Journal of Building Engineering 95 (2024) 110158

Contents lists available at ScienceDirect

Journal of Building Engineering

journal homepage: www.elsevier.com/locate/jobe

Use of Semi-Indirect Evaporative Cooling in HVAC systems: experimental study

Luca Socci [a,*], Javier M. Rey-Hernandez [b,c,e], Andrea Rocchetti [a], Fernando Dominguez-Muñoz [b,c], Alberto Rey-Hernandez [d], Francisco J. Rey-Martínez [d,e]

[a] *Thermodynamics and Heat Transfer Research Group, Department of Industrial Engineering - University of Florence, Italy*
[b] *Department of Thermal Engines and Machinery, Engineering School, University of Malaga, 29016, Málaga, Spain*
[c] *GEUMA Energy Research Group - University of Malaga, Andalucia, Spain*
[d] *Department of Energy and Fluid Mechanics, School of Engineering (EII), University of Valladolid (UVa), 47002, Valladolid, Spain*
[e] *GIRTER Research Group. Consolidated Research Unit (UIC053) of Castile and Leon, Spain*

ARTICLE INFO

Keywords:
Evaporative cooling
HVAC
Energy saving
Decarbonisation
Low carbon building

ABSTRACT

This study investigates the application of a Semi-Indirect Evaporative Cooler (SIEC) to develop a Decarbonised Evaporative-Based Air Conditioning System (DEBACS). The research aims to show the benefit of using the SIEC in combination with a traditional Air Conditioning Unit to enhance the energy efficiency of an HVAC system. The SIEC, constructed from ceramic material, operates in both dry and wet modes. By spraying water on the inner side, it functions as an efficient air-to-air recuperator, with the ceramic material improving water distribution and device performance. The SIEC device has been experimentally tested. Tests were conducted in both dry and wet modes across three airflow rates and three temperature levels. Moreover, a simple model that describes the SIEC behaviour in general operative conditions has been derived. Results indicated that under optimal conditions (lowest supply airflow), the SIEC achieved an efficiency ratio between 50 % and 70 % in dry mode, and nearly 100 % in wet mode, with the wet mode improving efficiency ratio by 30–50 %. These findings underscore the potential of the ceramic SIEC device as an effective technology for air conditioning systems, promoting energy efficiency, compliance with EPBD standards, and significant decarbonisation in the HVAC sector.

1. Introduction

Heating-Ventilation-Air Conditioning (HVAC) systems are one of the most energy-intensive components in the building sector, accounting for up to 30 % of its electricity consumption [1–4]. Considering that residential building sector is responsible for 35 % of European emissions in 2021 [5] and bearing in mind the prescriptions of the Energy Performance of Buildings Directive (EPBD), which mandates that building stocks in Europe should be converted to reach zero emissions target by 2050 [6], it is clear that all the strategies to make HVAC equipment more efficient are necessary and valuable. Under the perspective to promote a less energy-intensive cooling sector, evaporative cooling is a well-known technology and represents an established alternative to traditional systems for generating cooling effect (such as Vapour Compression Refrigeration cycles). It is based on producing cooling power through the evaporation of

---

[*] Corresponding author.
E-mail address: luca.socci@unifi.it (L. Socci).

https://doi.org/10.1016/j.jobe.2024.110158
Received 21 March 2024; Received in revised form 1 July 2024; Accepted 6 July 2024

water, employing combined mechanisms of mass and sensible/latent transfers. Actually, there are two main types of evaporative cooling: direct (DEC) and indirect (IEC). In Direct Evaporative Cooling, water evaporates directly within the air stream to be cooled. Various types of devices can be used: wet pads, sprays, and ultrasonic humidifiers. As a result, the air stream exits the treatment at a lower temperature but with a higher humidity ratio, following an iso-enthalpic transformation (close to saturation conditions, near the wet-bulb point, depending on the control and efficiency of the treatment). In Indirect Evaporative Cooling, water evaporation happens within a secondary air stream (that flows in the wet channels of the device), which, in turn, removes heat from the primary air stream (that flows in the dry channels of the device) that is the useful product of the process. Unless under specific circumstances, the cooling of the primary air is at constant humidity ratio. The scientific literature investigates the topic of evaporative cooling by analysing various aspects of it: physical-mathematical modelling, geometry and materials of exchangers, experimental tests, practical applications.

