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Sustainable cooling system for Kuwait hot climate combining diurnal radiative cooling and indirect evaporative cooling system

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ABSTRACT

This study investigates the performance of a hybrid passive cooling system that combines a hydronic radiative cooling (RC) panel integrated with a cross-flow dew-point indirect evaporative cooler DPIEC equipped with a closed cycle water reclamation using air-water harvesting (AWH) system. The study was performed on a typical residential house located in the hot and mostly dry climate of Kuwait. The house hourly cooling load was calculated using the transient simulation software TRNSYS. A mathematical model integrating the hydronic RC panel and the DPIEC models was developed and simulated to predict the system operation over the cooling season. The integrated hybrid system's performance was compared with two systems: i) the DPIEC unit standalone, and ii) the conventional cooling system, while focusing on the role of the RC system.

It was found that the use of the RC panel's power during nighttime and daytime reduced the water consumption of the DPIEC unit by an average of 44.2% in comparison to that of a DPIEC unit operating alone during the cooling season. Moreover, a significant reduction of 53.4% in the electrical energy consumption was achieved by hybrid system compared to a typical AC system during the entire cooling season in Kuwait.

1. Introduction

The building sector accounts for 40–50% of the total worldwide energy consumption. Buildings' cooling holds the majority of this energy consumption, especially in hot weather countries, where 70% of the utilized energy is being consumed in Heating, Ventilation, and Air Conditioning systems. Thus, there is a pressing need to decrease the reliance on active cooling systems by the introduction of passive cooling strategies and efficient sustainable buildings. Passive cooling systems have been implemented successfully in moderate dry climates, but this integration can be challenging when considering high ambient climates in which air temperatures reach values above 45 °C. This means that a number of passive cooling interventions would need to be combined in an integrated system to provide the necessary cooling and fresh air requirements of the building.

Many passive cooling techniques that are adequate for high ambient and arid climate applications have gained the attention of researchers in the past decades. One known method is Radiative cooling (RC), which has been studied for centuries and its feasibility has been established [1]. RC panels proved their high applicability in the scale of office and residential houses cooling in low relative humidity (RH) and clear skies conditions [2–4]. Such panels emit long-wave thermal radiation to the sky through the infrared atmospheric window (8–13 μm) [5], pumping energy thereby into the outer space [6]. The cooling power of these panels is usually harvested to cool a working fluid (water or air) and reaches its highest value during nighttime, under clear skies and dry weather [4,7]. However, humid locations were reported in literature to have a higher effective sky emissivity and thus less radiative cooling potential [8]. Rephaeli et al. [9] showed that with an optimized design and convenient material usage, nocturnal radiative cooling offered a cooling power of more than 100 W/m^2. Nevertheless, during the daytime, RC becomes more challenging due to the effect of direct sunlight. Therefore, a material that can highly reflect in the solar spectrum (0.5–2.5 μm) and emit in the atmospheric window

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Nomenclature

A	Area (m^2)
AWH	Air water-harvesting
$DPIEC$	Dew-point indirect evaporative cooler
HVAC	Heating, ventilation and air conditioning
L	Length (m)
LCC	Life cycle cost ($)
$\dot{m}$	Mass flowrate (kg/s)
h_m	Mass transfer coefficient (m/s)
Q_{net}	Net cooling power of the RC panel (w/m^2)
RC	Radiative cooling
RH	Relative humidity (%)
I	Solar radiation (w/m^2)
C_p	Specific Heat (J/kg·K)
T	Temperature (°C)
V	Volume (m^3)
Greek letters	
ρ	Density (kg/m^3)
ω	Humidity ratio (kg H_2O/kg dry air)

is needed in order to make use of the daytime cooling power of the RC panel [5]. Hua et al. [10] proposed and tested a panel made of double-layer nanoparticle-based coatings (one for solar reflection and one for long-wave emission). They proved that diurnal cooling power could be achieved yet with less effectiveness than that during nocturnal cooling because of the presence of solar radiation. As a result, many studies integrated the RC panels with thermal storage systems to harvest the high cooling power during night and use it during day when peak cooling needs arise [11]. Katramiz et al. [2] found that by implementing diurnal hydronic RC panels in a hot and arid climate, the thermal storage tank was downsized by 12.3%. Moreover, Katramiz et al. [12] integrated RC panels with thermal storage to assist conventional air conditioning (AC) unit for cooling an office in Kuwait. The diurnal cooling power was utilized in pre-cooling the air entering the condenser in the aim of increasing its COP. They reported reduction in the energy consumption of the AC unit by 37.74% during the summer.

From the above-mentioned studies, it is clear that the RC system cannot be implemented as a stand-alone cooling system and needs to be integrated with other passive cooling techniques to establish a hybrid sustainable cooling system. One of the emerging new technologies that are adequate for dry and high ambient climate conditions is the Maisotsenko cycle (M-cycle) [13]. The latter is a dew point indirect evaporative cooling (DPIEC) apparatus that received worldwide recognition for cooling applications as it has been successfully tested by the National Renewable Energy Lab (NREL) [14,15]. A DPIEC unit is a heat and mass exchanger that is proven to be three to four times more efficient than conventional air conditioners [16]. By losing its heat to a cool stream of water, the supply air is cooled below its wet bulb temperature without any moisture addition [17]. Such system is reported to perform best under dry conditions since its effectiveness increases with reduced inlet air relative humidity (RH) and temperature [18]. Jradi and Riffat [19] performed a numerical and experimental examination of the performance of a regenerative cross-flow M-cycle unit. They reported that the wet-bulb and dew point effectiveness reached 112% and 78% respectively. Note that the cross-flow configuration of the DPIEC is commercially available and has higher energy efficiency in comparison to other configurations such as the counter-flow due to the lower resultant pressure drop across the exchanger [20].

However, the use of M-cycle for air-cooling is based on water consumption - a precious commodity that is in perpetual shortage, especially in the Gulf countries [21]. Bakeem at al [22] showed that in Gulf cities weather, the minimum and maximum water consumption were 2.4–4.6 L/kWh of DPIEC cooling power. This calls for the use of water reclamation techniques. A well-known method is extracting water from moist air, named "air or atmospheric water harvesting" (AWH) [23]. Based on the sorption technique, AWH can be utilized to capture and collect vapor from the saturated air leaving the DPIEC unit using a solid sorbent material [23,24]. It involves two working processes: i) adsorption (separation of water vapor from the air) and ii) desorption (release of the vapor using a thermal source). Note that literature studies showed that low-grade thermal energy sources are adequate for the desorption process [24,25].

