ADVANCED REVIEW

Direct evaporative cooling from wetted surfaces: Challenges for a clean air conditioning solution

Ana Tejero-González[1] [iD] | Antonio Franco-Salas[2] [iD]

[1]Department of Energy Engineering and Fluidmechanics, School of Engineering, Universidad de Valladolid, Valladolid, Spain

[2]ETSIA, University of Sevilla, Sevilla, Spain

Correspondence
Ana Tejero-González, Department of Energy Engineering and Fluidmechanics, School of Engineering, Universidad de Valladolid, Paseo del Cauce 59, 47011 Valladolid, Spain.
Email: anatej@eii.uva.es

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Abstract

Evaporative cooling has a major role to play in fighting climate change and in achieving a low-carbon economy. As it helps to reduce energy demand for air conditioning, it is gaining attention in terms of improving energy efficiency in buildings. Evaporative cooling from wetted media can enhance water–air contact, thereby improving heat and mass transfer further and avoiding aerosols. Wetted media are commonly called evaporative cooling pads and are widely used in greenhouses, intensive livestock farming, and industrial facilities. However, a deep understanding of evaporative cooling pad performance can enhance their application to indoor occupied spaces such as residential or commercial cooling, or in hybrid air conditioning systems. Most studies analyze pad performance mainly in terms of pressure drop and saturation effectiveness. However, some studies propose alternative cooling efficiency parameters and others provide insights into key aspects such as power requirements and the coefficient of performance, water consumption, risk of water entrainment, material decay, and air quality, as well as the effect of water temperature and salinity, solar radiation, or wind speed. Existing results on these less studied performance issues are reviewed, and we identify the gaps in the literature in addition to highlighting the main challenges encountered, in an effort to guide future researchers in the field and enhance the application of direct evaporative cooling.

This article is categorized under:
    Energy Efficiency > Systems and Infrastructure
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KEYWORDS
air conditioning, cooling efficiency, direct evaporative cooling, evaporative cooling pads, performance assessment

1 | INTRODUCTION

Evaporative cooling is one of the passive cooling techniques that can reduce energy consumption in buildings (Oropeza-perez & Østergaard, 2018). Due to its simplicity and the many examples that can be found in nature

(Watt, 1986), it is in fact the oldest strategy humankind has used to cool ambient air. As water evaporates within the surrounding non-saturated air, this leads to heat absorption due to the latent heat required for vaporization. Consequently, there is heat and mass transfer. Moist air becomes further saturated, while its dry bulb temperature (DBT) decreases towards its wet bulb temperature (WBT). Contact between air and water can be enhanced in two ways: by providing a large, wetted surface, or by directly spraying water. The former option can increase the water evaporation rates that can be achieved (Naveenprabhu & Suresh, 2020).

Direct evaporative cooling (DEC) refers to the application of this phenomenon to cool an airstream that is directly supplied to a target space. Although indoor humidification is sometimes required, this technique may yield excessive relative humidity and lead to a risk of material degradation and microorganism proliferation. Indirect evaporative cooling (IEC) overcomes this issue by separately driving the airflow to be conditioned from a secondary airstream that is evaporatively cooled, sensibly cooling the former in an air-to-air heat exchanger. Duan et al. (2012) and more recently H. Yang et al. (2021) reviewed existing IEC technologies, which have developed rapidly over the last few decades. Particular attention is currently being paid to dew point indirect evaporative cooling (DPIEC) systems, which can ideally cool air down to dew point temperature (DPT) (Pacak & Worek, 2021). Although, given the nature of the phenomenon, evaporative cooling is gaining interest in hot and dry climates, IEC and multiple-stage options also enable evaporative cooling applications to be used in more humid climates (Tejero-González et al., 2016). Another alternative for improving the evaporative cooling effect is to combine it with desiccant techniques (Y. Yang et al., 2019).

Nevertheless, DEC is still the preferred option in applications such as greenhouses (Ghani et al., 2019), intensive livestock farming (Al Assaad et al., 2021), industrial facilities (Xuan et al., 2012), and urban spaces (L. Pérez-Urrestarazu et al., 2016; Ulpiani, 2019).

1.1 | Objectives, methodology, and structure of the review

Evaporative cooling technologies have been subject to previous review articles. These provide a general approach (Amer et al., 2015; Okafor, 2017), sometimes focusing on one technology in particular (Pacak & Worek, 2021; H. Yang et al., 2021), or on research in a certain region (Xuan et al., 2012), their integration in buildings (Cuce & Riffat, 2016; Emdadi et al., 2019), a particular application (Misra & Ghosh, 2018; Odesola & Onyebuchi, 2009; Ulpiani, 2019), or the use of alternative materials (Emdadi et al., 2016; S. He et al., 2015; Kumar et al., 2020). The main factors influencing DEC operation (Tejero-González & Franco-Salas, 2021) and the possibilities of enhancing evaporative cooling (Y. Yang et al., 2019) have also been the target of existing reviews.

To guide future research in DEC from wetted surfaces, this review article identifies the main challenges and gaps in the related literature. With this aim, existing research on the topic has been systematically reviewed. The literature has been examined through Scopus, Web of Science, and Google Scholar databases, and includes both experimental and simulation studies and has not been confined to the most recent developments.

All DEC systems based on evaporation from wetted surfaces have been considered. Both commercial pads and new prototypes were thus taken into account. Although some articles focusing on spray systems are cited for descriptive or comparative purposes, these are not targeted in the review. Section 2 relates existing DEC pad types studied in the literature. Special attention has then been given to research providing insights into unusual or less widely studied applications, performance parameters, and operating factors. The results are presented in Sections 3–5. And Section 5 highlights the main gaps observed with a view to enhancing future research on these issues. Finally, the main conclusions are presented in Section 6.

2 | EVAPORATIVE COOLING WETTED MEDIA

Evaporative cooling pads work with water that flows down through the wetted porous medium due to gravity, while the target airflow is usually forced crossflow. In DEC systems, this same cooled and humidified airflow is driven to the occupied space and mixes with the existing air, with the wetted media acting as a heat and mass exchanger between air and water. An optimal design would result in: (1) maximum water-to-air contact surface that favors air saturation, but (2) minimum resistance to airflow; in other words, a minimum pressure drop; (3) ensuring total humidification through maximum water-to-air contact surface, which (4) constitutes a rigid media that facilitates easy assembly and dismantling, as well as (5) easy cleaning and maintenance.
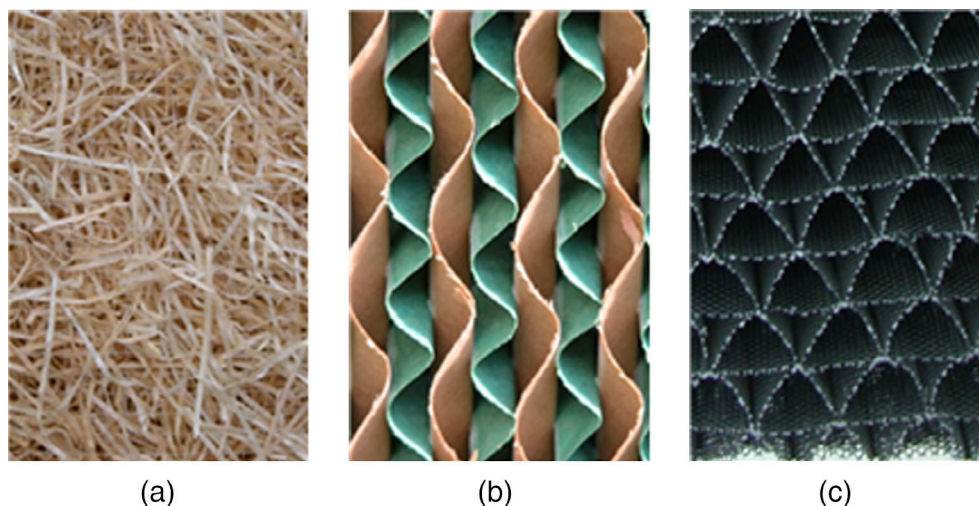
FIGURE 1 Detail of a (a) fiber pad, (b) rigid media pad, and (c) package or fill pad

The performance of evaporative pads depends both on their material and their configuration as well as on air psychrometric properties together with air and water flow rates. As regards their material and configuration, they can be classified into fiber pads, rigid media pads, and packages or fill pads (Figure 1). Although the two former are currently the most widespread wetted media among those available on the market, packaged fills are gaining interest.