Xiao et al. focused on the efficiency parameters of evaporative coolers and made a huge list of experimental tests conducted on different kinds of evaporative coolers [7]. Zhu et al. dealt in-depth with possible materials useable in these devices and with the most common methods to model and analyse evaporative technologies [8,9]. Here it is underlined that water distribution in wet channels is a crucial factor to achieve good efficiency of IEC systems. Mohammed et al. proposed a review of the main patents registered over the years on heat exchangers based on the evaporative cooling mechanism. Additionally, they focused on a series of technical standards that regulate the evaluation of the efficiency of these devices [10]. Yang H. et al. analysed the feasibility of evaporative cooling in humid climates and underlined that, under specific conditions and employing particular strategies, it is possible to act also the dehumidification of primary air in IEC devices [11]. In this sense, this work is very important because it well explained that, in hot and humid climates, it is possible to remove humidity from the primary air (indeed, in the work, the *condensation states* of an IEC devices are introduced, with their specific equations). Sajjad et al. reported exhaustively a list of materials useful in evaporative cooling applications [12–14]. The work of Cui et al. is particularly interesting because they proposed a 3E methodology (Energy, Economic, Environmental) analysis of evaporative coolers, pointed out and compared the CO_2 emissions of different devices and applications [15]. Yang Y. et al. evaluated the effectiveness of advanced solutions obtained by the simultaneous utilisation of evaporative coolers with other technologies (desiccants, membranes, …) to favour a widespread diffusion of evaporative technology in the HVAC sector [16]. Cuce et al. focused on exergy-based evaluation of evaporative coolers, and in particular they reviewed their possible applications for buildings [17]. In most review papers, significant attention is given to the materials used in evaporative coolers. Referring to IEC devices, the type of material, combined with the type of exchanger (finned tubes, plates, channels …) and the airflow arrangement for primary and secondary air (concurrent, counter current, crossflow), indeed plays a significant role in the performance of the exchanger. An in-depth review of possible materials has been done by Zhao et al. [18]. Traditional IEC devices are made of metal foil or polymer. Among metals, aluminium is the most used due to its high thermal conductivity and ease of realisation. Polymeric materials, despite having a much lower thermal conductivity, offer advantages such as durability and corrosion resistance. However, both types of materials present a challenge in terms of low hydrophilicity. This fact implies that the mass transfer in the wet channels is not so enhanced, resulting in scarce humidification of secondary stream and consequently in a low cooling effect of the primary air. Moreover, to obtain favourable conditions in the wet channels, it is often necessary to spray continuously water, leading to a large quantity of circulating water and non-negligible expenditure for pumps. A possible solution to these problems is represented by the utilisation of porous materials. Moreover, these materials could allow moisture transfer inside the porous matrix (this could be useful if a moisture addition in the primary airflow is necessary). Over the years, ceramic materials have emerged as a promising option, as recently pointed out in the review work of Alam et al. about IEC technology [19], due to their high porosity, small volume density, important specific surface and high thermal conductivity [20]. Thanks to their porosity and capillary behaviour, ceramic materials are characterised by high hydrophilicity (thus enhancing heat and mass transfer in the wet channels) and can also act as water storage, avoiding the continuous operation of spraying water. For these reasons, porous materials have gained attraction also for DEC application, as recently highlighted for example in the experimental study of Dogramci [21–23]. Lv and al. made extensive research work on the utilisation of porous materials for indirect evaporative cooling [24]. They highlighted that choosing a wetting material with good surface hydrophilicity and rapid moisture transfer is fundamental to improving the cooling effect of IEC. In this sense, porous materials are the perfect candidate. In this study, they focused on structural and characteristic parameters of different porous materials and also proposed physical models to select the most suitable materials for different applications. Sun et al. proposed a theoretical and experimental study of an IEC device in which the wet channels are made in porous ceramic materials (mostly α-aluminium oxide crystals) [25]. The primary air flows inside the ceramic tubes, while the secondary air flows outside the tubes where there is a water film obtained by intermittent spraying. The mass transfer between dry and wet channels is not permitted due to an impermeable layer inside the channels. The Authors focused on the optimisation of geometric parameters and on the primary/secondary air ratio. Alharbi et al. have modelled and experimentally tested an IEC exchanger made by finned tubes and ceramic cuboids [26]. The proposed solution can provide a wet-bulb efficiency of 1.05 and a dew-point efficiency of 0.73. Boukhanouf et al. and Kanzari et al. made a computer model and an experimental setup of an IEC device with ceramic flat shells in the wet channels, while the dry channels are sealed with an impermeable thin layer [27–30]. The reported wet-bulb and dew-point efficiencies are 1.23 and 0.78 respectively. Shi et al. have proposed a plate heat exchanger with the secondary channels sintered with porous materials to enhance water retention [31]. Shi et al. and Ma et al. [32–35], more in-depth, have pointed out how fundamental is the topic of proper water spraying and surface wettability in ceramic IEC. Moreover, between the advantages of using porous materials, in particular ceramic ones, it is worth noting that, due to their structure, they are able to prevent the passage in the primary air flow, which will be the supply air stream in HVAC applications, of harmful pathogens that could potentially grow in the secondary air flow because the presence of water (such as legionella). This is an important concept underlined by Rey Martinez et al., that proposed for the first time a new concept of evaporative cooling with porous materials: the Semi-Indirect Evaporative Cooling (SIEC) [36]. The concept of SIEC is the following: in porous ceramic material tubes the secondary air flows in contact with a layer of water, the primary air flows outside the tubes, there is the possibility of mass transfer between the two sides. Indeed, the porous material lets water molecules pass through it, but it blocks the passage of harmful agents. This concept of evaporative cooling has been in-depth studied by the Research Group that has worked on the experimental prototype of SIEC placed in the University of Valladolid. Velasco Gomez et al. carefully described the prototype and investigated the first preliminary results, pointing out that SIEC can work in summer also in dehumidification mode and it can be used in winter as a humidifier [37]. Herrero Martin et al. conducted a study based on the Fanger approach for thermal comfort of the SIEC prototype combined with a heat pipe: the device acts as an energy recovery system [38]. Membrane-based SIEC technology, that employs collected rainwater as fed water, has recently proposed by Englart [39].

In a broader sense, considering an HVAC system that supplies outdoor air properly treated for cooling purposes in the hot season, a SIEC exchanger could act effectively as an enhanced energy recuperator, through two operative modes: as a “dry” exchanger, so a classic air-to-air recuperator, or as a “wet” exchanger, with the humidification of secondary air to enhance the cooling effect of the primary air. However, ceramic SIEC devices have not yet achieved widespread adoption, and their study, both experimental and modelling, is not a common theme in the literature, although ceramic materials have undeniable advantages over other materials, as previously explained.

In this paper, the integration of a Semi-Indirect Evaporative Cooler with an Air-Conditioning Unit (ACU), in order to obtain a Decarbonised Evaporative Based Air Conditioning System (DEBACS), is presented. The SIEC acts as a pre-cooler of the supply air that needs to be cooled, then the ACU operates as backup. A prototype of the entire system, including the SIEC and ACU, has been realised and tested. The SIEC has been used both in dry and wet mode, to explain how the utilisation of the evaporative technology can enhance the performance of the system. In this paper, the general concept of a SIEC device is explained, then the employed experimental setup is presented, with the results obtained from a series of tests, both in dry and wet mode.

This work demonstrates the effectiveness of a ceramic SIEC systems in combination with traditional air conditioning systems, additionally offering a simple model that generalise the behaviour of a cheap and safe ready-to-market SIEC device beyond its tested operating conditions.

The obtained results lead to consider the utilisation of the SIEC technology as an interesting option to reduce energy consumption in HVAC systems according to the prescriptions of EPBD requirements and towards a substantial decarbonisation of the building cooling sector.

Nomenclature

General nomenclature		SIEC geometry nomenclature	
ACU	Air Conditioning Unit	Di	Internal diameter (mm)
AHU	Air Handling Unit	De	External diameter (mm)
c	Specific heat at constant pressure (kJ/kg/K)	y	Thickness (mm)
CC	Climatic Chamber	t	Section t (mm)
DEBACS	Decarbonised Evaporative Based Air Conditioning System	l	Section l (mm)
DT	Temperature difference (°C)	d	Section d (mm)
Dx	Humidity ratio difference	**Subscripts**	
m	Mass airflow (kg/s)	1,2 …	State points of air
Q	Heat	I,II	Primary and secondary side of SIEC
Q	Efficiency ratio	a	Air
Rm	Mass flow ratio	req	Required
Rs	Indicator of polynomial goodness of fitting	s	Sensible
SIEC	Semi-Indirect Evaporative Cooling	**Superscripts**	
T	Temperature (°C)	*	Referred to Rm
X	Humidity ratio		

2. Materials and methods

In the following, the concept of Semi-Indirect Evaporative Cooling and its modelling are presented, then the employed experimental set-up is described. Moreover, the equations used to evaluate the integrated system SIEC-ACU are introduced.

2.1. Scheme of proposed SIEC

The proposed SIEC device is a heat and mass exchanger composed of porous ceramic tubes. The primary air, which constitutes the supply air of an HVAC system, flows outside the tubes. The secondary air flows inside the tubes and could be humidified by the presence of water sprayed in the tubes. A schematic representation of the system is reported in Fig. 1.

In the context of a 100 % outdoor air system HVAC application, the primary air is the outdoor supply air, while the secondary air is the extraction air from the application (e.g. the building served by the HVAC system). The device can operate in two different modes.

