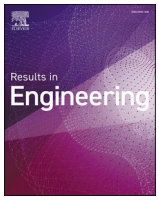
Results in Engineering 18 (2023) 101059



Contents lists available at ScienceDirect

Results in Engineering

journal homepage: www.sciencedirect.com/journal/results-in-engineering



Review article



A comprehensive review on evaporative cooling systems

N. Kapilan [a,*], Arun M. Isloor [b], Shashikantha Karinka [c]

[a] Department of Mechanical Engineering, Nitte Meenakshi Institute of Technology, Bangalore, 560064, Karnataka, India
[b] Department of Chemistry, National Institute of Technology, Srinivasnagar, 575025, Karnataka, India
[c] NITTE (Deemed to Be University), Dept. of Mechanical Engineering, NMAM Institute of Technology, Nitte, 574110, Karnataka, India

ARTICLE INFO

Keywords:
Alternative cooling
Evaporative cooling
Types
Performance
Natural fiber

ABSTRACT

The evaporative cooling system (ECS) is one of the cheapest and oldest cooling technologies. The conventional single stage ECS is most widely used in domestic application, particularly in hot and dry regions. However, in this system, the temperature of the air cannot be reduced below the wet bulb temperature of the air. The multistage ECS system helps to overcome this problem. The combination of direct and indirect ECS helps to reduce the temperature of the air below its wet bulb temperature. The further reduction in air temperature may be achieved with the help of the cooling coil driven by vapour compression system. The energy consumed by the ECS is lower as compared to vapour compression refrigeration system. The ECS can be driven with the help of solar power. The conventional cooling pad used in ECS can be replaced with locally available natural fibers to reduce initial cost and to reduce dependence on import of cooling pads. The performance of the ECS can be improved with the help of heat pipe. Various techniques are used to enhance ECS's performance. The performance of the vapour compression refrigeration system can be improved with the help of ECS. This paper discusses basics and types of ECS, methods used to increase the performance of ECS, types of natural fiber cooling pad material, process variables affecting ECS, recent technical advancements, challenges and opportunities.

1. Introduction

The global energy requirement has increased exponentially from 8588 to 13,147 million tonnes from 1995. In energy polices of any country, the energy performance is considered as one of the important key pillars as it helps in the sustainable development of the country. The low energy consumption devices reduce the energy requirement and carbon footprint and directly improves the energy security. It is reported that the fossil fuels are the main source of primary energy and it is equal to about to 80%. The various government agencies such as the WEC, OPEC etc have done several forecasting studies related to global energy. The countries growth depends upon the energy sector and as it directly influences the manufacturing activities. However, the energy sector also directly and indirectly affects the sustainability and environment [1].

The population growth and climate change will be driving force in the energy requirement. The technology is driven by the renewable energy, gas and oil sectors and economics of any country in recent years [2]. The economic growth of any country depends upon the availability of energy resources. The availability of energy sources for longer periods will enhance the economic growth of any country. It is estimated that the world energy consumption may expand by 50%, during the years 2005–2030. It is also reported that the developing countries such as China and India will be key energy consumers in the future [3]. Internal combustion engines are most widely used for various industrial and automotive applications and the increase in number of engines may increase the emissions. The use of fossil fuels to produce energy increases greenhouse gas emissions as well as global warming. Hence, many researchers are carrying out studies to find suitable renewable fuels. Recent research is focused on development of energy sources which are of sustainable and renewable. In few countries, renewable energy sources such as wind, biofuel, solar, geothermal etc gradually replacing the non-renewable energy sources. It is suggested that the biofuels can be substitute for the petroleum fuels as it is renewable and helps in sustainability [4]. The ozone depletion is high in the last few decades and refrigerants used in air-conditioning and refrigeration system is one of the major reasons for the same [5]. The ECS is considered as substitute for the vapour compression-based cooling systems.

In general, compressor-based cooling systems like air conditioners consume more energy than non-compressor-based cooling systems. This

* Corresponding author.
E-mail address: kapil_krecmech@yahoo.com (N. Kapilan).

https://doi.org/10.1016/j.rineng.2023.101059
Received 7 January 2023; Received in revised form 18 March 2023; Accepted 27 March 2023
Available online 31 March 2023
2590-1230/© 2023 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

is because they use electricity to power the compressor, which pumps refrigerant through the system to cool the air. The non-compressor-based system such as ECS causes lower environmental degradation with satisfactory cooling performance [6]. An efficient water spray system can improve the cooling effect and efficiency of an ECS as the spray system increases the surface area of the water that is exposed to the air, which enhances the heat transfer from the air to the water and literature reveals several numerical and experimental work related to this aspect [7]. Various cooling pad designs are developed and among all these designs, best one is honeycomb design which provides better surface area for water evaporation [8]. The vapour compression refrigeration system reduces both the humidity and temperature of the air. However, the ECS increases humidity and reduces temperature of the air. Hence ECS can be used for storing of agriculture products, fruits etc, which does not require very low temperature [9].

It is reported that the shelf life of the agricultural products and fruits such as tomato, potato, mango, grapes, orange, santara, sapota, banana, plums, aonla, bitter gourd, capsicum, cauliflower, pineapple, peach, green pepper, cluster bean, brinjal, cucumber, chili, ladies finger, beat, peas, carrot, radish and leafy vegetables [10–12] increased with the ECS. The ECS are widely used in domestic, industrial applications such as manufacturing process, greenhouses, poultries etc in hot climates [13]. Hence ECS may be called as sustainable cooling system and can be used for various domestic and industrial applications and for the short term and long-term preservation of vegetables, fruits etc.

The motivation behind writing a review paper on ECS as a replacement for conventional cooling system is to explore the potential benefits of using ECS in various applications. Vapour compression systems are widely used in air conditioning and refrigeration systems, but they have several disadvantages, including high energy consumption, high maintenance costs, and environmental concerns. The ECS, on the other hand, are relatively simple, efficient, and cost-effective, making them an attractive alternative to conventional cooling system. By reviewing the existing literature and research on evaporative cooling systems, this paper aims to provide a comprehensive analysis of the advantages and limitations of these systems and their potential applications.

The paper will also discuss the technological advancements in ECS and how they can be used to replace traditional vapour compression systems in various settings, such as residential and commercial applications. Also, various natural materials which can be used as replacement to conventional cooling pad materials. Overall, the review paper on evaporative cooling systems as a replacement for vapour compression systems seeks to provide valuable insights and recommendations for researchers, engineers, and policymakers on how to adopt this technology to reduce energy consumption and improve sustainability in various sectors. The research papers related to ECS were searched in various databases and 175 papers were chosen and included in this paper.

1.1. Types of evaporative cooling system

The ECS is classified into three types [14] and is shown in Fig. 1.

1. Direct ECS (DECS)
2. Indirect ECS (IECS)
3. Multistage ECS

It is suggested that the COP of the ECS is about 15–20 and this value is higher than other refrigeration methods such as vapour compression, vapour absorption and thermoelectric cooling systems [15].

1.2. Direct evaporative cooling system (DECS)

The direct ECS is one of the popular ECS and its design is simple. A direct ECS consists of fan or blower, water tank, pump, wettable evaporative media and water distribution system. Fig. 2 shows the schematic of the same. The cost and efficiency of this system is better than other types of ECS. In this ECS, there is a direct contact between the water and air. The water is sprayed into the air in the form of fine droplets. These droplets absorb the heat from the air and changes phase from liquid to vapour phase. This heat absorption reduces the temperature of air and increases the humidity of the air due to evaporation of water. In this ECS, the evaporation process is the adiabatic cooling process and the enthalpy of the air remains constant during this process. The sensible heat of supply air is absorbed by the water and the air temperature decreases. The humidity of air increases due to evaporation of water in the air stream. The cooling effect produced by the ECS is good, however the power consumption of this ECS is very low as compared to the conventional refrigeration system. This type of ECS is suitable for dry and hot climates. In moist environment, the relative humidity may reach 80% and this high humidity is not suitable for building as it may cause

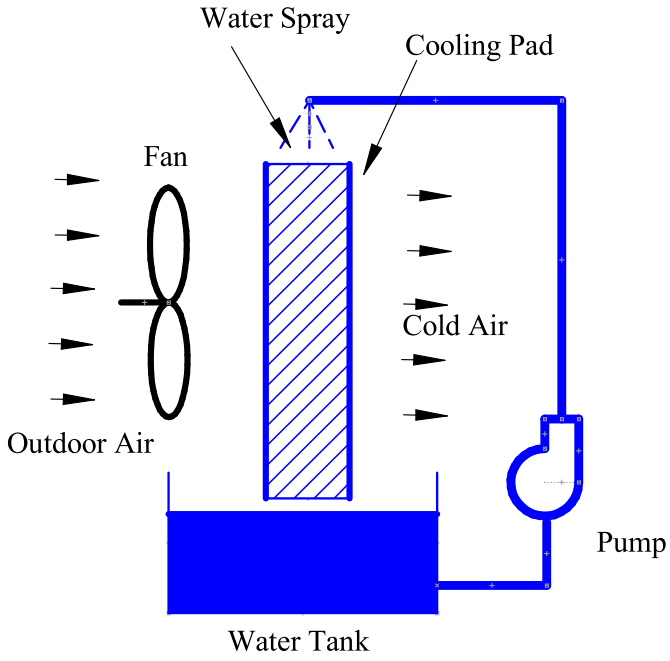


Fig. 2. Direct ECS

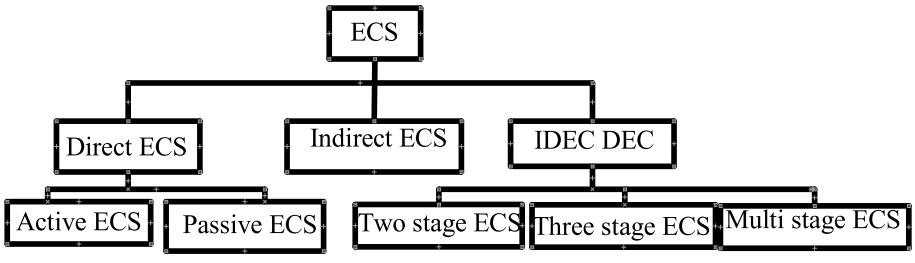


Fig. 1. Types of ECS

rusting of metallic components made of iron, warping etc [14–17].

In direct ECS, the temperature of the air cannot be cooled below the wet-bulb temperature. It is reported that the wet-bulb effectiveness of this type of system is about 70–95% and depends on flowrate of air, weather condition, type of application, evaporative pad thickness etc. The direct ECS is divided into active and passive ECS. The active direct ECS are driven by the electrical devices. The passive direct ECS is naturally driven system with power consumption is negligible [15–17].

1.3. Types of direct ECS

a) Active ECS

The active direct ECS are driven by electrical systems for the circulation of air and water. The electrical energy required for this type of ECS is small as compared to conventionally used vapour compression system. Hence this type of ECS is considered as less energy intensive system and there is a possibility in energy saving up to 90% [18].

b) Passive ECS

The passive ECS does not require energy to drive the system and use natural phenomena. However, it may require small capacity fan or pumps. This type of system depends upon climate condition. It is reported that this type of system can reduce indoor air temperature by about 9 °C [19].

1.3.1. Indirect evaporative cooling system (IECS)

In IECS, temperature of the air is reduced without varying the humidity. This is the advantage of this ECS over direct ECS. The main components of this type of ECS are fan, pump, water tank, water distribution system and indirect heat exchanger. Fig. 3 shows the schematic of the indirect ECS. It is reported that the effectiveness of this type of ECS is lower than the direct ECS [15–17].

1.4. Two-stage; indirect-direct evaporative cooling system (IDECS)

The effectiveness of the direct ECS is higher than the indirect ECS, however the direct ECS results in lower effectiveness in high humid condition. The combination of indirect ECS and direct ECS or in conjunction with other cooling technologies to get better performance. This system results in higher cooling capacity, better humidity control, higher efficiency etc as compared to sole operation. This makes this type of system is an alternative to conventional cooling system to reduce global warming and ozone layer depletion. The important parts of this type of ECS are evaporative cooling pad, indirect heat exchanger, water tanks, blower, water circulation system etc. Fig. 4 shows the indirect-direct ECS [15–17].