Realizing that both the RC and DPIEC systems operate at highest efficiency under dry weather conditions, the integration of such systems for building cooling application would emerge as rewarding, eliminating the need for conventional active cooling means. This takes into consideration a typical operation where the RC system can effectively work during nighttime, while pre-cooling the air entering the DPIEC unit that is used to meet the cooling loads during daytime. This strategy can help in the reduction of the DPIEC water consumption, hence, downsizing thereby the AWH system. Moreover, no DPIEC water consumption is incurred when the cooling power of the RC system is sufficient (typically during night operation), and there is no need to operate the DPIEC system. To the author's knowledge, no previous study has investigated the performance of such a hybrid passive system. Consequently, the interest resides in investigating the performance of the RC integrated with the DPIEC system in the application of air conditioning of a typical house in Kuwait, which is known for its arid climate with hot and dry summer months.

In this work, a typical Kuwaiti residential house is air-conditioned by the proposed low-energy hybrid cooling system. The aim is to investigate the ability of this system in meeting the cooling load while providing acceptable thermal comfort and air quality over the whole cooling season (from March until October). To achieve this objective, mathematical models are developed for the RC panel and the DPIEC unit to examine the performance of the proposed system and a building simulation is conducted via TRNSYS [26]. The latter estimates the cooling load for the whole cooling season in Kuwait. The predicted passive cooling system performance is compared to that of a conventional AC system in order to evaluate the energy savings. Furthermore, the effect of the RC implementation on the DPIEC operation in terms of water consumption savings is investigated.

2. System description

A hybrid passive cooling system is designed to meet the cooling needs of a residential house located in Kuwait. The main components of the proposed system are the hydronic RC panel and cross-flow DPIEC apparatus. Both systems are placed on the rooftop of the Kuwaiti residential house under study. The RC system is mainly used during nighttime to meet the required cooling needs of the residential house, while pre-cooling the intake air of the DPIEC unit during daytime using its relatively small diurnal power. An AWH system that uses low-grade thermal heat source is combined with the DPIEC system to re-generate the consumed water.

Fig. 1(a) presents the proposed hybrid cooling system. Fresh air is cooled via an air-air heat exchanger (HE) at [1] with part of the return air [2] from the space, which is at lower temperature than the ambient air that usually exceeds 45 °C during peak daytime

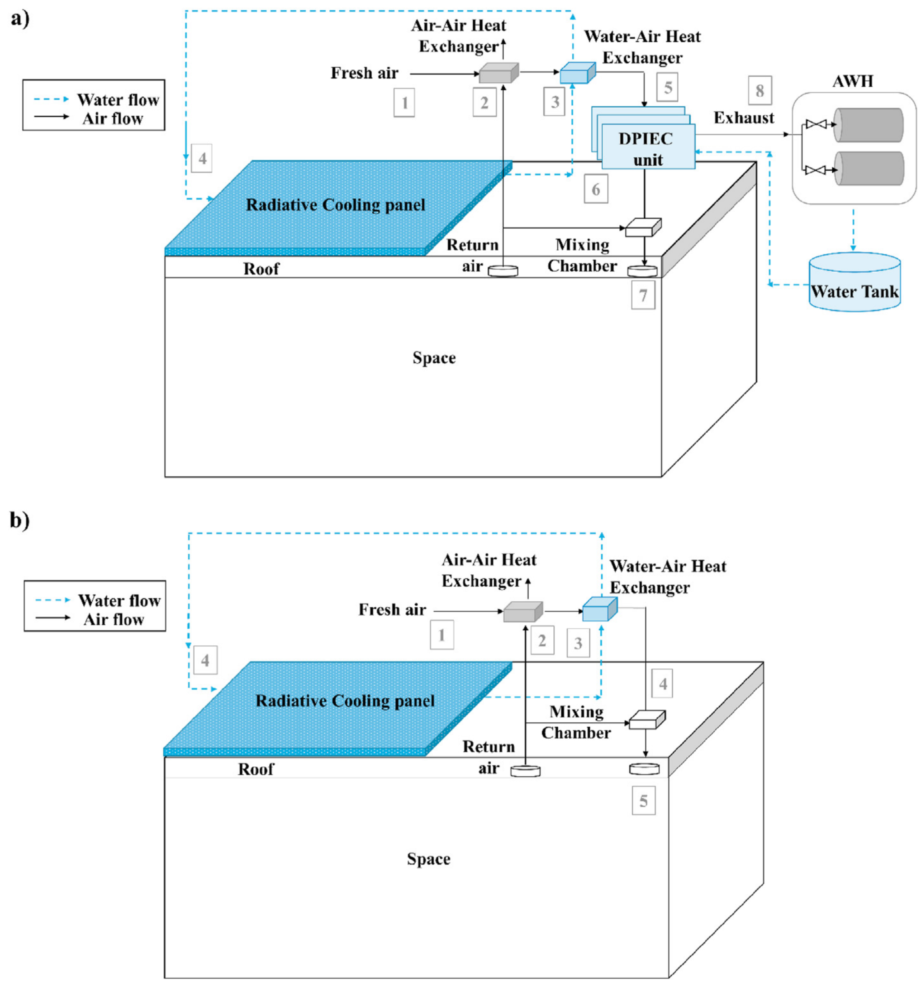

Fig. 1. Schematic of the passive cooling system: a) RC panel with DPIEC operation; b) RC panel operation alone.

hours. The cooled air flows into a water-air HE at [3] where the cold water produced by the RC panel via radiative thermal exchange further cools the airflow. The water exiting the water-air HE is circulated back to the RC panel to lose the gained heat in a closed loop [4]. The cooled air exiting the water-air HE at [5] is supplied to the cross-flow DPIEC system for further cooling. This produces cool air near its dew-point temperature. Product cool air is mixed with portion of the return air [6] and supplied to the inner space of the house [7] and working air is exhausted to the AWH unit [8]. The AWH consists of a batch system formed of several sorbent beds. A daily cyclic adsorption-desorption process occurs during the DPIEC system operation, and the collected water vapor is condensed and stored in a tank for future usage [23, 24]. When the RC system is able to meet the cooling load of the space (typically occurring during nighttime), the DPIEC unit is no longer operating: at stage [4] (Fig. 1(b)), the cooled air exiting the water-air heat exchanger is supplied directly to the mixing chamber before entering the space.

3. Mathematical modeling

To investigate the performance of the proposed passive cooling system, simplified models were developed for each of the subsystems: i) a hydronic RC model, ii) a DPIEC system with AWH model and iii) a space model. These models were integrated to size the system components to deliver the needed space supply temperature and flow rate for peak load removal and simulate the operation of the system to predict the savings of both energy and water consumption.