1. In dry mode, no water is sprayed inside the ceramic tubes. The device acts as a standard air-to-air static recuperator: the supply air enters hot (1) and exits colder (2), while the secondary air enters cold (3) and exits hotter (4). The primary air undergoes a cooling at constant humidity ratio, the secondary air undergoes a heating at constant humidity ratio.

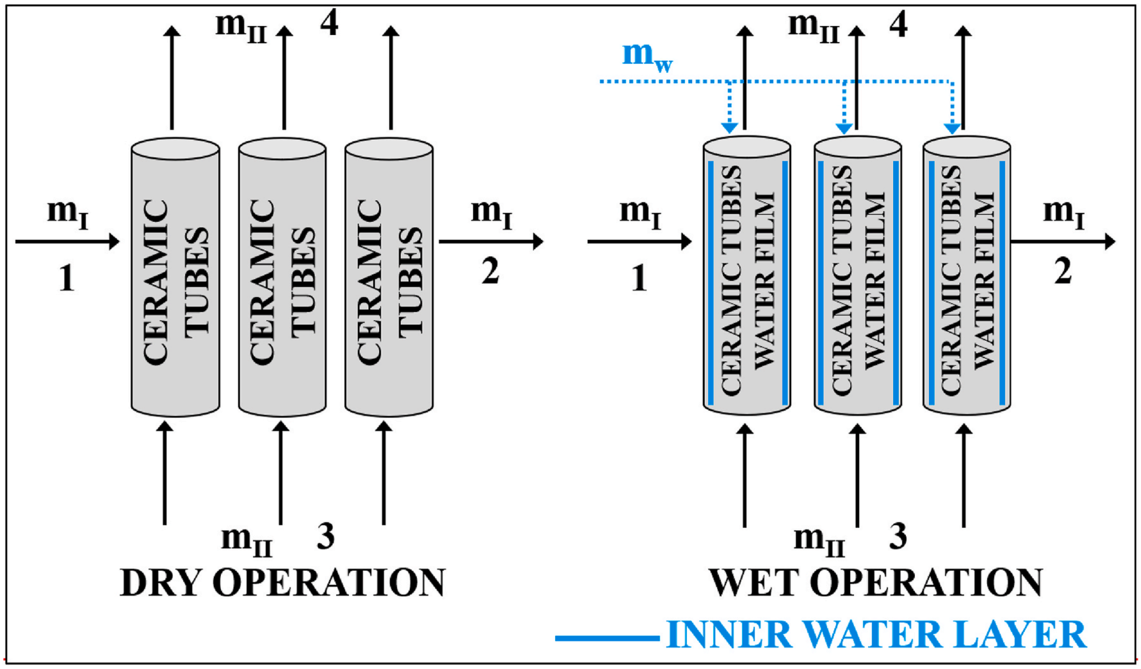

Fig. 1. SIEC: representation of the exchanger in dry (left) and wet (right) operations.

2. In wet mode, water is sprayed inside the ceramic tubes, forming a thin film on the ceramic surface. The device acts as enhanced air-to-air recuperator: the secondary air is humidified when it enters in contact with the water film, making possible a further cooling effect on primary air.

Water is fed into the channels in such a way as to form a thin film, so that evaporation is promoted (in fact, the secondary air results saturated at the exit).

3. Experimental assessment

The employed experimental setup is schematically represented in Fig. 2, where there are reported the most important components (excluding fans and pumps for air and water circulation and the sensors): an Air Handling Unit, a Semi-Indirect Evaporative Cooler, a Climatic Chamber and the Air Conditioning Unit.

The Air Handling Unit (model *TKM-30* produced by *TROX TECHNIK*) draws in outdoor air (m_I, point 0) and processes it to the desired values of temperature and humidity, in order to simulate different climatic conditions (point 1). The AHU is equipped with

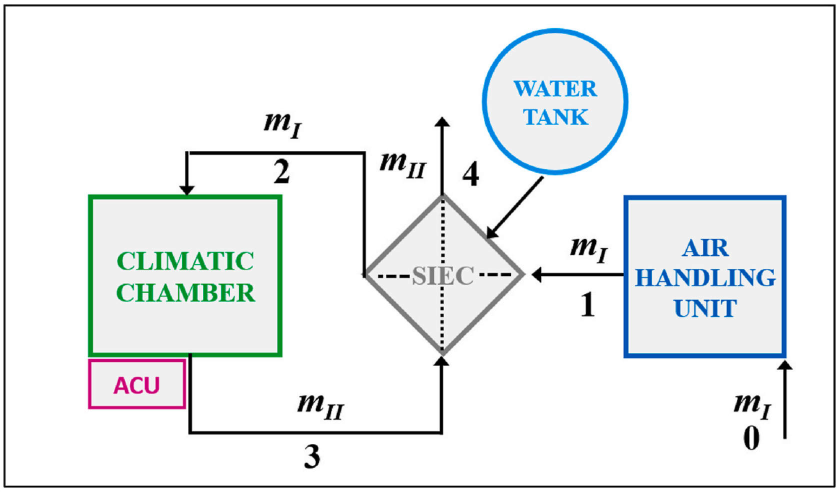

Fig. 2. Representation of the experimental setup.

direct expansion coils (DX) for temperature and humidity control, moreover the heating could be ensured by additional electric coils. The DX coils are the heat exchangers of a refrigeration/heat pump cycle (model *RXC-75-100-125* produced by *TRANE*). The airflow treated by AHU is sent to the Semi-Indirect Evaporative Cooler. The dimensions of the SIEC recuperator are: 230 mm wide x 185 mm deep x 600 mm high. It is made up of ceramic tubes arranged vertically, through the inside of which the return air from the climatic chambers circulates and the outside of which the primary air from the AHU circulates (Fig. 3, Table 1). When the SIEC operates in wet mode, the water inside the channels is taken from a dedicated water tank.

The Climatic Chamber, at which the supply air m_I is provided, represents the environment to be conditioned and its setpoint temperature is ensured by the presence of the Air Conditioning Unit (model *Diamond Inverter 9000* produced by *Ferroli*). The air is extracted from the climatic chamber and becomes the secondary air (m_{II}, point 3) sent to the SIEC device, where it cools the primary air eventually adding water in the ceramic tubes in the wet mode, then it is expelled outside (point 4). The points in Fig. 2 are monitored with sensors that acquire: temperature, humidity, pressure and air flow. All the data has been acquired with an *AGILENT 34890* data recorder. For both operative modes, three different levels of primary air flow have been tested (100.0, 200.0 and 300.0 m^3/h) and for each level, three temperature conditions have been analysed: 40.0, 35.0 and 30.0 °C (Table 2). The secondary air flow rate, taken from the climate chamber, is 200 m^3/h. The climate chamber is maintained at a temperature of 22.5 ± 2.0 °C and a relative humidity of 55.0 ± 5.0 %. These conditions are consequently the ones of air at point 3 that goes to the SIEC device. In the experimental practice, the setup control system has been used to achieve flow rates and temperatures as close as possible to the setpoint values.