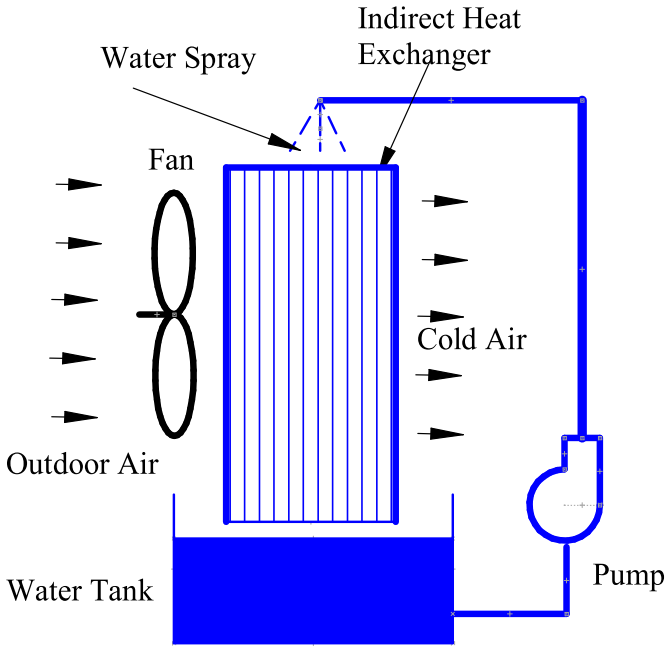


Fig. 3. Indirect ECS

It is reported that the effectiveness of this type of systems is about 90–115%. However, the main drawback of this type of systems are complex design, higher initial cost. The two-stage ECS consists of Indirect ECS stage followed by a direct ECS stage. The first indirect stage ECS cools the outdoor air and then this air can flow through a direct stage for further cooling. In this system, it is possible to cool the air below its wet-bulb temperature. The effectiveness of this type of ECS is high, however, requirement of water increases to about 55% [20,21].

1.5. Three-stage evaporative cooling system

This type of ECS consists of two-stage IDECS and a cooling cycle which produces low temperature. Similarly, a direct and/or indirect ECS can be integrated with solid desiccant dehumidification system. It is reported that the COP of this system is about 20. The combinations can be changed to meet the requirements or applications. It is reported that the sensible and adiabatic cooling can be provided by indirect ECS and a direct ECS system and integrating it with a desiccant system for dehumidification can reduce energy requirements and there is an energy saving is about 54–82% as compared to conventional cooling system [22,23]. Figs. 5 and 6 shows multistage ECS with desiccant wheel or cooling coil.

1.6. Types of pad materials

In ECS, the evaporative cooling pads are wetted with water continuously and air is flows through the surface of the cooling pad. The wetted cooling pad results in mass and heat transfer between water and air. The ideal requirements of ECS cooling pads are minimum pressure drop, higher wetted water-to-air contact surfaces, easy to clean, assemble and dismantle and maintenance. For coarse sponge mesh, recommended air velocity is 0.75 m/s and 1.50 m/s [24]. The quality and type of pad materials affects the efficiency of the ECS. The cooling pad is made of natural and synthetic materials. The materials such as sand, clay, brick bats, date palm fibres and leaves, clay, wood saving, sack, saw dust, wheat straw, jute, ploy vinyl chloride sponge, morum, pumice stone, coconut coir, rice husk, charcoal, cotton fabric, green house shedding net can be used to manufacture the cooling pad. It is reported that the cooling pad performance depends on outdoor humidity, temperature and weather. The cooling pad materials which has good air-water contact and better porosity provides better performance as compared to other type of materials. The enhancement in cooling efficiency of the cooling pad can be done by increasing the pad density and pad thickness at certain level with proper water flow rate and pad-face velocity, then decreases for a specific material. Hence the design of pad density, pad thickness, air flow rate and water flow rate should be good to get better performance. Few researchers used rice husk and recycled polyethylene which has high-density as a wetted pad in ECS [9,25]. It is suggested that the materials which are easily available local areas can be used as cooling pad material to reduce the operating cost [26,27].

1.6.1. Natural fibers

The natural fibers available in local area can be used to manufacture the cooling pad and discussed below.

1.6.1.1. Aspen. The aspen cooling pads looks like grass and are made up

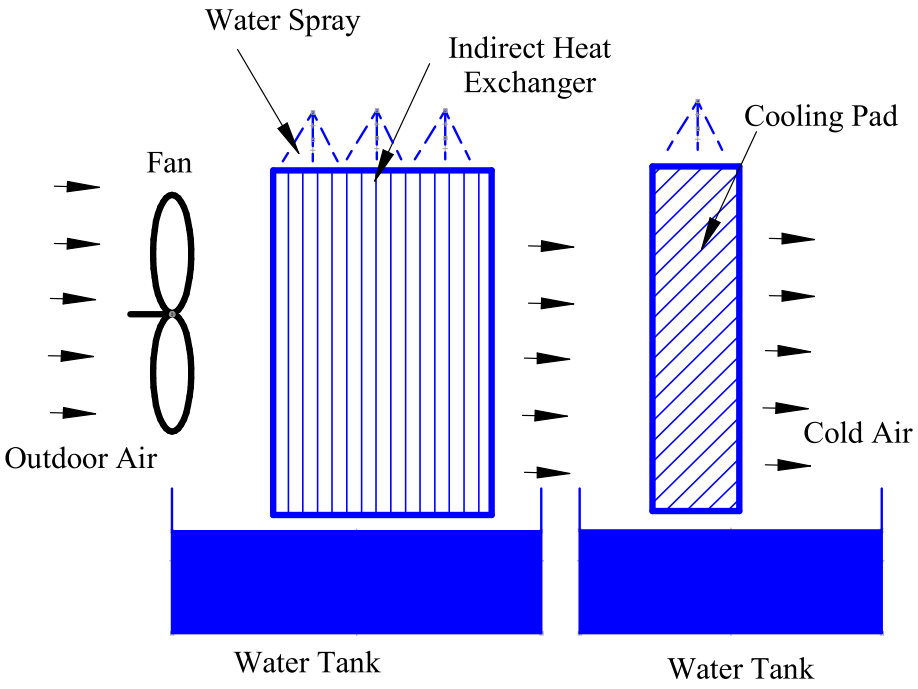


Fig. 4. Two stage (combination of indirect and direct) ECS.

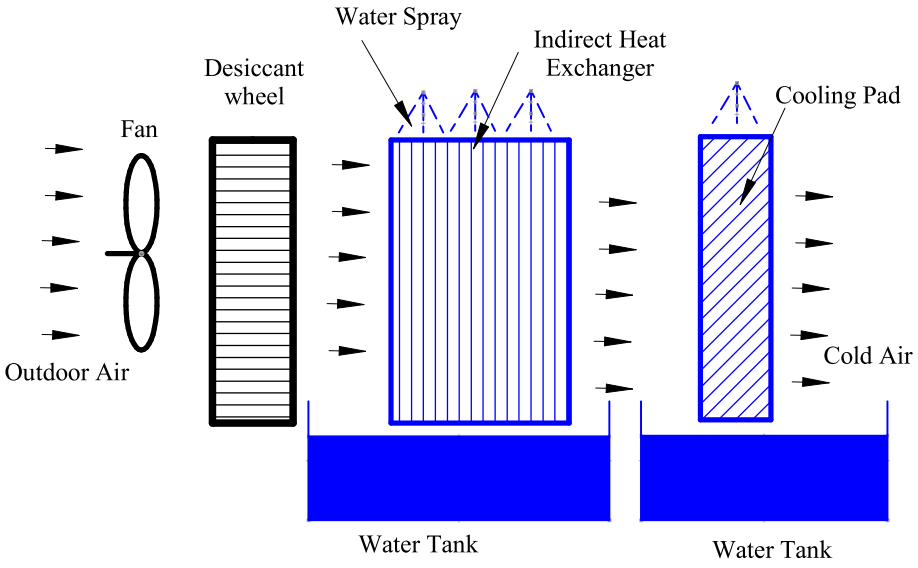


Fig. 5. Multistage ECS with desiccant system.

of wood shavings and synthetic fibre. This type of natural fibers is cheap and hence economical and reduces the cost of the ECS. This type of fibers needs higher maintenance and less durable. The cooling effect produced by this type of pads are moderate and generally less effective compared to the home comb cooling pads [28]. It is reported that the aspen pad results in higher pressure drop as compared to khus, palash and coconut. This fiber gives saturation effectiveness of about 72% and the pressure drop of about 49 N/mm^2 [29].

1.6.1.2. Coconut. The coconut coir is the fibrous material which is located between the outer and internal shell and it processed to use as cooling pad materials. Several researchers successfully used coconut coir as cooling pad material in ECS. It results highest cooling efficiency of about 85% [30]. The experimental work carried out with coconut coir and with the air supply velocity between 1.88 and 2.79 m/s, provides satisfactory efficiency as compared to commercial paper pad. It is also reported that the pressure drop of coconut coir pad was about 5.1 Pa. The outlet temperature of the air leaving the coconut pad varies from 23 to 28° [31].

1.6.1.3. Palm. The palm fiber is a leaf fiber extracted from the dwarf palm leaf and the palm fruit fiber also can be used as cooling media in the ECS [32,33]. This fiber results in cooling efficiency of about 39% and this fiber can be used as cooling pad materials where the palm trees are available as the operating cost is negligible [32]. However, palm fiber cooling pad thickness and mass per unit volume has to be optimized before commercially using it in ECS. It is reported that the palm fiber results in better performance as compared to rice straw. Also, relative humidity produced by palm fiber is low as compared to rice straw. The highest cooling efficiency obtained with this type of fiber is about 67%

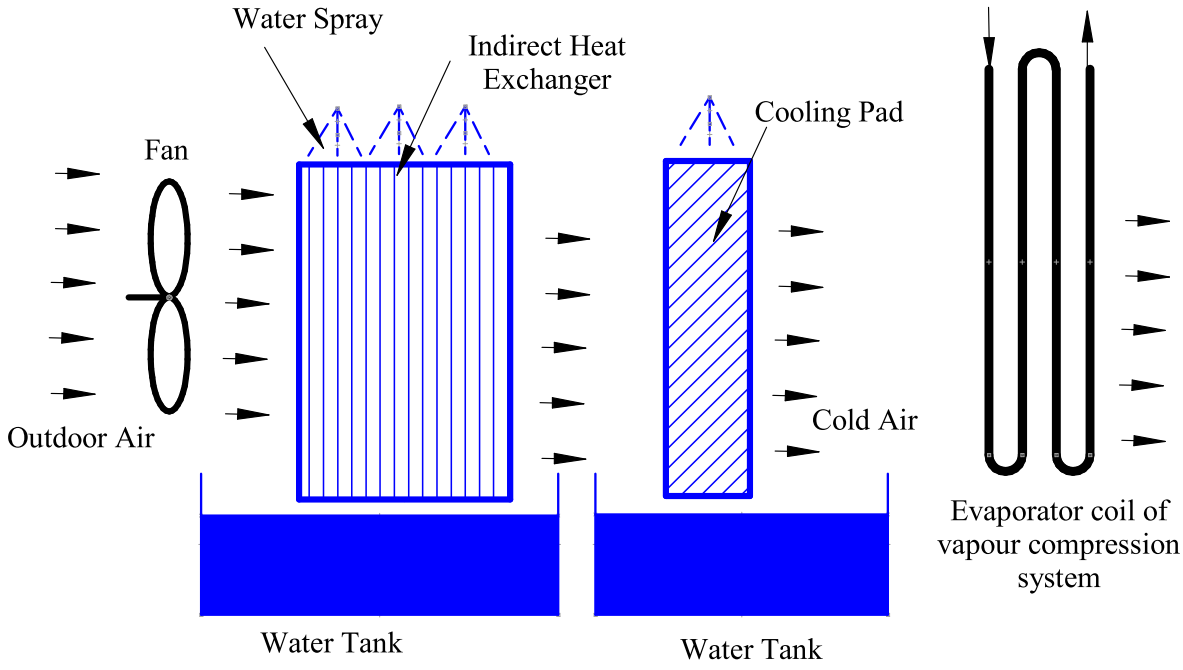


Fig. 6. Multistage ECS with cooling coil.

[34].

