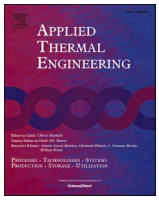
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Research Paper



A vision of dew point evaporative cooling: Opportunities and challenges

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ABSTRACT

The increasing energy demand for air-conditioning systems has prompted a need to find an energy-efficient alternative to conventional vapor compression cooling systems. Dew point evaporative cooling (DPEC) is an advanced configuration of indirect evaporative cooling (IEC) technology, which has been regarded as a game changer. This vision paper presents recent progress, prevailing challenges, and prospective directions for the advancement of this technology. After a general introduction and a brief overview of the current knowledge, open issues are discussed in five aspects: i) optimizing channel configuration; ii) improving the precision of numerical modelling; iii) developing advanced wetting materials with superior thermal transfer properties; iv) enhancing energy efficiency; v) minimising the physical footprint and energy consumption of the hybrid systems. In each aspect, a brief description of the existing knowledge and the current research status is provided while remarking on their importance in applications. Subsequently, key challenges are highlighted, and promising avenues for future research are delineated. The identified challenges include trade-offs between thermal and economic performance in the structure optimisation, advanced model development, durability and service to new wicking materials, energy efficiency in the water reduction and intermittent water spray technique, and physical footprint and energy consumption of hybrid systems.

1. Introduction

Population expansion and economic growth have led to an escalated demand for an improved living standard, which in turn has driven up the energy consumption to meet the thermal comfort criteria [1]. About 40 % of total electricity is used in buildings worldwide, of which air conditioning systems account for 70 % [2,3]. Moreover, the utilisation of chemical refrigerants in conventional vapor compression cooling technologies has the potential to generate environmental concerns such as ozone depletion issues [4]. As an energy-efficient and environment-friendly alternative to traditional vapor compression cooling systems, dew point evaporative cooling (DPEC) technology presents a promising solution due to its ability to operate without using energy-intensive compressors and harmful refrigerants [5]. The air conditioning market share attributed to evaporative cooling technology in Australia has reportedly grown to 20 % since 2005, owing to prevailing hot and arid environmental conditions [6]. Furthermore, predictions indicate an anticipated global market ratio of 20 % for this technology by the year 2035 [6].

DPEC is a distinctive variant of the indirect evaporative cooling (IEC) technology, which possesses the capability to lower the cooling limit of the traditional IEC, namely the wet bulb temperature of the inlet air [7–9]. The schematic diagram of a DPEC is presented in Fig. 1. A DPEC system consists of distinct air channels, specifically categorised as dry and wet channels. The liquid water is sprayed in the wet channel to ensure that the wet channel is enveloped by a layer of saturated water. The progression of the system involves the circulation of hot outdoor air over the dry channel. Towards the terminus of the dry channel, a fraction of the process air or a return air from the room is directed into the adjacent wet channel, initiating an evaporation process. Part of water vaporizes and the phase change of water from liquid to vapor facilitates the notable latent heat of water evaporation resulting substantial transference of sensible heat from the dry air in the dry channel into the latent heat of water evaporation in the wet channel. This process involves the absorption of a considerable amount of sensible heat from both dry and wet air. Consequently, the temperature of the dry channel air decreases due to heat transfer across the separation wall between the dry and wet channels. This process of water evaporation within DPEC

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allows for the cooling of supply air to approach the dew point temperature of the ambient without introducing extra moisture [10]. As the cooling process relies solely on water evaporation, it is reported that this eco-friendly approach exhibits a considerably lower energy consumption of four times less when compared to conventional air conditioning systems [11]. Simultaneously, DPEC incurs a low level of capital expense, as it eliminates the necessity for hardware components such as compressors [12]. Due to these advantages, in addition to its role in affording thermal comfort within residential and commercial buildings, DPEC has been extended to the potential application in diverse domains such as thermal management for electric vehicles [13], cooling for data centres [14], heat dissipation for electronic chips [15], desalination processes [16], pre-cooling of gas turbine [17], and agriculture storage [18], among other potential areas of utilisation.