3.1. Radiative panel model

The RC panel is considered as an integrated part of the roof, with pipes underneath the RC surface, running parallel along its length from an inlet to an outlet manifold [27]. Offering high reflectivity in the solar spectrum and high emissivity in the atmospheric window region, the RC surface is formed of nanoparticle-based double-layer coating, an approach that can be easily applied to sizeable areas, facilitating thereby the possibility of large-scale application of the radiative cooling technology [10]. The area of the panel covering the roof plays an important role in the performance of the RC panel: the larger the panel is, the higher is its harvested cooling power. The solar radiation, RH and weather conditions alongside the optical properties of the material forming the RC surface are accounted for in the model. All these inputs lead to the evaluation of the temperature of the water exiting the RC panel.

The model of the hydronic radiative cooler developed by Katramiz et al. [2] was adopted. The 1-D transient model predicts the temperature of the water flowing through the pipes of the RC panel system. The panel is divided into distinct segments along its length, each having uniform surface temperature as presented in Fig. 2. The latter depicts the different heat transfer processes of the net cooling power that the RC panel exhibits: the longwave

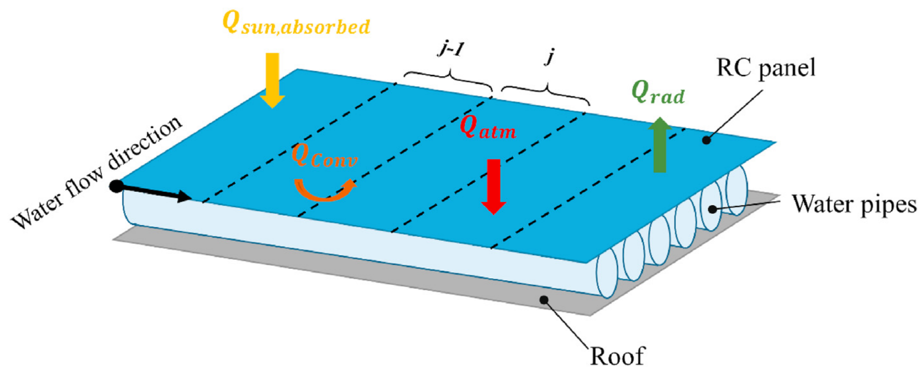

Fig. 2. Schematic of the RC panel with the different heat transfer processes.

radiative power emitted by the surface Q_{rad}, the absorbed power due to the incident atmospheric thermal radiation Q_{atm}, the absorbed power due to the incident solar radiation Q_{sun} and the power lost/gained due to convection with the ambient air at the upper side of the RC panel Q_c. Note that the roof is insulated and the heat conduction from the lower side of the RC panel through the roof is neglected.

Equation [1] presents the energy balance on a segment j of the RC panel and water tubes as follows:

$$\rho_w V_j C_{p_w} \frac{dT_{w,RC(j)}}{dt} = \dot{m}_{w,RC} C_{p_w} \left(T_{w,RC}(t,j-1) - T_{w,RC}(t,j)\right) - Q_{net}(\mathrm{t},\mathrm{j}) A_j \quad (1)$$

where the transient storage term (the term to the left) is equal to the difference between the net convective heat flow (first term to the right) and the net cooling power of the RC panel (last term). In equation [1], ρ_w and C_{p_w} are respectively the water density and the specific heat capacity, V_j is the volume of the water in segment j, $\dot{m}_{w,RC}$ is the water mass flowrate in the segment. $T_{w,RC}(t,\ j-1)$ and $T_{w,RC}(t,j)$ are the inlet and outlet water temperature of segment j at time t respectively and A_j is the area of the considered segment of the panel. $Q_{net}(t,j)$ is the time-dependent net cooling power per unit area of segment j of the RC panel.

3.2. DPIEC apparatus and AWH model

The DPIEC cross-flow heat and mass exchanger is formed of dry and wet channels. Accordingly, the fresh air intake is divided into two streams: the product air and the working air. The product air is sensibly cooled in the dry channels, while the working air is sensibly pre-cooled in the dry channels while being gradually diverted from the dry working channels to the wet channels via numerous regularly distributed holes (See Fig. 3). In the wet channels, the working air absorbs both the heat released from the product air and the evaporated water before it is discharged as hot humid air. Anisimov et al. [28] extensively developed a cross-flow M-cycle model, which is implemented in this study. Based on the intake air conditions, the water temperature and flowrate as well as the size of the adopted DPIEC apparatus, the model predicts the temperature and humidity of the product air exiting the dry channels, the conditions of the working air leaving the wet channels as well as the water consumption.

The DPIEC mathematical model is developed by applying heat and mass balance equations on the dry and wet channels of the cross-flow DPIEC apparatus following the effectiveness NTU method [28]. To solve for the governing heat and mass equations, a control volume formed of half the dry channel, half the wet channel and the water non-permeable wall separating them is considered. It is assumed that the system is operating in a 2-D steady periodical manner with no heat transfer with the surrounding, and that the thermal properties in a single control volume are constant [28].

In the dry channel, heat is transferred from the product air to the water film by convection and conduction through the channel walls, which yields a sensible cooling of the product air. The energy balance of this heat transfer is presented in equation [2] as follows:

$$\frac{\partial T_{pa}}{\partial y} = \frac{U_{da}\, A}{\dot{m}_{pa}\, Cp_{pa}\, L_d} \left(T_w - T_{pa}\right) \quad (2)$$

where T_{pa} and T_w are respectively the primary air and water temperatures, $\dot{m}_{pa}$ and Cp_{pa} are the flow rate and specific heat of the primary air, L_d is the length of the dry channel, U_{da} is the overall heat transfer coefficient and $A$is the area through which the heat exchange occurs.

In the wet channel, mass and energy transfer take place between the working air and the water film. Equation [3] presents the mass balance and equation [4] shows the sensible (first term to the right) and latent (second term to the right) energy balance respectively.

$$\frac{\partial \omega_{wa}}{\partial x} = \frac{h_m\, A}{L_w\, \dot{m}_{wa}} \left(\omega_s - \omega_{wa}\right) \quad (3)$$

$$\frac{\partial T_{wa}}{\partial x} = \frac{h_{wa}\, A}{Cp_m\, \dot{m}_{wa}\, L_w} \left(T_w - T_{wa}\right) + \frac{Cp_v}{Cp_m} \frac{\partial \omega_{wa}}{\partial x} \left(T_w - T_{wa}\right) \quad (4)$$

where T_{wa} and ω_{wa} are the temperature and humidity ratio of the working air, h_{wa} is the convective heat transfer coefficient, ω_s is the saturation humidity ratio at the water film temperature. $h_m$is the mass transfer coefficient given by Lewis relation [29], $\dot{m}_{wa}$ is the mass flowrate of the working air, L_w is the length of the wet channel, Cp_v and Cp_m are the specific heat of water vapor and moist air respectively.