1.6.2. Palash fibers and khus roots

In recent years, palash and khus fibers are used as cooling pad materials in ECS. It is reported that the pad with palash fibers results in better efficiency and it is higher than the cooling pads made of aspen and khus. However, the Khus pad offers lowest pressure drop and it is suggested that the palash and khus fibers can be used as alternative to conventionally used cooling pad material. The pressure drop with palash fiber is less than the aspen fiber [35]. The cooling efficiency provided by Khus is about 34% [36].

1.6.2.1. Rice husk pads. The rice husk is a natural sheath that forms around rice grains and is considered as agricultural waste. However, it can be used as substitute for the conventionally used materials as it is cheap and easily available. The experimental work carried out with rice husk pads shows that the saturation efficiency of this pad is satisfactory. However, this pad results in higher pressure drop as compared to conventionally used cooling pad material. It is suggested that the rice husk pad has the potential to replace the conventional material [37,38]. The highest cooling efficiency obtained with rice husk is about 56% [38].

1.6.2.2. Straw. The dry stalks of cereal plants are called as straw and is a useful agricultural by-product. It has significant potential to use as cooling pad materials as it is cheap and easily available in the market. It is a natural cellulose fiber abundantly available and renewable. The experiments conducted with straw as cooling pad shows an average efficiency of about 72%. It is suggested that the straw cooling pad may be used in ECS [39,40].

1.6.2.3. Jute. The jute is a soft, long, shinybast fiber extracted from corchorus and it is cheap and available in the market. It is one of the most affordable natural fibers and its length is between 1 and 4 m. Few research work was carried out with jute fiber rope as cooling pad materials shows that the outlet air can be cooled to about 25 °C and saturation efficiency varies from 59 to 69%. It is suggested that the cooling capacity of the jute fiber rope varies from 6173 to 11,979 kJ/h. Hence, it is suggested that the jute fiber rope can be used as substitute for the conventional used cooling pad material [41,42].

The stem sponge [43] and sliced wood can be used as cooling pad material of ECS used in greenhouse and it provides cooling efficiency of 90% [44]. The cooling pad designs are modified to enhance the evaporation rate. The thickness of commercially available cooling pad material varies between 0.10 and 0.30 m and this cooling pad expensive [45]. It is reported that the fiber panel has lower lifespan and various techniques such as corrugated plates assembled with resin adhesives are developed [46,47]. It is suggested that the dynamic packing performance is better than the static packing at all operating conditions and the maximum humidification efficiency is about 81% [48]. The fabric-based pad can be used as cooling pad material with comparable performance [49]. It is suggested that the increase in inlet air velocity causes reduction in humidity and effectiveness variation and the maximum effectiveness of about 82% at the air velocity of 1.8 m/s [50]. The experimental work carried out with jute and cotton waste results in average cooling efficiency of about 86 and 76% respectively. It is suggested that the jute has better performance as compared to other materials [51]. It is suggested that the activated carbon foam (ACF) cooling pad is better than the luffa fiber as the ACF provides better wettability as compared to luffa cooling pad and the maximum cooling efficiency provided by luffa fiber is about 63% [52].The experimental work carried out with gunny sack as cooling pad materials shows that it can be used as an alternative to the CELDEX Pad at the air velocity of 1 m/s [53].

The pottery materials can be used as cooling medium with saturation efficiency between 49 and 66% with temperature reduction up to 7 °C [54]. It is suggested that the adsorption of air moisture before the air entering the cooling pad results in better evaporation of water and improvement in the cooling effect [55]. It is suggested that the thickness of cooling pad must be optimized as the thicker cooling pad results in higher pressure drop. Also, as the thickness of the pad increases, the ECS takes more time to reach steady state condition and it gives maximum cooling efficiency of about 90% at the velocity of 1.5 m/s [56]. The thickness of cooling pad also affects the ECS efficiency and air velocity [57]. It is suggested that the saturation effectiveness reaches steady state at the air velocity range of 1–1.5 m/s for thicker cooling pad [57]. The thicker cooling pad causes poor distribution of air and affects the efficiency significantly [58]. It is suggested that the higher velocity reduces the saturation efficiency due to lower residence times [59]. The optimal

air velocity reported in the literature is between 0.6 and 0.9 m/s and air mass flow rate suggested is −1 or 0.06–0.08 kg/s [60]. The higher-pressure drop was reported for the thicker cooling pad as the water flow rate increases for pad thickness of 0.3 m [61]. Few researchers were designed and developed coconut coir cooing pad which giver performance of the ECS comparable to commercially available cooling pad [62,77].

2. Results and discussion

The energy saving potential of indirect/direct evaporative cooling system can be enhanced with the help of liquid desiccant system retrofitting. The addition of enthalpy exchanger before the LD unit improves the COP and cooling capacity. The dew point IECS results in 41% higher cooling capacity as compared to base case [63]. It is suggested that automotive fuel consumption and emission can be reduced by using ECS integrated with desiccant dehumidification and regeneration system and suggested that the COP of the ECS is between 0.7 and 0.9 [64].

The hybrid refrigeration system which uses evaporative cooling system for sub cooling of refrigerant improves the performance of the refrigeration system [65]. The liquid desiccant and dew point ECS require less energy as compared to conventional systems. The simulation work shows that the dew point ECS with liquid desiccant can save primary energy up to 12% [66]. The dewpoint ECS is better than other types of ECS. The regenerator can be integrated with solar pond and solar thermal collectors to reduces its energy consumption and it is suggested that the saturation efficiency based on dew point is between 55 and 85% [67].

In recent years, high efficiency dew point indirect ECS are developed and used commercially. The performance of this type of ECS can be improved by enhancing its geometry, design, new cooling pad material (porous materials) and water distribution [68]. The performance of dewpoint ECS can be improved by optimising the working ratio for different conditions and channel length and it is reported that the working ratio and optimal channel length is 0.4 and 0.5 respectively [69]. The Maisotsenko cycle (M-Cycle) dew-point air coolers are better than the conventional crossflow M − cycle exchangers in humid climates and the temperature difference obtained with this type of heat exchange is between 10.6 and 17.5 °C [70].

In high humid climatic conditions, the solar assisted desiccant ECS can be used in greenhouse applications. It is revealed that this system can reduce inside temperature close to 6 °C compared to conventional ECS [71]. The solar assisted desiccant cooling system can be used an alternative to conventional cooling system. The experimental results show that this system is suitable for hot climates, particularly southern European climatic condition [72]. The liquid desiccant dehumidifier with Indirect ECS can be used in hot and humid climate. It is also suggested that the polymer plate heat exchanger is better than the heat exchanger made of metal and effectiveness based on dew and wet bulb points are 0.42 and 0.61 respectively [73]. The desiccant wheel is used to remove moisture from the air before it is cooled, which can improve the overall efficiency of the system. The high-temperature chilled water from a natural cold source, such as a lake or river, can be used to cool the air more efficiently than traditional air conditioning systems that use refrigerant and compressors [74]. The simulation study carried out with hybrid desiccant cooling system shows improvement in thermal comfort condition and efficiency of the system when the capacity of desiccant is increased [75].

In hot weather conditions, vapour compression system performance is reduced, and power consumption increases significantly. The use of ECS in condensing unit of vapour compression system improves condensation and reduces energy requirement. The use of water condenser instead of air condenser reduces energy consumption significantly and improves the COP [76]. The performance of the split air-conditioning system can be improved by retrofitting ECS with condensing unit. The use of ECS with 100 mm thick cooling pad provides best performance as compared to other thickness of cooling pad and results in reduction of power consumption of about 11% and improvement in cooling capacity and COP are 1.8 and 10.6% respectively [77]. Other researchers also reported that the performance of the air conditioning system can be improved with ECS [78]. The air-conditioning system integrated with ECS and heat pipes reduces the energy consumption of the air conditioning system by 31% and the improvement in the COP is about 29% [79]. The use of heat pipe in ECS improves its performance due to passive heat transfer with nominal additional cost [80].

The performance of indirect ECS which uses luffa fiber's can be improved with the help of finned heat pipe. This heat pipe is arranged in a staggered manner and results in highest difference temperature of about 17 C and wet-bulb effectiveness of 99% [81]. The use of coiled channel heat exchanger in two-phase ECS can be used in cooling of moving electronic unit [82]. The outlet air temperature of the ECS can be reduced below the wet bulb temperature using dew point ECS and this system has significant potential in sensible cooling of air below its entering WBT. It is also reported that the water evaporation intensity reaches a minimum at a distance of 0.2–0.3 m from the entry point [83] and hence it is suggested that the ECS has a great potential to reduces energy requirement in hot and arid climatic regions [84]. When indirect ECS is used to cool fresh air in air conditioner, the condensation area ratio is positively correlated with total heat transfer, dehumidification rate and latent heat transfer [85].

The experiments carried out with desiccant dehumidifier coupled with direct ECS reveals decrease in COP with increase in specific humidity, decreasing flowrate and ambient temperature. The power consumption of this combined system increases due to usage of electric heater in desiccant regeneration system [86]. The higher efficiency with cooling effectiveness can be obtained with higher channel length, channel with triangle shape, higher inlet temperature of air, and lower inlet humidity and low velocity of air [87]. Fig. 7 shows the important variables affecting the performance of the cooling pad.

It is reported that the ECS components such as cooling pad, water pump and sump can be substitute with vermicompost. The solar assisted drying of vermicompost can be integrated with ECS, to provide better indoor environment and can help in cooling applications related to building [88]. The computational fluid dynamics (CFD) is the simulation tool which can be used in analysing the performance of the ECS. Several research works have been carried out to predict the performance of the ECS using CFD. The results of the CFD are matches with the experimental work and hence the CFD plays a crucial role in the design of ECS [89] and the CFD results are comparable to the experimental work [90]. The simulation work carried out with indirect ECS reveals that the increase in water inlet velocity and coil diameter improves the performance of this ECS. The saturation efficiency increases with increase in coil diameter [91]. Similar type of work carried out by other researcher suggest that the copper coil design must be optimized to get better performance of the Indirect ECS [92]. A simple numerical model was developed to find out the effect of water spray on the building cooling load. It is reported that this model drastically reduces the calculation load as compared to conventional methods [93]. Table 1 shows the summary of the research work carried out on ECS and Table 2 shows the summary of effect of using natural fiber as alternative to conventionally used cooling pad materials.

Table 3 compares various natural fiber materials in terms of cooling efficiency, strength and limitations.

2.1. Effect of process variables

It is suggested that certain meteorological parameters such as relative humidity, wet and dry bulb temperature, enthalphy and dew point temperature and system performance parameters affects the thermal performance of different ECS [122]. The fibrous material (cellulose paper, fibre or textile) is considered as replacement to evaporation

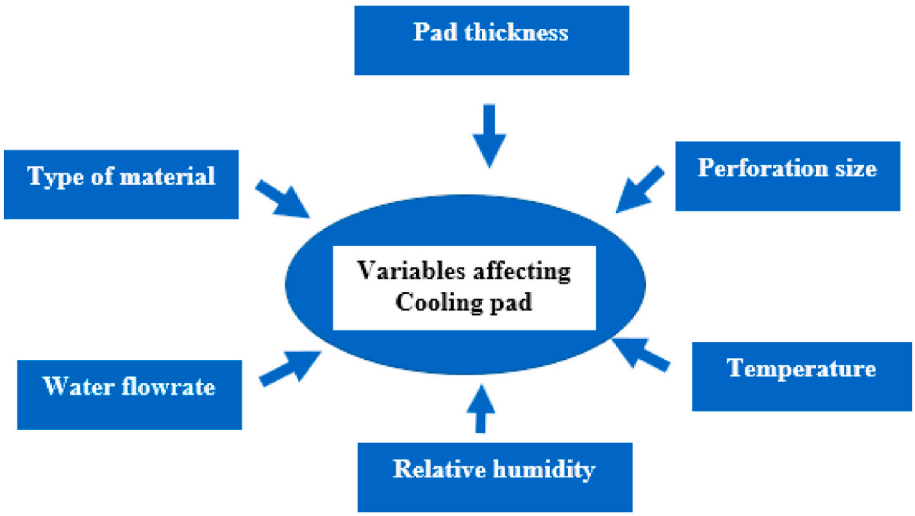


Fig. 7. Important variables affecting cooling pad performance.

material used in ECS. The mass and heat transfer in ECS depends on the cooling pad material's wettability and evaporation characteristics inside the ECS [123]. The intergradation of ECS with air conditioning system helps in enhancing the performance of the ECS and to reduce electrical power consumption [124]. The higher mass and heat transfer in dew point ECS results in higher thermal performance and increases the energy conservation, however there is a limitation in film distribution and temperature region [125]. Fig. 8 shows the important variables affecting the performance of ECS.