3.1. Decarbonised SIEC model

The general model that allows to evaluate the performance of the SIEC device, according to experimental results, is here presented.

3.1.1. Dry mode

Considering the dry mode, with no water used in the ceramic tubes, the primary air is cooled from (1) to (2), releasing heat to the secondary air:

$$DT_I = T_1 - T_2 \tag{1}$$

$$Q_s = c_a * m_I \bullet (T_1 - T_2) \tag{2}$$

The subscript *s* highlights how this heat is in the form of sensible one, due to the fact that no moisture is added or removed to the primary air. The same quantity is released to the secondary air, which is heated from (3) to (4). The required cooling capacity, $Q_{s,req}$, necessary to bring the supply air from the inlet temperature (1) to the required temperature (i.e. the temperature of the climatic chamber), is:

$$Q_{s,req} = c_a * m_I \bullet \left(T_1 - T_{req}\right) \tag{3}$$

To evaluate the capacity of the system to act as pre-cooler, it is possible to introduce the Efficiency Ratio as follows:

$$q = \frac{Q_s}{Q_{s,\mathrm{req}}} \tag{4}$$

3.1.2. Wet mode

Considering the wet mode, all the previous equations could be still used. Moreover, it is useful to check the value of the humidity ratio between the inlet and the outlet of the supply air at the SIEC. Indeed, when the device is used in wet mode, it is possible that some water passes through the ceramic matrix (depending on the humidity condition of the inlet air), enhancing the cooling effect but with a

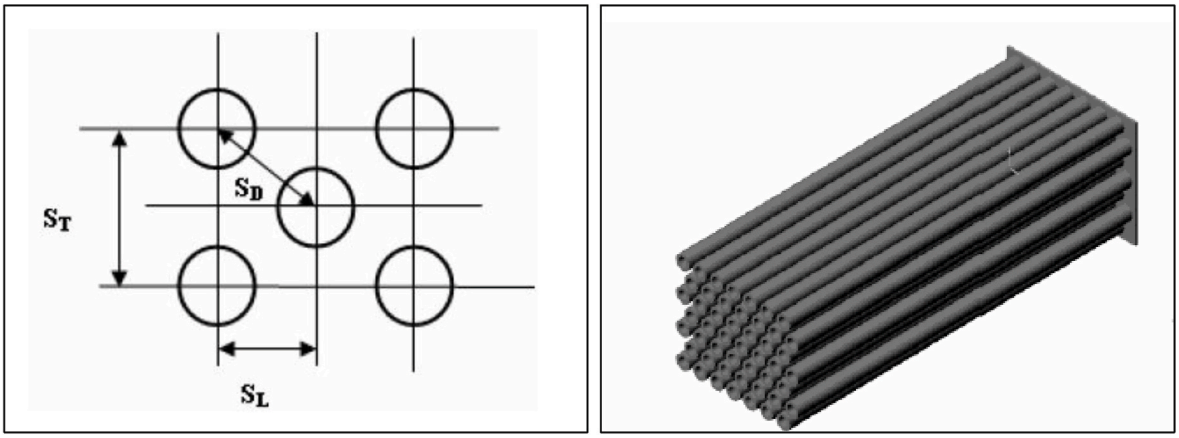

Fig. 3. Geometry (left) and schematisation (right) of the tested SIEC device [Courtesy of University of Valladolid].

Table 1
Geometry characteristics of the tested SIEC device.

Columns	Rows	Tubes	Di mm	De mm	y mm	t mm	l mm	d mm
7	7	49	15	25	5	30	25	29

Table 2
Samples of the experiments for dry mode operation.

V_I m^3/h	T ° C	Sample	V_I m^3/h	T ° C	Sample	V_I m^3/h	T ° C	Sample
100.0	40.0	1	200.0	40.0	1	300.0	40.0	1
	35.0	2		35.0	2		35.0	2
	30.0	3		30.0	3		30.0	3

possible consequence on the thermo-hygrometric comfort needs. So *Dx* parameter is evaluated:

$$Dx = x_2 - x_1 \tag{5}$$

3.1.3. *Equations for general conditions*

To analyse the performance of SIEC in general conditions of airflow, it is useful to refer the introduced quantities DT_I, Q_s , q , Dx to the mass flow ratio between primary and secondary airflows *Rm:*

$$R_m = \frac{m_I}{m_{II}} \tag{6}$$

In this way, when the SIEC works with values of *mI* and *mII* different from the values experimentally tested with the previously described set-up, it is possible to easily predict its performances. Using the *Rm* value, the following specific quantities are obtained:

$$DT_I{}^* = \frac{DT_I}{R_m} \tag{7}$$

$$Q_s{}^* = \frac{Q_s}{R_m} \tag{8}$$

$$q^* = \frac{q}{R_m} \tag{9}$$

$$Dx^* = Dx/R_m \tag{10}$$

In the equations from {6} to {10} all the perforamance quantites are written with an asterisk in the superscript to indicate that they are referred to the mass flow ratio.

Knowing the ratio between the airflows and the specific quantities, it is possible to write general mathematical correlations that could be used to predict the behaviour of SIEC device by varying inlet air temperature and airflows ratio. These general correlations are:

$$G = p_0 + p_{10} \bullet T_1 + p_{01} \bullet R_m \tag{11}$$

where *G* is one of the specific quantities. The coefficients *p* of the polynomial will be shown in the *Results and Discussion* session where the experimental data are reported. The polynomials of each specific quantity are characterised by a *rs* value, which could vary between 0 and 1 and indicates the goodness of model adaptation to the experimental results: a value closer to 1 indicates a good fitting.

This approach will be used only for *Rm* between 1.0 and 1.5, because at *Rm* = 0.5 a different performance of the device emerges which could not be fitted with this mode.

4. Results and discussion

In this section, the results obtained from experiments for both dry and wet modes are presented. For both operative modes, the following parameters are reported: absolute and specific temperature difference, absolute and specific exchanged heat, absolute and specific efficiency ratio. Moreover, the results for the generalisation of the behaviour of the SIEC are shown.

4.1. *Experimental results*

4.1.1. *Dry mode*

In the dry mode, the following graphs represent: absolute and specific temperature difference DT_I and $DT_I{}^*$ (Fig. 4), absolute and

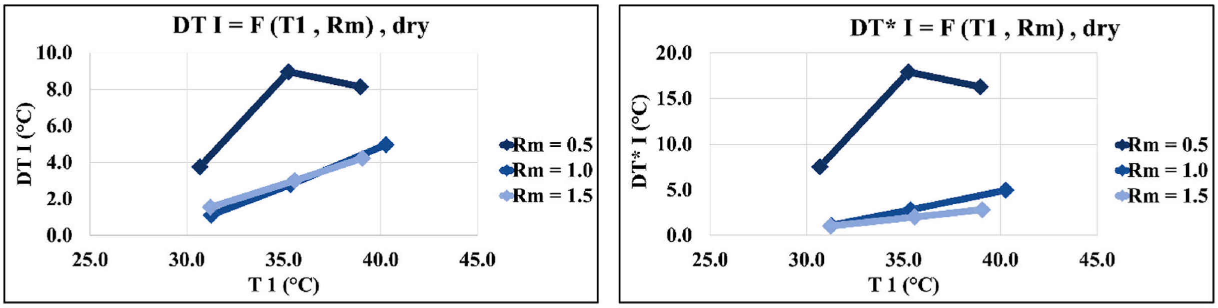

Fig. 4. DT_I (left) and DT_I* (right) function of T_1 and R_m, dry mode.

