{c\rightarrow W}}.A_c\left(T_{c,s} - T_w\right) \tag{3}$$

High air velocity affects condenser heat transfer. Air velocity rises, enhancing the Nusselt number and heat transmission by increasing the Reynolds number along the coil surface. High heat transmission reduces SCT and compression. Practical uses reduce condenser-fan power and SCT.

Phase two warms the layer of water on the coil and moves air around. The rate of heat transfer is calculated by the enthalpy of the air entering the condenser and the enthalpy of the air that has been saturated (closest to the water surface) at the temperature of the condensing refrigerant. Eqs. (4) and (5) describe heat removal.

$$Q_{w\to a} = h_w . \dot{A}_{w\to a}(T_a - T_w) \quad (4)$$

$$Q_{w\to a} = k_m . \dot{A}_{w\to a}(\omega_{ws} - \omega_a) . h_{fg} \quad (5)$$

Evaporative condensers dissipate heat by evaporating water sprayed into the air. Thus, these condensers' operational efficiency depends on ambient wet-bulb temperature. In addition, the factors that impact the outcome include the surface area, coil material, ambient circumstances, airflow, and spray-water rate. The operational efficiency of the evaporative condenser. Equation (6) links air flow and water spray rates to evaporative-condenser heat transfer capacity.

$$H = K . G^{0.48} \dot{L}^{0.22} \quad (6)$$

This scenario uses H for condenser capacity, k for constant, G for water spray, and L for airflow.

This remark suggests that water spray rate affects condenser capacity more than airflow. Water flow is rarely actively regulated in practice. However, airflow velocity is often regulated by the optimization of condensing temperatures, condenser-fan power, and consumption is being considered.

5. Evaporative condenser research and achievements

5.1. Theories

Modeling an evaporative condenser with three fluids that flow in different directions and affect heat and mass transport is difficult. The literature describes many modeling methods with varied approximations [32, 33]. Previous investigations of evaporative-condenser models [34, 35] assumed constant water stream temperature. Later, this assumption caused thermal efficiency errors [36]. A simple analytical model was presented to account for water temperature variations. After Parker's work, Peterson et al. [37] adapted their analytical model to an evaporative condenser. Analysis showed the model underestimated heat load by 30%. Ettouney et al. observed that the external heat transfer coefficient impacts the efficiency of a superheated water vapor evaporative condenser. Dreyer [38] created mathematical models to evaluate the thermal performance of evaporative coolers and condensers. This investigation comprised models ranging from Poppe and Gener's comprehensive model [39] to Mizushina et al. simpler models [40,41]. However, there is a lot of research on evaporative condenser thermal efficiency in refrigeration, air conditioning, and applications involving heat pumps.

5.1.1. Refrigeration models

Bykov et al. [42], they studied refrigerator evaporative condenser fluid flow and heat mass transfer. Water temperature and air enthalpy have a complex relationship. They optimized heat and mass transmission gaps and expanded surfaces to cool the surrounding air prior to air-cooled condensers. The compressor output from these systems decreased as the condensing temperature rose. Yu and Chan [43] found that direct evaporative coolers improve air-cooled chiller energy efficiency under various operating circumstances and condenser fan staging. These coolers Cool the outside air first, then use air to cool the condensers. As the condensing temperature decreased throughout the regular operation, these systems' compressor power slowed down. But cooler pressure drop required greater condenser fan power. Chiller power savings were 1.4-14.4%.

Bilal and Syed [44] studied fouling and evaporative fluid cooler and condenser mathematical models. Experiments and literature confirm the findings with numbers. Figure 2 shows the evaporative condenser schematic. The risk-based performance characteristics of the counter flow evaporative cooler and condenser, including the performance index effect of fouling, were evaluated using a cooling tower-like asymptotic fouling model and the numerical model. Both evaporative cooler and condenser efficiency declined by 50%. The fouling model raises process fluid exit temperature by 5%.

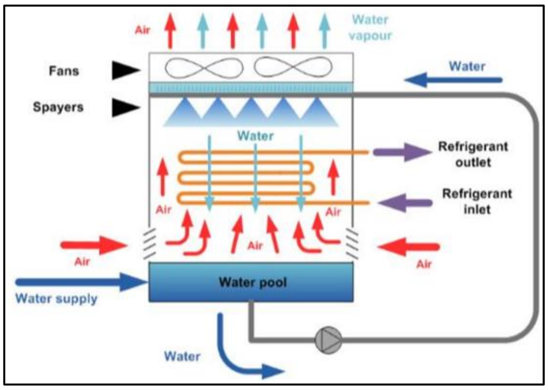


Fig. 2 Evaporative condenser with counter-flow evaporative fluid cooler schematic.

Xiaoli [45] researched employing an air-cooled chiller and a direct evaporative cooler to lower the condenser's entering air temperature to increase performance (Fig. 3). EACC energy mathematical model performance helped him measure energy savings. Analyzing many factors on energy-saving potential found an appropriate pad thickness. Pad thickness optimization results from 31 major Chinese cities were shown. EACC might save 2.4% to 14.0% of Chinese energy, depending on climate. Water–air impact was more essential than other models.

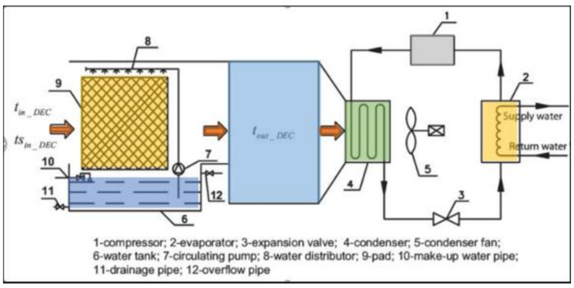


Fig. 3 Schematic diagram of (EACC).

Spraying density and tube geometry affect cooler heat performance for the interface region. A new counter-current evaporative cooler mathematical model was studied by Wojciech [46]. Figure 4 shows the evaporative cooler schematic. They suggested adapting the model to bare-tube heat exchangers. Calculations were compared to evaporative-water cooler tests. Mathematical model matches experiments. More than other models examined spraying density and tube geometry on water–air interface area and cooler heat performance.

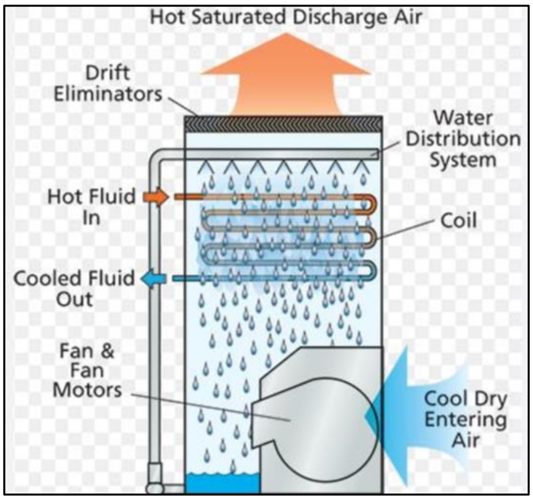


Fig. 4 Schematic diagram of evaporative fluid cooler.

Salah and Youssef [47] created a spinning disk evaporative condenser theoretical model to predict refrigeration system performance across multiple parameters. Figure 5 shows experimental findings compared to Hwang et al. [36]. System COP is similar to evaporative condensers.

Water-cooled condensers with cooling towers. At 20–80% inlet relative humidity and 35 rpm disk speed, 3 m/s was ideal air-inlet velocity.