Considerable research endeavours have been dedicated in the DPEC research field in the last decades. According to the literature database Scopus, more than 340 research papers have been published in the DPEC field since 1984, with 38 % of these publications emerging within the past three years. Researchers reported that the main challenges of broadening the application of the DPEC systems are effectively enhancing the cooling effectiveness, particular in humid regions, and reducing the water consumption rate considering the water availability [20,21]. To address these challenges of DPEC systems, researchers have devoted substantial efforts to the following aspects: configuration optimisation, enhancement of modelling accuracy, wetting material, reduction of water consumption, improvement of water spray system, and hybrid systems. Much research progress in DPEC technology has been made in the previously mentioned fields although barriers and challenges still exist. This vision article presents an up-to-date discussion of the research progress and obstacles towards improving DPEC technology and widening its application domain, as well as the future research and development directions of DPEC systems.

2. Current research areas, trends and challenges

In general, the cooling capacity and Coefficient of Performance (COP) are two performance indexes to represent the performance of the cooling systems. However, in the DPEC system, the wet bulb effectiveness and dew point effectiveness are another two important parameters that indicate the potential of the possible minimum supply air temperature and maximum cooling capacity. The former parameter indicates how close the minimum supply air temperature is to the outdoor wet bulb temperature and the later one shows the potential of the supply air temperature close to the dew point temperature. In the traditional IEC systems, the supply air temperature is limited by the outdoor wet bulb temperature. However, in the DPEC system, researchers put a lot of efforts to improve the structure and design of the system to overcome this traditional limit and hence lower the supply air temperature to dew point temperature of the ambient air. These two parameters reflect the advances of the technologies. Another important parameter is water consumption rate in the DPEC system. This parameter does not connect to the energy consumption; however, it directly connects to the cost of the system operation. The following sections details the current research and challenges on improving dew point effectiveness and hence cooling performance, reducing water consumption and improving the system COP through system configuration optimisation, enhancement of modelling accuracy, development of new wetting material, improvement of water spray system, and application of hybrid systems.

2.1. *Novel configuration structure*

The flat plate type of heat and mass exchanger is the most commonly used configuration in DPEC systems, which can easily create counter-flow or cross-flow arrangements [6]. In DPECs, sensible heat transfers to adjacent wet channels through the channel wall and wicking material in the plate type of heat exchangers. Many studies have focused on