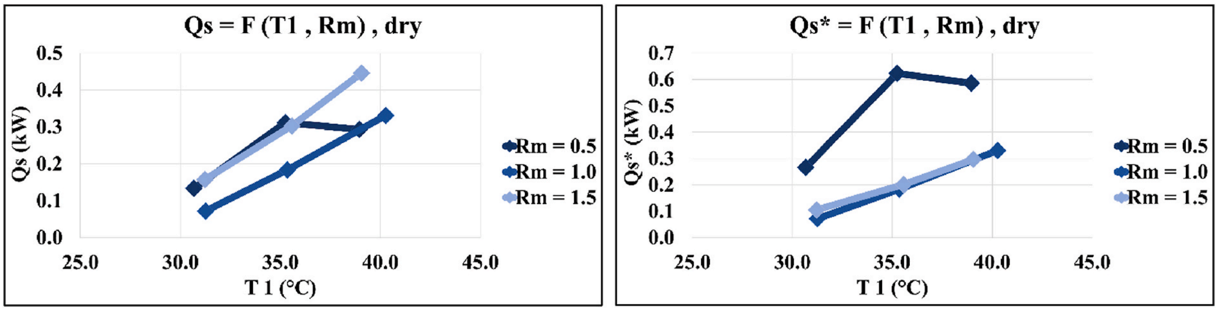

Fig. 5. Q_S (left) and Q_S* (right) function of T_1 and R_m, dry mode.

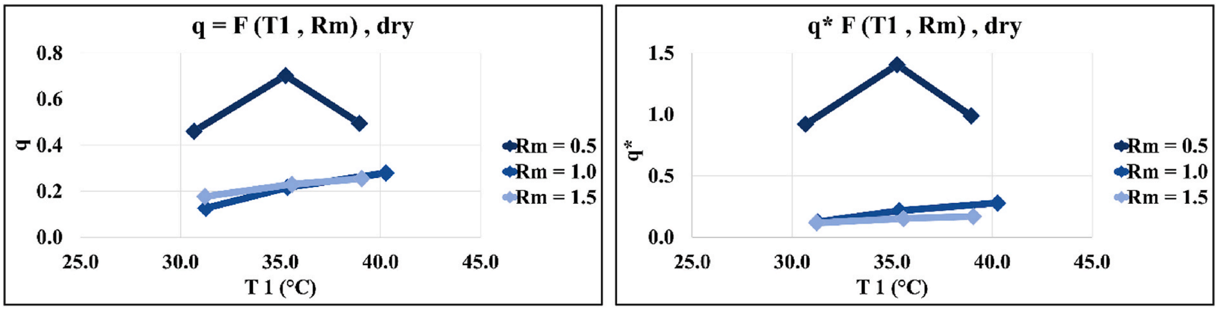

Fig. 6. *q* (left) and *q** (right) function of T_1 and R_m, dry mode.

specific exchanged heat Q_S and Q_s* (Fig. 5), absolute and specific efficiency ratio *q* and *q** (Fig. 6). As shown in the graphs, the system shows a better performance at a lower quantity of supply air ($Rm = 0.5$). In this condition, the secondary air of the SIEC has the potential to extract more heat from the supply air and can ensure a great amount of recovered heat. In this case, the value of the Efficiency Ratio *q* is between 0.5 and 0.7, showing a high performance of the SIEC, that leads to minimise the utilisation of ACU. Moreover, for the lowest value of m_I, an optimum point of functioning emerges, in correspondence with $T_1 = 35.0$. At these conditions, 70 % of the requested cooling capacity is ensured only by the SIEC. When the quantity of supply air equals that of the return ($Rm = 1.0$), or even when there is more supply air than return air ($Rm = 1.5$), the device performance decreases but still allows for substantial thermal recovery. For these cases, analysing the trends of specific values like *DT**, *Qs**, and *q**, it is observed that the SIEC is able to ensure fairly similar thermal recovery. Rising the ratio *Rm*, it is possible to deduce that the performance decreases: the higher velocity, even if could bring some benefits in terms of convective heat transfer coefficient, causes phenomena like by-pass or circuitation with consequent lower exchange surface.

4.1.2. Wet mode

In the wet mode, the following graphs represent: absolute and specific temperature difference DT_I and DT_I* (Fig. 7), absolute and specific exchanged heat Q_S and Q_s* (Fig. 8), absolute and specific efficiency ratio *q* and *q** (Fig. 9).

In this case, the trends seen above with regard to the increase in the *Rm* ratio are confirmed. The optimal ratio remains $Rm = 0.5$, for which the cooling capacity of the device is high, covering the entire cooling requirement of the system (*q* approximately 1). In this case, it is possible to turn off the Air-Conditioning Unit, considering that the efficiency ratio is almost equal to 1. It can also be seen that, for the lower value of the supply air flow rate, there is not the optimum seen previously. This is clear from the graph of Efficiency Ratio *q*

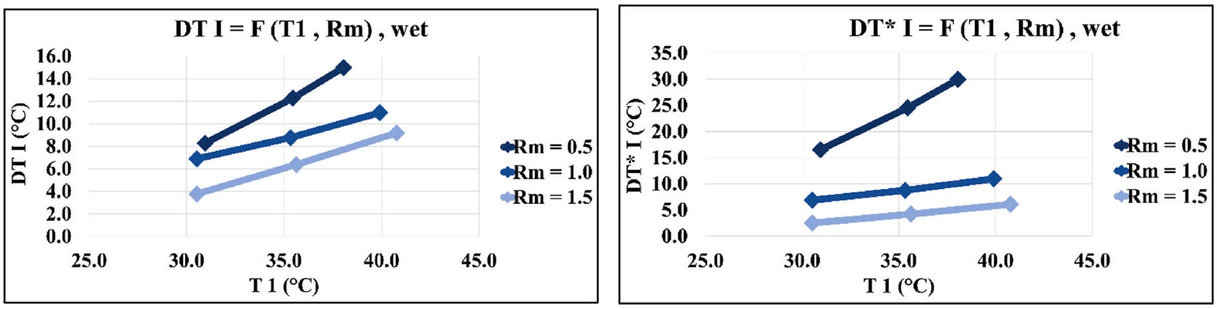

Fig. 7. DT_I (left) and DT_I* (right) function of T_1 and R_m, wet mode.