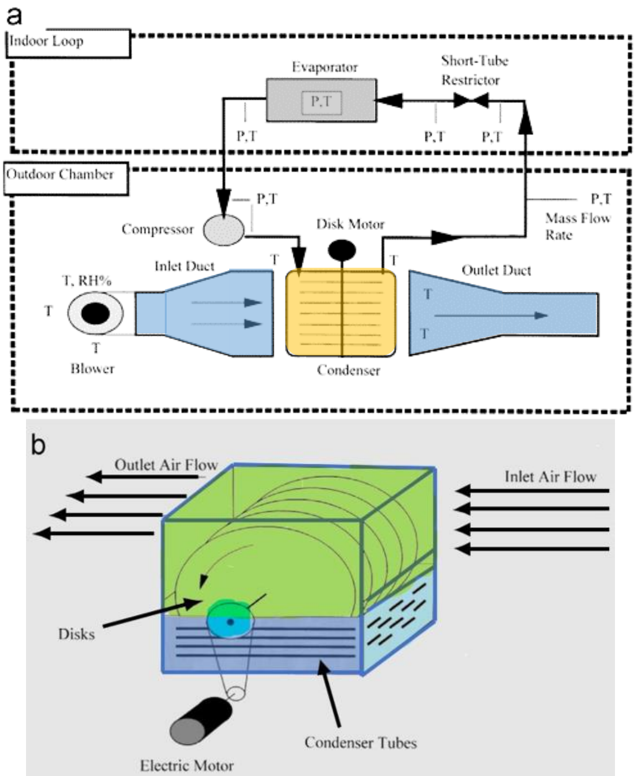


Fig. 5 Evaporating condenser arrangement (a) and system (b).

Youbi et al. [48] suggested Fig. 6 shows water flowing in front of the air-cooled condenser to cool the air. A numerical simulation of a sprayed cooled-by-air refrigerator condenser that is only partly local was built. They anticipated refrigeration system COP increases of up to 55%. The literature offers several modeling methods with varying approximations [32–34]. An air-conditioning system evaporative-cooled condenser heat transfer coefficient numerical model.

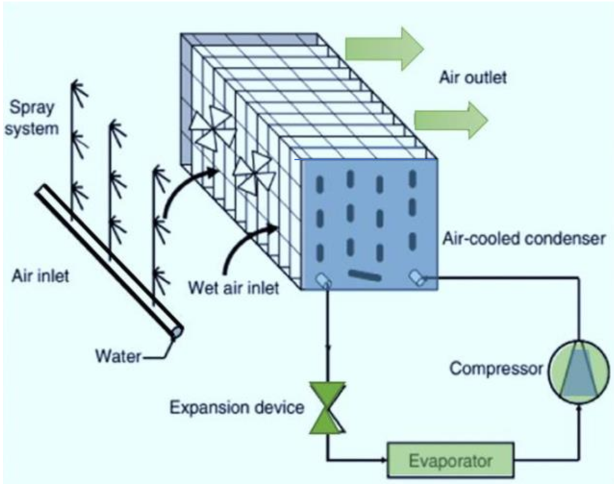


Fig. 6 Simulated system schematic.

Developed by Jahangeer et al. [7] it used the simulation of one un-finned air-flowing condenser tube. Figure 7 shows the water-film condenser area. Numerical simulation employs finite difference. The flow rate was regulated by spraying fine water on the tube for 0.075, 0.1, and 0.15 mm film thicknesses. Since refrigerant condensation takes place at the saturation temp. for most of the tube, the tube wall temperatures were assumed constant. They were comparing results to literature-based experimental and numerical data. With evaporative cooling, wall-to-air heat transmission reached 2000 W/m^2 K.

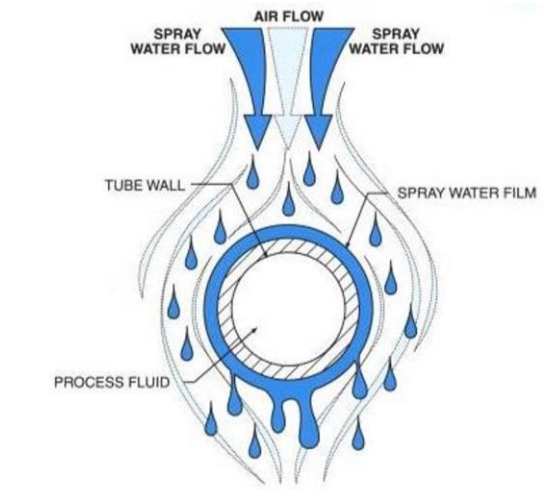


Fig. 7 Film-covered condenser.

5.1.2. Heating, ventilation, and air-conditioning systems

Yu and Chan [49] increased air-cooled screw chiller COP with evaporative pre-cooling and several-speed fans thermodynamically modeled air-cooled screw chillers. The symbol uses equations of the empirical condenser. Staged fan number and speed are calculated using condenser components and algorithms. The model was validated using chiller parameters and several steady-state operating data. Chiller load and external air wet bulb temperature determine the best condensing set-point. Depending on load and weather, the altered condenser design and fan operation boosted chiller COP by 5.6–113.4%. Chillers can handle more load with 3.8–28.2%.

5.2. Model validation and experiments

Evaporative cooling has improved air-cooled condensers in several experiments.

5.2.1. Refrigeration

Using linen wrapped over home refrigerator condenser tubes, Nasr and Salah [50] tested and theorized a unique evaporative condenser water was extracted from a receptacle by sheets via capillary suction (Fig. 8). The basin and sheets around the condenser tubes cool as air and water evaporate. Experiments show that condenser temperature drops 0.40 °C every degree more cooling capacity evaporator temperature at 2.5 m/s, 29 °C, 37.5% humidity. The drop was 0.88 °C at (1.15) m/s air velocity, 30 °C ambient temperature, and 47.1% relative humidity. Based on this idea, the suggested evaporative condenser might work at a temperature 21 °C lower than an air-cooled condenser with a heat flux of 150 W/m2 and an air speed of 3 m/s. The suggested cooling condenser worked well for them and rejected 13 times more heat than the air-cooled one.

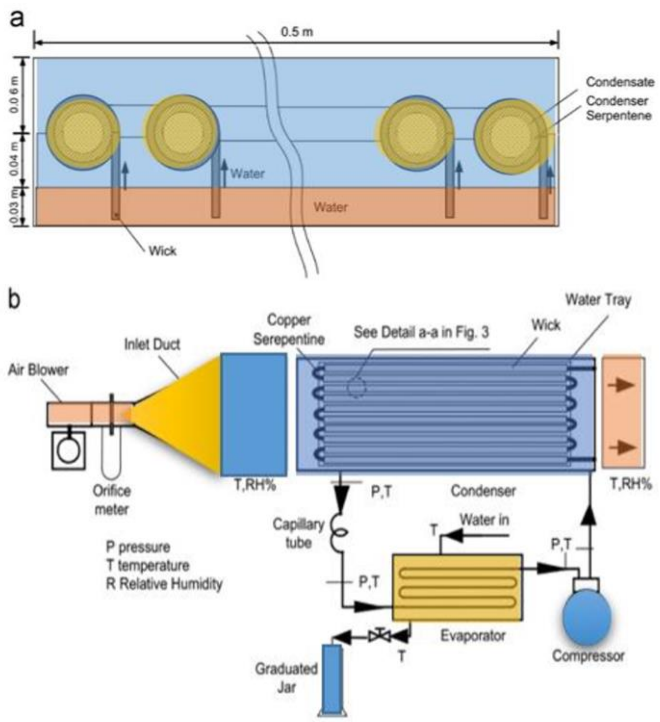
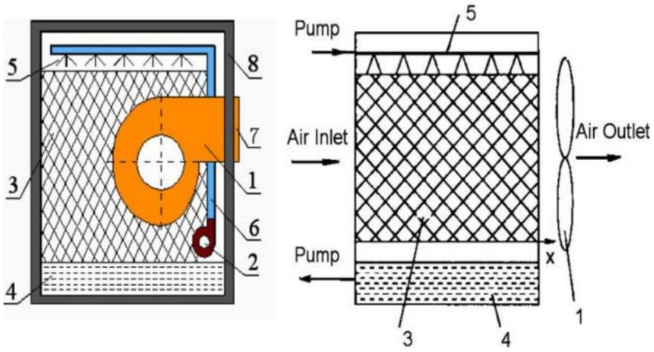


Fig. 8 (a) Experimental apparatus layout and (b) evaporative condenser schematic.