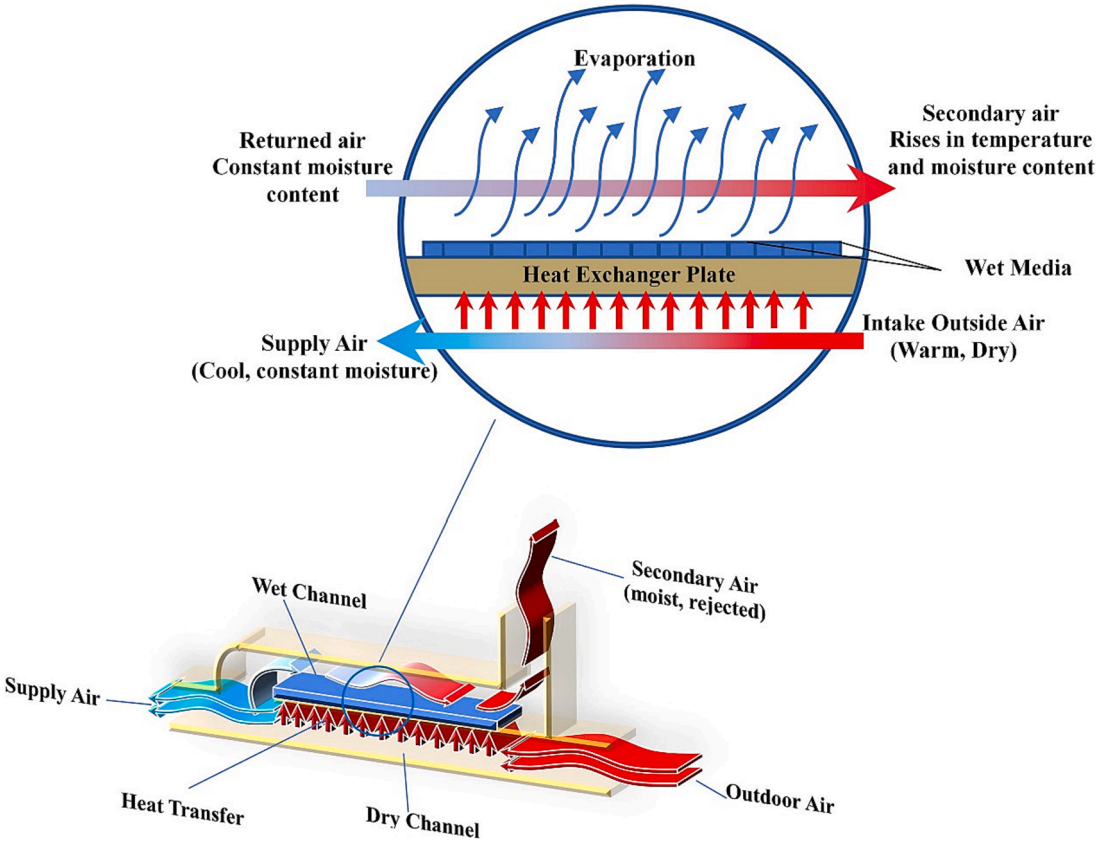


Fig. 1. Schematic diagram of a DPEC [19].

developing and improving configuration structures to improve DPEC's dew-point effectiveness and COP, mainly from the following two aspects: (i) enlarge heat transfer areas and (ii) minimise thermal resistance between the primary and secondary air stream channels. Liu et al. [22] numerically and experimentally investigated a highly efficient DPEC in which a corrugated plate surface was introduced to increase the heat transfer area, and the channel supports were removed to lower the thermal resistance. The results showed that the wet bulb efficiency of the proposed DPEC exhibited a 10 % higher than that of a flat plate type DPEC. Kashyap et al. [23] numerically compared the impact of the plate surface modification on the performance enhancement of the DPEC. The results revealed that the capsule-embossed surface exhibited superior performance among the four tested surfaces via exergy analysis. Alharbi et al. [24] conducted a comprehensive study on a novel heat pipe-porous ceramic-based DPEC. They reported that the tested prototype's wet bulb and dew point effectiveness were 1.05 and 0.73, respectively. In another novel structure design of DPEC carried out by Shahzad et al. [25], the hydrophilic layer was eliminated to diminish the thermal resistance due to the occurrence of the water evaporation process in an external humidifier. It was shown that the maximum COP reached 45 when the ambient air temperature and humidity ratio were 45 °C and 55 %. Gao et al. [26] numerically evaluated a novel tubular DPEC and compared its performance with a conventional plate-type cooler. The results showed that the tube-type DPEC produced a lower supply air temperature of 1.6 to 3 °C than that of the plate-type cooler, in addition to a 0.18 increase in dew point effectiveness. Castillo-González et al. [27] developed an innovative DPEC system manufactured using emerging additive manufacturing technology. It was reported that the dew-point effectiveness can be up to 0.9. The application of additive manufacturing technology has shown promise in the realm of air conditioning system production, particularly in the fabrication of heat exchangers [28,29], suggesting its potential applicability to the development of DPEC systems as well.

The above-mentioned studies proved that the wet bulb effectiveness, dew point effectiveness and COP of DPEC could be effectively improved by adopting advanced channel structures and using emerging manufacturing technologies. Notwithstanding the potential advantages of novel configurations, it was worth noting that any gains in cooling efficiency might be offset by a significant increase in pressure loss within the air channels [30] and manufacturing cost [31]. Therefore, a prevailing challenge to be overcome in the future is to conduct a thorough evaluation of these novel configuration structures, encompassing not only the enhancement of cooling performance but also considering economic costs and energy consumption. Furthermore, currently, most studies in this area focus on the improvement of system performance. Very little research has been conducted on the long-term system reliability which is very important in the wide application of the DPEC system.

2.2. Enhancement of modelling accuracy

In comparison to experimental studies, numerical, analytical, and statistical approaches are widely used for predicting and optimising DPEC performance due to their cost-effectiveness and time-saving features [4,32,33]. In order to enhance the accuracy of models, it is customary to substitute the simplified assumptions employed during the modelling process with conditions that more closely reflect actual situations. Pakari and Ghani [34] presented a comparative study of one-dimensional (1D) and three-dimensional (3D) models of a DPEC and validated the numerical models against the experimental data. Their findings revealed that the 3D model yielded a higher level of accuracy, with a discrepancy of 8.5 % observed between the numerical and experimental results. Liu et al. [35] considered the non-uniform airflow presented in dry channels of DPEC by incorporating the momentum and mass transfer equations into a two-dimensional (2D) model. The outcomes indicated an excellent agreement between the numerical and experimental data, with a maximum deviation of less than 5 %. In recent years, researchers have embarked upon developing numerical models that incorporate the phenomenon of moist air condensation within the dry air channels of IEC, a consideration often overlooked in previous studies [36–40]. This occurs when the plate temperature falls below the ambient air's dew point temperature, which enhances the overall heat transfer rate of the DPEC due to the pre-dehumidification of the condensation phenomenon [41]. Considering this phenomenon, the model's predictive accuracy can be significantly improved when predicting the DPEC performance in a humid environmental context. Wan et al. [42] numerically examined the condensation phenomenon occurring in a counter-flow DPEC. The authors observed a sharp decrease in the supply air temperature and humidity ratio dropped rapidly near the entrance region, which they attributed to the entrance effect.