As presented in Fig. 3, part of the water entering the DPIEC unit evaporates while the remaining water is recuperated back to the water tank. An AWH system is thus needed to re-generate the water from the saturated exhaust air stream of the DPIEC apparatus, since the latter consumes a fairly large amount of water, which is a crucial issue in the Kuwaiti region.

An adsorption-based system is considered in this work, operating as a multi-tank batch (see Fig. 3). The DPIEC unit's exhaust air enters the bed where the water vapor is adsorbed by a sorbent material, causing the increase of the bed temperature due to the release of the heat of adsorption. The hot dry air leaves the bed to

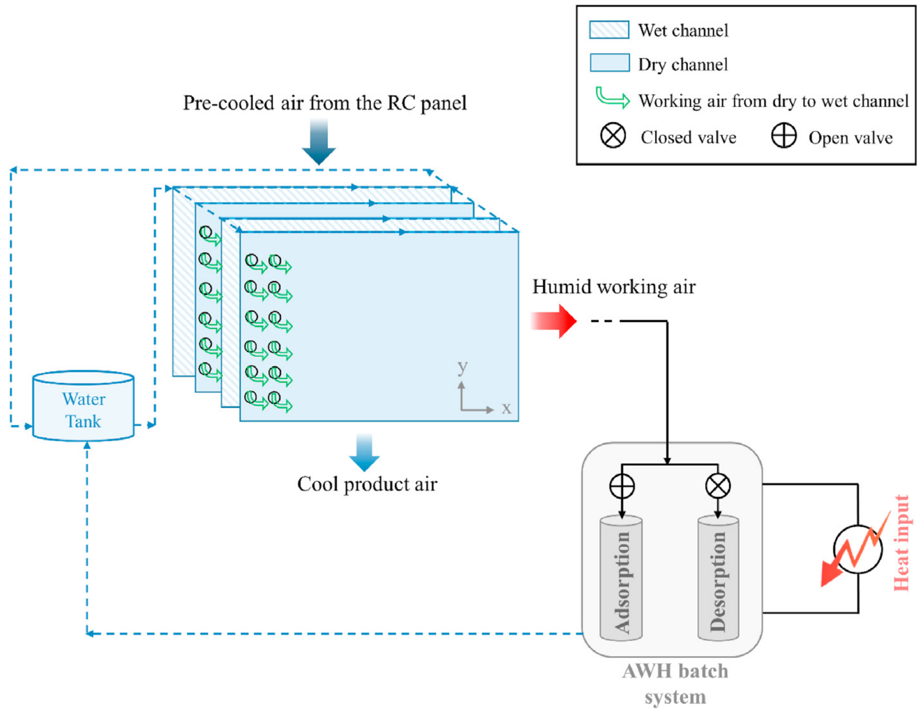

Fig. 3. Schematic of the DPIEC and AWH systems.

the surrounding, while the bed is cooled with the ambient air. To collect the water for reuse, the bed undergoes a desorption phase where the water vapor is released from the sorbent material [30]. The latter requires heat input to overcome the enthalpy of adsorption and reach the regeneration temperature of the sorbent material used [24]. With the dew point temperature of the saturated air leaving the desorption bed being higher than typical Kuwaiti ambient air temperature, the environment can be considered as an effective heat sink for condensation [24,31].

Several sorbents have been proposed in literature for water harvesting including solid adsorbents such as silica gel – Type A. The latter is suitable since it has low regeneration energy compared to other commercial solid adsorbents (regeneration capability at low heat source temperature from 50 °C to 90 °C) [32]. This low desorption temperature permits the AWH system to be driven by low-grade heat sources such as solar thermal sources [24]. The corresponding thermal energy needed for desorption is reported by Wang et al. [33] to be around 2.7×10^3 kJ/kg of silica gel. Each bed will undergo multiple adsorption/desorption cycles during the day. The gravimetric adsorption isotherm shows the equilibrium mass of water which can be taken up by the silica gel at a given RH and temperature [32]. Subsequently, a rough estimation on the size of the bed (i.e. the mass of silica gel needed) can be made based on the equilibrium uptake properties.

3.3. Space model

The required cooling load of the Kuwaiti house during the cooling months is calculated via a space model that is developed via TRNSYS [26], which is a transient simulation software revealing accurate results in the estimation of the cooling load in buildings [34,35]. The latter can be determined using the multi-zone building model, type56 subroutine in TRNSYS. In this study, energy rate mode is adopted, where the air temperature inside the space was maintained at 23 °C with 50% RH, which are typical indoor design conditions in Kuwait [36]. The peak and hourly cooling loads needed to maintain the specified set indoor conditions were determined based on the heat gain in the space [37]. The model takes as input the physical makeup of the walls, roof and floor, the weather data, window parameters, thermal capacitance, the ventilation rate and internal gains. The geometrical representation of the building and the plan section of the second floor are presented in Fig. 4(a) and **(b)** respectively.

4. Numerical methodology

The adopted calculation algorithm is presented in Fig. 5. The numerical simulation of the Kuwaiti residence was carried out via TRNSYS [26]. The geometrical and thermal properties of the building and the outdoor conditions as well as the indoor set conditions were the inputs to the multi-zone building model type56 that estimates the hourly cooling load for the six months of the cooling season.

The RC hydronic cooling panel system energy balance [2] and mass and energy balances of the DPIEC system [28] were discretized and simulated using a simplified transient numerical model code written in MATLAB [38]. The numerical model consisted of an implicit first-order time integration scheme. After performing a time step independence test, a time step of 100 s was adopted.

The developed numerical model requires the weather data, the RC panel properties, as well as the DPIEC apparatus' properties. The minimum fresh air requirement is 30% of the air supply [39]. The RC sub-model solves the differential equations iteratively to find the water temperature flowing in the RC panel and the resulting cool air exiting the water-air HE. When the RC system is able to meet the load of the residential house (typically during nighttime), no need for the DPIEC operation. On the other hand, during typical daytime operation and when the RC system is not able to remove the cooling load, the DPIEC system operates. Thus, the DPIEC sub-model