Shaheen and Hmmadi [51] (studied a hybrid refrigeration-evaporative air cooler system. This research aims to enhance evaporative air coolers, reduce air moisture, and generate fresh water. They were studied intake, evaporator, relative humidity, and wetted pad thickness. As relative humidity, coil temperature, and front air velocity decreased, outlet temperature dropped by 1-3, and freshwater increased. Pad thickness also improved effectiveness. Figs. 9, 10, and 11.



1 fan, 2 pumps, 3 pad material, 4 water basin, 5 water distribution system, 6 water supply pipes, 7 air outlets, 8 frames.

Fig. 9 Sketches of the inner configuration and the working principle of the direct evaporative cooler.

Fig. 10 The Photograph illustrates the hybrid system.

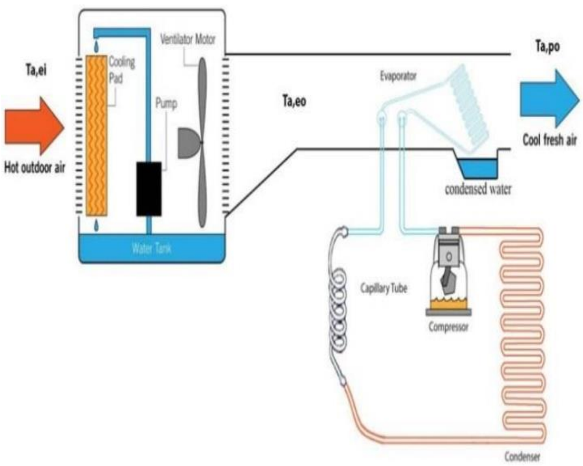
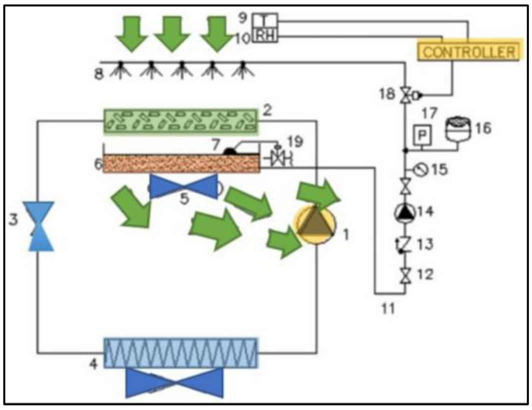


Fig. 11 Schematic diagram of apparatus working.

Hammadi and Fadhil [52] connected an evaporative cooling unit to a split-type air conditioner's condenser to save energy and improve cooling system performance. A glass wool-covered aluminum evaporative cooling unit has a cellulose pad on its face. Major results included a 23% energy saving. Performance increases when ambient temperature drops and power network maximum load drops in hot weather.

Eidan et al. [53] investigated direct evaporative cooling to enhance a small air conditioner. It was developed to simulate a hot climate with 55 °C summer dry bulb temperatures. Air flows across moist platforms before entering the condenser. Performance factors, compressor shutdown at high temperatures, energy savings, and cooling capacity were studied. Significant system performance improvements include increased cooling capacity and lower power utilization. The compressor-maintained working despite the voltage loss, a major concern in most Middle Eastern countries, including Iraq, when air temperatures rise. Air conditioning was supplemented with R22 refrigerant and evaporative cooling. Three gears kept the pads saturated with water from the water distribution system through the pump and tank. A digital data recorder collected it. Heater and fan airflow approximated atmospheric conditions, electric heaters controlled relative humidity, and the Taylor approach was used for all element data. System performance was examined with and without evaporative cooling. Evaporative cooling saves energy because low air velocity lowers pressure and improves efficiency mathematically and empirically.

Michalis et al. [54] An evaporating condenser with a fin was developed., a water condensate basin, and a drop cloud spraying mechanism (Fig. 12). It is intended to increase cooling performance by:



1. Compressor, 2. Condenser, 3. Expansion device, 4. Evaporator, 5. Fan, 6. Water tank, 7. Float, 8. Nozzles, 9. Temperature and Humidity gauges, 13. Strainer, 14. Pump, 15. Gauge, 16. Booster, 17. Pressure gauge, 18. Sentoid valve.

Fig. 12 Schematic of incorporated evaporative condenser.

It is causing dew. COP rose 110% with the evaporating condenser. It extends cooling unit life and saves 58% energy by decreasing temperature differential. The potential for equipment corrosion existed due to the direct induction of air-containing water droplets into the condensing unit.

Ertunc and Osoz [55] estimated evaporative condenser cooling system performance with ANNs. An experimental evaporative condenser cooling system was installed. ANN predictions matched experimental values with 1.90–4.18% relative errors. Manske et al. [56] studied how evaporative condenser operation affects refrigeration system performance. Evaporative condenser sizing, head pressure control, and results are presented in this study. The refrigeration system's modeling showed that design and control changes cut annual energy use by 11%.

Hwang et al. [57] conducted experiments on a novel evaporative condenser with tubes in a water bath (Fig. 13) and an air-cooled split heat pump condenser. System testing was done in an environmentally controlled chamber that simulated ASHRAE Standard conditions [58]. Air flows across disks partially submerged in the water bath as a motor rotates them. The disks are coated with a thin layer of water obtained from the bath to the air model. A water film evaporates into the air. Heat is inadmissible to the air stream and water bath through film and condenser tube evaporation. Evaporative condensers exhibit a capacity of 8.1% greater and a coefficient of performance of 21.6% higher than their cooled-by-air counterparts.

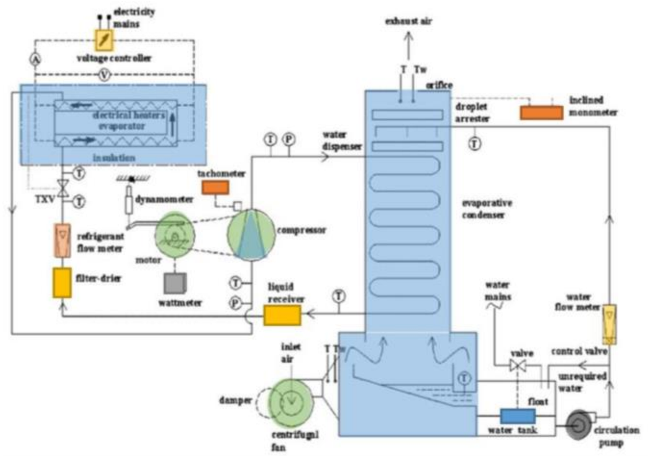
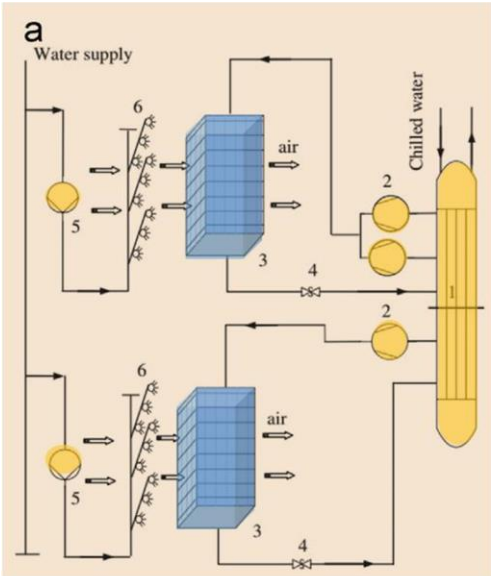


Fig. 13 A diagram illustrating the configuration of the experimental apparatus featuring an evaporative condenser.