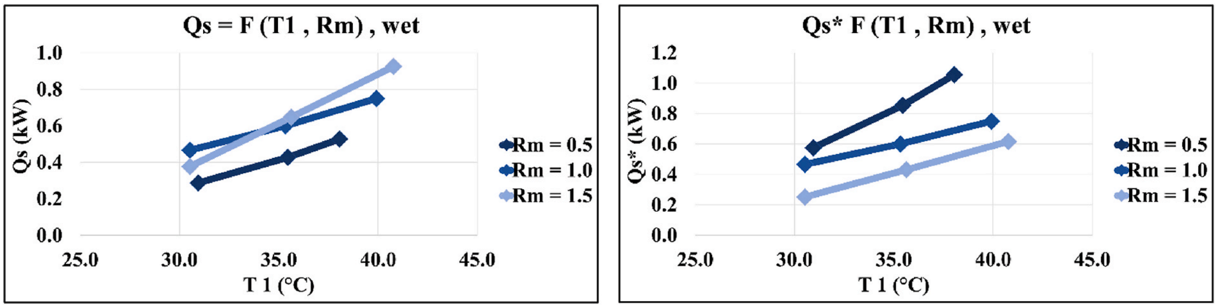

Fig. 8. Q_S (left) and Q_S* (right) function of T_1 and R_m, wet mode.

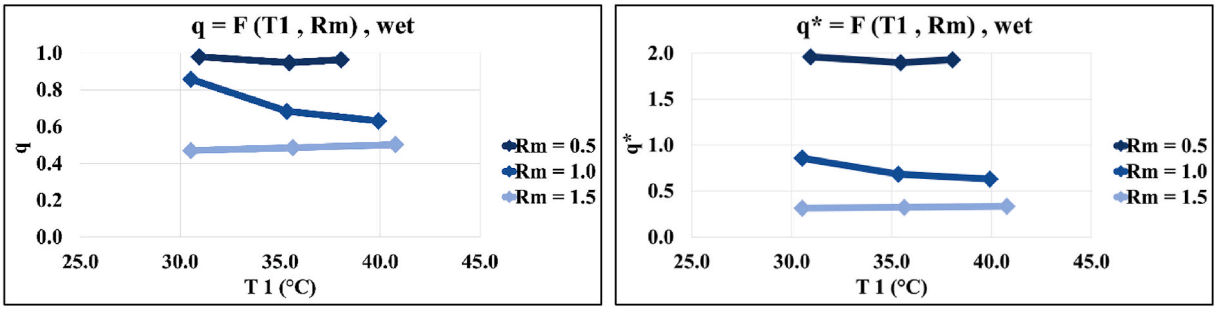

Fig. 9. q (left) and q* (right) function of T_1 and R_m, wet mode.

and q* (Fig. 9), which are quasi-constant at this mass flow ratio. Again, for higher primary flow values, there is a decrease in cooling capacity due to the smaller contact surface between the exchanger and the primary air (by-pass phenomena limiting heat transfer). But it is very interesting that also for $Rm = 1.0$, at a temperature of about 30 °C, it is possible to achieve an almost complete coverage of required cooling capacity only with the SIEC ($q = 0.86$). Finally, the SIEC shows competitive performances, in the wet mode, even at Rm = 1.5, with a cooling efficiency of about 0.5. These results lead to consider that the modality of wetting the inner side of ceramic tubes is very effective, and that the porous material facilitates a good distribution of water over all the surfaces. It is also worth noting that the enhancement in cooling effect obtainable with the wet mode does not alter significantly the amount of humidity ratio in the supply air (Fig. 10). Indeed, the amount of water vapour in the supply air is very limited and absolutely compatible with the request of the climatic chamber.

4.1.3. Results of the modelling generalisation

Following the approach explained in the *Materials and Methods* section, using the experimental results for $Rm = 1.0$ and $Rm = 1.5$ in both operative modes, it is possible to obtain a model able to generalise the performance of SIEC device. Thus in general conditions of inlet air temperature and mass flow ratio between 1.0 and 1.5. In this sense, Table 3 reports the coefficient of the polynomials which describe the operation of the SIEC device in dry and wet mode.

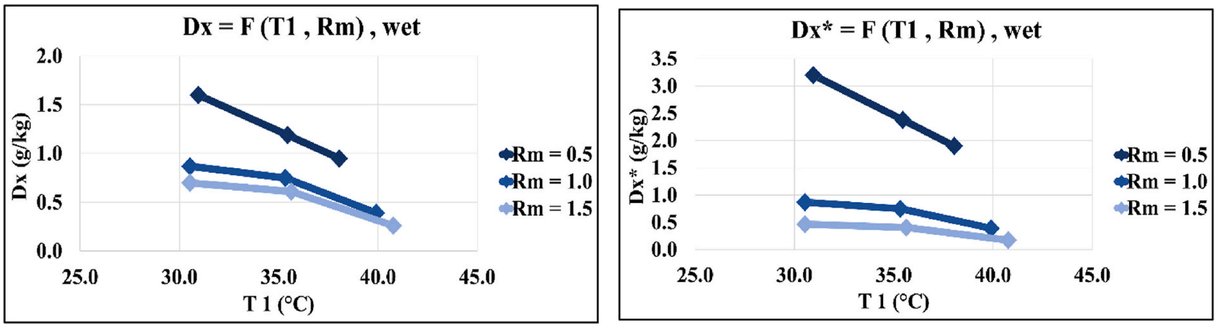

Fig. 10. *Dx* (left) and *Dx** (right) function of T_1 and R_m, wet mode.

Table 3
Coefficient of polynomial model for specific quantities under analysis.

	p00	p10	p01	rs
DRY				
DT*	−7.462	0.342	−1.772	0.933
Qs*	−0.801	0.027	0.038	0.988
q*	−0.104	0.012	−0.118	0.887
WET				
DT*	4.574	0.391	−9.469	0.996
Qs*	−0.194	0.033	−0.372	0.993
q*	1.856	−0.009	−0.793	0.923

Table 4
Comparison between dry and wet mode for the SIEC device.

V_I	q	q	Gain Wet/dry	V_I	q	q	Gain Wet/dry	V_I	q	q	Gain Wet/dry
m^3/h	Dry	Wet	%	m^3/h	Dry	Wet	%	m^3/h	Dry	Wet	%
100.0	0.49	0.96	51.33	200.0	0.28	0.63	44.31	300.0	0.26	0.50	44.31
	0.70	0.95	74.11		0.22	0.68	31.76		0.23	0.49	31.76
	0.46	0.98	46.97		0.13	0.86	14.77		0.18	0.47	14.77

Table 3 shows that the adopted polynomial model perfectly agrees with the experimental data: the goodness indicator of the polynomial approsimation, the rs index, is much over 0.90 in all cases except for one at 0.887. With this model, it is possible to predict the behaviour of the SIEC at different conditions of the range. It has been decided to not model the *Dx**, even if reported in the previous part of the graphical results, because this quantity depends also on the inlet humidity ratio of primary air, which is not included in this model.