2.1 | Fiber pads

Fiber pads are usually made with vegetable fibers, although synthetic fibers are becoming increasingly common. Given their simple manufacturing, the first DEC systems traditionally used this type of pad, and they are still widely used, as in the case of Aspen pads (American Society of Agricultural and Biological Engineers, 2008).

The use of locally available vegetable fibers has the advantage of using indigenous resources and thus becomes more sustainable. Examples include coconut fiber (Alam et al., 2017; Jain & Hindoliya, 2011; Liao et al., 1998; Rawangkul et al., 2008; Shekhar et al., 2016), cotton fibers and woven fabric (Liao et al., 1998; Pandelidis et al., 2020; Velasco-Gómez et al., 2020), eucalyptus fibers (Doğramacı et al., 2019; Doğramacı & Aydın, 2020; Khosravi et al., 2020), jute fibers (Abdullah et al., 2019; Alam et al., 2017;Al-Sulaiman, 2002; Ndukwu & Manuwa, 2015), Kraft paper (Barzegar et al., 2012; Pandelidis et al., 2020), luffa fibers (Al-Sulaiman, 2002; De Melo et al., 2019), palash fibers and khus roots (Jain & Hindoliya, 2011, 2014), palm fibers (Al-Sulaiman, 2002; Ndukwu & Manuwa, 2015), sack cloth (Alam et al., 2017), wood chips (Ahmed et al., 2011; Khosravi et al., 2020), straw (Ahmed et al., 2011), wood charcoal (Korese & Hensel, 2016; Ndukwu & Manuwa, 2015), rice husk (Soponpongpipat & Kositchaimongkol, 2011), and synthetic fibers (Pandelidis et al., 2020).

Fiber pads have been widely used and are still being installed, mainly due to their high porosity and capacity to retain water, their low cost and usually widespread local availability. However, fiber processing and packaging may be complicated, requiring complex structures to build the pad. Bending, fiber decay, and decomposition of the organic materials limit their lifespan and general use. Faced with these disadvantages, and despite their greater cost, rigid media pads are gaining prominence due to their longer lifespan and the possibility of achieving high saturation effectiveness with low pressure drop.

2.2 | Rigid media pads

Rigid media pads correspond to corrugated plates fixed to each other with resin adhesives. Their assembly forms two different flute angles from the horizontal. Pad thickness usually varies from 5 to 30 cm. The most widely used material is cellulose, which dominates the world market through the Swedish company Munters Corp. with the trade names

Celdesk and Glasdek, and the US company KUUL Corp. with the trade name KUUP pads, although new manufacturers from other countries are appearing on the market (Barzegar et al., 2012).

Other materials are also used, such as plastic PVC (S. He, Guan, Gurgenci, Hooman, Lu, & Alkhedhair, 2014; Sohani et al., 2017), or polyethylene (Fouda & Melikyan, 2011), glass fiber (Sreeram et al., 2015). These systems dispense with a support structure, avoid the risk of fiber carryout, and have longer lifespans compared to fiber panels. Moreover, they enable larger specific contact areas (air–water contact area related to pad volume), mechanical resistance and they favor both air and water flow through the pad. Consequently, this design permits air flow through the pad at relatively large velocities without excessive pressure drop and water entrainment. Saturation effectiveness in rigid media pads varies between 70% and 90%, depending on pad thickness and air velocity, and is greater for cellulose pads compared to plastic corrugated plates (Ahmed et al., 2011; Czarick & Fairchild, 2012). Other pads made of plastic or metal mesh offer a good alternative to rigid media pads, provided that investment and maintenance costs are affordable. These are the so-called "packages" or "fill pads."

2.3 | Packages or fill pads

Packages or fill pads use less structured materials that consequently require a case to house the wetted media and distribute the air and waterflows within. Although this can also be the case of certain pads made of fibers, "fill pads" refers to all porous, inorganic materials, whether natural—such as volcanic stones—or artificial, like expanded clay (Gunhan et al., 2007; Khosravi et al., 2020; Rosa et al., 2011; Wanphen & Nagano, 2009). Alternative prototypes also consider the use of bricks or ceramic pipes (W. Chen et al., 2015; Doğramacı & Aydın, 2020; J. He & Hoyano, 2011; Zeitoun et al., 2014). Over the last few years, different configurations of alternative pads made of plastic or metal mesh have been introduced; namely Trickle fills. Water flows through the mesh, with a combined effect of small water drop generation and a water film over the mesh surface. They present less incrustations and admit larger air and water flows with limited pressure drop and high saturation effectiveness (A. Franco et al., 2014; P. Martínez et al., 2018). There are also infill panels made of unstructured recycled plastic materials (Soponpongpipat & Kositchaimongkol, 2011).

3 | POTENTIAL APPLICATIONS OF DEC PADS

DEC can be a suitable solution for large indoor spaces with large cooling thermal loads (ASHRAE, 2019), where vapor compression systems would not be feasible and natural ventilation would not achieve the required indoor conditions. Indeed, this is the common cooling solution applied in industrial facilities and intensive agriculture and farming. Evaporative cooling can also prove effective for storing certain products in different climates (ASHRAE, 2019), which is particularly attractive for developing countries, given the high cost related to cold storage rooms and controlled environments. The main limitation of applying DEC vis-à-vis other indoor spaces is the risk of imposing an excessive latent load. However, in non-humid climates, proper air renovation can prevent this. The main gaps in the literature concerning DEC application are now identified.

3.1 | Industrial facilities, intensive agriculture, and livestock farming

Despite their widespread application, the existing literature on DEC in industrial facilities is very scarce (Kowalski & Kwiecień, 2020) and further research is required. In contrast, there is abundant research into how DEC pads improve indoor climate conditions in greenhouses (Ghani et al., 2019; Misra & Ghosh, 2018), and intensive livestock farming (Fidaros et al., 2018; Vitt et al., 2017). As regards food storage, DEC has been widely studied to reduce spoilage of horticultural products (Brosnan & Sun, 2001; Lal Basediya et al., 2013) as well as in certain tropical and subtropical countries (Odesola & Onyebuchi, 2009).

Some results provide insights into key issues concerning DEC use in intensive agriculture and farming, but may require further study. For example, (López et al. (2012) explored the need for DEC integration in Mediterranean greenhouses to reduce excess heat and maintain the relative humidity levels required from spring to autumn. Fogging systems evidenced greater efficiency through less electrical consumption but implied a greater consumption of water. Horizontal and vertical temperature gradients had to be avoided by combining with shading devices.

Although most research focuses on arid regions, more humid climates are occasionally considered. Experiments conducted by Xu et al. (2015) demonstrated that DEC pads were also effective in subtropical climates. By combining them with shading strategies, indoor air was kept 2–3°C below ambient air, at 80% RH.

Finally, DEC has the potential to reduce livestock heat stress in intensive farming in hot and arid or semi-arid regions, thereby improving their milk, egg, and so on production. However, not all studies have observed this improvement in production response (R. S. Martínez et al., 2021). Raza et al. (2021) achieved an average temperature decrease in the indoor environment of 8.5°C with DEC pads in Pakistan, resulting in better thermal conditions than when using IEC, although indoor RH was excessive.

3.2 | Outdoor and semi-outdoor spaces

Evaporative cooling is an appropriate air conditioning solution for outdoor or semi-outdoor spaces where conventional systems are not feasible. However, misting systems are the most widespread solution as they allow greater flexibility with the facility. Mist spray systems for outdoor cooling are the subject of published review work (Ulpiani, 2019) and lie outside the scope of this review. One alternative to spraying water is to wet large porous surfaces such as pavements (Kubilay et al., 2021; Parison et al., 2020). Some authors examine the effect generated by wetted porous elements behaving as passive evaporative cooling walls, such as the pipe ceramics humidified through capillary action developed by J. He (2011) and J. He and Hoyano (2010, 2011), or wetted sun blinds (Del Rio et al., 2020). Green walls also operate as evaporative cooling surfaces and can be installed not only outdoors but also indoors (L. Pérez-Urrestarazu et al., 2015). Further research on the use of wetted surfaces for urban spaces is required.

3.3 | Residential and commercial use

Portable evaporative coolers are widely marketed for residential and small commercial use, despite which the existing literature has paid little attention to this application. Although their functioning strongly depends on climate conditions, such that higher air velocities are required as the climate becomes more humid (ASHRAE, 2019), DEC is recognized as a more economical solution than vapor compression systems for residential use (Navon & Arkin, 1993). However, when acquiring portable DEC many users are not advised about the appropriate operation, maintenance, and climate applications (Watt & Brown, 1997), which may result in inadequate performance and the technology's subsequently poor reputation. Research providing information about the optimal operating conditions would thus help to enhance its use, with the consequent reduction in electricity demand in buildings during summer.