A study by Hosoz and Kilicarslan [59] investigated the operational efficiency of refrigeration systems that employ air-cooling technology, water-cooled, and evaporative condensers.



1. chiller, 2. Lifting water pump, 3. Air-cooled condensed, 4. the valve, 5. Air-cooled Lifting water pump condenser pump, 6. The nozzles.

Fig. 14 (a) depicts A diagram illustrating the water vapor system, whereas (b) shows a snapshot with pertinent data.

Both systems utilized identical temperatures and conditions of condensation and evaporation. Fig. 14 shows the air-cooled, evaporative condenser experiment. Evaporative-condenser experiments demonstrated a 14.3% COP increase and a 31% reduction of compressor power over air-cooled condensers. Water-cooled condensers exhibited better refrigeration capacity (2.9-14.4%) and COP (1.5-10.2%) than evaporative condensers.

Yang et al. [60] the effectiveness of evaporating the mist of water prior to cooling on air-cooled chillers was examined. In a subtropical region to enhance efficiency. Figure 15 shows a water mist system schematic and photo. According to tests, water mist pre-cooling lowers the dry bulb temperature of the air entering the condenser by 9.38 °C from the air in the environment. Possible chiller (COP) improvement: 18.6%. According to the study, water mist systems with air-cooled chillers save energy and are environmentally friendly. Said water mist pre-cooling is rare in chillers. The water mist system was anticipated to gain popularity owing to its numerous advantages. A second study by Yu and Chan used water mist systems [61].

5.2.2. HVAC and pumps of heat

Islam et al. [62] the present study involved the modeling and experimental testing of a commercial AC system with an evaporative-cooled condensing coil. The evaporative-cooled AC unit has a 28.5 % larger COP than the traditional model. Evaporative-cooling condenser-based air-conditioning system COP was investigated by Wang et al. [63]. In Figure 15, an evaporative cooling device is upstream of the condenser. COP is inversely correlated with condenser inlet dry bulb temperature. Evaporative-cooling condenser pre-cooling increased saturation temperature reduction from 2.4 to 6.6 °C. Results showed increased evaporator refrigerant mass flow. The bulk increase in liquid entering the evaporator raised COP from 6.1% to 18%. Up to 14.3% power loss was also achieved on the compressor.

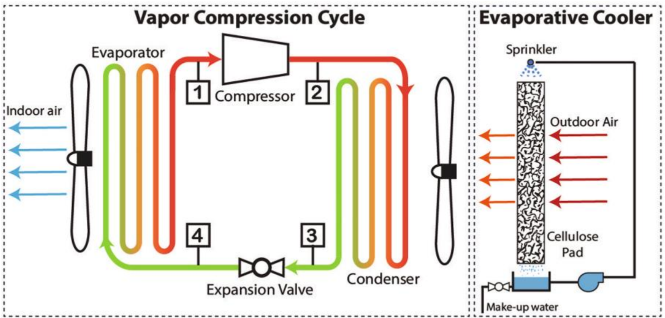


Fig. 15 the study focuses on an experimental AC system in which the condenser uses evaporative cooling. Higher dry bulb temperatures reduced power, but the cost-optimal temperature was 33.75 °C.

Pongsakorn and Thepa [64], An experimental and numerical investigation was conducted to determine the optimal operating methods, capillary tube length, and refrigerant charge for inverter air conditioners.

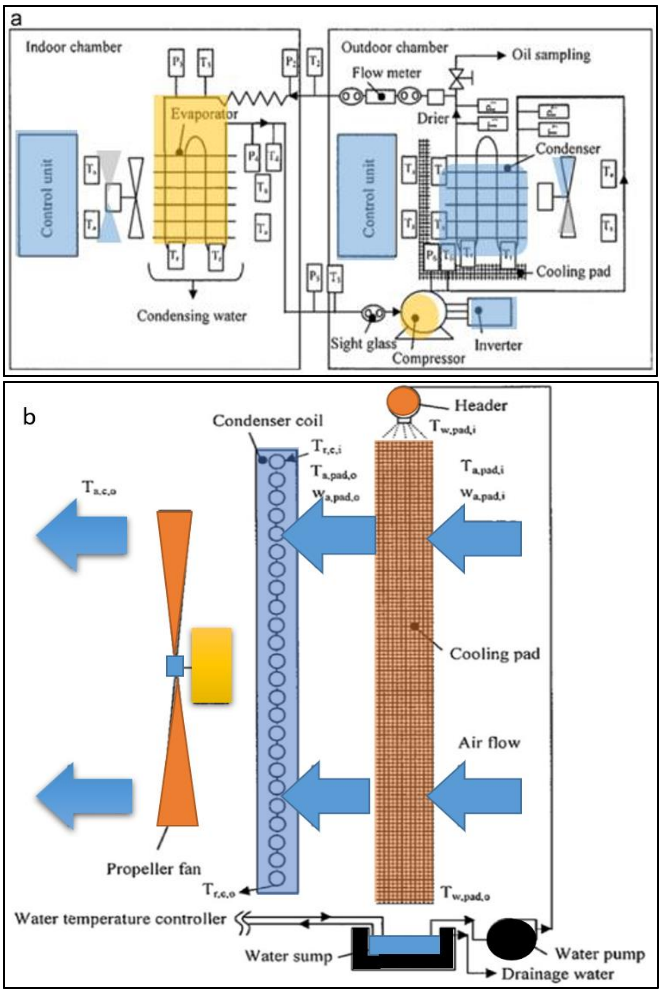


Fig. 16 shows the experimental setup (a) and the condensing unit-equipped evaporative cooling system (b).

Figures 16 (a) and (b) illustrate the experimental setup and condensing unit evaporative cooling system. The adaptive system was tested with different frequencies, water flow, and spraying temperature. At low frequencies, 200 l/h water injection provides the best COP at high frequencies 100. The models matched the test findings well.

Tolesa and Workneh [65] presented the steady-state with the isothermal model used to study airflow inside storage rooms subject to EC, CBAC, and EC+CBAC cooling. The results showed that the airflow distribution was not uniform inside the storage room under the three cooling methods. However, comparatively, EC+CBAC was found to be the best in informing air speed and distribution, which CBAC and EC, respectively, followed. The models were validated by comparing the experimental air speed with the calculated air speed at different locations inside the storage rooms.

Adarsh et al. [66] humidified coming air with a 1.5 Ton Refrigerant air conditioner with a cellulose pad between the condenser unit and the blower Fig. 17. The trial COP was 8.03, more than the typical split air conditioner value of 5.98. Lowered condenser air temperature improved air conditioner efficiency and reduced electricity use.

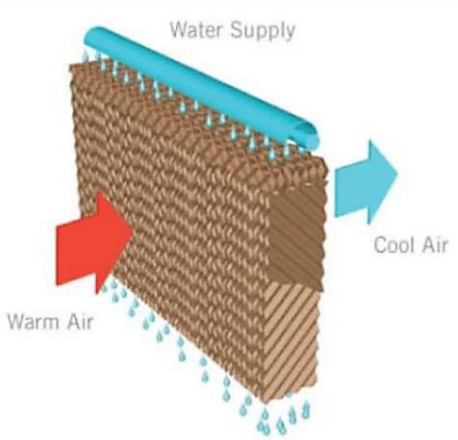


Fig. 17 Photograph of the cellulose pads.

Hajidavalloo and Eghtedari [67] examined how an evaporative-cooled air condenser affects a split-air conditioner. COP and power consumption were examined under varied ambient air conditions to estimate evaporative cooling's influence. Fig. 18 depicts the suggested system. A hot-weather evaporative-cooled air condenser can boost COP by 50%, and the rate rises with the temperature of the outside air. Their power utilization dropped 20%.