The selection of ECS is based on design guideline under operating boundary condition and specific climate [126]. The water requirement of cooling pad varies and depends upon the type of cooling pad material and water temperature impacts the ECS performance. The increasing the heat flux around the water tank and decreasing the relative humidity of the inlet air through the wetting pad will lower both the inlet water and pad exhaust temperatures. The Increase in the heat flux around the water tank and reducing the inlet air relative humidity can lead to lower inlet water temperature and pad exhaust temperature [127].

Efficient cooling and optimal performance of an ECS depend significantly on the properties of the material used for the wet channel surface. The material's moisture wicking ability, diffusivity, and evaporation capacity play a crucial role in altering the cooling efficiency and performance. The use of irregular fibers in the material is beneficial as they help to divert moisture and increase the wet area, which promotes faster evaporation and ultimately enhances cooling performance. Therefore, careful consideration and selection of the wet channel surface material are essential to achieve maximum cooling efficiency and optimal performance from the ECS [128]. The pre-cooled air from the IEC is conditioned to provide the required thermal condition by employing the thermal energy storage which uses latent heat. The use of PCM (spherical balls) dehumidify and to pre-cool inlet air in the tropics simultaneously and air temperature and humidity can be reduced.

The use of geothermal energy to cool the feedwater used in the two stage ECS (Combination of IECS and DECS) improves its performance and this system was used in the residential building cooling [129]. The ECS integrated with hollow fiber membrane is suggested as a better method in space air conditioning. The membrane resistance is the major contributor of the total mass transfer resistance and the air-side convective resistance dominates in the total heat transfer resistance [130]. The ECS can be used in hot and humid environment with better performance by integrating it with solar assisted solid desiccant unit. The increase in air recirculation ratio from 0 to 60% results in reduction in inlet air temperature and humidity by about 23% and 42% respectively and hence recirculation air ratio should be selected based on climatic condition to get better ECS performance [131].

The evaporation efficiency of porous structures can be improved with capillary evaporation by enhancing the interfacial area. The heat transfer performance of evaporation is closely linked to the porous structure's nature due to the counter interactions of flow resistance and capillary force [132]. The ECS selection is based on availability of water and weather conditions [133]. The ECS's process variables affects is performance and hence the process variables such as secondary and primary air resistance, flow rate of water, inlet air temperature and humidity and air flow rate ratio based on secondary-to-primary air [134].

The swirl flow and porous carbon tube use as a humidification medium enhances the ECS performance. The optimization of the air flow in helical flow channel reduces the size of the ECS and helps to overcome the ECS's poor wettability [135]. The selection of the ECS should consider the sustainability and efficiency of the ECS [136]. The Integration of IECS with a desiccant system can solve the problem faced by the DECS, however this system needs energy source with higher temperature for regeneration [137]. The performance of the split-type air conditioner with evaporative condenser is affected by the ambient temperature and humidity. The better performance of this system is obtained at higher outdoor humidity and temperature [138]. The addition of biochar to the cooling medium increases the evaporation rate [139] as heat-moisture migration in the wet surface composed of porous materials enhances both mass and heat transfer. The porous material selection is based on properties such as specific surface, porosity, tortuosity etc [140]. In a hot-humid climate, outlet air temperature can be reduced by increasing mass ratio of feedwater to the circulating air. In a hot-dry climate, if the WBT is lower than the feedwater temperature, reduction in the mass ratio helps for the reduction of air temperature [141].

In the IECS, porous material increases the water reduction in channel surface and reduces water requirements. The ECS with a plate-type cross-flow HE that is sintered with porous layer results in higher value of COP, lower power consumption and lower pressure drop as compared to conventional system due to the water absorbed and retained in the porous layer, which indicates the intermittent water spraying [142]. The water power consumption can be reduced by intermittent water spraying [143]. The cooling system based on bio-inspired design enhances cooling capacity with height increment and wool pads derived from wood. This type of cooling system is preferred in hot arid region [144]. The vacuum spray flash evaporation results in faster cooling as compared to traditional cooling methods and the cooling performance is affected by nozzle discharge coefficient, vacuum level and multi-nozzle

Table 1
Summary of the research work carried out on ECS.

Type of ECS	Research work description	Results reported	Ref. No
M-cycle IDECS	Plate-type HX with cross flow, based on M-cycle IDEC. It is reported that this system is suitable for cooling applications in residential and commercial sectors with wide range of operating conditions.	Wet bulb effectiveness (WBE) is 124 and 106% for residential and commercial applications respectively.	[96]
IECS	A counter-flow, plate-type HX consists of rectangular hollow porous channels filed with water	The WBE is 117%	[97]
M-cycle based IECS	A polygonal plate-fin, counter flow, HX made from flat sheets and corrugated triangular cross-section fins as flow guides. Optimization of the geometrical sizes was done to get better performance.	WBE and DPE is in the range of 54–130% and 36–82% respectively.	[98]
Counter-flow M-cycle based IECS	HX consists of flat-sheets-stacked structure. Polyethylene as water-proof material, and thin-film cotton sheet as wettable material. Tests conducted at various inlet air conditions.	WBE and DPE is in the range of 92–114% and 58–84% respectively.	[99]
Plate-type IDECS	HX with 4-flow configurations in IECS	WBE is in the range of 109–131%	[100]
Hybrid dewpoint ECS	A dewpoint ECS and a VAC system forms the hybrid system and gives COP of 3.47. The channel length and flow rate affect the pressure drop. The optimal wet and dry channel gaps is 5 and 6 mm, respectively.	WBE is 137%	[101]
DECS	DEC is provided with porous ceramic evaporators and it provides a maximum cooling of 224 W/m^2	This system can provide 6–8 °C in DBT with a 30% rise in humidity.	[102]
IDECS and DECS	Two-stage IDECS and DECS can be substitute for VCS in region where WBT is high, to reduce the energy consumption.	Water consumption is 55% higher than the conventional DEC	[103]
Counterflow IDECS	11.8 was the maximum average EER recorded and the air temperature at exit was 14.9 °C for atmospheric temperature of 34.7 °C.	WBE is in the range of 118–129%. The DPE is in the range of 58–84%	[104]
DECS and IDECS	The effectiveness of the cooling coil unit was 47.4% and the hourly average effectiveness of the DECS was 75.12%.	The overall effectiveness of combined cooling system is higher than 100%.	[105]
IDECS	The experiments were conducted by providing wet medium on the top surface of material reference plate which has the thickness of 5 mm. The velocity of air varied from 1.6 to 3.4 m/s for optimization.	The maximum heat absorption rate is about 13.9 W with 3.4 m/s and perpendicular direction of air	[106]
IDECS	The IDEC is manufactured with HXs having different geometry is carried out and studied the effect of different plates protrusion and pitch on IDEC WBE and pressure drop.	The HX plate geometry affects surface wettability as well as heat transfer rate. It is suggested that a reticular plates protrusion greatly enhances IDEC effectiveness.	[107]
IDECS	The effect of various water spray configurations such as internal, external spray and mixed mode spray systems on IDECS was studied.	The mixed mode results in better perform than other modes. The internal spray was better than external spray system.	[108]
Dew point ECS	The effect of nylon coated counter-crossflow cooler on the wet channel surface was studied. Proposed.	Nylon coating improved performance. The dew point effectiveness varies from 46.7 to 78.6%.	[109]
Regenerative ECS	The regenerative ECS (multiple pairs of finned channels made of aluminium in counter flow) was developed and tested. The wet channel's internal surface was coated with thin porous layer to enhance surface wettability.	The regenerative ECS enhances the performance. In this system, the outlet temperature was reduced below the inlet wet-bulb temperature.	[110]
DECS and IDECS	The combinations aspen fiber, corrugated cellulose and a combination of fiber aspen and corrugated cellulose were used instead of conventional cooling pad.	The effectiveness of IEC-DECS is between 95 and 110% and effectiveness of DECS is between 85 and 93%. It is reported that the combination of corrugated cellulose and fiber aspen and resulted in better performance	[111]

array [145]. The air temperature and relative humidity greatly influence the ECS performance as compared to other roof heat gain reduction methods [146]. The wetting of the fabric wall during daytime results in cooling of the structure interior [147]. The hybrid ventilator integrating the IEC and heat recovery results in superior adaptability to the temperate region [148]. Table 4 summaries the optimized performance parameters of the ECS.

2.2. Challenges and opportunities

The commercially available cooling pad results in better efficiency, however this cooling pads are expensive and imported. The use of locally available materials such as natural fibers can be used as substitute for the commercially available cooling pad. The durability and lower efficiency are the major issues of the natural fibers. The size of the ECS is large as compared to vapour compression system and there is opportunity to reduce the size of the ECS. There are several methods to drive the ECS using renewable energy sources such as solar energy. The components of the ECS can be modified to improve the efficiency of the ECS. The design of water distribution system used in ECS can be improved to reduce water consumption. There is an opportunity to use grey water in the ECS [33,70,94,95].

The market penetration of ECS is insignificant in society and the higher performance and compact ECS has to be developed to meet the requirements of the customers [159]. The unscientific disposal and recycling of conventionally used ECS cooling pad materials affects the environment and increases carbon footprint [160]. The cooling and water generation can be achieved by integrating desalination unit with

Table 2
Summary of the research work carried out on ECS with various natural fibers.

Fiber materials	Type of ECS	Results	Ref No
Straw, celdex and sliced wood pads	DECS	Saturation efficiency, 76%, 85% and 90% for straw, celdex and sliced wood pad.	[112]
Jute, luffa, commercial pad and palm fibers	DECS	Cooling efficiency of about 62, 55, 39 and 50% and 38.9% for jute, luffa, palm and commercial pad respectively	[113]
rice husk wetted pad and high-density polyethylene.	DECS	Efficiency (saturation) of about 56 and 29% for rice husk and high-density polyethylene respectively	[114]
wood chips	direct and desiccant assisted ECS	Average WBE and DPE are 50.6 and 52.5% respectively and these values are higher than the ECS.	[115]
Coconut coir	DECS	Coconut coir performance is comparable to conventional paper pad. Also, the value of pressure drop is small.	[116]
Khus	DECS	Efficiency is 62 and 68.6% for normal and chilled water respectively.	[117]
Luffa	DECS	Cooling efficiency luffa (55.1%) is better than the jute and palm fibers	[118]
Cotton fabric	DECS	Saturation efficiency is between 80 and 95% and this fiber provides better wetted surface with small pressure drop.	[119]
Wood shaving	DECS	Humidification efficiency is about 78.33% and the performance is close to conventionally used cellulose cooling pad.	[120]
Palash	DECS	The palash fiber provides better efficiency as compared to aspen and khus pads. It results in saturation effectiveness between 81.04 and 83.89%.	[121]

solid desiccant ECS and the performance of this system can be improved with reduction in its cost [161]. The ECS can be driven by renewable energy sources such as solar energy, as the ECS can be used in remote and rural areas which lacks electricity for the storage of perishables and helps the smallholder farmers [162]. In low income countries, locally available materials can be used for the manufacturing of cooling pad materials as it reduces the price of the ECS and encourages the farmers and increases the adoption of ECS, however the properties of this natural fiber materials can be augmented [163]. In the IECS, dry side convective heat transfer value can be improved as it greatly affects the cooling capacity of IECS [164].

The estimation of production and investment costs related design of system needs cooling efficiency knowledge of and it is an important criterion. The contamination in the ECS causes improper wetting of the pad and air duct clogging which reduces the ECS performance [165]. The energy consumption of ECS can be reduced by optimising the performance parameters [166] and adopting various sustainable techniques [167]. The payback period of the ECS can be reduced as it will attract the customer in rural areas and reduces carbon footprint [168].

A new hybrid system combining IECS and underground air tunnel is considered as alternative to the VAS which is environmentally friendly. This system increases cooling performance and reduces water consumption [169]. The water droplet carryover problem of the cooling system is overcome by the use of hollow fiber membrane based semi-DECS without affecting the indoor air quality. This system can be further optimized in design and to increase the application of the ECS [170]. The improvement in mass and heat transfer process will help to overcome ECS design challenges and complexities in design. The porous ceramic tube modules and heat pipe can be used as an alternative to plate HE [171].