Based on the current state-of-the-art, it can be inferred that the accuracy of the various modelling methods has been progressively improving, allowing for precise prediction of the performance of the DPEC. Nonetheless, a prevailing challenge to overcome in the future is improving the model accuracy in situations where the DPEC experiences transient conditions. A number of prior studies presumed that the DPEC functioned at a consistent and unchanging operational state. Only a few investigations [43,44] explored its dynamic operational characteristics. However, these models were subjected to simplifications, particularly regarding the neglect of the water spraying effect, which would lead to notable temperature fluctuations within the wet channels. Furthermore, excessive water within the wet channels is a practical concern that can exert a discernible impact on the device's cooling performance. Remarkably, this factor tends to be disregarded in the context of numerical simulations in the existing literature.

2.3. Surface wetting material selection

Based on the operational mechanism of DPEC, latent heat exchange only transpires inside the wet channels [45]. Therefore, selecting an appropriate wetting material to enhance surface wettability and thermal transfer ability within wet channels is critical for improving DPEC wet bulb efficiency and cooling capacity[46]. The use of porous materials and hydrophilic coatings are the two primary methods for achieving this objective [1].

The commonly used porous materials for IEC are categorised into two broad groups: ceramic and fiber [47]. Given that DPEC is a specific type of IEC, it follows that the wetting material utilised in IEC can be readily employed in applications of DPEC. The utilisation of porous ceramics as a wetting material can be attributed to its favourable characteristics, including but not limited to its low density, large porosity, exceptional thermal conductivity, and high specific surface area [48]. Boukhanouf et al. [49] proposed a DPEC system employing porous ceramic as wetting media for water adsorption. The findings demonstrated a remarkable cooling capacity of 225 W/m^2 and a wet bulb effectiveness of 1.024. Fiber is another frequently used wetting material in DPEC due to its outstanding wick ability and water retention properties [50]. Given the pliability of fiber material, it is common practice to affix it to a thin metallic plate, typically constructed from aluminium, to constitute a wet channel through adhesive bonding [47]. In order to evaluate the performance attributes of fiber materials, the following parameters are commonly chosen: wicking speed, wicking height, and evaporation rate [51]. Abada et al. [19] tested the application potential of six different types of fabrics in evaporative cooling. The results suggested that the tight straight weave fiber fabrics and polypropylene geotextile felt were particularly suitable for IEC applications and hence for DPEC applications. Xu et al. [52] analysed six cloth fabrics and compared their performance with traditionally used wet channel material, kraft paper. The results proved that the Coopass bird-eye mesh fabric was the most favourable among the investigated materials. With the advancement of material science, some composite

fibers with distinct hydrophilic and hydrophobic properties on opposite sides have been developed [15]. Such materials have captured researchers' attention due to the potential to replace the metallic plates, significantly reducing the system's overall weight [53]. Chen et al. [54] experimentally studied a novel IEC based on plant fiber-polymer composite as a wetting material. The authors pointed out that the dew point efficiency of the proposed system is comparable to a fabric-coated IEC but with lightweight and low cost. Lv et al. [55] opted for a porous fibrous membrane comprising polypropylene and nylon to enhance the water distribution in the DPEC. The results indicated that the diffusivity and wicking height rates were 0.118 cm^2/s and 0.203 cm/min, respectively.