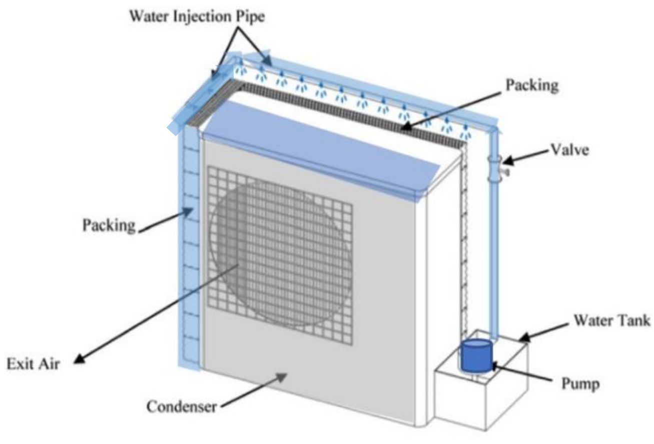


Fig. 18 Retrofitted condenser schematic.

In hot weather, Hajidavalloo [68] presented a media-pad design using evaporative cooling in a 1.5 Ton Refrigerant condenser to minimize window-type air conditioner condensing temperature. Water was injected into two cooling pads on each side of the air conditioner before transferring it to the condenser. Exchanging heat with hot air lowered cooling pad water droplets. Figure 19 shows the retrofitted AC. The new system's thermodynamic characteristics improved after the tests were conducted, reducing power usage by 16% and increasing COP by 55%.

Chainarong and Doungsong [69] used Indirect evaporative cooling to lower the energy use of a split-type home air conditioner. This unit cools the air utilizing a media for the pad-curving evaporative of the chiller. A water source, water sprayers, and a pump are also included Fig. 20. Front and inside cellulose-corrugated pad cool condensing unit air. Water curtain and spray add water to the air. Results showed that ambient conditions considerably impact COP and electricity consumption. Rising ambient temperature increases condensing pressure and electricity use, lowering COP. Air entering the condensing unit is greatly cooled by indirect evaporative cooling.

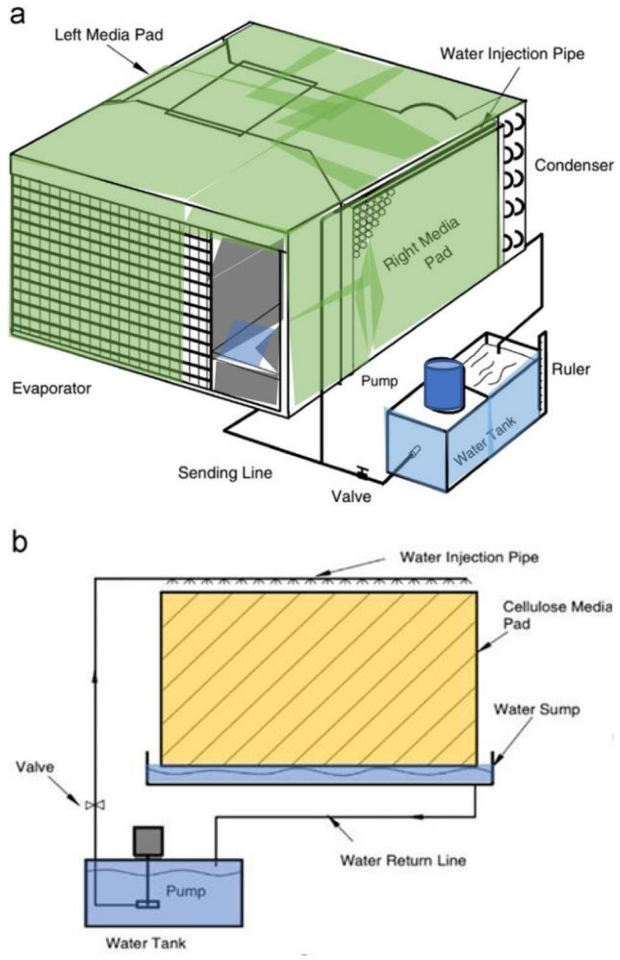


Fig. 19 Refitted air conditioner schematic (a) and evaporative media pad water circulation diagram (b).

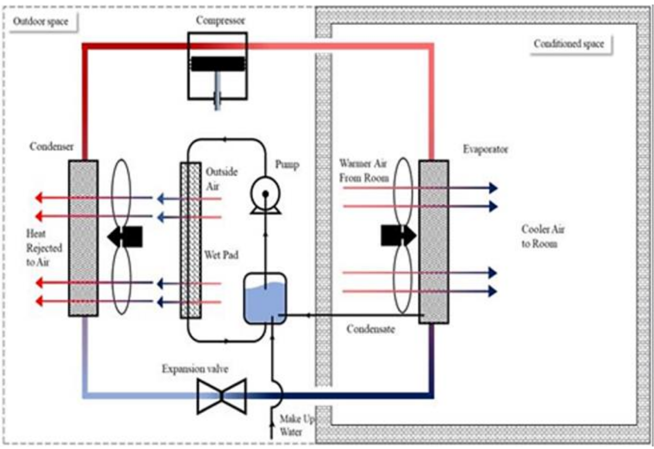


Fig. 20 the water distribution model of evaporation of the media of the pad.

Fig. 21 Hybrid air conditioner outdoor unit with storage.

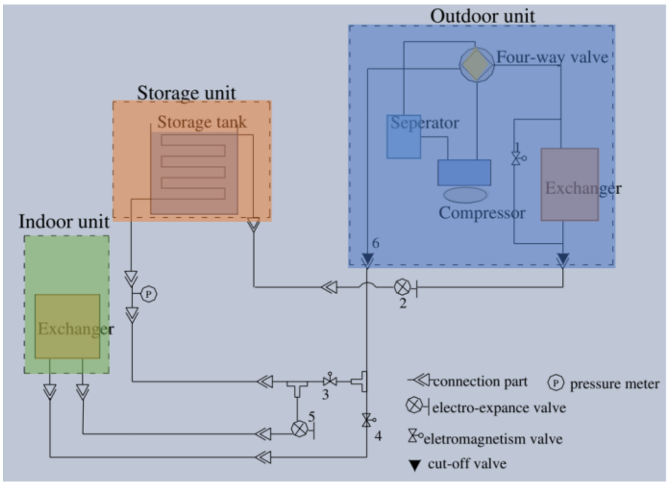


Fig. 22 Schematic diagram of ACWES.

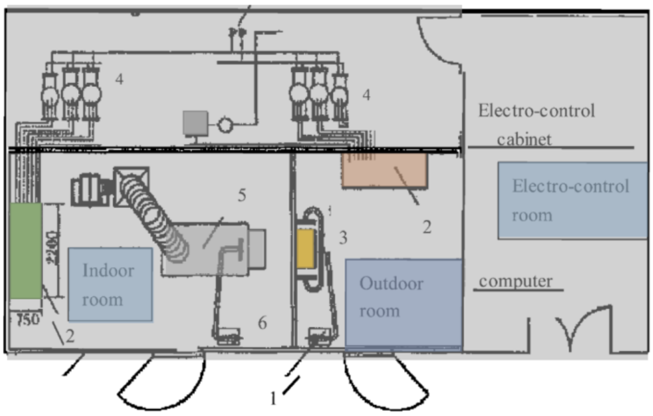


Fig. 23 Diagram of enthalpy difference lab: 1. temperature and humidity sampling system, 2. air parameters readjusting unit, 3. outdoor unit of the air conditioner to be tested, 4. cooling system, and 5. air flux measure.