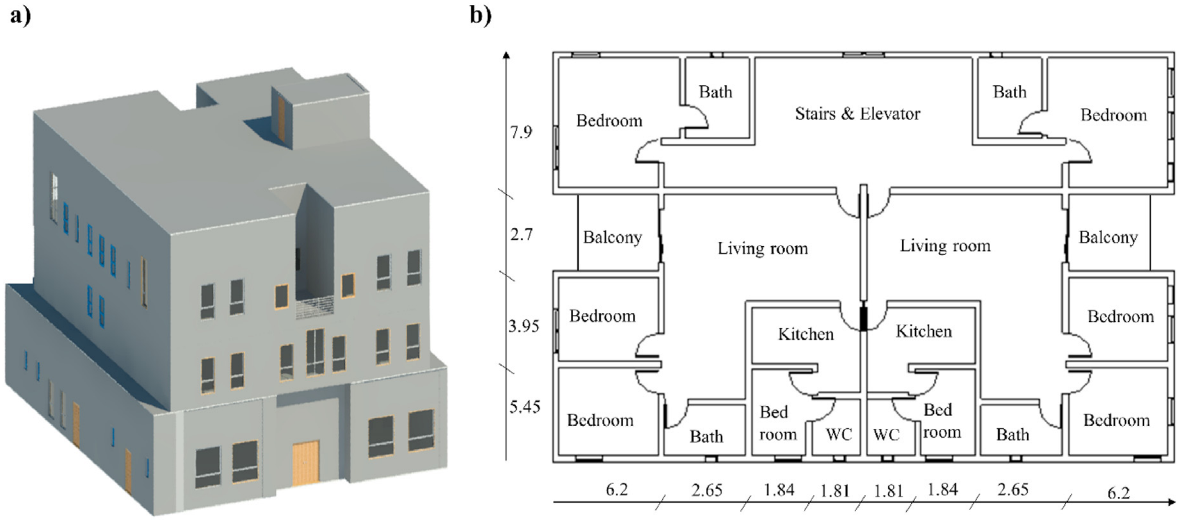

Fig. 4. Illustration of a) the residential house under study and b) the plan section of the second floor.

receives the output cool air from the RC sub-model as input along with the DPIEC properties to obtain the temperature of the air supplied from the DPIEC unit. Consequently, the obtained cooling load from the integrated model is computed and compared with the required cooling load provided by the building simulation model. If the latter is met by the proposed RC and DPIEC systems, the simulation code moves to the next time step. Otherwise, the supplied fresh air to be cooled is changed accordingly, and the simulation is repeated. Once simulations end, the water consumption obtained from the DPIEC model is used to size the AWH system. A steady periodic solution was reached following the repetition of simulations over a number of cycle days. The convergence criterion was set when the residuals of the temperature between two consecutive iterations is less than 10^{-5} °C.

5. System sizing

Selecting the proper size of the main components of the proposed hybrid system is essential for its successful operation. The principal parameters that affect the sizing operation are the characteristics of the house under study (envelop properties and space geometry), the weather conditions in terms of hourly ambient temperature, humidity and solar radiation, and the resulting cooling load.

The sizing of the different system components is based on the peak day and night loads of the residential house. These components are placed on the roof of the house. The RC area is usually based on the peak nighttime load. In this work, a maximum RC panel area of 300 m^2 is installed on the rooftop of the house, covering 60% of the total roof area. The roof cannot be fully overlaid by the RC panels due to the need for space for the other system components such as the DPIEC apparatus. As for the DPIEC system, its sizing depends on the required supply temperature needed to remove the peak diurnal cooling load of the considered house. Accordingly, the size of the AWH system is related to the amount of water evaporated in the DPIEC unit. A batch system formed of silica gel - Type A beds is considered. The amount of water that can be harvested in a single adsorption cycle using silica gel Type A can be evaluated based on the adsorption isotherm [32]. The equilibrium uptake is estimated to be around 0.25 kg of water per kg of silica gel. Thus, by knowing the amount of water that is daily consumed by the DPIEC unit during peak conditions, the number of the adsorption/desorption silica gel beds as well as their mass can be approximated.

6. Case study

The building under investigation is a two-story residential house (25 m × 20 m × 13.65 m) located in Kuwait. The performance of the proposed system is studied for the whole cooling season: March through October. Fig. 6 shows the ambient temperature T_{amb} (°C) and the relative humidity RH (%) for the representative day of each considered summer month. The horizontal solar radiation I (W/m^2) is also presented in Table 1 for each of the considered months. Note that this weather data was obtained from the Kuwait meteorological center [40].

6.1. Space characteristics

The building simulation is performed using the simulation platform TRNSYS. The latter requires the weather data of Kuwait, geometrical representation of the building under study, physical make-up of the walls, roof and floor, internal gains, operation schedules as well as the indoor set values. The house is divided to four zones: Living room, Bedroom, Kitchen and Bathrooms. Exhaust fans were considered for the bathroom and kitchen zones. The physical composition of the walls, floor and the roof are defined in the model, and their thermal properties are presented in Tables 2 and 3 [41]. Internal gains in the model account for occupants, electrical equipment and lights in the house. Appliances and electrical equipment that were considered in the house under study are: Refrigerator (800 W), water cooler (150 W), microwave oven (1000 W), two laptops (50 W each), three televisions (130 W each) [42]. Since internal gains are not constant throughout the simulation, schedules are used for occupancy, lighting, and electrical equipment depending on the zone type as presented in Fig. 7 [43]. The peak lighting loads are assumed to be 5 W/m^2 for each room. The peak electrical loads are taken to be 5 W/m^2 for bedrooms, and 10 W/m^2 for living spaces. The assumed sensible and latent loads per person are 75 W and 55 W, respectively. The number of people is taken to be 0.012 person/m^2. As for the windows, the glazing U-value and SHGC are given to be 3.33 W/m^2·°C and 0.36 respectively [41].