Hasani Balyani et al. (2015) evaluated the applicability of evaporative cooling in residential buildings for different climates in Iran, and concluded that DEC was appropriate for the country's dry areas. Another study focusing on Iranian climates evidenced substantial electricity and water savings, especially in the city with the lowest WBT (Naderi et al., 2020).

W. He et al. (2018) performed experiments with an evaporative cooler in an experimental house. In order to prevent indoor relative humidity from rising above 70% they introduced a pre-dehumidifying system. The result was a reduction in indoor temperature below 28°C.

DEC can be an affordable, easy-to-build solution in deprived regions under harsh climate conditions. Moran et al. (2021) built a prototype for refugee shelters, and improved indoor conditions by 6°C.

Applying DEC systems to the tertiary sector beyond small businesses is unusual. Indeed, related research on the matter is almost non-existent. For office buildings, Tewari, Mathur, and Mathur (2019) and Tewari, Mathur, Mathur, Kumar, and Loftness (2019) evaluated the thermal comfort perceived by occupants from an adaptive thermal comfort approach. Although 86% of occupants reported comfortable sensations and the humidity sensation vote only reached a slightly humid sensation, care should be taken with the maximum values of indoor relative humidity recorded in their experiments.

3.4 | Adiabatic condensation and hybrid air conditioning

As seen before, there is a reluctance to install DEC systems in occupied spaces beyond small applications. This is justified, given the limitations on indoor relative humidity. Researchers consequently focus on IEC, two-stage EC, regenerative and DPIEC, or desiccant EC. However, DEC displays enormous potential to reduce cooling demand through

hybrid systems (Kojok et al., 2016), or to improve heat recovery by implementing an evaporative cooling stage in the return air (IEC heat recovery) (ASHRAE, 2019).

The trend in the room air conditioner market is towards hybrid designs (N. Shah et al., 2021). The most widespread solution proposed in the literature is coupling an evaporative cooling pad to the condenser of a split air conditioner. P. Martínez et al. (2016) performed experiments for different pad thicknesses and recommended 100 mm thickness for maximum reduction in compressor power consumption without an excessive pressure drop that would hinder airflow through the condenser. This recommendation agrees with results provided by Harby and Al-amri (2019), who studied a broader range of outdoor conditions, highlighting the improvement in the system's coefficient of performance (COP) as climate conditions become harsher. B. Shah et al. (2019) also reported optimum results for 100 mm cellulose thickness, with worse performances of grass and PVC pad materials. However, there are some gaps in the methodology and the results should be approached with caution. Nevertheless, thinner pads might also make the difference. Ramzan et al. (2021) observed a COP decrease from only 2.93 to 2.56 as outdoor air temperature increased from 40 to 50°C if the condenser outdoor unit was equipped with a 50 mm thick pad, compared to a decrease from 2.31 to 1.83 without the EC pad. Finally, Ketwong et al. (2021) showed that DEC could improve the COP of vapor compression air conditioning units better in hot-dry climates than in hot-humid climates, as is to be expected.

Sharma and Katarey (2019) reported the COP improvement and energy consumption reduction of a DEC pad installed in a window type air conditioner. Dhamneya et al. (2018) also focused on a window air conditioner, and investigated performance improvement theoretically through two effects: precooling of outdoor air before being treated by the evaporator coil, and improved heat-rejection through outdoor air precooling before passing through the condenser coil. Their study predicted a decline in the system performance for outdoor air WBT over 23°C and recommended a pad thickness of at least 100 mm.

A trend towards hybrid systems with DEC can also be seen in the air condensing units of chiller plants (Rey-Martínez et al., 2020) and in dry cooling towers (S. He, Guan, Gurgenci, Hooman, Lu, & Alkhedhair, 2014; S. He et al., 2015). In these applications, evaporative cooling pads are being incorporated to precool the working air towards its WBT during particularly harsh outdoor conditions.

3.5 | Passive cooling combinations

DEC is often considered in combination with other passive cooling strategies, especially with natural ventilation. DEC can be integrated within windcatchers. Although some researchers propose the use of spray systems (Ghoulem et al., 2020; Spentzou et al., 2021), the use of porous wetted surfaces is also possible (Abdullah et al., 2019; Saif et al., 2021). In the same line, Mohamed et al. (2021) proposed a double skin wall with a porous ceramic layer filled with water. Exhaust ventilation can be solar driven through solar chimneys (Abdallah et al., 2014; Eghtedari & Mahravan, 2021; Soto et al., 2021), or carefully designed and located openings (Khalvati & Omidvar, 2019). Some authors propose evaporatively cooling the glazing areas, either with wetted shadings (Li & He, 2021), or through a partially glazed solar chimney with water sheets (Hweij et al., 2017). More elaborate solutions also incorporate an earth-air heat exchanger (Abed et al., 2021).

3.6 | Climate applicability

DEC performance dependence on climate conditions has led many researchers to evaluate its applicability in different regions and to seek guidelines for climatic applicability.

Bishoyi and Sudhakar (2017) study the hot-dry, warm-humid, composite, temperate, and cold regions of India, although they highlight that DEC was applied more in composite and hot-dry climatic zones, because relative humidity stays within 30%–50%. Tewari, Mathur, Mathur, Loftness, and Abdul-Aziz (2019) focused on this composite climate in India and observed that perception of thermal comfort varied substantially depending on expectations and air velocities.

Several authors have focused on the Mediterranean region. Chiesa et al. (2019) targeted different cities identified through the Köppen–Geiger climate classification as BSh, BSk, BWh, Cfa, Csa, and Dfb. They applied three methods to evaluate the geo-climatic applicability of DEC, which displayed significant potential to reduce the number of hours of discomfort during the cooling season, but which differed noticeably between climates. Greater potential was identified

in the eastern Mediterranean (hot-dry) and in southern Spain. This potential was also highly dependent on the system's saturation effectiveness, although even 60% saturation effectiveness proved to yield significant cooling in some locations. Baca et al. (2011) provide further insights into the diverse climates in Spain and rate the expected improvement in thermal comfort. Campaniço et al. (2019) study the whole of the Iberian Peninsula and provide maps of DEC potential for both present climates as well as prospective conditions arising from climate change. Laknizi, Mahdaoui, et al. (2019) determined that DEC would be appropriate for the six Moroccan cities analyzed.

Other regions are also studied in the literature. Guan et al. (2015) explored the applicability of DEC in different Australian climates (hot humid summer, warm humid summer, hot-dry summer, warm summer or temperate, mild to warm) and provided a climate assessment calculator. Xia et al. (2021) distinguished different Chinese climate zones for passive evaporative cooling applications. Xu et al. (2015) focused on the humid-subtropical city of Shanghai, and concluded that DEC was also effective in humid climates for avoiding overheating in greenhouses when combined with appropriate shadowing. Aparicio-Ruiz et al. (2018) explored the whole range of climates in the United States (BWh, BWk, BSh, BSk, Af, Am, Aw, Csa, Csb, Cwa, Cwb, Cfa, Cfb, Cfc, Dsa, Dsb, Dsc, Dsd, Dwa, Dwb, Dwc, Dwd, Dfa, Dfb, Dfc, Dfd, ET, and EF) and provided maps of potential applicability. Finally, Sohani et al. (2018) consider potential climatic zones worldwide (BWh, BWk, BSh, BSk, Csa, Csb, Cfa, Cwb, Dsa, and Dsb) and state that DEC design must be pertinent to the climate conditions, as they will affect the system retrofit.

Some studies do not focus on particular climates but provide a general approach to evaporative cooling applicability. Tejero-González et al. (2016) propose studying applicability limits in terms of WBD. Crow (1972) presents the typical WBT coincident with DBT ranges at representative locations in the United States and Canada. El-Refaie and Kaseb (2009) establish theoretical limits of climatic applicability and Lomas et al. (2004) provide bioclimatic charts. The climatic applicability of DEC is thus known. However, evaluating the feasibility of particular applications at specific locations is always recommendable.

4 | EVAPORATIVE COOLING PERFORMANCE

Evaporative cooling pads have been investigated thoroughly in terms of their pressure drop and cooling performance. Other relevant but less studied performance issues involve pad decay, risk of water carryout, air quality, and time to steady state operation or to total stop of the humidification effect. The main results available in the published literature on different pad performance are now presented, focusing further attention on those issues which have been less studied or that are subject to controversy. Results are summarized in Table 1.