Improves system performance. Water spray and cellulose cooling pad save the most energy. Evaporative cooling systems improve the Coefficient of Performance by 6–48% and reduce energy consumption by 4–15%. A year-round split air conditioner with energy storage and water heater was presented by Wang et al. [70]. Summer ice coils evaporate. Energy is stored in a reservoir that absorbs condenser heat. During heating, store winter heat. Picture of hybrid AC with storage units in Fig. 21, 22, 23. Over the old AC, they gained 28% cooling capacity and 21.5% COP. According to Goswami and Mathur [71], air-cooled condensers improve air conditioner performance. Air was cooled via evaporation before condensing. The media pad-type evaporative cooler, water source, and pumping have been added to an existing 2.5 TR (8.8 kW) AC condenser. The system's efficiency was measured with and without a condenser evaporating cooler. Evaporative-cooled condensers saved 20% more energy than ambient ones. They predicted energy savings may pay for condenser retrofitting in two years. Hajidavalloo [72] compared a 1.5 TR window-air conditioning system with a media pad evaporative cooling system in hot conditions. Water injection into the condenser cut electricity use by 10%.

6. Condenser-evaporative water evaporation

Evaporative condensers replace evaporation and air-stream water molecules with makeup water. The drift eliminators in the condenser get back most of the molecules that get stuck. So, this loss is usually low. Evaporative cooling loses the most water and is climate-zone-dependent. Hotter/dryer climates use more water. The following equation estimates evaporation-only water loss with 100% drift eliminators.

$$M_{weva} = Q_{latent}/\dot{h}_{fg} \tag{7}$$

Treated water is needed for evaporative condensers because pollutants create scaling and impede heat transfer. To prevent sump water mineral buildup, cooling water must be changed regularly. You can do this by purging the sump or using a bleed line to continuously drain water from the high-pressure side of the circulating pump. The review shows that an evaporative-cooled condenser can immediately reduce power consumption and improve cooling system performance. Most of the examined experiments modified air-cooled condensers to be evaporative-cooled. Some novel evaporative condenser designs have been shown. This study defines the refrigeration system's energy performance when cooled by air and evaporative-cooled condensation chambers as the ratio of cooling capacity (Qevap) to total power provided (consumed):

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

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

COPACC and COPEC were calculated. The percentage COP increase utilizing the evaporative-cooled condenser is,

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

Figures 24 and 25 compare the percentage increase in COP utilizing the evaporative cooled condenser (ϵ) and energy savings with cooling capacity. Evaporative-cooled condensers can enhance COP from 14.3 to 113.4% and reduce power consumption from 15 to 58% in systems with cooling capacities from 0.7 to 3000 kW.

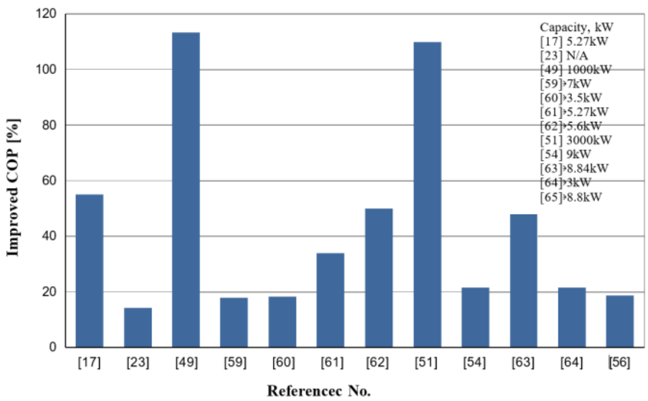


Fig. 24 COP improvement and cooling capacity research compared.

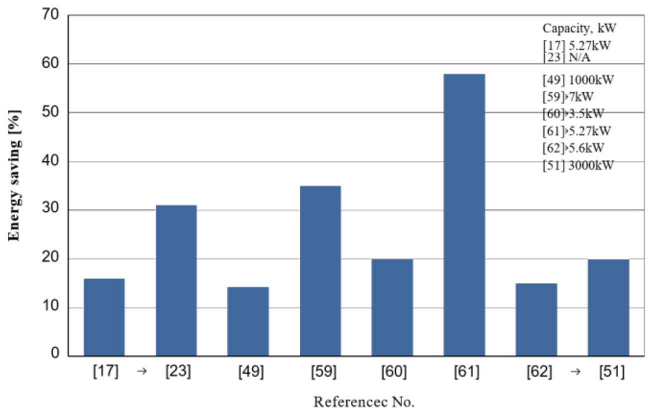


Fig. 25 Energy-saving and cooling capacity studies compared.

8. Conclusion

the study underscores the importance of energy conservation in the face of increasing global energy demand. Evaporative condenser technology emerges as a promising solution to enhance the efficiency of cooling systems, particularly in regions with high ambient temperatures. The comprehensive review of theoretical models, experimental studies, and achievements in the field provides valuable insights into the potential of evaporative condensers to reduce power consumption and improve the coefficient of performance in refrigeration and air conditioning systems. The findings suggest that incorporating evaporative cooling in condenser design can lead to significant energy savings and increased cooling capacity. The use of an evaporative condenser, as opposed to an air-cooled condenser, leads to a significant reduction of 58 % in power consumption and a notable improvement of 113.4 % in coefficient of performance (COP). However, challenges in accurately modeling evaporative condenser behavior highlight the need for further research and development in this area. Overall, the paper advocates for continued exploration of evaporative condenser technology as a viable and sustainable approach to address the growing energy demands of cooling systems.

Recommendations

The research focused on the topic of Evaporative Condenser Technology as a good solution for enhancing the efficiency of cooling systems, especially in regions with high ambient temperatures. The comprehensive review incorporated theoretical models, experimental studies, and achievements in the field to explore the potential of evaporative condensers in reducing power consumption and improving the coefficient of performance in refrigeration and air conditioning systems. A new technical approach for system improvement involved the integration of evaporative air coolers and window-type air conditioners, playing a crucial role in enhancing system efficiency. This integration was found to improve the performance of both air conditioning and evaporative air cooler units, leading to a reduction in the moisture content of the air leaving the system and the generation of fresh water. Notably, this technique aligns with references [51, 52].

References

[1] C. F. Gao, W. L. Lee, and H. Chen, “Locating room air-conditioners at floor level for energy saving in residential buildings,” Energy Conversion and Management, vol. 50, no. 8, pp. 2009–2019, Aug. 2009. https://doi.org/10.1016/j.enconman.2009.04.009

[2] Z. Xu, H. Wu, and M. Wu, “Energy performance and consumption for biogas heat pump air conditioner,” Energy, vol. 35, no. 12, pp. 5497–5502, Dec. 2010. https://doi.org/10.1016/j.energy.2010.01.040

[3] J. C. Lam, “Energy analysis of commercial buildings in subtropical climates,” Building and Environment, vol. 35, no. 1, pp. 19–26, Jan. 2000. https://doi.org/10.1016/s0360-1323(98)00067-5

[4] B. Choudhury, P. K. Chatterjee, and J. P. Sarkar, “Review paper on solar-powered air-conditioning through adsorption route,” Renewable and Sustainable Energy Reviews, vol. 14, no. 8, pp. 2189–2195, Oct. 2010. https://doi.org/10.1016/j.rser.2010.03.025

[5] H. Liu, Q. Zhou, Y. Liu, P. Wang, and D. Wang, “Experimental study on cooling performance of air conditioning system with dual independent evaporative condenser,” International Journal of Refrigeration, vol. 55, pp. 85–92, Jul. 2015. https://doi.org/10.1016/j.ijrefrig.2015.03.012

[6] M. M. Rahman and H. Y. Rahman, “Performance of Newly Developed Integrated Space Conditioning and Domestic Water Heating Device,” Journal of Energy and Environment, vol. 3, no. 1, Mar. 2013.