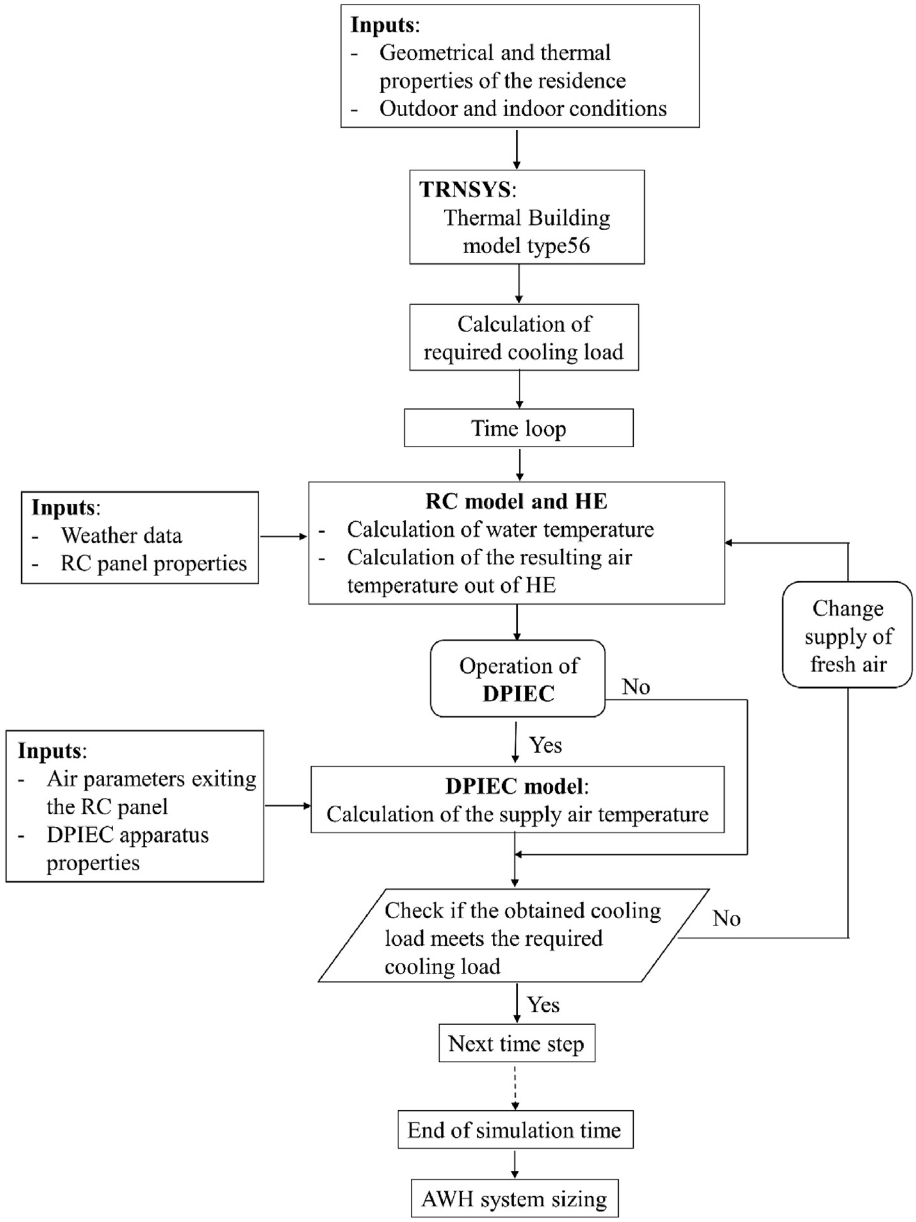

Fig. 5. Flow chart of the adopted methodology.

6.2. *The system components' properties*

The diurnal RC panel by Hua et al. [10] adopted in this study consists of an emissive layer topped by a reflective layer, both associated with an aluminum substrate. The emissive bottom layer is formed of Silicon dioxide SiO2 of thickness 20 μm, known for its high emissivity in the atmospheric window ($\varepsilon = 0.9$). The reflective layer is required to reflect the incoming solar radiation, enhancing thereby the diurnal cooling power. This layer is formed of Titanium dioxide TiO_2 of thickness 25 μm, offering high reflectivity in the solar spectrum ($\alpha = 0.95$) and high transparency in the mid to far-infrared spectrum. Regarding the cross-flow DPIEC apparatus, its channels are generally made of aluminum sheets of 0.5 mm thickness [20], with a cotton wick covering the wet channels. To form a water impermeable surface between the channel walls and the cotton wick, the latter is usually coated with polyurethane [20].

7. Results and discussion

The performance of the proposed hybrid cooling system integrating the DPIEC apparatus and the RC panel system is investigated. In this hybrid case referred to as **case 1**, a proper system component sizing is accomplished to provide the cooling energy needed to remove the space load and yield the necessary comfort and indoor air quality for the entire cooling season during night and day hours. The time-period during which the operation of the two subsystems is inevitable is also identified. Moreover, to highlight the importance of the RC usage in the reduction of the water consumption of the DPIEC apparatus, **case 2** is introduced and investigated when the DPIEC is used exclusively as a passive cooling system. Finally, the base case (**case 3)** of having a typical HVAC system operating to meet the cooling needs of the space is considered. **Case 3** is examined to determine the electrical energy savings achieved by the proposed hybrid system.

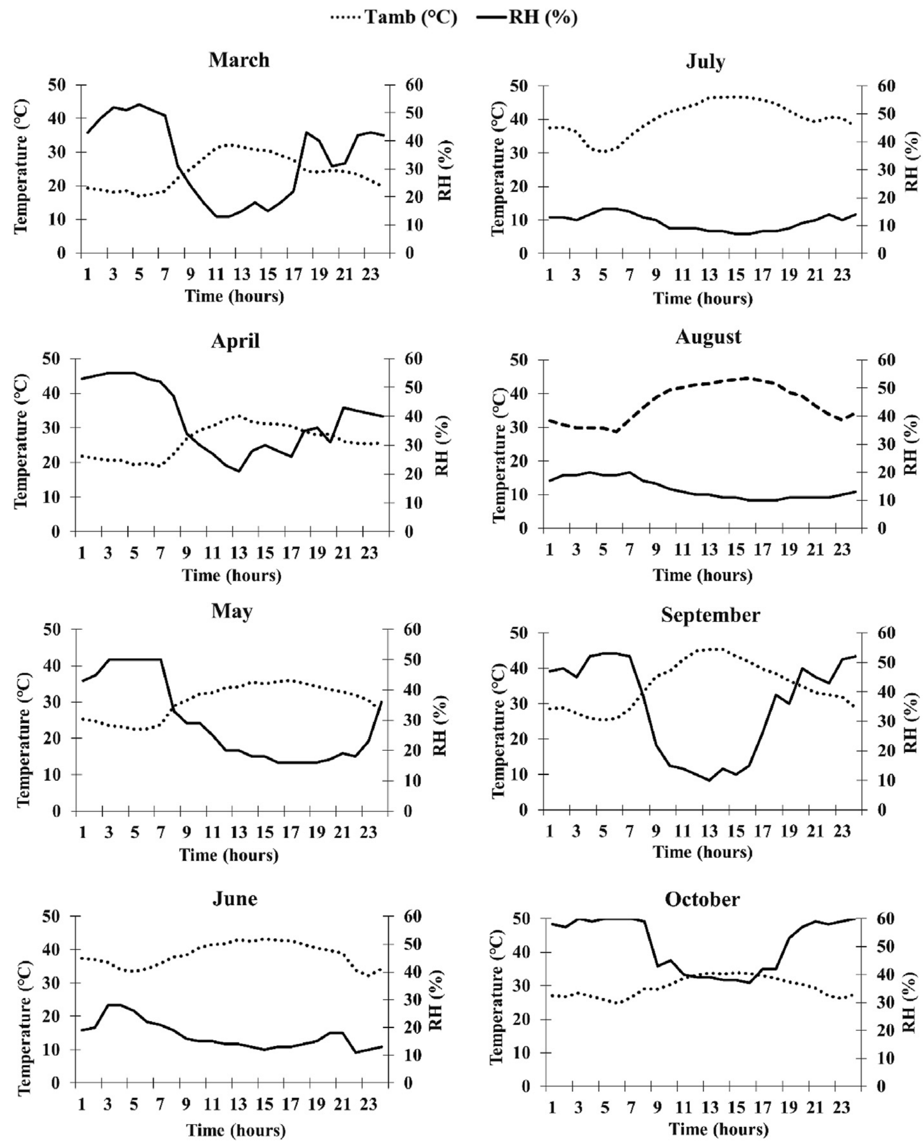

Fig. 6. Hourly variation of the ambient temperature T_{amb} (°C) and RH (%) for the representative day of each cooling month.