The uniform distribution of water in the working channel of the ECS can be achieved by introducing new geometry, however this geometry is complicated in structure and increases pressure drop and limits its use in ECS [172]. For ECS, structural optimization and efficient wicking of polyethylene textile enhances the water evaporation. This results in conservation of water and energy and lower carbon footprint. The interdisciplinary approach can offer many advances and develops better cooling system [173].

The major challenge faced by the ECS is its suitability to local climatic and agronomic conditions [174]. There is a hygienic risk associated with ECS and it allows water contaminated with legionella causes dispersion into the air [175]. There are lot of scope in developing energy efficiency and simple ECS [122]. The carbon–neutral strategies has to be developed for the ECS and hence there is great potential in future research [125].

3. Conclusion

The evaporative cooling is one of the low-cost cooling techniques used for thermal comfort and for short term preservation vegetables and fruits. The cooling efficiency of the ECS can be improved with the help of various design modifications of the ECS components. The ECS can be

Table 3
Comparison of cooling pad materials.

Fiber name	Cooling efficiency	Strength	Limitations	Ref No
Coconut coir	51.5%	1. Higher heat and mass transfer 2. Efficiency and pressure drop similar to conventional pad 3. Cheap and easily available 4. Biodegradable	1. Lack of durability study 2. Mold formation	[116]
Khus	62%	1. Higher efficiency compared to coconut coir 2. Better evaporation 3. Environmentally friendly	1. Costlier than coconut coir 2. Limited research work	[117]
Luffa	55.1%	1. Better performance than jute and palm fibers 2. Low mold formation compared to jute and palm fibers	1. Costlier than coconut coir 2. Lack of biodegradable study	[118]
Cotton fabric	80–95%	1. Higher efficiency 2. Better wetted surface 3. Small pressure drop	1. Costlier	[119]
Wood shaving	78.33%	1. Higher efficiency than other fibers except cotton fabric and Palash 2. Performance comparable to cellulose cooling pad.	1. Costlier 2. Higher degradation period	[120]
Palash	81–84%	1. Better efficiency as compared to aspen and khus pads. 2. Higher saturation efficiency	1. Limited availability 2. Costlier	[121]
Jute		1. Low salt deposit compared to palm fiber 2. Easily available	1. Higher mold formation 2. Higher maintenance	[118]

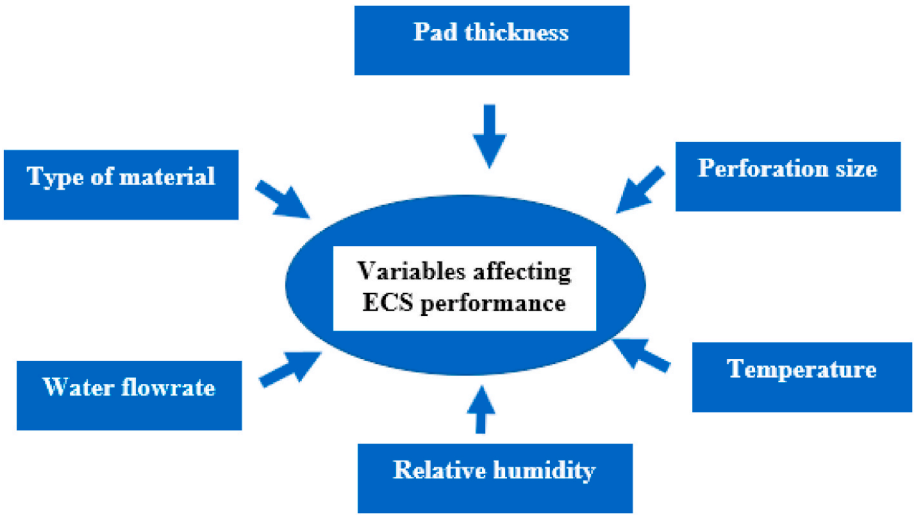


Fig. 8. Important variables affecting ECS performance.

Table 4
Summary of the optimized performance parameters.

Type of ECS	Performance parameters	Results	Ref No
M-Cycle IECS	Supply air ratio, DPT	When supply air ratio and inlet tempearture range is 0.6 and 35–41 °C respectively, then entropy production value is less than 0.06.	[149]
Dew point IECS	Tempearture, humidity and velocity at inlet	Optimal condition: Inlet air tempearture, velocity and humidity are 41.31 °C 3.61 m/s and 12 g/kg respectively	[150]
IECS	Pump power and water consumption	Reduction of air temperature and mositure content by IECS is about 27 °C and 18 g/kg respectively. IEC results in COP of 8.23.	[151]
			[152]
Thermoelectric assisted IECS Self circulating ECS	With and without thermoelectric system Coolant vapour flowrate at condenser inlet	Attachment of thermoelectric system results in improvement of IECS and improvement in COP is about 65%. Flow can be smoothened by introducing an inlet box with an apex angle of 30°, which reduces flow resistance and the pressure drop.	[153]
IECS	Mass and heat transfer process	Higher effectiness can be obtained by introducing regenerative counter-flow HE	[154]
Hybrid ECS	Air velocity	Optimal design significantly reduces the operating cost	[155]
DECS	CFD	phase velocity and droplet characteristics affects the performance	[156]
DECS and IECS	Moisture entransy dissipation	Entransy dissipation can be reduced by decreasing DBT of moist air	[157]
ECS	Automation in distribution of water	Better performance and reduction in wáter consumption.	[158]

used in hot and humid conditions using two or three stage systems. In recent years, desiccant based ECS are developed. The solar energy which is a renewable energy source can be used to drive the ECS. The cooling pad material used in ECS can be substituted by locally available materials. Several studies show that the locally available material can be used as alternative to conventionally be used cooling pad material. The energy requirement of ECS is very low with reference to conventional system. In hot climates, the performance of the vapour compression refrigeration system performance can be improved with the help of ECS based cooling, for the condenser.

The intergradation of ECS with heat pipe results in highest temperature reduction of about 17 °C and wet-bulb effectiveness of 99%. For residential application, the M-cycle IDECS results in WBE and DPE of 124 and 106% respectively. The Plate-type IDECS results in WBE is in the range of 109–131% and the counter-flow M-cycle based IECS results in WBE and DPE is in the range of 92–114% and 58–84% respectively. The water requirements of ECS can be greatly reduced using two-stage IDECS and DECS and can be substitute for VCS in region where WBT is high.

There are several challenges in the use of ECS for various applications and hence the research opportunities are significant. The low cost, locally available, environmentally friendly and better evaporation properties of cooling pad can be developed and can be used as substitute. The design of the ECS components can be modified to improve its efficiency, cost, size, capacity, effectiveness and water requirement. The integration of renewable energy sources can reduce the operating cost of the ECS and reduce carbon footprint.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgment

The support provided by the ASHRAE, United States is acknowledged.

Nomenclature

ACF	Activated carbon foam
CFD	Computational fluid dynamics
COP	Coefficient of performance
DBT	Dry bulb temperature
DECS	Direct evaporative cooling
DPE	Dew point effectiveness
DPT	Dew point temperature
ECS	Evaporative cooling system
EER	Energy efficiency ratio
HX	Heat exchanger
IDECS	Indirect direct evaporative cooling system
IECS	Indirect evaporative cooling system
DECS	Direct evaporative cooling system
M-Cycle	Maisotsenko cycle
OPEC	Organization of the Petroleum Exporting Countries
PCM	Phase change material
VCS	Vapour compression system
WBE	Wet bulb effectiveness
WBT	Wet bulb temperature
WEC	World Energy Council

References

[1] Tanveer Ahmad, Dongdong Zhang, A critical review of comparative global historical energy consumption and future demand: the story told so far, Energy Rep. 6 (2020) 1973–1991.

[2] S. Ghasemian, A. Faridzad, P. Abbaszadeh, An overview of global energy scenarios by 2040: identifying the driving forces using cross-impact analysis method, Int. J. Environ. Sci. Technol. (2020).

[3] Energy Information Administration, U.S. Department of Energy, World Consumption of Primary Energy by Energy Type and Selected Country Groups, 2006, pp. 1980–2004. http://www.eia.doe.gov/pub/international/.

[4] K.A. Abed, A.K. El Morsi, M.M. Sayed, A.A. ElShaib, M.S. Gad, Effect of waste cooking-oil biodiesel on performance and exhaust emissions of a diesel engine, Egyptian Journal of Petroleum 27 (2018) 985–989.

[5] Stephen O. Andersen, Marcel L. Halberstadt, Nathan Borgford-Parnell, Stratospheric ozone, global warming, and the principle of unintended consequences—an ongoing science and policy success story, J. Air Waste Manag. Assoc. 63 (2013) 607–647.

[6] Wijaksana Hendra, Nyoman Suprapta Winaya, Sucipta Made, Ainul Ghurri, An overview of different indirect and semi-indirect evaporative cooling system for study potency of nanopore skinless bamboo as an evaporative cooling new porous material, Journal of Advanced Research in Fluid Mechanics and Thermal Sciences 76 (2020) 109–116.

[7] N. Zhou, F. Chen, Y. Cao, M. Chen, Y. Wang, Experimental investigation on the performance of a water spray cooling system, Appl. Therm. Eng. 112 (2017) 1117–1128.

[8] D. Bishoyi, K. Sudhakar, Experimental performance of a direct evaporative cooler in composite climate of India, Energy Build. 153 (2017) 190–200.

[9] Nitipong Edward A. Awafoa, Samuel Nketsiah, Mumin Alhassan, Ebenezer Appiah–Kubi, Design, construction, and performance evaluation of an evaporative cooling system for tomatoes storage, Agric. Eng. 24 (2020) 1–12.

[10] M. Ganesan, K. Balasubramaniam, R.V. Bhavani, Studies on the application of different levels of water on zero energy cool chamber with reference to the shelf-life of brinjal, Journal Indian Institution of Science 84 (2004) 107–111.

[11] B.K. Mishra, N.K. Jain, S. Kumar, D.S. Doharey, K.C. Sharma, Shelf life studies on under evaporative cooled storage structure in Southern Rajasthan, Journal of Agricultural Engineering 46 (2009) 26–30.

[12] A. Samira, K. Woldetsadik, T.S. Workneh, Postharvest quality and shelf life of some hot pepper varieties, J. Food Sci. Technol. 50 (2011) 842–855.

[13] Dağtekin Metin, Cengiz Karaca, Levent Sangün, Yilmaz Yildiz, Determination of the relationship among air velocity, cooling efficiency and temperature decrease at a cellulose based evaporative cooling pad, Afr. J. Agric. Res. 5 (2010) 3477–3482.

[14] O. Amer, R. Boukhanouf, H.G. Ibrahim, A review of evaporative cooling technologies, Int. J. Environ. Sustain Dev. 6 (2015) 111–117.

[15] Z. Duan, Indirect evaporative cooling: past, present and future potentials, Renew. Sustain. Energy Rev. 16 (2012) 6823–6850.

[16] M. Darwesh, S. Abouzaher, T. Fouda, M. Helmy, Effect of using pad manufactured from agricultural residues on the performance of evaporative cooling system, Jordan Journal of Agricultural Sciences 5 (2009) 111–127.

[17] Li Rong, Poul Pedersen, Thomas Ladegaard Jensen, Svend Morsing, Guoqiang Zhang, Dynamic performance of an evaporative cooling pad investigated in a wind tunnel for application in hot and arid climate, Biosyst. Eng. 156 (2017) 173–182.

[18] N. Lechner, Heating, Cooling, Lighting: Sustainable Design Methods for Architects, third ed., Wiley, New Jersey, U.S.A., 2009, pp. 276–293, ch. 10.

[19] D. Kolokotsa, M. Santamouris, A. Synnefa, T. Karlessi, Passive solar architecture, Comprehensive Renewable Energy 3 (2012) 637–665.

[20] Ali Hammoodi Mahdi, M. Issam, Aljubury Ali, Experimental investigation of two-stage evaporative cooler powered by photovoltaic panels using underground water, J. Build. Eng. 44 (2021), 102679.

[21] H. El-Dessouky, H. Ettouney, A. Al-Zeefari, Performance analysis of two-stage evaporative coolers, Chem. Eng. J. 102 (2004) 255–266.