4.1.4. *Final comparison between dry and wet mode*

Concluding the analysis part of the experimental results, it is useful to directly show a comparison of the performance of the SIEC device in the two modes, in terms of Efficiency Ratio.

The utilisation of wet mode significantly rises the performance of the device, globally between 30 and 50 %, with a peak of 74 % for the lowest value of supply air, at a temperature of 35 °C (Table 4).

5. Conclusions

In this paper, the utilisation of a ceramic Semi-Indirect Evaporative Cooler in integration with an Air-Conditioning Unit to realise a Decarbonised Evaporative Based Air Conditioning System (DEBACS) has been introduced. The SIEC is the pre-cooler of the supply air that has to be cooled, the ACU acts as backup. A prototype of the integrated system has been realised, tested and presented in the paper. The shown results refer to the utilisation of the SIEC both in dry and wet mode. In dry mode, it is an air-to-air recuperator. In wet mode, the utilisation of water on the secondary side of the exchanger drastically increases its performances. From the analysis of the experimental data, some conclusions can be drawn. The best performances of the devices are obtained for a mass flow ratio of primary/secondary air *Rm* = 0.5. This in particular happens for the dry mode. At higher *Rm,* the performances are quite similar. In dry mode, for *Rm* = 0.5 it is possible to obtain an efficiency ratio *q* between 0.5 and 0.7, with a maximum *q* in correspondence with the inlet temperature of 35.0 °C. In wet mode, for *Rm* = 0.5 it is possible to cover almost the totality of the cooling request, with an efficiency ratio of about 1.0. The utilisation of water on the secondary side does not much affect the comfort conditions required for the primary air, with a limited increase in the humidity ratio. Moreover, for the case of *Rm* = 1.0 and *Rm* = 1.5, it has been derived a simple polynomial model that could predict the behaviour of the SIEC device in general conditions of Rm between 1.0 and 1.5 and general inlet temperatures. This model could be very useful for calculations on SIEC prototype in general operative conditions.

In-deeper studies, such as experimental test by varying the inlet humidity conditions or CFD analysis, could offer a wider range on which affine the mathematical model and more detailed explaiantion regarding the best conditions of Rm for the SIEC device.

The results obtained from the experimental tests, taking also into account the so interesting advantages of porous ceramic materials (safety for human health, low cost, recyclability, low environmental impact), lead to consider the SIEC technology as a valid option if used in integration with standard air conditioning devices. The SIEC solution can be an attractive option for both new HVAC installations and the revamping of existing systems. In this context, it can be a viable alternative for all systems requiring fresh air renewal: the SIEC, acting as a high-efficiency heat recuperator in wet mode, would handle a significant portion of the cooling load without overburdening the existing cooling equipment.

This technology, perfectly in line with the prescription of EPBD directive, could represent a disruptive solution in order to achieve a widespread decarbonisation of HVAC sector. European Green Deal goals are affordable with this sustainable technology.

CRediT authorship contribution statement

Luca Socci: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation. **Javier M. Rey-Hernandez:** Validation, Supervision, Formal analysis. **Andrea Rocchetti:** Supervision, Investigation, Data curation. **Fernando Dominguez-Muñoz:** Writing – review & editing, Validation, Supervision. **Alberto Rey-Hernandez:** Validation, Methodology, Data curation. **Francisco J. Rey-Martínez:** Supervision, Project administration, Data curation.

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

The data that has been used is confidential.

Acknowledgements

We would like to acknowledge the University of Valladolid for providing access to the site and for facilitating this research work, through the provision of equipment, space and facilities.

This paper has been made possible due to the support received from: “OESTE” Project by University of Valladolid, Spain; “Lime4Health” Project by Technical University of Madrid (UPM); ITAP at University of Valladolid.

References

[1] International Energy Agency, The future of cooling. https://www.iea.org/reports/the-future-of-cooling, 2018.
[2] International Energy Agency, Net Zero by 2050 - A Roadmap for the Global Energy Sector, 2021. https://www.iea.org/reports/net-zero-by-2050.
[3] International Energy Agency, World energy outlook 2022. https://www.iea.org/reports/world-energy-outlook-2022, 2022.
[4] G. Grazzini, A. Milazzo, Tecnica del Freddo, Esculapio Editore, 2017. ISBN: 9788874889969.
[5] European Environment Agency, Greenhouse gas emissions from energy use in buildings in Europe. https://www.eea.europa.eu/en/analysis/indicators/greenhouse-gas-emissions-from-energy, 2023.
[6] European Union, Energy Performance of Buildings Directive, 2024. https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/energy-performance-buildings-directive_en.
[7] X. Xiao, J. Liu, A state-of-art review of dew point evaporative cooling technology and integrated applications, Renew. Sustain. Energy Rev. (2024), https://doi.org/10.1016/j.rser.2023.114142.
[8] G. Zhu, T. Wen, Q. Wang, X. Xu, A review of dew-point evaporative cooling: recent advances and future development, Appl. Energy (2022), https://doi.org/10.1016/j.apenergy.2022.118785.
[9] G. Zhu, W. Chen, D. Zhang, T. Wen, Performance evaluation of counter flow dew-point evaporative cooler with a three-dimensional numerical model, Appl. Therm. Eng. (2023), https://doi.org/10.1016/j.applthermaleng.2022.119483.
[10] R.H. Mohammed, M. El-Morsi, O. Abdelaziz, Indirect evaporative cooling for buildings: a comprehensive patents review, J. Build. Eng. (2022), https://doi.org/10.1016/j.jobe.2022.104158.
[11] H. Yang, W. Shi, Y. Chen, Y. Min, Research development of indirect evaporative cooling technology: an updated review, Renew. Sustain. Energy Rev. (2021), https://doi.org/10.1016/j.rser.2021.111082.
[12] U. Sajjad, N. Abbas, K. Hamid, S. Abbas, I. Hussain, S.M. Ammar, et al., A review of recent advances in indirect evaporative cooling technology, Int. Commun. Heat Mass Tran. (2021), https://doi.org/10.1016/j.icheatmasstransfer.2021.105140.
[13] I. Hussain, F. Bibi, S.A. Bhat, U. Sajjad, M. Sultan, H.M. Ali, et al., Evaluating the parameters affecting the direct and indirect evaporative cooling systems, Eng. Anal. Bound. Elem. (2022), https://doi.org/10.1016/j.enganabound.2022.09.016.
[14] S.A. Bhat, U. Sajjad, I. Hussain, W.-M. Yan, H.M.U. Raza, H.M. Ali, et al., Experiments and modeling on thermal performance evaluation of standalone and M-cycle based desiccant air-conditioning systems, Energy Rep. (2024), https://doi.org/10.1016/j.egyr.2024.01.019.
[15] Y. Cui, J. Zhu, S. Zoras, L. Liu, Review of the recent advances in dew point evaporative cooling technology: 3E (energy, economic and environmental) assessments, Renew. Sustain. Energy Rev. (2021), https://doi.org/10.1016/j.rser.2021.111345.
[16] Y. Yang, G. Cui, C.Q. Lan, Developments in evaporative cooling and enhanced evaporative cooling - a review, Renew. Sustain. Energy Rev. (2019), https://doi.org/10.1016/j.rser.2019.06.037.
[17] P.M. Cuce, S. Riffat, A state of the art review of evaporative cooling systems for building applications, Renew. Sustain. Energy Rev. (2016), https://doi.org/10.1016/j.rser.2015.10.066.
[18] X. Zhao, S. Liu, S.B. Riffat, Comparative study of heat and mass exchanging materials for indirect evaporative cooling systems, Build. Environ. (2008), https://doi.org/10.1016/j.buildenv.2007.11.009.