4.1 | Cooling performance parameters

When analyzing the performance of evaporative cooling pads, the temperature drop achieved is among the most useful information. Saturation effectiveness, ε, relates this temperature drop (difference between the air DBT at the inlet, T_{in}, and outlet, T_{out}), to the maximum decrease achievable in an adiabatic process; that is to say, to the difference between the DBT (T_{in}) and the WBT ($T_{\text{wb in}}$) of ambient air, or wet bulb depression (WBD):

$$\varepsilon = \frac{T_{\text{in}} - T_{\text{out}}}{T_{\text{in}} - T_{\text{wb in}}}. \tag{1}$$

DEC pad saturation effectiveness is well known. As expected, the literature agrees that the drop in temperature increases when the WBD increases (X. Chen et al., 2018, 2017; S. He, Guan, Gurgenci, Jahn, Lu, & Alkhedhair, 2014; Velasco-Gómez et al., 2020). However, in Equation (1) this increased temperature drop would be compensated by the larger WBD causing it. Simulation studies have concluded that inlet air psychrometric conditions would have almost no effect on saturation effectiveness (Kovačević & Sourbron, 2017; Sellami et al., 2019; Wu et al., 2009a), although several experimental studies have reported greater saturation effectiveness with increasing outdoor air DBTs (Camargo et al., 2005; Nada et al., 2020, 2019; Sheng & Agwu Nnanna, 2012). Because most of the experimental research conducted has not controlled air relative humidity at the inlet airstream, further studies are needed to properly evaluate the effect of the inlet air psychrometric conditions on saturation effectiveness. Existing research also concurs in that lower air velocities and thicker pads imply higher saturation effectiveness values, which is due to the shorter residence times.

TABLE 1 Less studied DEC pad performance issues

Factor	Related research	Comments
Water consumption	Franco et al. (2010), Nada et al. (2020), Sohani et al. (2017)	Specific water consumption
	Naderi et al. (2020)	Optimization of water consumption
	Samam et al. (2009)	Water bleed-off
	Purswell et al. (2018)	Maps of water consumption
	Doğramacı et al. (2019), A. Franco et al. (2010), J. He and Hoyano (2011), S. He, Guan, Gurgenci, Hooman, and Alkhedhair (2014), S. He, Guan, Gurgenci, Hooman, Lu, and Alkhedhair (2014), S. He, Guan, Gurgenci, Jahn, Lu, and Alkhedhair (2014), Kabeel and Bassuoni (2017), Korese and Hensel (2016), Yan, He, Gao, et al. (2020)	Water scarcity
	Pistochini and Modera (2011)	Water-use efficiency
	A. Cooperman et al. (2012), B. A. Cooperman et al. (2011)	Power plant water use
Water entrainment	He, Guan, Gurgenci, Hooman, and Alkhedhair (2014); He, Guan, Gurgenci, Hooman, Lu, and Alkhedhair (2014)	Cellulose and PVC pads
	Martínez et al. (2018), Zeitoun et al. (2014)	High-density polyethylene mesh pad
	Liao et al. (1998)	Coir fiber pads
	Liao and Chiu (2002)	PVC sponge pad
	Velasco-Gómez et al. (2020)	Cotton-fabric pad
Material decay	Abdullah et al. (2019), J. He and Hoyano (2010, 2011)	Material aging experiments
	Suranjan Salins et al. (2021)	Wood shaving pads
	Alodan and Al-Faraj (2005)	Galvanized metal sheets pads
	Franco-Salas et al. (2019)	Cellulose pads
	Al-Sulaiman (2002)	Different natural fiber pads, both alternative (jute, palm, and luffa) and commercial pads (aspen)
Transient and steady-state operation	Fouda and Melikyan (2011), Wu et al. (2009b)	Steady-state operating conditions
	Rong et al. (2017)	Transient regime by setting pump operation
	Liao and Chiu (2002)	Determining the time required for the pad to reach steady-state
	Alam et al. (2017)	One hour to reach steady state in alternative fiber pads
	Zeitoun et al. (2014)	5–35 min to reach steady conditions in ceramic tube pads.
	Laknizi, Ben Abdellah, et al. (2019), Laknizi, Mahdaoui, et al. (2019)	Over 3 h required to reach steady conditions
	X. Chen et al. (2018)	Recording data each 20 s until their temperature and humidity sensors provided steady measurements
	Kabeel and Bassuoni (2017), Jain and Hindoliya (2011), Nada et al. (2020, 2019), Laknizi, Ben Abdellah, et al. (2019), Doğramacı and Aydın (2020), Doğramacı et al. (2019), Sheng and Agwu Nnanna (2012), Malli et al. (2011)	Avoid non-steady operating conditions by starting to wet the pad a certain period after running the experiments. They start the pump between 20 min and 5 h before the experiment, depending on the investigator, and even wait 24 h

T A B L E 1 (Continued)

Factor	Related research	Comments
Air quality	Periannan (2013)	Indoor air quality can actually benefit from filtration
	Paschold et al. (2003)	Experiments on two commercial DEC. They found that PM_{10} was reduced by approximately 50%, and $PM_{2.5}$ concentration varied between 10% and 40%
	Velasco-Gómez et al. (2020)	DEC prototype made with cotton fabric removes particulate matter larger than 0.3 μm
	Naderi et al. (2020)	Comfort levels in terms of indoor relative humidity
Economic analysis	Ndukwu and Manuwa (2015), Sharma and Katarey (2019), Dhamneya et al. (2018), Ketwong et al. (2021)	Different researchers found recovery payback periods of between 1 and 3.76 years
	Shekhar et al. (2016)	Manufacturing costs of DEC systems with conventional and alternative materials
	Lotfizadeh et al. (2013)	Estimated costs of the three pads proposed: namely, conventional (apparently aspen), cellulose and metal foam pads, and calculated a payback of 5–10 years
	Rey-Martínez et al. (2010)	Economic viability of a ceramic evaporative cooler compared to a conventional air conditioning system
	Navon and Arkin (1993)	Direct evaporative cooler for residential use was more economical than a conventional vapor compression air conditioning system
Potential energy savings and carbon reduction	Hasani Balyani et al. (2015), Rey-Martínez et al. (2010, 2020)	Reduction in annual primary energy consumption and carbon emissions decrease in temperate dry, hot semi-dry, and hot-arid climates

Another useful parameter to characterize pad cooling performance is cooling capacity (CC). As it considers both the temperature drop achieved and the air mass flow, m_a, this parameter is better able to describe the system's capacity to cool a given airstream.

$$CC = \dot{m}_a \cdot Cp_a \cdot (T_{in} - T_{out}). \qquad (2)$$

Contrary to what occurred with saturation effectiveness, inlet air psychrometric conditions do play a major role in the CC of DEC systems. A larger WBD would result in increased humidification of the airstream and, consequently, greater temperature drops. Published research also agrees that higher air velocities improve the CC (Doğramacı et al., 2019; Laknizi, Mahdaoui, et al., 2019; Nada et al., 2020, 2019). This demonstrates that its detrimental effect on temperature drop is largely offset by the increase in the airflow rate treated. Because pad thickness favors temperature drop but has no effect on the airflow rate treated, it also has a positive effect on CC.

Beyond these two widely studied parameters, some research analyses different cooling performance parameters that can provide a better approach to system efficiency in non-adiabatic processes. Table 2 presents these performance parameters defined in the literature.

Dai and Sumathy (2002) define the parameter of "non-dimensional evaporation rate" as the saturation effectiveness in terms of air absolute humidity, but with the sole purpose of validating the proposed model.

The parameters shown in Table 1, "performance factor" (Al-Badri & Al-Waaly, 2017) and "effectiveness of the humidifier" (Nada et al., 2020) also aim to characterize system efficiency in terms of the difference in the psychrometric conditions of air achieved, the same as saturation effectiveness does, although in this case for non-adiabatic processes.