[22] G. Heidarinejad, H. Pasdarshahri, Potential of a desiccant-evaporative cooling system performance in a multi-climate country, Int. J. Refrig. 34 (2011) 1251–1261.

[23] M.-H. Kim, J.-W. Jeong, Cooling performance of a 100% outdoor air system integrated with indirect and direct evaporative coolers, Energy 52 (2013) 245–257.

[24] A. Tejero-Gonzalez, A. Franco-Salas, Optimal operation of evaporative cooling pads, A review Renewable and Sustainable Energy Reviews 151 (2021), 1116382.

[25] K.V. vala, F. Saiyed, D.C. Joshi, Evaporative cooled storage structures: an Indian scenario, Trends in Post-Harvest Technology 2 (2014) 22–32.

[26] T. Gunhan, V. Demir, A.K. Yagcioglu, Evaluation of the suitability of some local materials as cooling pads, Biosyst. Eng. 96 (2007) 369–377.

[27] J.F.V. Rosa, I.F.F. Tinoco, C.M. Fernandes, S. Zolnier, M.M. Bueno, An' alise da Eficîencia de Resfriamento de Pain'eis Porosos Preenchidos com Argila Expandida em comparação aos de Celulose Usando Túnel de Vento, Rev Eng Na Agric – REVENG 19 (2011) 516–523.

[28] H. Lotfizadeh, H. Razzaghi, M. Layeghi, Experimental performance analysis of a solar evaporative cooler with three different types of pads, J. Renew. Sustain. Energy 5 (2013) 1–14.

[29] J.K. Jain, D.A. Hindoliya, Experimental performance of new evaporative cooling pad materials, Sustain. Cities Soc. 1 (2011) 252–256.

[30] Md Ferdous Alam, Ahmad Sharif Sazidy, Asif Kabir, Gowtam Mridha, Nazmul Alam Litu, Md Ashiqur Rahman, An experimental study on the design, performance and suitability of evaporative cooling system using different indigenous materials, AIP Conf. Proc. 1851 (2017), 020075.

[31] R. Rawangkul, J. Khedari, J. Hirunlabh, B. Zeghmati, Performance analysis of a new sustainable evaporative cooling pad made from coconut coir, Int. J. Sustain. Eng. 1 (2008) 117–131.

[32] F. Al-Sulaiman, Sadam-Houcine Sellam, Abdelhafid Moummi, Charaf-Eddine Mehdid, Amar Rouag, Abdelmoumen-Hakim Benmachiche, Mohammed-Amin Melhegueg, Adel Benchabane, Experimental performance evaluation of date palm fibers for a direct evaporative cooler operating in hot and arid climate, Case Stud. Therm. Eng. 35 (2022), 102119.

[33] M.C. Ndukwu, S.I. Manuwa, A techno-economic assessment for viability of some waste as cooling pads in evaporative cooling system, Int. J. Agric. Biol. Eng. 8 (2015) 151–158.

[34] Waleed A. Abdel-Fadeel, M. Attalla, Experimental study on the palm fiber using as a direct evaporative cooler pad, Int. J. Mech. Mechatron. Eng. (2014) 14–19.

[35] J.K. Jain, D.A. Hindoliya, Correlations for saturation efficiency of evaporative cooling pads, J Inst Eng Ser C 95 (2014) 5–10.

[36] Kaustubh Sontakke, Swapnil Ghode, Akshay Dhabliya, Mayur Mendhule, A review paper on effectiveness of evaporative cooling system, International Journal of Innovations in Engineering and Science 4 (2019) 6–11.

[37] Shekhar Nitipong Soponpongpipat, Sukum Kositchaimongkol, Recycled high-density polyethylene and rice husk as a wetted pad in evaporative cooling system, Am. J. Appl. Sci. 8 (2011) 186–191.

[38] Nitipong Soponpongpipat, Sukum Kositchaimongkol, Recycled high-density polyethylene and rice husk as a wetted pad in evaporative cooling system, Am. J. Appl. Sci. 8 (2011) 186–191.

[39] E.M. Ahmed, A. Lal Basediya, D.V. Samuel, V. Beera, Evaporative cooling system for storage of fruits and vegetables - a review, J. Food Sci. Technol. 50 (2013) 429–442.

[40] A. Tejero-González, A. Franco-Salas, Optimal operation of evaporative cooling pads: a review, Renew. Sustain. Energy Rev. 151 (2021), 111632.

[41] R.K. Kulkarni 1, S.P.S. Rajput, Laboratory performance of evaporative cooler using jute fiber ropes as cooling media, Int. J. Eng. Res. Afr. 4 (2014) 60–66.

[42] Timothy Adekanye, Kunle Babaremu, Abiodun Okunola, Evaluation of an active evaporative cooling device for storage of fruits and vegetables, CIGR Journal 21 (2019) 203–208.

[43] A.U. Dzivama, U.B. Bindir, F.O. Aboaba, Evaluation of pad materials in construction of active evaporative cooler for storage of fruits and vegetables in arid environments, Agricultural mechanization in Asia, africa and Latin America, AMA 30 (1999) 51–55.

[44] Md Ferdous Alam, Ahmad Sharif Sazidy, Asif Kabir, Gowtam Mridha, Nazmul Alam Litu, Md Ashiqur Rahman, An experimental study on the design, performance and suitability of evaporative cooling system using different indigenous materials, AIP Conf. Proc. 1851 (2017), 020075.

[45] M. Chung, S. Liao, S. Tin, Characterizing the Performance of Alternative Cooling Pad Media in Thermal Environmental Control Applications, Taiwan 10617, Republic of China, 2010.

[46] E.M. Ahmed, O. Abaas, M. Ahmed, M.R. Ismail, Performance evaluation of three different types of local evaporative cooling pads in greenhouses in Sudan, Saudi J. Biol. Sci. 18 (2011) 45–51.

[47] M. Czarick, B. Fairchild, Plastic less effective than paper evaporative cooling pads, World Poultrymeat 28 (2012) 26–29.

[48] Shiva Kumar, Sampath Suranjan Salins, S.V. Kota Reddy, Prasanth Sreekumar Nair, Comparative performance analysis of a static & dynamic evaporative cooling pads for varied climatic conditions, Energy 233 (2021), 121136.

[49] Eloy Velasco-Gómez, Ana Tejero-González, Javier Jorge-Rico, F. Javier Rey-Martínez, Experimental investigation of the potential of a new fabric-based evaporative cooling pad, Sustainability 12 (2020) 7070.

[50] Abdollah Malli, Hamid Reza Seyf, Mohammad Layeghi, Seyedmehdi Sharifian, Behravesh Hamid, Investigating the performance of cellulosic evaporative cooling pads, Energy Convers. Manag. 52 (2011) 2598–2603.

[51] William Adebisi Olosunde, J.C. Igbeka, Taiwo Olufemi Olurin, Performance evaluation of absorbent materials in evaporative cooling system for the storage of fruits and vegetables, Int. J. Food Eng. 5 (2009) 22–30.

[52] Radhiyah Abd Aziz1, Nurul Farahin Zamrud, Nurrina Rosli, Comparison on cooling efficiency of cooling pad materials for evaporative cooling system, Journal of Modern Manufacturing Systems and Technology 1 (2018) 61–68.

[53] Hendra Wijaksana, I. Nyoman Suprapta Winaya, Made Sucipta, Ainul Ghurri, Nengah Suarnadwipa, The investigation on cooling capacity and CELdek material pad classification of evaporative cooling pad system using different pad material with water temperature and water discharge variations, AIP Conf. Proc. 1983 (2018), 020019.

[54] Azzeddine Laknizi, Abdellatif Ben Abdellah, Mustapha Faqir, Elhachmi Essadiqi, Said Dhimdi, Performance characterization of a direct evaporative cooling pad based on pottery material, Int. J. Sustain. Eng. (2019), https://doi.org/10.1080/19397038.2019.1677800.

[55] M. Samer, E. Abdelsalam, Y.B. Abd Elhay, Enhancing the efficiency of evaporative cooling pads for livestock barns and greenhouses by moisture adsorption, Agric Eng Int: CIGR Journal 17 (2015) 104–115.

[56] A. Fouda, Z. Melikyan, A simplified model for analysis of heat and mass transfer in a direct evaporative cooler, Appl. Therm. Eng. 31 (2011) 932–936.

[57] A. Beshkani, R. Hosseini, Numerical modeling of rigid media evaporative cooler, Appl. Therm. Eng. 26 (2006) 636–643.

[58] A. Malli, H.R. Seyf, M. Layeghi, S. Sharifian, H. Behravesh, Investigating the performance of cellulosic evaporative cooling pads, Energy Convers. Manag. 52 (2011) 2598–2603.

[59] J.C.F. De Melo, J.V.M. Bamberg, N.S. MacHado, E.N.G. Caldas, M.S. Rodrigues, Evaporative cooling efficiency of pads consisting of vegetable loofah, Comun. Sci. 10 (2019) 38–44.

[60] C.M. Liao, S. Singh, T. Wang, Sen, Characterizing the performance of alternative evaporative cooling pad media in thermal environmental control applications, J Environ Sci Heal - Part A Toxic/Hazardous Subst Environ Eng 33 (1998) 1391–1417.

[61] M. Yan, S. He, M. Gao, M. Xu, J. Miao, X. Huang, Comparative study on the cooling performance of evaporative cooling systems using seawater and freshwater, Int. J. Refrig. (2020) 25–35.

[62] Rawangkul Abdulmajeed Almaneea, Talal Awad Alshammari, Fahad Yousef Aldhafeeri, Muhammed Hamdan Aldhfeeri, Abdullah Abdulaziz Allaboun, Talal Sryan Almutairi, Experimental investigation of air cooler using local palm tree waste, Heliyon 8 (2022), e10265.

[63] Min-Hwi Kim, Dong-Seop Yoon, Hui-Jeong Kim, Jae-Weon Jeong, Retrofit of a liquid desiccant and evaporative cooling-assisted 100% outdoor air system for enhancing energy saving potential, Appl. Therm. Eng. 96 (2016) 441–453.

[64] Alahmer Ali, Thermal analysis of a direct evaporative cooling system enhancement with desiccant dehumidification for vehicular air conditioning, Appl. Therm. Eng. 98 (2016) 1273–1285.

[65] Xiaohui She, Yonggao Yin, Yaming Dong, Xiaosong Zhang, Investigation on air flow patterns of evaporative cooling and dehumidification process for a hybrid refrigeration system, Appl. Therm. Eng. 95 (2016) 79–94.

[66] Sang-Woo Ham, Sung-Joon Lee, Jae-Weon Jeong, Operating energy savings in a liquid desiccant and dew point evaporative cooling-assisted 100% outdoor air system, Energy Build. 116 (2016) 535–552.

[67] Esam Elsarrag, Opubo N. Igobo, Yousef Alhorr, Philip A. Davies, Solar pond powered liquid desiccant evaporative cooling, Renew. Sustain. Energy Rev. 58 (2016) 124–140.

[68] Pacak Anna, William Worek, Review of dew point evaporative cooling technology for air conditioning applications, Appl. Sci. 11 (2011) 1–18.

[69] K.J. Chua, R. Wang, C. Li, S. Wang, J. Long, K.J. Chua, Towards a thermodynamically favorable dew point evaporative cooler via optimization, Energy Convers. Manag. 203 (2020), 112224.

[70] D. Pandelidis, A. Cichoń, A. Pacak, P. Drąg, M. Drąg, W. Worek, S. Cetin, Performance study of the crossflow Mai-sotsenko cycle in humid climate conditions, Int. Commun. Heat Mass Tran. 115 (2020), 104581.

[71] N.H. Abu-Hamdeh, K.H. Almitani, Solar liquid desiccant regeneration and nanofluids in evaporative cooling for greenhouse food production in Saudi Arabia, Sol. Energy 134 (2016) 202–210.

[72] F. Comino, J.C. González, F.J. Navas-Martos, M.R. de Adana, Experimental energy performance assessment of a solar desiccant cooling system in Southern Europe climates, Appl. Therm. Eng. 165 (2020), 114579.

[73] Anita A. Nene, Solaisamy Ramachandran, Experimental Investigation of Solar Based Liquid Desiccant Indirect Evaporative Cooling System, Energy Sources, Part A: Recovery, Utilization, and Environmental Effects vol. 2021, 2021, pp. 1–11, https://doi.org/10.1080/15567036.2021.1948636.