[7] K. A. Jahangeer, A. A. O. Tay, and Md. Raisul Islam, “Numerical investigation of transfer coefficients of an evaporatively-cooled condenser,” Applied Thermal Engineering, vol. 31, no. 10, pp. 1655–1663, Jul. 2011. https://doi.org/10.1016/j.applthermaleng.2011.02.007

[8] N. Kalkan, E. A. Young, and A. Celiktas, “Solar thermal air conditioning technology reducing the footprint of solar thermal air conditioning,” Renewable and Sustainable Energy Reviews, vol. 16, no. 8, pp. 6352–6383, Oct. 2012. https://doi.org/10.1016/j.rser.2012.07.014

[9] Wimolsiri P. Solar cooling and sustainable refrigeration, http://www.egi.kth.se/proj./courses/4A1623/files/ARHPTSustainRefrig2005WP.pdf

[10] J. C. Lam, “Residential sector air conditioning loads and electricity use in Hong Kong,” Energy Conversion and Management, vol. 41, no. 16, pp. 1757–1768, Nov. 2000. https://doi.org/10.1016/s0196-8904(00)00018-2

[11] T. T. Chow, Z. Lin, and X. Y. Yang, “Placement of condensing units of split-type air-conditioners at low-rise residences,” Applied Thermal Engineering, vol. 22, no. 13, pp. 1431–1444, Sep. 2002. https://doi.org/10.1016/s1359-4311(02)00068-6

[12] Y. A. Cengel, M. A. Boles, Thermodynamics: an engineering approach, 3rd edition, Boston, McGraw-Hill, 1998.

[13] N. Sharma and J. Singh, “Study and optimization of parameters of air-conditioner by using wastewater of water-cooler,” International Journal of Emerging Technology and Advanced Engineering, vol.4, Issue 8, pp. 513-518, 2014.

[14] R. J. Dossat, Principal of refrigeration, New Jersey, Prentice Hall, 1991.

[15] C. Backman et al., “Evaporative Condenser Lab and Field Test Results,” Jan. 2012.

[16] H. M. Ettouney, H. T. El-Dessouky, W. Bouhamra, and B. Al-Azmi, "Performance of Evaporative Condensers," Heat Transfer Engineering, vol. 22, no. 4, pp. 41–55, Jul. 2001. https://doi.org/10.1080/014576301750215797

[17] E. Hajidavalloo, "Application of evaporative cooling on the condenser of window-air-conditioner," Applied Thermal Engineering, vol. 27, no. 11–12, pp. 1937–1943, Aug. 2007. https://doi.org/10.1016/j.applthermaleng.2006.12.014

[18] W. K. Brown, "Fundamental concepts integrating evaporative techniques in HVAC systems", ASHRAE Trans, vol. 96, Part 1, pp. 1227-1235, 1990.

[19] K. A. Manske, "Performance optimization of industrial refrigeration systems", M.Sc. thesis, Mechanical Engineering, Solar Energy Laboratory, University of Wisconsin Madison, United States, 1999.

[20] A. I. ElSherbini and G. P. Maheshwari, "Impact of shading air-cooled condensers on the efficiency of air-conditioning systems," Energy and Buildings, vol. 42, no. 10, pp. 1948–1951, Oct. 2010. https://doi.org/10.1016/j.enbuild.2010.05.031

[21] V. Vakiloroaya, B. Samali, and K. Pishghadam, "A comparative study on the effect of different strategies for energy saving of air-cooled vapor compression air conditioning systems," Energy and Buildings, vol. 74, pp. 163–172, May 2014. https://doi.org/10.1016/j.enbuild.2014.01.042

[22] E. Bari, J.-Y. Noël, G. Comini, and G. Cortella, "Air-cooled condensing systems for home and industrial appliances," Applied Thermal Engineering, vol. 25, no. 10, pp. 1446–1458, Jul. 2005. https://doi.org/10.1016/j.applthermaleng.2004.10.004

[23] M. Hosoz and A. Kilicarslan, "Performance evaluations of refrigeration systems with air-cooled, water-cooled and evaporative condensers," International Journal of Energy Research, vol. 28, no. 8, pp. 683–696, May 2004. https://doi.org/10.1002/er.990

[24] D. Murphy, "Cooling towers for free cooling", ASHRAE Journal, pp. 16-26, 1991.

[25] H. Goshayshi, J. F. Missenden, R. Tozer, G. G. Maidment, "Improving cooling tower performance for sustainable refrigeration", Proceedings of Joint CIBSE/ ASHRAE Conference, 2000

[26] T. D. Saulles, Free cooling system: design and application guidance, Bracknell UK: BSRIA; Volumes 16-96, 1996.

[27] H. Chen, W. L. Lee, and F. W. H. Yik, "Applying water cooled air conditioners in residential buildings in Hong Kong," Energy Conversion and Management, vol. 49, no. 6, pp. 1416–1423, Jun. 2008. https://doi.org/10.1016/j.enconman.2007.12.024

[28] K. Sreejith, S. Sushmitha, and V. Das, "Experimental investigation of a household refrigerator using an air-cooled and water-cooled condenser", International Journal of Engineering and Science, vol. 4, Issue 6, pp. 13-17, 2014.

[29] S. S. Hu and B. J. Huang, "Study of a high efficiency residential split water-cooled air conditioner," Applied Thermal Engineering, vol. 25, no. 11–12, pp. 1599–1613, Aug. 2005. https://doi.org/10.1016/j.applthermaleng.2004.11.011

[30] Y. Chang, R. Tsai, and J.-W. Hwang, "Condensing heat transfer characteristics of aluminum flat tube," Applied Thermal Engineering, vol. 17, no. 11, pp. 1055–1065, Nov. 1997. https://doi.org/10.1016/s1359-4311(97)00011-2

[31] ASHRAE, HVAC systems and equipment handbook, Atlanta, GA: ASHRAE, Inc.; 1992.

[32] E. Hajidavalloo, "Increasing COP of window air conditioner in very hot weather of Khoozestan", Research Project Report to Management and Programming Organization, 2001.

[33] D. D. Wile, "Evaporative condenser performance factors", Refrigeration Engineering, Vol. 58, pp. 55-63, 1950.

[34] W. Goodman, "The evaporative condenser, Heating, Piping and Air Conditioning", Vol. 10, pp. 165-168, 1938.

[35] E. G. Thomsen, "Heat transfer in an evaporative condenser", Refrigeration Engineering, vol. 5, pp. 425-443, 1946.

[36] R. O. Parker, R. F. Treybal, "The heat, and mass transfer of evaporative coolers", Chemical Engineering Progress Symposium Series, vol. 57, 1961.

[37] D. Peterson, D. Glasser, D. Williams, and R. Ramsden, "Predicting the Performance of an Evaporative Condenser," Journal of Heat Transfer, vol. 110, no. 3, pp. 748–753, Aug. 1988. https://doi.org/10.1115/1.3250555

[38] A. A. Dreyer, "Analysis of evaporative coolers and condensers", M.Sc. thesis, University of the Stellenbosch, Rep of South Africa, 1988.

[39] M. Poppe, H. R. Gener, Evaporative cooling systems, VDI Warm eatlas, Section Mh, 1984.

[40] T. Mizushina, R. Ito, H. Miyashita, "Experimental study of an evaporative cooler", International Journal of Chemical Engineering, vol. 7, pp. 727-732, 1967.