P. Martínez et al. (2018) state that saturation effectiveness, which is usually studied to describe the behavior of DEC pads, does not determine the actual optimal operating conditions as it does not consider the irreversibility of the process. Moreover, under almost adiabatic evolutions an "energy efficiency" parameter is useless. The authors propose

TABLE 2 Alternative cooling performance parameters defined in the literature

Parameter	Definition	Associated studies
Non-dimensional evaporation rate	$\eta = \frac{w_{out} - w_{in}}{w_{wb\ in} - w_{in}}$ Where w is the humidity ratio (kg_v/kg_{da}) at the air inlet (in), outlet (out), and at saturated conditions at the air inlet WBT (wb in).	Dai and Sumathy (2002)
Performance factor	For non-adiabatic processes $F = \frac{h_{in} - h_{out}}{h_{in} - h_{w*}}$ Where h is the air enthalpy at the air inlet (in), outlet (out), and at the water inlet temperature (w*)	Al-Badri and Al-Waaly (2017)
Effectiveness of the humidifier	For non-adiabatic processes $\varepsilon_{hum} = \max\left(\frac{h_{a\ out} - h_{a\ in}}{h_{a\ out\ ideal} - h_{a\ in}}, \frac{h_{w\ out} - h_{w\ in}}{h_{w\ out\ ideal} - h_{w\ in}} \right)$	Nada et al. (2020)
Overall exergetic efficiency	$\eta_{ex,overall} = \frac{\dot{m}_{a\ out} \cdot ex_{out}}{\dot{m}_{a} \cdot ex_{in} + \dot{m}_{w} \cdot ex_{w} + \dot{W}_{f} + \dot{W}_{p}}$ Where ex is the exergy flow and W refers to the power of the fan (f) and pump (p)	P. Martínez et al. (2018), Nada et al. (2019)
Cooling performance	$Cooling = \frac{CC}{A_{ce}}$ Where A_{ce} is the surface of the ceramic evaporative element	Ibrahim et al. (2003)
Dew point effectiveness	$\varepsilon_{dp} = \frac{T_{in} - T_{out}}{T_{in} - T_{dp\ in}}$ Where $T_{dp\ in}$ is the DPT at the air inlet	X. Chen et al. (2018), Khosravi et al. (2020)
Specific cooling capacity	$SCC = \frac{CC}{\dot{m}_{a} \cdot \Delta w}$	Doğramacı et al. (2019), Suranjan Salins et al. (2021)

Abbreviation: n.a., not applicable.

"exergetic efficiency" instead, although care must be taken when determining the dead state, as ambient conditions vary for each test. However, the larger heat and mass exchanges that are preferred in evaporative cooling processes also result in greater exergy destruction, with the subsequent lower exergetic efficiency. Exergetic efficiency is an appropriate parameter when approaching the study from a wider perspective, including the energy consumed by the pump (almost constant) and fans, through the "overall exergetic efficiency", which was also studied by Nada et al. (2019). This parameter can provide a complete picture of system performance but needs to consider the reduction in the additional air conditioning requirements of conventional systems.

One specific parameter defined for ceramic evaporative cooling media is defined by Ibrahim et al. (2003), where system performance is approached by relating the CC to the total surface of the evaporative cooling media. Doğramacı et al. (2019) propose another specific parameter for pad performance by relating CC to the evaporation rate. In addition to the parameters presented in Table 1, Laknizi, Mahdaoui, et al. (2019) define the "rate of operability" as the percentage of the operating period when the temperature drop achieved through the DEC pad is greater than 5°C.

4.2 | Pressure drop

As stated in the introduction, ideal DEC pad operation implies, among other factors, a minimum pressure drop. The main factors influencing pad resistance to airflow are air face velocity and pad thickness. Results available in the literature provide evidence on the effect of air velocity and pad thickness on the pressure drop for rigid media (A. Franco et al., 2010, 2011; Malli et al., 2011; Nada et al., 2019; Yan, He, Gao, et al., 2020), fiber pads (Doğramacı et al., 2019; Liao et al., 1998; Soponpongpipat & Kositchaimongkol, 2011), and fill pads (Gunhan et al., 2007; S. He, Guan, Gurgenci, Hooman, Lu, & Alkhedhair, 2014; P. Martínez et al., ; Rosa et al., 2011). In corrugated, rigid media, flute size, and angles would also play a role in pressure drop, which increases for flute sizes that yield a smaller separation between layers (Barzegar et al., 2012; Beshkani & Hosseini, 2006; A. Franco et al., 2010; Laknizi et al., 2021; Malli et al., 2011).

The effect of waterflow rate has been studied to a lesser extent. Slightly larger pressure drops have also occasionally been measured for increasing water flow rates in rigid media pads (A. Franco et al., 2011; S. He, Guan, Gurgenci, Hooman, Lu, & Alkhedhair, 2014; Yan, He, Gao, et al., 2020; Yan, He, Li, et al., 2020), fiber pads (Alam et al., 2017),

or fill pads (Gunhan et al., 2007; Korese & Hensel, 2016). This effect is nonetheless minor compared to that of air velocity or airflow rate through the pad, and is only noticeable when comparing resistance to the air flow between dry and wetted media (A. Franco et al., 2011; Rong et al., 2017; Sreeram et al., 2015; Yan, He, Li, et al., 2020).

Pad aging and decay also imply salt deposition and possible organic proliferation that increase the pressure drop and reduce the airflow through the pad. This effect is of great importance but rarely studied and will be further described in Section 4.6.

4.3 | Power requirements and coefficient of performance

Although evaporative systems are considered passive cooling solutions due to the small amount of energy required for their operation, their actual power needs do merit analysis. These are sometimes reflected in the COP. For evaporative cooling systems, the COP would relate the CC (Equation (4)) to the electric input power due to the pump (W_p) and fan (W_f):

$$COP = \frac{CC}{\dot{W}_p + \dot{W}_f} \tag{3}$$

The COP can thus provide an insight into CC and pressure drop simultaneously.

Despite being a key parameter in terms of comparing DEC performance and consequent energy savings to that of conventional HVAC systems, the COP is rarely analyzed. Furthermore, existing results do not always agree. While some authors achieve better COPs for larger air velocities (Doğramacı et al., 2019; Nada et al., 2020, 2019), additional fan requirements may indeed hinder the COP value (Laknizi, Ben Abdellah, et al., 2019; Laknizi, Mahdaoui, et al., 2019). As regards pad configuration, Suranjan Salins et al. (2021) obtain a better performance for the more common crossflow configuration than with counterflow.

In terms of pad thicknesses, CC has been seen to improve for thicker wetted media, although the pressure drop, and hence the fan power needs, also increase. This is why, although simulation results relate larger pad thicknesses to a decrease in the COP value (Laknizi, Mahdaoui, et al., 2019), some experimental results demonstrate the opposite (Nada et al., 2020, 2019). Consequently, it is not possible to offer general conclusions concerning what effect pad thickness has on the COP of evaporative cooling pads, and this must be analyzed for each system.

Some studies provide detailed information on the system's power requirements. Camargo et al. (2005) correlate power consumption to the air velocity of the system in either ventilation or in cooling mode; in other words, only that of fans or fans and pumps, respectively. The power required at the maximum airflow of 1600 m³/h is 200 W. Rawangkul et al. (2008) evaluate the different fan power requirements for different configurations of an alternative coconut fiber media compared to a cellulose pad. Naderi et al. (2020) study the electricity consumption of residential DEC in four climate regions in Iran.

4.4 | Water consumption

Most research gauging the performance of evaporative cooling pads studies the water evaporation rate (Equation (4)):

$$\dot{m}_{ew} = \dot{m}_a \cdot (w_{out} - w_{in}). \tag{4}$$

Some authors relate this water evaporation rate to the temperature drop achieved in order to define "specific water consumption" (A. Franco et al., 2010; Nada et al., 2020; Sohani et al., 2017).

As the cooling performance of DEC systems improves for drier climate conditions, so does water consumption. Water consumption may be optimized by adjusting the indoor set point temperature. In this sense, Naderi et al. (2020) reported water savings of up to 68.9% for a DEC system operating in Iranian houses at higher indoor set-point temperatures of 26–28°C.

However, although the water evaporation rate is commonly called "water consumption," most research on evaporative cooling pad performance does not study the actual water requirements beyond calculating the evaporation rate; that is to say, considering continuous bleed-off and periodic draining for maintenance purposes. If bleed-off is properly

designed and implemented, water evaporation is indeed the dominant water consumption. However, bleed-off requirements depend on water salinity and can be of the same order of magnitude as the evaporation rate if not properly adjusted, with the subsequent water wastage (Samam et al., 2009). Consequently, research on different types of DEC pads should provide insights into the bleed-off requirements at each particular application.

Purswell et al. (2018) create maps of water consumption for DEC systems in the United States, although they only consider the evaporation rate. They point out that additional, continuous bleed-off would be needed for maintenance purposes, and they reiterate the recommended bleed-off rates of 5%–10% or a full monthly system flush, while for greenhouse applications a continuous bleed-off at 16%–50% is needed for water salinity from 700 to 1500 ppm, respectively.