74 L. Chen, Y. Tan, The performance of a desiccant wheel air conditioning system with high-temperature chilled water from natural cold source, Renew. Energy 146 (2020) 2142–2157.

[75] J.H. Kim, J. Ahn, Performance analysis of hybrid desiccant cooling system with enhanced dehumidification capability using TRNSYS, Appl. Sci. 11 (2021) 3236–3241.

[76] K. Harby, Doaa R. Gebaly, Nader S. Koura, Mohamed S. Hassan, Performance improvement of vapor compression cooling systems using evaporative condenser: an overview, Renew. Sustain. Energy Rev. 58 (2016) 347–360.

[77] P. Martínez, J. Ruiz, C.G. Cutillas, P.J. Martínez, A.S. Kaiser, M. Lucas, Experimental Study on Energy Performance of a Split Air-Conditioner by Using Variable Thickness Evaporative Cooling Pads Coupled to the Condenser, Applied Thermal Engineering, 2016.

[78] Bogdan Porumb, Mugur Bălan, Raluca Porumb, Potential of indirect evaporative cooling to reduce the energy consumption in fresh air conditioning applications, Energy Proc. 85 (2016) 433–441.

[79] Zongwei Han, Yanqing Zhang, Xin Meng, Qiankun Liu, Weiliang Li, Yu Han, Yanhong Zhang, Simulation study on the operating characteristics of the heat pipe for combined evaporative cooling of computer room air-conditioning system, Energy 98 (2016) 15–25.

[80] Evi Sofia, Putra Nandy, Evaporative cooling innovations - a review, AIP Conf. Proc. 2255 (2020), 020036.

[81] Evi Sofia, B. Nandy Putra, Ali gunawan, evaluation of indirect evaporative cooling performance integrated with finned heat pipe and Luffa cylindrica fiber as cooling/wet media, Journal of Advanced Research in Experimental Fluid Mechanics and Heat Transfer 3 (2021) 16–25.

[82] Xiang Yin, Feng Cao, Lei Jin, Bin Hu, Pengcheng Shu, Xiaolin Wang, Numerical and experimental investigations of electronic evaporative cooling performance with a coiled channel, Appl. Therm. Eng. 94 (2016) 256–265.

[83] J. Lin, K. Thu, T.D. Bui, R.Z. Wang, K.C. Ng, K.J. Chua, Study on dew point evaporative cooling system with counter-flow configuration, Energy Convers. Manag. 109 (2016) 153–165.

[84] Pinar Mert Cuce, Saffa Riffat, A state of the art review of evaporative cooling systems for building applications, Renew. Sustain. Energy Rev. 54 (2016) 1240–1249.

[85] C. Guo, Q. Liu, B. Zheng, Y. You, Y. Li, Development of model based on condensation area ratio and effect on heat transfer capacity of indirect evaporative cooling, Appl. Therm. *Eng.* 164 (2020), 114557.

[86] A. Basit, M. Mahmood, A. Waqas, M. Ali, W. Designing Khalid, Modelling and experimental investigation of direct evaporative cooling system coupled with commercial desiccant dehumidifier, ASME. J. Thermal Sci. Eng. Appl. 14 (2022), 071006.

[87] Uzair Sajjad, Naseem Abbas, A review of recent advances in indirect evaporative cooling technology, Int. Commun. Heat Mass Tran., 122, 105140.

[88] Sujatha Abaranji, Karthik Panchabikesan, Velraj Ramalingam, Experimental investigation of a direct evaporative cooling system for year-round thermal management with SolarAssisted dryer, International Journal of Photoenergy Article ID 6698904 (2020) 1–24.

[89] A. Francoa, D.L. Valer, A. Pena, A.M. Pérez, Aerodynamic analysis and CFD simulation of several cellulose evaporative cooling pads used in Mediterranean greenhouses, Comput. Electron. Agric. 76 (2011) 218–230.

[90] N. Kapilan, M. Manjunath Gowda, H.N. Manjunath, Computational fluid dynamics analysis of an evaporative cooling system, Journal of Mechanical Engineering – Strojnícky časopis 66 (2016) 117–124.

[91] E. Fatahian, H. Salarian, H. Fatahian, A parametric study of the heat exchanger copper coils used in an indirect evaporative cooling system, SN Appl. Sci. 2 (2020) 112, https://doi.org/10.1007/s42452-019-1915-0.

[92] Esmaeel Fatahian, Hesamoddin Salarian, Hossein Fatahian, A parametric study of the heat exchanger copper coils used in an indirect evaporative cooling system, SN Appl. Sci. 2 (2020) 1–10.

[93] Ajaya ketan Nayak, Aya Hagishima, Jun Tanimoto, A simplified numerical model for evaporative cooling by water spray over roof surfaces, Appl. Therm. Eng. 165 (2021), 114514.

[94] A. Laknizi, M. Mahdaoui, A.B. Abdellah, K. Anoune, M. Bakhouya, H. Ezbakhe, Performance analysis and optimal parameters of a direct evaporative pad cooling system under the climate conditions of Morocco, Case Stud. Therm. Eng. 13 (2019), 100362.

[95] M.C. Ndukwu, S.I. Manuwa, Review of research and application of evaporative cooling in preservation of fresh agricultural produce, Int. J. Agric. Biol. Eng. 7 (2014) 85–102.

[96] F. Bruno, on-site experimental testing of a novel dew point evaporative cooler, Energy Build. 43 (2011) 3475–3483.

[97] R. Boukhanouf, A. Alharbi, H. Ibrahim, M. Kanzari, Investigation of a sub-wet bulb temperature evaporative cooler for buildings, Proceedings of Sustainable Building Conference (2013).

[98] X. Zhao, J.M. Li, S.B. Riffat, Numerical study of a novel counter-flow heat and mass exchanger for dew point evaporative cooling, Appl. Therm. Eng. 28 (2008) 1942–1951.

[99] B. Riangvilaikul, S. Kumar, An experimental study of a novel dew point evaporative cooling system, Energy Build. 42 (2010) 637–644.

[100] A. Hasan, Indirect evaporative cooling of air to a sub-wet bulb temperature, Appl. Therm. Eng. 30 (2010) 2460–2468.

[101] R. Somsanuk, T. Kamonsan, E. Schulz, A. Koonsrisuk, Simulation of a hybrid dew-point evaporative cooling system, Transactions of the TSME 8 (2020) 114–134.

[102] E. Ibrahim, L. Shao, S.B. Riffat, Performance of porous ceramic evaporators for building cooling application, Energy Build. 35 (2003) 941–949.

[103] G. Heidarinejad, M. Bozorgmehr, S. Delfani, J. Esmaeelian, Experimental investigation of two-stage indirect/direct evaporative cooling system in various climatic conditions, Build. Environ. 44 (2009) 2073–2079.