7.1. Model validation

The accuracy of each of the adopted models in predicting their actual operational performance defines the precision of the obtained results. These models were experimentally validated, yielding good results with small relative errors.

The RC panel model of Katramiz et al. [2] was based on the experimentally validated model of Hua et al. [10]. The latter conducted experimental measures in the moist weather of Shanghai to assess the theoretical performance of the double-layer nanoparticle-based RC panel. Their tested panel managed to achieve about 5 °C below ambient at night, similarly to the theoretical results that reported 4−6 °C below ambient during the high humidity night conditions. For validation purpose, the developed RC model in this work was adjusted to consider the same climatic and operating conditions taken by Hua et al. [10] (solar radiation I = 860 W/m^2, air temperature T_a = 20 °C, convective coefficient between the surface and ambient air h_c = 6.9 W/m^2.K). A maximum error of 5.8% was found between the reported results of Hua et al. [10] and the results obtained from the developed RC model.

As for The DPIEC model with cross-flow configuration of Anisimov et al. [28], it was reported suitable for use in analyzing the heat and mass transfer processes taking place in the cross-flow DPIEC apparatus and predicting its operational performance. This was established based on positive validation results against available experimental data. The highest discrepancies between the simulation and the measured values for the primary stream outlet temperature were 5%. Taking the same geometric dimensions (height 1 m, width 1 m, plate thickness 0.076 m and channel height 3.2 mm) and operating conditions (ambient air temperature 20 °C, RH 40%) as in the experimental data, the developed DPIEC model gave an output air temperature of 11.38 °C, 4.85% higher than the reported data (10.85 °C).

7.2. Performance of the proposed hybrid system (***case 1***)

7.2.1. The hybrid system components' size

To provide the residential house with the needed cooling power, the proposed hybrid system in **case 1 is** needed to be properly sized. First, the cooling loads for each month were obtained and

Table 1
Hourly variation of the solar radiation on a horizontal surface I (w/m^2) for the representative day of each cooling month.

Time	March	April	May	June	July	August	September	October
1:00 AM	0	0	0	0	0	0	0	0
2:00 AM	0	0	0	0	0	0	0	0
3:00 AM	0	0	0	0	0	0	0	0
4:00 AM	0	0	0	0	0	0	0	0
5:00 AM	0	0	0	0	0	0	0	0
6:00 AM	0	64	128	137	113	80	34	17
7:00 AM	125	217	354	339	311	282	212	139
8:00 AM	337	452	596	570	520	509	413	406
9:00 AM	546	672	762	726	683	695	587	405
10:00 AM	714	835	849	818	754	837	720	618
11:00 AM	811	939	900	856	785	913	793	687
12:00 PM	854	958	881	856	787	933	806	753
1:00 PM	852	955	827	820	1006	915	809	714
2:00 PM	791	903	831	830	959	878	736	716
3:00 PM	691	793	741	808	874	823	649	535
4:00 PM	530	586	638	694	708	689	497	349
5:00 PM	311	413	467	529	509	486	298	164
6:00 PM	106	143	258	303	274	251	92	14
7:00 PM	0	0	49	90	77	33	0	0
8:00 PM	0	0	0	0	0	0	0	0
9:00 PM	0	0	0	0	0	0	0	0
10:00 PM	0	0	0	0	0	0	0	0
11:00 PM	0	0	0	0	0	0	0	0
12:00 AM	0	0	0	0	0	0	0	0

benchmarked with typical cooling load data for Kuwaiti residences [43,44]. It was found that the peak loads were reached during the month of **July**: the daytime cooling load (from 6:00 a.m. until 7:00 p.m.) ranged between 18 and 38 W/m^2, and the nighttime cooling load (from 7:00 p.m. until 6:00 a.m.) fluctuated between 17 and 30 W/m^2. Accordingly, the sizing of the system was based on this month. The mass flowrate of air supplied to the space was fixed at 5 kg/s [43], and the mass flowrate of the water flowing in the RC loop was set to 0.9 kg/s. This value was fixed after running many simulations of the RC panel and water/air HE loop to obtain the lowest possible output air temperature. Based on the obtained nighttime cooling load, the area of the RC panel needed to meet the load was larger than the maximum area allocated for the RC system. Therefore, the area of the RC panel was fixed at a maximum 60% of the total area of the roof.

For the DPIEC apparatus, the needed supply temperature at the diurnal peak load was found to be 17 °C at around 6:00 p.m. during the month of July. Accordingly, the DPIEC unit was sized and its geometric and operational parameters are presented in Table 4. After running the simulation of the adopted DPIEC unit for the peak-load day, the hourly amount of water consumed was found, which was important for the sizing of the AWH system. Since the DPIEC unit might work during night hours during some months, adsorption beds need to work during nighttime to be later desorbed during sunshine hours. Subsequently, with the silica gel adsorbing 25% of its weight in water, 4-bed batch system could be used, each bed including 160 kg of silica gel Type A and operating in a cyclic manner.

7.2.2. Operation of the hybrid system

After sizing the system, simulations were performed for the entire considered cooling season. As previously mentioned, due to its typically high nocturnal cooling power, the RC system was operated during nighttime in the aim of meeting the cooling requirements of the residence. When failing to do so, the DPIEC system was operated. The latter was usually used during daytime when the cooling loads are generally higher and when the cooling power of the RC system is insufficient. Accordingly, the amount of water consumed by the DPIEC unit is estimated and the adequate AWH system is implemented.

Fig. 8 shows the operation schedule of the RC system alone and when operating with the DPIEC system for each considered month. The day and night hours for each month are presented as well. The DPIEC system was not needed to operate during the month of March, as the RC system was able to meet the cooling load of the residential house. Furthermore, the system was shut down during the month of March between 11:00 p.m. and 9:00 a.m., and during the month of April between 1:00 a.m. and 8:00 a.m. This is due to the outdoor air temperatures that were low enough to meet the cooling load and thus no further cooling was required. During May (Fig. 8), the cooling load of the residential house was met by the RC system from 9:00 p.m. until 10:00 a.m. This means that the RC system was able to meet the space load during the nighttime as well as at the early sunshine hours. In the remaining day period (between 10:00 a.m. and 7:00 p.m.), the DPIEC unit was required to operate to remove the space load. Note that even after 2-hours from the daytime period (between 7:00 p.m. and 9:00 p.m.), the operation of the DPIEC system was still necessary to meet the cooling load. As it can be noticed from Fig. 8, the RC panel was able to meet the cooling needs of the studied space without the operation of the DPIEC unit during March, April, May, September and October for a relatively large amount of time: 14 h in March, 7 h in April, 13 h in

Table 2
Thermal details of wall layers (Inside to Outside).