Many authors highlight the limitations of evaporative cooling systems in the event of water scarcity (Doğramacı et al., 2019; A. Franco et al., 2010; J. He & Hoyano, 2011; S. He, Guan, Gurgenci, Hooman, & Alkhedhair, 2014; S. He, Guan, Gurgenci, Hooman, Lu, & Alkhedhair, 2014; S. He, Guan, Gurgenci, Jahn, Lu, & Alkhedhair, 2014; Kabeel & Bassuoni, 2017; Korese & Hensel, 2016; Yan, He, Gao, et al., 2020), although they fail to provide further insights into this limitation. Nor do they consider power plant water use and the water savings related to the reduction in electricity consumption.

To enable a comparison of different cooling solutions in terms of water consumption, Pistochini and Modera (2011) define "water-use efficiency" as the volume of total water consumed, in liters, related to the CC achieved, in megajoules. Total water consumed includes both on-site water consumption and off-site water consumption due to electricity use. Similarly, A. Cooperman et al. (2012) and B. A. Cooperman et al. (2011) analyze power plant water use, and compare electrical energy and water consumption due to evaporative cooling and conventional vapor compression systems. However, because off-site water consumption strongly depends on the means of power generation, conclusions from the studies of Pistochini and Modera, and Cooperman et al. only apply to the corresponding locations in the United States and need updating.

4.5 | Water entrainment

Implementing evaporative cooling from a wetted surface instead of water pulverization has the advantage of non-generation of aerosols, at least intrinsically. Airflow through the humid pad may lead to water carryout.

S. He, Guan, Gurgenci, Hooman, Lu, and Alkhedhair (2014) observe no carryout of water in cellulose media, working with air velocities in the range from 0.5 to 3 m/s, although water entrainment in PVC pads does prove to be relevant even at low air velocities; hence, the authors propose studying water carryout drop size as a future line of research. Liao et al. (1998) observe water entrainment off a coir fiber alternative pad when air velocities exceed 2 m/s. In addition to this, carryout also occurred for water flow rates above 11 L/min/m^2, at which the two pads studied became thoroughly humidified. Liao and Chiu (2002) reported water entrainment in a coarse fabric PVC sponge pad when air velocities exceeded 1.75 m/s. P. Martínez et al. (2018) measure an additional cooling of air downstream a high-density polyethylene mesh pad that they link to possible water carryout, an effect that becomes visible for air velocities above 2 m/s when working with the thickest (25 cm) plastic pad tested. Zeitoun et al. (2014) also observe a certain cooling of air downstream the pad, supposedly due to the evaporation of possible droplets entrained, although they do not study the phenomenon.

Despite the risk of water entrainment off DEC pads, airflow through humid media can remove particles from the airstream. Velasco-Gómez et al. (2020) note the removal of particles of over 0.3 μm in a cotton-fabric pad, observing that 99.6% of the particles measured at the pad outlet could not be Legionella carriers due to their size.

4.6 | Material decay

Material decay is a key issue in DEC pad behavior and viability, especially when organic materials are used, despite which it is rarely addressed in the literature. Although some researchers explicitly state the relevance of material aging and possible decay, only rarely is this dealt with in their experiments (Abdullah et al., 2019; J. He & Hoyano, 2010, 2011). Indeed, actual pad decay and its effect on performance are seldom studied. Some authors conclude that alternative materials such as wood shavings (Suranjan Salins et al., 2021) or galvanized metal sheets (Alodan & Al-Faraj, 2005) can stretch pad life compared to conventional cellulose rigid media, although their claims are not supported by actual data.

Franco-Salas et al. (2019) compare the performance of a 3-year used cellulose pad to a new one and observe that salt incrustation increases pressure drop by 170.04%, although larger air–water contact times improve saturation effectiveness by 6.6%. Al-Sulaiman (2002) compare the decay of different natural fibers, both alternative (jute, palm, and luffa) and commercial (aspen), over a 60-h operating period, in terms of mold formation, salt deposition, and the effect on saturation effectiveness. Contrary to the results observed for cellulose pads by Franco-Salas et al. (2019), saturation effectiveness decreases with use. Indeed, effectiveness decreases to about 25% for jute, palm, and commercial aspen pads after 60 h use, while that of luffa is barely affected. Although no possible explanation is given, incrustations do not appear to be a possible cause in this case, as salt depositions reach 38.07, 24.44, 18.42, and 4.65 g in commercial aspen, luffa, palm, and jute pads, respectively. These contrasting results between the two studies can be explained in terms of the pad operating period (3 years and 60 h), but also with regard to pad type (corrugated rigid cellulose pads or fiber pads): in fiber pads, waterflow may create preferred paths after a certain operating period, leaving dry areas and thus reducing saturation effectiveness.

As regards mold formation, Al-Sulaiman (2002) observes that it reaches 96.6% of the jute pad, 76% of the commercial pad, and 52.6% of the palm pad, although only 8.6% for of that made of luffa. The overall results achieved lead the authors to propose luffa as a better alternative to commercial aspen pads. In contrast, and despite its high initial saturation effectiveness (above 60%), the rapid degradation of jute makes it inappropriate unless the fibers are treated to improve its mechanical robustness and resistance to mold formation, which agrees with the recommendations made by Abdullah et al. (2019). The lack of dedicated research, coupled with the economic and health problems involved, makes the study of DEC pad decay an essential factor that requires dedicated investigation.

4.7 | Transient and steady-state operation

The overall existing research is based on steady-state conditions, whereas transient periods are rarely addressed. Indeed, Fouda and Melikyan (2011) validate their mathematical model with results from Wu et al. (2009b) on steady-state operating conditions thanks to the short transient period achieved at 2.5 m/s air velocity through wetted media. Rong et al. (2017) provide some insights into transient regime by setting pump operation—and hence water supply—in periods from 3 to 120 s. As they state in their work, the challenges concerning the optimization of DEC pad operation also include the times required for water to evaporate from the pad once the recirculating pump stops. In the same line, Liao and Chiu (2002) suggest the need to determine the time required for the pad to reach steady-state when the operating conditions are modified.

Some works evaluate the time required to steady state operating conditions or actively check when this steady-state is achieved. For alternative materials (coconut, jute fiber, and sack cloth), Alam et al. (2017) find that maximum saturation effectiveness is achieved after 1-h operation. In the experiments performed by Zeitoun et al. (2014), it took 15–35 min to reach steady conditions in ceramic tubes. Laknizi et al. (2021) recorded data for periods of over 3 h and found that outlet temperature and relative humidity remained constant. X. Chen et al. (2018) started recording data each 20 s until their temperature and humidity sensors provided steady measurements.

Other authors simply avoid non-steady operating conditions by starting to wet the pad a certain time after running the experiments, although they do not analyze whether this is the optimal period or not. In this sense, Kabeel and Bassuoni (2017) and Jain and Hindoliya (2011) wait 20 min after running the experiments, while Nada et al. (2020, 2019) wait for 30–40 min. Laknizi, Ben Abdellah, et al. (2019) and Doğramacı and Aydın (2020) maintain the pump recirculating water up to 1 h before the experiments, although in a previous work Doğramacı et al. (2019) had considered only a 30-min wetting period before the experiment. Sheng and Agwu Nnanna (2012) connect the pump up to 5 h in advance. Being even more cautious, Malli et al. (2011) start wetting the pads 24 h before the experiments and wait 15 min for data acquisition when air velocity was changed between tests. Doğramacı and Aydın (2020) observe an almost steady evaporation rate of 0.05 g/s at 0.1 m/s air velocity, although for larger face velocities the evaporation rate fluctuates.

4.8 | Air quality

Contrary to the negative effects commonly associated to DEC systems, indoor air quality can actually benefit from filtration and the 100% outdoor air that characterizes these systems (Periannan, 2013). However, little research has focused on this issue.

From tests carried out in accordance with ASHRAE Standard 52-76: Dust Spot Efficiency Test, a particulate removal efficiency of 16% is achieved for a 12″ Rigid Media Pad working with an air velocity of about 2.5 m/s and a water flow rate near 0.0102 kg/s/m². Results show that "Dust Spot Efficiency" increases with larger pad thickness, air velocity, and water flow rate, while better efficiencies could have been obtained if the treated air had contained a greater percentage of sizes within 5–10 μm, as wetted media prove to be more effective for removing large particles (Periannan, 2013). Paschold et al. (2003) conducted experiments on two commercial DEC and found that PM_{10} was reduced by approximately 50%, while the reduction in $PM_{2.5}$ concentration varied between 10% and 40%. Velasco-Gómez et al. (2020) observed that their DEC prototype made with cotton fabric removes particulate matter larger than 0.3 μm. They also noticed that 99.6% of the aerosols in the air at the system outlet are small and could not carry airborne *Legionella* bacteria.