Applying hydrophilic coatings to the wet channel of DPEC is another feasible technology. You et al. [56] examined the effect of two types of hydrophilic coatings, TiO_2 and Graphene, on the heat transfer efficiency. The results revealed that the wet bulb efficiency of both coatings was, at minimum, 9.91 % higher than that observed in an IEC without hydrophilic coating. Chen et al. [57] implemented a TiO_2/SiO_2 nano-coating onto the wet channels of IEC. The results displayed that the coating was durable, as evidenced by a stable water contact angle of 30.9°. Furthermore, the exploration of innovative technologies for the production of wetting materials has been a subject by some researchers. Fang et al. [58] employed direct femtosecond laser nano/micro structuring method to fabricate microgrooves on Nylon 6 polymer. The experimental results revealed an excellent capillary phenomenon on the polymer material, demonstrating its potential applicability in the context of DPEC system.

State-of-the-art wet channel materials of DPEC can achieve high wettability and thermal transfer efficiency. A prevailing challenge to be overcome in the future is performing long-term assessments for novel materials and considering durability as a fundamental performance index. This is because, in practical applications, the maintenance of these materials is imperative to prevent fouling and sedimentation, which could lead to the deterioration of the cooling system's performance. Furthermore, many studies focused on the performance of the wetting material alone and very little research has been conducted by incorporating these novel materials in the real DPEC system. A long-term onsite operating test for the DPEC system with these new materials should be comprehensively studied.

2.4. Water consumption reduction

The large-scale implementation of DPEC technology relies on freshwater consumption, which may impose an undue burden on the existing drinking water system, particularly in areas with limited water resources [59]. In order to address this issue, a lot of efforts have been made to use the humid exhaust air from the wet channels of DPEC. Tariq et al. [60] proposed the incorporation of a dehumidification coil, driven by a closed-loop water circulation system, into the wet channel of DPEC. The integration of this water-recovery mechanism led to a significant reduction in water usage rate by 63 % and a corresponding improvement in EER by 26 %. Chen et al. [61] exploited the waste air discharged from wet channels of DPEC to enhance the water production rate of a humidification-dehumidification (HDH) desalination unit. The results showed that freshwater production at a rate of 25 to 125 L/hr was achievable, with a gain output ratio (GOR) ranging from 1.6 to 2.5. Katramiz et al. [62] investigated a novel hybrid cooling system that combined DPEC, radiative cooling and air–water harvesting system. They stated that the proposed system yielded a mean water saving of 44.2 % compared to stand-alone DPEC.

As discussed above, the recently employed water consumption reduction techniques in DPEC demonstrate promising potential to curtail or fully offset the system's water usage significantly. However, a prevailing challenge to be addressed in the future pertains to the elevated energy expenditure associated with retrieving water from waste air. To solve this problem, integrating renewable energy sources into the existing system appears to be a viable solution, for example, employing shallow geothermal energy [63] as a cold source to condense the water and humid exhaust air from DPEC, harnessing solar energy [64] to power the water recovery unit.

2.5. Water spray system optimisation

The water spray technique is regarded as having a critical role in ensuring uniform water distribution within the wet channels, thereby directly influencing surface wettability and subsequently affecting the thermal performance of DPEC [48]. Al-Zubaydi and Hong [65] proposed three water spray modes and reported that the mixed mode, consisting of both external and internal spray, presented superior performance, with a maximum wet bulb effectiveness of 76 %. Ma et al. [66] investigated the effect of spray nozzle arrangement on the cooling performance improvement of the system. The results showed that the COP could be improved by 16 % with the optimised nozzle arrangement.

Typically, the water spray system operates continuously, resulting in a consistent consumption of electrical power by the pumping system and leading to an additional pressure drop due to the excess water [67]. Recent studies have explored the practicability of employing an intermittent water spray strategy or even eliminating the water spray system, which takes advantage of the water retention capacity of porous materials and capillary phenomenon. Sun et al. [68] conducted an experimental study on various intermittent spray schemes. It was recommended that the appropriate spraying duration for a porous ceramic IEC was 10–12 s, while the ideal intermittent period was 1 min. Shi et al. [44] built a validated simulation model of a porous IEC and tested its dynamic behaviour by considering intermittent spraying strategies. The results indicated that the maximum intermittent period was 2410 s, resulting in a substantial reduction of 95.2 % in energy consumption by the pumping system. Zhou et al. [69] proposed a novel design of DPEC that eliminated the need for a water spraying system. The design utilised a thin, inclined membrane to achieve automatic wicking within the system. The numerical results revealed that the optimal inclined angle for the membrane was 15°/75°.