[104] Frank Bruno, An indirect evaporative cooler for supplying air near the dew point, Solar2010, 1-3 December, in: The 48th AuSES Annual Conference, 2010 (Canberra, ACT, Australia).
[105] Sirelkhatim K. Abbouda, Emad A. Almuhanna, Improvement of evaporative cooling system efficiency in greenhouses, Int. J. Latest Trends Agric. Food Sci. 2 (2012) 83–89.
[106] Tri Ayodha Ajiwiguna, Fadhlin Nugraha Rismi, Mukhammad Ramdlan Kirom, Effect of air velocity and direction for indirect evaporative cooling in tropical area, IOP Conf. Ser. Mater. Sci. Eng. 211 (2017), 012022.
[107] S. De Antonellis, L. Cignatta, C. Facchini, P. Liberati, Effect of heat exchanger plates geometry on performance of an indirect evaporative cooling system, Appl. Therm. Eng. 173 (2020), 115200.
[108] A.Y.T. Al-zubaydi, G. Hong, Experimental study of a novel water-spraying configuration in indirect evaporative cooling, Appl. Therm. Eng. 151 (2019) 283–293.
[109] L. Jia, J. Liu, C. Wang, X. Cao, Z. Zhang, Study of the thermal performance of a novel dew point evaporative cooler, Appl. Therm. Eng. 160 (2019), 114069.
[110] J. Lee, D.-Y. Lee, Experimental study of a counter flow regenerative evaporative cooler with finned channels, Int. J. Heat Mass Tran. 65 (2013) 173–179.
[111] A. Al-Mogbel, S. Hussain, M.Z. Rafique, M.A. Almeshaal, Experimental investigations of evaporative cooling system for buildings in hot and dry environments, Heat Tran. Res. 51 (2020) 825–835.
[112] Egbal Mohammed Ahmed, Osama Abaas, Mohammed Ahmed, Mohd Rodzi Ismail, Performance evaluation of three different types of local evaporative cooling pads in greenhouses in Sudan, Saudi J. Biol. Sci. 18 (2011) 45–51.
[113] Faleh Al-Sulaiman, Evaluation of the performance of local fibers in evaporative cooling, Energy Convers. Manag. 43 (2002) 2267–2273.
[114] N. Soponpongpipat, S. Kositchaimongkol, Recycled High-Density polyethylene and rice husk as a wetted pad in evaporative cooling system, Am. J. Appl. Sci. 8 (2011) 186–191.
[115] N. Khosravi, D. Aydin, M. Karim Nejhad, P.A. Dogramaci, Comparative performance analysis of direct and desiccant assisted evaporative cooling systems using novel candidate materials, Energy Convers. Manag. 221 (2020), 113167.
[116] R. Rawangkul, J. Khedari, J. Hirunlabh, B. Zeghmati, Performance analysis of a new sustainable evaporative cooling pad made from coconut coir, Int. J. Sustain. Eng. 1 (2008) 117–131.
[117] R. Shekhar, M.K. Chopra, R. Purohit, Design of compact evaporative cooler to improve cooling efficiency and to evaluate performance of different cooling pad material, Int J Sci Res Dev 4 (2016) 21–27.
[118] F. Al-Sulaiman, Evaluation of the performance of local fibers in evaporative cooling, Energy Convers. Manag. 43 (2002) 2267–2273.
[119] V.W. Khond, Experimental investigation of desert cooler performance using four different cooling pad materials, Am. J. Sci. Ind. Res. 2 (3) (2011) 418–421.
[120] Eloy Velasco-Gómez, Ana Tejero-González, Javier Jorge-Rico, F. Javier Rey-Martínez, Experimental investigation of the potential of a new fabric-based evaporative cooling pad, Sustainability 12 (2020) 70–80.
[121] J.K. Jain, D.A. Hindoliya, Experimental performance of new evaporative cooling pad materials, Sustain. Cities Soc. 1 (2011) 252–256.
[122] Imtiyaz Hussain, Farzana Bibi, Showkat Ahmad Bhat, Uzair Sajjad, Muhammad Sultan, Hafiz Muhammad Ali, Muhammad Waheed Azam, Sachin Kumar Kaushal, Sajid Hussain, Wei-Mon Yan, Evaluating the parameters affecting the direct and indirect evaporative cooling systems, Eng. Anal. Bound. Elem. 145 (2022) 211–223.
[123] Zhiyin Duan, Minghui Wang, Xuelin Dong, Jingjing Liu, Xudong Zhao, Experimental and numerical investigation of wicking and evaporation performance of fibrous materials for evaporative cooling, Energy Build. 255 (2022), 111675.
[124] Hua Yang, Na Pei, Man Fan, Liansheng Liu, Dongji Wang, Experimental study on an air-cooled air conditioning unit with spray evaporative cooling system, Int. J. Refrig. 131 (2021) 645–656.
[125] Guangya Zhu, Tao Wen, Qunwei Wang, Xiaoyu Xu, A review of dew-point evaporative cooling: recent advances and future development, Appl. Energy 312 (2022), 118785.
[126] Jing Yang, Xiaoyun Xie, Yi Jiang, Performance comparison and suitable climatic zones of three water-mediated evaporative cooling technologies, Energy Convers. Manag. 277 (2023), 116637.
[127] M.C. Ndukwu, Mathew Imagwuike Ibeh, Godwin Edem Akpan, Elijah Ugwu, Akuwueke Leonard, Linus Oriaku, VictorE. Ihediwa, FidelisI. Abam, Hongwei Wu, C.A. Kalu, Augustine Edet Ben, Jude Mbanasor, Analysis of the influence of outdoor surface heat flux on the inlet water and the exhaust air temperature of the wetting pad of a direct evaporative cooling system, Appl. Therm. Eng. 226 (2023), 120292.
[128] D. Abada, C. Maalouf, O. Sotehi, D. Rouag-Saffidine, G. Polidori, A.F. Boudjabi, Z. Derghout, Performance evaluation of fabrics for evaporative cooling applications, Energy Build. 266 (2022), 112120.
[129] Yangda Wan, Zhifeng Huang, Alexander Soh, Kian Jon Chua, On the performance study of a hybrid indirect evaporative cooling and latent-heat thermal energy storage system under commercial operating conditions, Appl. Therm. Eng. 221 (2023), 119902.
[130] Weichao Yan, Xin Cui, Xiangzhao Meng, Chuanjun Yang, Yilin Liu, An Hui, Liwen Jin, Effects of membrane characteristics on the evaporative cooling performance for hollow fiber membrane modules, Energy (2023), 126873.
[131] Lanbo Lai, Xiaolin Wang, Gholamreza Kefayati, Eric Hu, Performance evaluation of a solar powered solid desiccant evaporative cooling system with different recirculation air ratios, Energy Build. 270 (2022), 112273.
[132] Dan Wang, Tao Lin, Xiaojun Quan, Enhanced evaporative cooling heat transfer by bidirectional freeze-casting technique, Appl. Therm. Eng. 216 (2022), 119063.
[133] Ablimit Aili, Xiaobo Yin, Ronggui Yang, Passive sub-ambient cooling: radiative cooling versus evaporative cooling, Appl. Therm. Eng. 202 (2022), 117909.
[134] Tiezhu Sun, Tingzheng Tang, Chuanjun Yang, Weichao Yan, Xin Cui, Junjie Chu, Cooling performance and optimization of a tubular indirect evaporative cooler based on response surface methodology, Energy Build. 285 (2023), 112880.
[135] Emad M.S. El-Said, A.A. Hegazi, A.M. Awad, Study of heat and mass transfer through a porous carbon tube as a humidification media for evaporative cooling system with swirl flow, J. Build. Eng. 48 (2022), 103926.
[136] Gökhan Yıldız, Alper Ergün, Ali Etem Gürel, İlhan Ceylan, Ümit Ağbulut, Servet Eser, C. Asif Afzal, Ahamed Saleel, Exergy, sustainability and performance analysis of ground source direct evaporative cooling system, Case Stud. Therm. Eng. 31 (2022), 101810.
[137] Saba Zakeri Shahvari, Vahid Ahmadi Kalkhorani, Jordan D. Clark, Performance evaluation of a metal organic frameworks based combined dehumidification and indirect evaporative cooling system in different climates, Int. J. Refrig. 140 (2022) 186–197.
[138] İbrahim Atmaca, Şenol Ali, Ahmet Çağlar, Performance testing and optimization of a split-type air conditioner with evaporatively-cooled condenser, Engineering Science and Technology, Int. J. 32 (2022), 101064.
[139] Kanghao Tan, Yinghong Qin, Taiyang Du, Lingling Li, Lei Zhang, Junsong Wang, Biochar from waste biomass as hygroscopic filler for pervious concrete to improve evaporative cooling performance, Construct. Build. Mater. 287 (2021), 123078.
[140] Jing Lv, Haodong Xu, Mengya Zhu, Yuwei Dai, Hongzhi Liu, Li Zhao, The performance and model of porous materials in the indirect evaporative cooling system: a review, J. Build. Eng. 41 (2021), 102741.
[141] Wichakan Ketwong, Thoranis Deethayat, Tanongkiat Kiatsiriroat, Performance enhancement of air conditioner in hot climate by condenser cooling with cool air generated by direct evaporative cooling, Case Stud. Therm. Eng. 26 (2021), 101127.
[142] Wenchao Shi, Yunran Min, Xiaochen Ma, Yi Chen, Hongxing Yang, Performance evaluation of a novel plate-type porous indirect evaporative cooling system: an experimental study, J. Build. Eng. 48 (2022), 103898.
[143] Wenchao Shi, Yunran Min, Xiaochen Ma, Yi Chen, Hongxing Yang, Dynamic performance evaluation of porous indirect evaporative cooling system with intermittent spraying strategies, Appl. Energy 311 (2022), 118598.
[144] Amatalraof Abdullah, Experimental study of natural materials for an evaporative cooling design in hot-arid climate, Build. Environ. 207 (2022), 108564.
[145] Hao Fu, Rui Zhao, Wenjun Long, Wenlong Cheng, Study on cooling performance of rapid cooling system based on vacuum spray flash evaporation, Appl. Therm. Eng. 201 (2022), 117751.
[146] Arthur P. da Veiga, Saulo Güths, K. Alexandre, da Silva, Evaporative cooling in building roofs: local parametric and global analyses (Part-2), Sol. Energy 207 (2020) 1009–1020.
[147] Sangeeta Chopra, Norbert Müller, Devinder Dhingra, Indra Mani, Tushar Kaushik, Ankit Kumar, Randolph Beaudry, A mathematical description of evaporative cooling potential for perishables storage in India, Postharvest Biol. Technol. 183 (2022), 111727.
[148] Jue Wang, Jun Lu, Wuyan Li, Cheng Zeng, Fenghao Shi, Numerical study on performance of a hybrid indirect evaporative cooling heat recovery heat pump ventilator as applied in different climatic regions of China, Energy 239 (2022), 122431.
[149] Chenxia Jia, Daxi Sun, Xingfu Hu, Chengjun Jing, Optimization of the performance of M-Cycle indirect evaporative cooling via thermodynamic approach, J. Asian Architect. Build Eng. (2023), https://doi.org/10.1080/13467581.2023.2183774.
[150] Kousar R, Ali M, Amjad MK, Sheikh NA, Ahmad W. Performance characterization and optimization of counter-flow dew point indirect evaporative cooler through response surface methodology. Proc. Inst. Mech. Eng. A J. Power Energy. 235 (20217) 1789-1805.
[151] Q. Liu, C. Guo, Z. Wu, et al., Heat and mass transfer model optimization and annual energy efficiency analysis for energy recovery indirect evaporative cooling, Build. Simulat. 15 (2022) 1353–1365.
[152] Y. Zhou, T. Zhang, F. Wang, Numerical study and optimization of a combined thermoelectric assisted indirect evaporative cooling system, J. Therm. Sci. 29 (2020) 1345–1354.
[153] J. Li, F. Song, G. Gu, Optimization of Air-Cooling Condenser in Close-Loop Self-Circulating Evaporative Cooling System of Large Electrical Equipments, International Conference on Electrical Machines and Systems, Tokyo, Japan, 2009, pp. 1–5, https://doi.org/10.1109/ICEMS.2009.5382675.
[154] Sergey Anisimov, Demis Pandelidis, Danielewicz, Numerical study and optimization of the combined indirect evaporative air cooler for air-conditioning systems, Energy 80 (2015) 452–464.
[155] Ghassem Heidarinejad, Seyed Zia Miri, Hadi Pasdar Shahri, Optimization of hybrid cooling system including direct evaporative cooler- cooling tower in order to minimize operation cost using genetic algorithm, Modares Mechanical Engineering 15 (2015) 348–354.
[156] H. Montazeri, B. Blocken, J.L.M. Hensen, Evaporative cooling by water spray systems: CFD simulation, experimental validation and sensitivity analysis, Build. Environ. 83 (2015) 129–141.
[157] Qun Chen, Ning Pan, Zeng-Yuan Guo, A new approach to analysis and optimization of evaporative cooling system II: applications, Energy 36 (2011) 2890–2898.

[158] K.O. Babaremu, M.A. Omodara, O.S. I Fayomi, I.P. Okokpujie, Design and optimization of an active evaporative cooling system, Int. J. Mech. Eng. Technol. 9 (2018) 1051–1061.
[159] Shekh Abdullah, Mohd Nashrul Bin Mohd Zubir, Mohd Ridha Bin Muhamad, Kazi Md Salim Newaz, Hakan F. Öztop, Md Shadab Alam, Shaikh Kaleemullah, Technological development of evaporative cooling systems and its integration with air dehumidification processes: a review, Energy Build. 283 (2023), 12805.
[160] Md Sazan Rahman, Sarah MacPherson, Mark Lefsrud, Experimental investigation of a novel evaporative cooling pad made of cement-free porous concrete, Build. Environ. 228 (2023), 109867.
[161] Lanbo Lai, Xiaolin Wang, Gholamreza Kefayati, Eric Hu, Analysis of a novel solid desiccant evaporative cooling system integrated with a humidification-dehumidification desalination unit, Desalination 550 (2023), 116394.
[162] Sangeeta Chopra, Norbert Müller, Devinder Dhingra, Pranav Pillai, Tushar Kaushik, Ankit Kumar, Randolph Beaudry, Design and performance of solar-refrigerated, evaporatively-cooled structure for off-grid storage of perishables, Postharvest Biol. Technol. 197 (2023), 112212.
[163] M.C. Ndukwu, M.I. Ibeh, E.C. Ugwu, D.O. Igbojionu, A.A. Ahiakwo, Hongwei Wu, Evaluating coefficient of performance and rate of moisture loss of some biomass humidifiers materials with a developed simple direct stand-alone evaporative cooling system for farmers, Energy Nexus 8 (2022), 100146.
[164] Ramy H. Mohammed, Mohamed El-Morsi, Omar Abdelaziz, Indirect evaporative cooling for buildings: a comprehensive patents review, J. Build. Eng. 50 (2022), 104158.
[165] Çaylı Ali, Akyüz Adil, Sait Üstün, Beyhan Yeter, Efficiency of two different types of evaporative cooling systems in broiler houses in Eastern Mediterranean climate conditions, Therm. Sci. Eng. Prog. 22 (2021), 100844.
[166] Hongxing Yang, Wenchao Shi, Yi Chen, Yunran Min, Research development of indirect evaporative cooling technology: an updated review, Renew. Sustain. Energy Rev. 145 (2021), 111082.
[167] Mohamad El Loubani, Nesreen Ghaddar, Kamel Ghali, Mariam Itani, Hybrid cooling system integrating PCM-desiccant dehumidification and personal evaporative cooling for hot and humid climates, J. Build. Eng. 33 (2021), 101580.
[168] Yuanlong Cui, Jie Zhu, Stamatis Zoras, Lin Liu, Review of the recent advances in dew point evaporative cooling technology: 3E (energy, economic and environmental) assessments, Renew. Sustain. Energy Rev. 148 (2021), 111345.
[169] Nasibeh Nemati, Amir Omidvar, Behnam Rosti, Performance evaluation of a novel hybrid cooling system combining indirect evaporative cooler and earth-air heat exchanger, Energy 215 (2021), 119216.
[170] Xin Cui, Weichao Yan, Yilin Liu, Min Zhao, Liwen Jin, Performance analysis of a hollow fiber membrane-based heat and mass exchanger for evaporative cooling, Appl. Energy 271 (2020), 115238.
[171] Rabah Boukhanouf, Omar Amer, Hatem Ibrahim, John Calautit, Design and performance analysis of a regenerative evaporative cooler for cooling of buildings in arid climates, Build. Environ. 142 (2018) 1–10.
[172] Pacak Anna, Korneliusz Sierpowski, Błażej Baran, Ziemowit Malecha, William Worek, Sabri Cetin, Demis Pandelidis, Impact of air distribution on dew point evaporative cooler thermal performance, Appl. Therm. Eng. 224 (2023), 120137.
[173] Yunsheng Fang, Xun Zhao, Guorui Chen, Trinny Tat, Jun Chen, Smart polyethylene textiles for radiative and evaporative cooling, Joule 5 (2021) 752–754.
[174] J. Xu, Y. Li, R.Z. Wang, W. Liu, P. Zhou, Experimental performance of evaporative cooling pad systems in greenhouses in humid subtropical climates, Appl. Energy 138 (2015) 291–301.
[175] Andreas Nocker, Lorenz Schulte-Illingheim, Frösler Jan, Laura Welp, Oliver Sperber, Achim Hugo, Microbiological examination of water and aerosols from four industrial evaporative cooling systems in regard to risk of Legionella emissions and methodological suggestions for surveillance, Int. J. Hyg Environ. Health 229 (2020), 113591.