Contrary to the generally accepted limitation of DEC systems, their operation can also be favorable for achieving comfort levels in terms of indoor relative humidity. This is subject to proper air renovation during operation. Naderi et al. (2020) observed that, due to air dehumidification, a conventional air conditioning unit only achieved acceptable indoor humidity levels for 24%–64% of the time, while a DEC system remained within these levels for 87%–96% of the time.

4.9 | Economic analysis

Although DEC systems are systematically described in the literature as economically viable solutions, only a few works actually provide insights into the cost. Ndukwu and Manuwa (2015) calculate a payback period of 1.75 years for southwest Nigeria, which therefore offers an economical solution for air conditioning. Shekhar et al. (2016) provide details on the overall manufacturing costs of DEC systems with conventional and alternative materials designed in rectangular or semi-circular shape. Similarly, Lotfizadeh et al. (2013) express the estimated costs of the three pads proposed: namely, conventional (apparently aspen), cellulose, and metal foam pads, and calculate a payback of 5–10 years. Rey-Martínez et al. (2010) study the economic viability of a ceramic evaporative cooler compared to a conventional air conditioning system in different Spanish climates, and conclude that the payback period would be less than 1 year. Navon and Arkin (1993) observed that, applying a life cycle economic analysis, a portable direct evaporative cooler for residential use was more economical than a conventional vapor compression air conditioning system. However, their results were obtained based on a method which was applicable decades ago and which would now need updating.

For hybrid window air conditioning units, payback periods estimated in the literature were less than 3 years (Sharma & Katarey, 2019) and 3.76 years (Dhamneya et al., 2018). Similarly, for a split air conditioner including a DEC pad on the condenser, the expected payback period was 2.87 years (Ketwong et al., 2021). Rey-Martínez et al. (2020) installed corrugated cellulose rigid media pads at the inlet of the air condensing units of a 8.9 MW chiller plant at a hospital, which enabled over 3700 € yearly savings, resulting in a payback period of less than 2 years.

4.10 | Potential energy savings and carbon reduction

Almost all the research published on evaporative cooling highlights its energy saving and carbon reduction potential. However, only a few works actually provide data on the energy and emissions savings than can be achieved.

Climate conditions are crucial to the actual energy and emissions savings that are achievable through DEC systems compared to conventional vapor compression systems. For a small residential application, Hasani Balyani et al. (2015) achieved a reduction in annual primary energy consumption of 3750, 4875, and 3964 kWh in temperate dry, hot semi-dry, and hot-arid climates, respectively. The subsequent carbon emissions decrease was 3.7, 5.6, and 4.5 tons of CO_2, respectively. IEC, DPIEC, and desiccant solutions were preferable for more humid climates. Rey-Martínez et al. (2010) compared the energy consumption and CO_2 emissions of an evaporative cooler prototype made of hollow bricks compared to a 2 kW conventional split air conditioning system with 2.3 COP. Up to over 250 kWh/month and 160 kg CO_2 /month energy and emissions savings were expected in arid regions during the summer season, while for more humid climates the prototype proved to be counterproductive.

Precooling air before air condensing units can considerably improve the EER of conventional vapor compression systems. Installing DEC pads at the air condensing unit inlet of a 8.9 MW chiller plant with 2.98 EER resulted in a reduction in the total equivalent warming impact of the chiller plant of 1000 tons CO_2 and energy savings of up to 32.6 MWh for a 15-year study (Rey-Martínez et al., 2020).

Previous results are specific for particular case studies and cannot be extrapolated. Further research on the actual energy consumption and carbon emissions reduction through the use of DEC pads is thus needed, as it can enhance their application.

5 | LESS STUDIED INFLUENCING FACTORS

Previous results on DEC pad behavior and performance are based on the study of the main influencing factors: air velocity, psychrometric conditions, and pad thickness. Although less influential in terms of pad performance, water flow rate is also widely studied. However, some studies do provide insights into other possible influencing factors, such as water temperature, water salinity, solar radiation, or wind speed. Results derived from the reviewed research are presented in Table 3 and discussed below.

5.1 | Water temperature

DEC from a wetted surface usually works with recirculated water. In this case, the process is ideally adiabatic and both air and water remain at the WBT of inlet air (ASHRAE, 2019). In practice, the process is indeed approximately adiabatic, and water does approach WBT despite the lower thermal loads that water may gain through the recirculating pump and the different temperature of supply water when replenished. This is a commonly assumed hypothesis (Beshkani & Hosseini, 2006; S. He, Guan, Gurgenci, Jahn, Lu, & Alkhedhair, 2014; Jain & Hindoliya, 2011; Kovačević & Sourbron, 2017; Rawangkul et al., 2008; Yan, He, Gao, et al., 2020), and has occasionally been tested in the literature (Kabeel & Bassuoni, 2017; Liao & Chiu, 2002; Liao et al., 1998; P. Martínez et al., 2018).

Some works offer different results. In their experiments at 35°C air DBT and 40% RH with a supply water temperature of 30°C, Dai and Sumathy (2002) observe that the recirculated water temperature remains about 4°C below ambient air DBT. The authors thus set this value for the mathematical model. Wu et al. (2009a, 2009b) expect slightly higher water temperatures in the basin than WBT. Similarly, the model developed by Ketwong et al. (2021) for a DEC pad to cool air for the condenser coil of an air conditioning unit resulted in supply temperatures of recirculated water above the WBT of ambient air. In contrast, Velasco-Gómez et al. (2020) recorded water temperatures in the water tank below the WBT.

Several articles examine the effect of water temperatures different from air WBT on DEC system performance. Sheng and Agwu Nnanna (2012) state that supply water temperature would differ from the WBT of recirculated water, and they thus study three water temperatures: tap water (12.6°C), room temperature (21.6°C), and at ground level during summer (36.1°C). They perform the experiments for constant air velocity (1.1 m/s), DBT (36.7°C), and relative humidity (17%), and obtain better saturation effectiveness with lower water temperatures, but conclude that cooling water below a certain value would not make any significant difference. The former result can easily be explained by resorting to the same expression of saturation effectiveness, as the maximum temperature drop achievable is expressed in terms of the WBD, while the actual maximum temperature drop increases if cold water is used. The latter result would not be determinant since only three water temperature levels are studied, such that further research is required. More studies focus on the effect of cooling water flow before its distribution on the humid media. Al-Badri and Al-Waaly (2017) achieve an improvement in system performance by chilling water at two temperatures between the WBT and the DPT of inlet air, and one temperature below the DPT that yields air dehumidification. They draw on their results to expect a wider application of DEC in more humid climates by precooling water flow. Shekhar et al. (2016) increase the temperature drop from 5.5 to 7.6°C through water chilling, but do not provide the water temperatures studied. Nada et al. (2020, 2019) study this effect by working with four levels of water temperature (25, 30, 35, and 40°C) for a constant inlet air DBT of 40°C. As the water temperature increases, latent heat transfer becomes dominant, thus enhancing the increment in the relative humidity while the temperature drop achieved decreases; hence, the CC and COP of the system. Nevertheless, small variations in uncontrolled water temperature would only have a small effect on the heat transfer coefficient (S. He, Guan, Gurgenci, Hooman, Lu, & Alkhedhair, 2014). However, existing works focusing on performance improvement by reducing the water flow temperature do not directly evaluate the additional energy requirements for water cooling, such that further research would be needed.