[41] T. Mizushina, R. Ito, and H. Miyashita, "Characteristics and Methods of Thermal Design of Evaporative Cooler," Kagaku kōgaku, vol. 32, no. 1, pp. 55-61, a1, Jan. 1968. https://doi.org/10.1252/kakoronbunshu1953.32.55

[42] A. Bykov, B. A. Гоголин, and N. V. Tovaras, "Investigation of heat, mass transfer and fluid flow characteristics in evaporative condensers," vol. 7, no. 6, pp. 342–347, Nov. 1984. https://doi.org/10.1016/0140-7007(84)90003-3

[43] F. W. Yu and K. T. Chan, "Application of Direct Evaporative Coolers for Improving the Energy Efficiency of Air-Cooled Chillers," Journal of Solar Energy Engineering, vol. 127, no. 3, pp. 430–433, Jul. 2005. https://doi.org/10.1115/1.1866144

[44] B. A. Qureshi and S. M. Zubair, "A comprehensive design and rating study of evaporative coolers and condensers. Part I. Performance evaluation," International Journal of Refrigeration, vol. 29, no. 4, pp. 645–658, Jun. 2006. https://doi.org/10.1016/j.ijrefrig.2005.09.014

[45] X. Hao, C. Zhu, Y. Lin, H. Wang, G. Zhang, and Y. Chen, "Optimizing the pad thickness of evaporative air-cooled chiller for maximum energy saving," Energy and Buildings, vol. 61, pp. 146–152, Jun. 2013. https://doi.org/10.1016/j.enbuild.2013.02.028

[46] W. Zalewski and P. Gryglaszewski, "Mathematical model of heat and mass transfer processes in evaporative fluid coolers," vol. 36, no. 4, pp. 271–280, Jul. 1997. https://doi.org/10.1016/s0255-2701(97)00006-8

[47] H. Salah, M. A. Youssef, "Theoretical model for a rotating disk evaporative con-denser used in a split air conditioner", Journal of Engineering Technology, vol. 32, pp. 1-20, 2013.

[48] M. Youbi-Idrissi, H. Macchi-Tejeda, L. Fournaison, and J. Guilpart, "Numerical model of sprayed air cooled condenser coupled to refrigerating system," Energy Conversion and Management, vol. 48, no. 7, pp. 1943–1951, Jul. 2007. https://doi.org/10.1016/j.enconman.2007.01.025

[49] F. W. Yu and K. T. Chan, "Improved condenser design and condenser-fan operation for air-cooled chillers," Applied Energy, vol. 83, no. 6, pp. 628–648, Jun. 2006. https://doi.org/10.1016/j.apenergy.2005.05.007

[50] M. M. Nasr and M. S. Hassan, "Experimental and theoretical investigation of an innovative evaporative condenser for residential refrigerator," Renewable Energy, vol. 34, no. 11, pp. 2447–2454, Nov. 2009. https://doi.org/10.1016/j.renene.2009.03.008

[51] 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://doi.org/10.31663/tqujes.10.1.357(2019)

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

[53] A. A. Eidan, K. J. Alwan, A. AlSahlani, and M. Alfahham, "Enhancement of the Performance Characteristics for Air-Conditioning System by Using Direct Evaporative Cooling in Hot Climates," Energy Procedia, vol. 142, pp. 3998–4003, Dec. 2017. https://doi.org/10.1016/j.egypro.2017.12.311

[54] M. Gr. Vrachopoulos, A. E. Filios, G. T. Kotsiovelos, and E. D. Kravvaritis, "Incorporated evaporative condenser," Applied Thermal Engineering, vol. 27, no. 5–6, pp. 823–828, Apr. 2007. https://doi.org/10.1016/j.applthermaleng.2006.09.021

[55] H. M. Ertunc and M. Hosoz, "Artificial neural network analysis of a refrigeration system with an evaporative condenser," Applied Thermal Engineering, vol. 26, no. 5–6, pp. 627–635, Apr. 2006. https://doi.org/10.1016/j.applthermaleng.2005.06.002

[56] K. A. Manske, D. T. Reindl, and S. A. Klein, "Evaporative condenser control in industrial refrigeration systems," International Journal of Refrigeration, vol. 24, no. 7, pp. 676–691, Jul. 2001. https://doi.org/10.1016/s0140-7007(00)00084-0

[57] Y. Hwang, R. Radermacher, and W. Kopko, "An experimental evaluation of a residential-sized evaporatively cooled condenser," International Journal of Refrigeration, vol. 24, no. 3, pp. 238–249, May 2001. https://doi.org/10.1016/s0140-7007(00)00022-0

[58] American Society of Heating, Refrigeration, and Air Conditioning Engineers, Inc. Methods of testing for seasonal efficiency of unitary air conditioners and heat pumps (ASHRAE Standard ANSI/ASHRAE 116-1995). Atlanta (GA).

[59] M. Hosoz and A. Kilicarslan, "Performance evaluations of refrigeration systems with air-cooled, water-cooled and evaporative condensers," International Journal of Energy Research, vol. 28, no. 8, pp. 683–696, May 2004. https://doi.org/10.1002/er.990

[60] J. Yang, K. T. Chan, X. Wu, X. Yang, and H. Zhang, "Performance enhancement of air-cooled chillers with water mist: Experimental and analytical investigation," Applied Thermal Engineering, vol. 40, pp. 114-120, 2012. https://doi.org/10.1016/j.applthermaleng.2012.02.001

[61] F. W. Yu and K. T. Chan, "Modelling of improved energy performance of air-cooled chillers with mist pre-cooling," International Journal of Thermal Sciences, vol. 48, no. 4, pp. 825–836, Apr. 2009. https://doi.org/10.1016/j.ijthermalsci.2008.06.016

[62] M. R. Islam, K. A. Jahangeer, and K. J. Chua, "Experimental and numerical study of an evaporatively-cooled condenser of air-conditioning systems," Energy, vol. 87, pp. 390–399, Jul. 2015. https://doi.org/10.1016/j.energy.2015.05.005

[63] T. Wang, C. Sheng, and A. G. A. Nnanna, "Experimental investigation of air conditioning system using evaporative cooling condenser," Energy and Buildings, vol. 81, pp. 435–443, Oct. 2014. https://doi.org/10.1016/j.enbuild.2014.06.047

[64] P. Sarntichartsak and S. Thepa, "Modeling and experimental study on the performance of an inverter air conditioner using R-410A with evaporatively cooled condenser," Applied Thermal Engineering, vol. 51, no. 1-2, pp. 597–610, Mar. 2013. https://doi.org/10.1016/j.applthermaleng.2012.08.063

[65] G. N. Tolesa and T. S. Workneh, "CFD modeling of airflow inside unloaded evaporative cooler, Coolbot-air-conditioner and combined operations," Acta Horticulturae, no. 1275, pp. 293–302, Mar. 2020. https://doi.org/10.17660/actahortic.2020.1275.40

[66] M. D. Adarsh, D. Aditya, V. Akshay, "Improving efficiency of the air conditioner by cellulose pad", Int J Eng. Sci Humanit, vol. 3, 2013.

[67] E. Hajidavalloo and H. Eghtedari, "Performance improvement of air-cooled refrigeration system by using evaporatively cooled air condenser," International Journal of Refrigeration, vol. 33, no. 5, pp. 982–988, Aug. 2010. https://doi.org/10.1016/j.ijrefrig.2010.02.001

[68] E. Hajidavalloo, "Application of evaporative cooling on the condenser of window-air-conditioner," Applied Thermal Engineering, vol. 27, no. 11–12, pp. 1937–1943, Aug. 2007. https://doi.org/10.1016/j.applthermaleng.2006.12.014

[69] C. Chaktranond, P. Doungsong, "Energy saving in a domestic spilt-type air conditioner with evaporative cooling system", Department of Mechanical Engineering, Faculty of Engineering, Thammasat University, Thailand.

[70] Wanga S, Liua Z, Lib Y, Zhaob K, Wangb Z. Experimental study on split air conditioner with new hybrid equipment of energy storage and water heater all year round. Energy Convers Manag. 2005; 46:3047 30. Engineering, Thammasat University, Thailand, 2009.

[71] 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," Journal of Solar Energy Engineering, vol. 115, no. 4, pp. 206–211, Nov. 1993. https://doi.org/10.1115/1.2930051

[72] E. Hajidavalloo, "Increasing COP of window air conditioner in very hot weather of Khoozestan", Research Project Report to Management and Programming Organization, 2001.