State-of-the-art water distribution system optimisation proves that the wettability and cooling performance can be improved by adjusting the nozzle arrangement and introducing intermittent water spray strategies. In addition, incorporating auto-wicking technology presents a promising potential for further enhancing the system's performance by saving the energy usage associated with conventional water spray systems. The current challenges to be overcome entail devising a comprehensive guideline for water spray schemes for various wetting materials and conducting further in-depth exploration of automatic wicking DPEC concerning structure optimisation and membrane material choice.

2.6. Desiccant-enhanced systems

The cooling capacity of DPEC is decreased in regions with high relative humidity due to the restricted water evaporation process caused by humid atmospheric conditions [70]. In the given scenario, it is suggested to employ a liquid [71] or solid [72] dehumidification process for managing the latent heating load of the incoming air stream before its conveyance to the DPEC for further cooling. Chen et al. [73] established a numerical model for a solar-powered liquid desiccant DPEC system. Their simulation results demonstrated that, in comparison to a conventional air conditioning system, the proposed system showed a significant reduction in energy consumption ranging from 22.4 % to 53.2 % across different ambient conditions. Lin et al. [74] performed a thermodynamic analysis on a membrane liquid desiccant-based DPEC system. It was found that the proposed system could supply an output air stream characterised by a temperature of 18.3 °C and a specific humidity of 10.9 g/kg. Arun et al. [75] conducted an experimental study on a liquid-assisted DPEC system, where ultrasonic technology was utilised to facilitate the regeneration process. It was found that the regeneration

temperature could be reduced as low as 35 to 50 °C while maintaining a minimum supply air temperature of 19 °C. Caliskan et al. [76] conducted an assessment of a solid desiccant-enhanced DPEC system, utilising exergy, energy and sustainability analyses. The results suggested that the desiccant wheel should be improved as the exergy efficiency was the lowest among the major components, 38.35 %. Lai et al. [21] conducted an investigation into the impact of recirculation air ratio on the cooling efficiency and water usage rate of a solid desiccant-assisted DPEC system. Their findings revealed that, as the recirculation air ratio reached its peak value of 60 %, there was a notable decrease in the supply air temperature by 23.1 %, while the water consumption rate exhibited a substantial increase of 57.94 %. Güzelel et al. [77] simulated a solid desiccant-based DPEC system operated for an educational building. The research outcomes indicated that the indoor thermal comfort criteria could be fully met during the cooling season, with a maximum monthly thermal COP of 0.78.

The integration of the liquid/solid desiccant dehumidification process with DPEC can effectively enhance the application of stand-alone DPEC in humid areas. However, the prevailing challenges to be overcome in the future are reducing the additional energy required for regenerating the desiccant material and optimising the overall system to make it less bulky.

3. Vision

The utilisation of dew point evaporative cooling (DPEC) is considered a highly viable alternative to traditional vapour-compression cooling technology in many applications, owing to its exceptional energy efficiency and environmental sustainability benefits. However, the wider adoption and further global expansion of DPEC are currently hindered by certain inherent limitations, such as dependence on ambient conditions and freshwater availability. Hence, the future research and development on the DPEC system are suggested to focus on addressing the following issues:

- Economic factors, encompassing manufacturing and maintenance costs, as well as the scrutiny of pressure losses along the air channels should be considered in the evaluation of novel DPEC structures.
- The precision of numerical modelling can be heightened through the avoidance of oversimplifications. Additionally, it is imperative to examine the influence of the water spray effect and the presence of excessive water on the dynamic performance of DPEC systems in real weather conditions.
- Develop advanced materials with superior thermal transfer properties and excellent water retention capacity, subjecting them to durability tests and comprehensive techno-economic analysis to ascertain practical viability for practical applications.
- Optimise water spray schemes for diverse materials to maximise the energy and water savings in DPEC. Concurrently, explore the feasibility of the emerging auto-wicking approach, currently in its preliminary stages, as a potential replacement for the water pumping system, necessitating further comprehensive studies.
- Incorporation of renewable energy sources to curtail the additional energy expended in water recovery or desiccant material regeneration of hybrid systems, concomitantly reducing the overall footprint of such systems, can be explored in future research.

CRediT authorship contribution statement

Lanbo Lai: Conceptualization, Investigation, Writing – original draft, Formal analysis. **Xiaolin Wang:** Conceptualization, Project administration, Supervision, Writing – review & editing. **Eric Hu:** Formal analysis, Supervision, Writing – review & editing. **Kim Choon Ng:** Conceptualization, Writing – review & editing.

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

No data was used for the research described in the article.

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