[19] M.S. Alam, M.N.B. Mohd Zubir, M.R.B. Muhamad, S.N. Kazi, H.F. Öztop, S. Abdullah, et al., A technological review of dew point evaporative cooling: experimental, analytical, numerical and optimization perspectives, J. Build. Eng. (2024), https://doi.org/10.1016/j.jobe.2024.109544.

[20] F. Wang, T. Sun, X. Huang, Y. Chen, H. Yang, Experimental research on a novel porous ceramic tube type indirect evaporative cooler, Appl. Therm. Eng. (2017), https://doi.org/10.1016/j.applthermaleng.2017.07.111.

[21] P.A. Doğramacı, D. Aydın, Comparative experimental investigation of novel organic materials for direct evaporative cooling applications in hot-dry climate, J. Build. Eng. (2020), https://doi.org/10.1016/j.jobe.2020.101240.

[22] N. Khosravi, D. Aydin, M. Karim Nejhad, P.A. Dogramaci, Comparative performance analysis of direct and desiccant assisted evaporative cooling systems using novel candidate materials, Energy Convers. Manag. (2020), https://doi.org/10.1016/j.enconman.2020.11316.

[23] P. Abohorlu Doğramacı, S. Riffat, G. Gan, D. Aydın, Experimental study of the potential of eucalyptus fibres for evaporative cooling, Renew. Energy (2019), https://doi.org/10.1016/j.renene.2018.07.005.

[24] J. Lv, H. Xu, M. Zhu, Y. Dai, H. Liu, Z. Li, The performance and model of porous materials in the indirect evaporative cooling system: a review, J. Build. Eng. (2021), https://doi.org/10.1016/j.jobe.2021.102741.

[25] T. Sun, X. Huang, Y. Qu, F. Wang, Y. Chen, Theoretical and experimental study on heat and mass transfer of a porous ceramic tube type indirect evaporative cooler, Appl. Therm. Eng. (2020), https://doi.org/10.1016/j.applthermaleng.2020.115211.

[26] A. Alharbi, A. Almaneea, R. Boukhanouf, Integrated hollow porous ceramic cuboids-finned heat pipes evaporative cooling system: numerical modelling and experimental validation, Energy Build. (2019), https://doi.org/10.1016/j.enbuild.2019.05.012.

[27] R. Boukhanouf, A. Alharbi, H.G. Ibrahim, Investigation of a sub-wet bulb temperature evaporative cooler for buildings, Sustainable Building Conference (2013). https://www.researchgate.net/profile/Abdulrahman-Alharbi-11/publication/285976956_Investigation_of_a_sub-wet_bulb_temperature_evaporative_cooler_for_buildings/links/57049fd308ae44d70ee06600/Investigation-of-a-sub-wet-bulb-temperature-evaporative-cooler-for-buildings.pdf.

[28] M. Kanzari, R. Boukhanouf, M.C. Zaghdoudiand, H.G. Ibrahim, Mathematical modeling of a sub-wet bulb temperature evaporative cooling using porous ceramic materials, World Academy of Science, Engineering and Technology-International Journal of Industrial and Manufacturing Engineering (2013). https://www.researchgate.net/publication/267209957_Mathematical_Modeling_of_a_Sub-Wet_Bulb_Temperature_Evaporative_Cooling_Using_Porous_Ceramic_Materials#fullTextFileContent.

[29] R. Boukhanouf, A. Alharbi, H.G. Ibrahim, O. Amer, M. Worall, Computer modelling and experimental investigation of building integrated sub-wet bulb temperature evaporative cooling system, Appl. Therm. Eng. (2017), https://doi.org/10.1016/j.applthermaleng.2016.12.119.

[30] R. Boukhanouf, O. Amer, H. Ibrahim, J. Calautit, Design and performance analysis of a regenerative evaporative cooler for cooling of buildings in arid climates, Build. Environ. (2018), https://doi.org/10.1016/j.buildenv.2018.06.004.

[31] W. Shi, Y. Min, X. Ma, Y. Chen, H. Yang, Performance evaluation of a novel plate-type porous indirect evaporative cooling system: an experimental study, J. Build. Eng. (2022), https://doi.org/10.1016/j.jobe.2021.103898.

[32] W. Shi, H. Yang, X. Ma, X. Liu, A novel indirect evaporative cooler with porous media under dual spraying modes: a comparative analysis from energy, exergy, and environmental perspectives, J. Build. Eng. (2023), https://doi.org/10.1016/j.jobe.2023.106874.

[33] X. Ma, W. Shi, H. Yang, Spray parameter analysis and performance optimization of indirect evaporative cooler considering surface wettability, J. Build. Eng. (2024), https://doi.org/10.1016/j.jobe.2023.108175.

[34] X. Ma, W. Shi, H. Yang, Study on water spraying distribution to improve the energy recovery performance of indirect evaporative coolers with nozzle arrangement optimization, Appl. Energy (2022), https://doi.org/10.1016/j.apenergy.2022.119212.

[35] W. Shi, Y. Min, X. Ma, Y. Chen, H. Yang, Dynamic performance evaluation of porous indirect evaporative cooling system with intermittent spraying strategies, Appl. Energy (2022), https://doi.org/10.1016/j.apenergy.2022.118598.

[36] Martínez FJ. Rey, E. Velasco Gómez, Martín R. Herrero, J. Martínez Gutiérrez, F. Varela Diez, Comparative study of two different evaporative systems: an indirect evaporative cooler and a semi-indirect ceramic evaporative cooler, Energy Build. (2004), https://doi.org/10.1016/j.enbuild.2003.10.010.

[37] E. Velasco Gómez, F.J. Rey Martínez, F. Varela Diez, M.J. Molina Leyva, R. Herrero Martín, Description and experimental results of a semi-indirect ceramic evaporative cooler, Int. J. Refrig. (2005), https://doi.org/10.1016/j.ijrefrig.2005.01.004.

[38] R. Herrero Martín, F.J. Rey Martínez, E. Velasco Gómez, Thermal comfort analysis of a low temperature waste energy recovery system: SIECHP, Energy Build. (2008), https://doi.org/10.1016/j.enbuild.2007.04.009.

[39] S. Englart, Analysis of rainwater use in membrane-based semi-direct evaporative cooling of air, J. Build. Eng. (2024), https://doi.org/10.1016/j.jobe.2024.109409.