TABLE 3 Less studied influencing factors

Factor	Related research	Comments
Water temperature	Beshkani and Hosseini (2006), S. He, Guan, Gurgenci, Jahn, Lu, & Alkhedhair (2014), Jain and Hindoliya (2011), Kovačević and Sourbron (2017), Rawangkul et al. (2008), Yan, He, Gao, et al. (2020)	Assume water temperature kept constant at WBT
	Kabeel and Bassuoni (2017), Liao et al. (1998), Liao and Chiu (2002), P. Martínez et al. (2018)	Check that water temperature is maintained at WBT
	Dai and Sumathy (2002)	Recirculated water temperature remains about 4°C below WBT
	Velasco-Gómez et al. (2020)	Recirculated water temperature below WBT
	Wu et al. (2009a, 2009b), Ketwong et al. (2021)	Recirculated water temperature above WBT
	Sheng and Agwu Nnanna (2012)	Study three supply water temperatures (12.6, 21.6, and 36.1°C)
	Al-Badri and Al-Waaly (2017)	Study two supply water temperatures between WBT and DPT and one temperature below DPT
	Shekhar et al. (2016)	Achieve an increased temperature drop from 5.5 to 7.6°C through water chilling, but do not provide the water temperatures studied
	Nada et al. (2020, 2019)	Study four supply water temperatures. Latent heat transfer becomes dominant as the water temperature increases
	S. He, Guan, Gurgenci, Hooman, Lu, and Alkhedhair (2014)	Small variations in uncontrolled water temperature have little effect on the heat transfer coefficient
Water salinity	Kabeel and Bassuoni (2017)	Achieve 1.5 L/h water savings working with saline water instead of tap water
	Yan, He, Gao, et al. (2020)	Negligible effect on pressure drop
Solar radiation	J. He and Hoyano (2010, 2011)	Influences the water evaporation rate. Shadowed ceramic tubes remain at about WBT, but exposed ones are at a higher temperature
	Alamdari et al. (2020)	Performance differs from adiabatic operation when exposed to solar radiation. They study different casing materials and shadowing options
	Bishoyi and Sudhakar (2017), Franco-Salas et al. (2019), Mohammad et al. (2013)	Measure solar radiation but do not correlate it to system performance

5.2 | Water salinity

As stated in Section 4.4, water scarcity is one of the main limitations of evaporative cooling devices. Some authors use saline water in their experiments in order to justify the use of more widely available sea water. Kabeel and Bassuoni (2017) compare water consumption when working with saline water (200,000 ppm) compared to tap water (270 ppm), and achieve 1.5 L/h water savings in the former case. Yan, He, Gao, et al. (2020) also study the effect of water salinity on the pressure drop, and conclude that it is similar for either tap or saline water, provided that the same pad thickness and water flow rate are used. However, saturation effectiveness decreases with water salinity. Nevertheless, none of the authors mentioned analyze the accelerated decay expected due to greater salt deposition and clogging.

5.3 | Solar radiation and wind speed

For systems installed outdoors, wind speed and solar radiation influence system performance (W. Chen et al., 2015; J. He & Hoyano, 2010). J. He and Hoyano (2010, 2011) identify solar radiation as a key factor in the water evaporation

rate. They observe that ceramic tubes which are not exposed to solar radiation maintain their surface temperature at about the WBT of ambient air, while exposed surfaces present higher temperatures, although still 2–4°C below ambient air DBT. Alamdari et al. (2020) observe that DEC system performance differs to a great extent from the ideally adiabatic operation when affected by solar radiation. They compare a metallic-casing to polycarbonate-casing DEC systems in warm, dry climate conditions. They also analyze further options, such as tilting the top surface or attaching a radiation shield to the cooler. Outlet air DBT from the polycarbonate-casing is about 3.4% lower than from the metallic-casing system, while either tilting the system or attaching the shield can achieve a further 5% temperature reduction. The improved performance yields a 20.6% reduction in water consumption in the case of the polycarbonate-casing, and up to 29% and 25% if it is further tilted or shielded, respectively. Other authors measure and present data on solar radiation, although they do not correlate it with their results on system performance (Bishoyi & Sudhakar, 2017; Franco-Salas et al., 2019; Mohammad et al., 2013).

6 | CONCLUSION

Evaporative cooling from wetted media is widely studied in the literature. Existing research addresses all types of pads and a wide array of materials as well as different applications. Further research is nonetheless needed concerning the following:

- DEC pads are extensively applied in industrial facilities, although the literature on the topic is almost non-existent. Research on the actual indoor conditions achievable can help to improve these applications. In contrast, intensive agriculture and farming applications have been dealt with extensively. Applications to greenhouses require a combination with shadowing devices.
- Outdoor cooling is mainly supplied by spray systems. Applications of DEC from wetted surfaces can be enhanced through integration with the surrounding street furniture.
- Portable DEC systems are widely marketed for residential and small commercial use, although related research is scarce. As their performance is strongly dependent on appropriate operation and maintenance, further investigation and a suitable dissemination of results is necessary for the appropriate use of these systems.
- The climatic applicability of DEC is well known, although the feasibility of each particular application should be evaluated at specific locations.
- The study of achievable thermal comfort in occupied, indoor spaces conditioned through DEC pads must be studied from an adaptive approach. Nevertheless, due to the achievable relative humidity, the use of DEC systems in office and educational buildings is limited and IEC or two-stage EC may be more appropriate.
- The use of DEC pads to precool ambient air for air condensing units is gaining interest. Further attention to hybrid air conditioning systems is also recommended.

As regards the operation of DEC pads, saturation effectiveness and pressure drop are well known. The study of pad cooling performance through other parameters may provide further insights into pad behavior. In this sense:

- CC may be a better parameter than saturation effectiveness for describing cooling system performance, as it also considers the airflow rate treated.
- The COP is a key parameter vis-à-vis comparing DEC to conventional HVAC systems in terms of actual energy savings achievable. Although the power requirements are low, they have rarely been studied. The effect of greater air velocities and pad thicknesses on the COP observed in a particular DEC pad cannot be extrapolated to other pad materials and configurations.
- Beyond analyzing the exergetic efficiency proposed in the existing literature, the exergetic approach might prove to be particularly useful for designing and selecting evaporative cooling systems in hybrid air conditioning systems or for air precooling, evaluating the reduced requirements of conventional systems.

Available knowledge is also scarce concerning the following performance issues:

- Most of the research providing results on water consumption only considers the evaporation rate while disregarding bleed-off requirements. Although the former is determinant if bleed-off is properly adjusted, research must be conducted to assess the actual bleed-off required in each case for optimal water use.

- Although DEC from wetted media does not intrinsically generate aerosols, there is a risk of water carryout. Careful selection of the optimal water flow rate can avoid this risk, ensure total humidification of the wetted media, and minimize salt deposition.
- Material decay has a key role to play in pad performance, despite which it has rarely been addressed. Further experimental study is needed to determine the lifetime of commercial and alternative pads, particularly for organic materials (due to microbial proliferation) and fiber pads (as water can create preferred paths).
- One of the main assets of evaporative cooling is the required ventilation, which can improve indoor air quality. Moreover, evaporative cooling pads are said to retain particulate matter from air. Supply air quality requires further assessment.
- Most research focuses on steady-state operating conditions. To ensure steady conditions, experiments are performed after an arbitrary period once the pump is connected. Only a few studies provide insights into the actual transient times required. Particular attention should be paid to the time required for the wetted media to become fully dry once the recirculation pump stops.
- Only a few studies perform an economic analysis and quantify the expected energy consumption and carbon emissions savings afforded by DEC pads compared to conventional systems. Moreover, these results cannot be extrapolated. Providing further information on the related energy and emissions savings can enhance DEC application.

Finally, the effect of air velocity, pad thickness, and psychrometric conditions has been studied in depth. The effect of the water flow rate supplied is also well known. However, the following gaps have been identified:

- Most published research fails to control the supply of air relative humidity. It is strongly recommended that future experiments should be conducted under wider ranges of humidity conditions.
- In adiabatic systems, recirculated water temperature is usually assumed to be close to the air WBT, yet when measured, experimental results sometimes show either higher or lower values. Measuring water temperature is thus also recommended in adiabatic systems in order to achieve a proper interpretation of the air conditions obtained at the system outlet and the saturation effectiveness.
- Some research works analyze the improvement in system performance by using chilled water. Future research should evaluate the additional energy requirements for water cooling.
- Systems exposed to the outdoor environment may have their performance affected by solar radiation and windspeed. This has scarcely been analyzed and further dedicated study is needed.

Evaporative cooling equipment can play a key role in achieving current carbon emission reduction targets, thanks to its low energy requirements and cooling potential. The main limitations put forward and the gaps highlighted entail the need for further research to enhance its application and subsequent energy consumption improvements in buildings.

CONFLICT OF INTEREST
The authors have declared no conflicts of interest for this article.

AUTHOR CONTRIBUTIONS
Ana Tejero-González: Conceptualization (lead); data curation (equal); formal analysis (equal); investigation (lead); methodology (lead); writing – original draft (lead). **Antonio Franco-Salas:** Data curation (equal); formal analysis (equal); investigation (supporting); methodology (supporting); writing – original draft (supporting).

DATA AVAILABILITY STATEMENT
Data sharing is not applicable to this article as no new data were created or analyzed in this study.

ORCID
Ana Tejero-González https://orcid.org/0000-0003-3843-7729
Antonio Franco-Salas https://orcid.org/0000-0001-6842-8685

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