Layer	Thickness (mm)	Density (kg/m^3)	**Cp**(kJ/kg.K)	RSI-Value (m^2-K/W)
Inside surface resistance	–	–	–	0.1206
102 mm LW concrete block	102	608.7	0.837	0.2668
RSI-1.2 board insulation	25.4	32.04	0.921	1.2229
203 mm common brick	203	1922.22	0.837	0.2795
203 mm HW concrete	203	2242.58	0.837	0.1174
Outside surface resistance	–	–	–	0.0586

Table 3
Thermal details of floor and roof layers (Inside to Outside).

Layer	Thickness (mm)	Density (kg/m^3)	**Cp**(kJ/kg-K)	RSI-Value (m^2-K/W)
Inside surface resistance	–	–	–	0.1206
102 mm LW concrete block	102	608.7	0.837	0.2668
RSI-3.3 batt insulation	152.4	8.00	0.837	3.3865
102 mm face brick	102	2002.3	0.921	0.0762
Outside surface resistance	–	–	–	0.0586

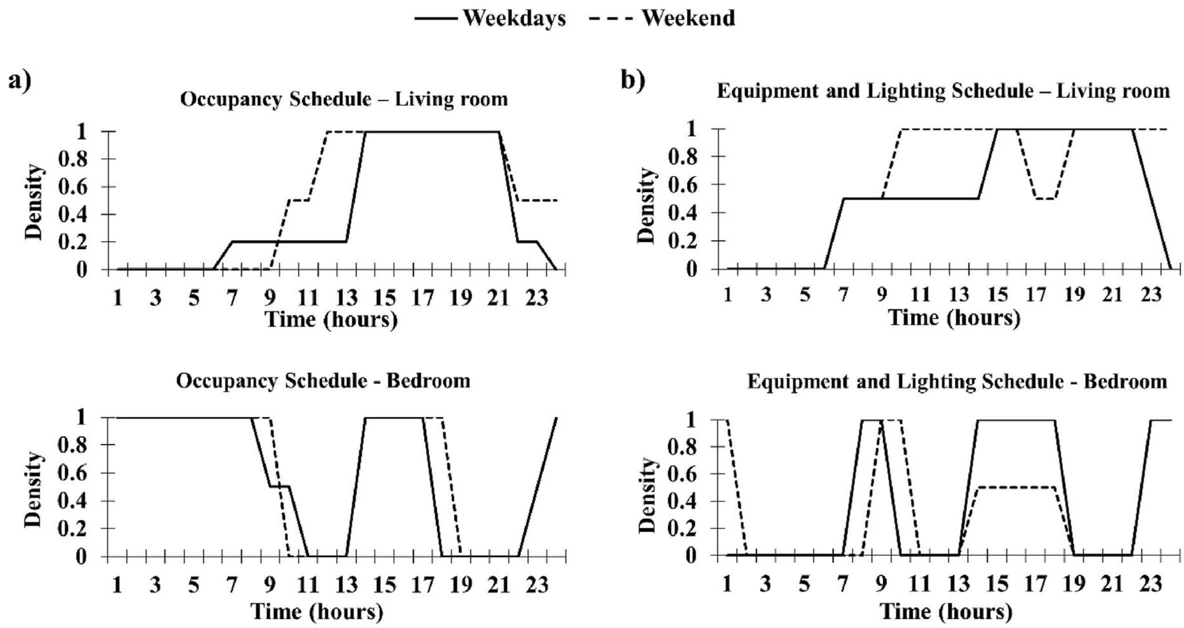

Fig. 7. Hourly variation of: a) Occupancy schedule and b) Equipment and lighting schedule for the living room and bedrooms.

Table 4
Geometric and operational parameters of the DPIEC unit.

Parameter	Value
Channel length (m)	1.2
Channel width (m)	1.2
Channel height (m)	3.5×10^{-3}
Sheet thickness (m)	0.5×10^{-3}
Number of channels	230
Intake volumetric flow rate (m^3/s)	5.2
Ratio of working to product air	0.3

May, 9 h in September and 12 h in October. It is noteworthy to mention that this was accomplished mostly during nighttime hours when the RC panel operates at its highest cooling power. For the months of June, July and August, the DPIEC unit's operation was greatly needed, even during nighttime, due to the high cooling loads and extreme weather conditions during such period of the year.

For further elaboration, the hourly variation of the ambient air temperature, T_{amb}, the air temperature leaving the RC system $T_{a_{RC}}$, the air temperature exiting the DPIEC unit $T_{a_{DPIEC}}$ and the cooling load $Q_{cooling}$ of the considered house are presented for the months of May and July in Fig. 9. In the month of May (Fig. 9(a)), between 9:00 p.m. and 10:00 a.m., the supplied air temperature from the RC system varied between 12.5 and 19.5 °C. The latter was able to meet the load of the space, which ranged between 8 and 16 kW. In the remaining period, $T_{a_{RC}}$ increased due to the increased solar radiation intensity. Thus, the DPIEC system needed to be operated to further reduce $T_{a_{RC}}$ to around 15 °C ($T_{a_{DPIEC}}$). During this operation period (between 10:00 a.m. and 9:00 p.m.), the DPIEC unit consumed a maximum of 12.3 kg/h at around 5:00 p.m. and a minimum of 3 kg/h at around 10:00 a.m. (the first operation hour), with a total daily water consumption of 91 kg. For the month of July (Fig. 9(b)), the RC system was not able to reduce the air temperature to low levels, since the minimum values of $T_{a_{RC}}$ was 18.7 °C at around 7:00 a.m. Thus, the RC system was not able to meet the space load and the operation of the DPIEC unit was necessary. The water consumed by the DPIEC unit in this month ranged between a maximum of 20 kg/h at around 2:00 p.m. and a minimum of 4 kg/h at 4:00 a.m., with a total daily water consumption of 300 kg.

7.3. Water consumption reduction (*case 2*)

To highlight the importance of the RC panel implementation and its beneficial effect on the DPIEC unit in terms of water consumption and resulting reduction of the AWH size and thermal energy requirement, a case study where the cooling system consisted of the DPIEC system operation solely was studied and referred to as **case 2**.

Since the DPIEC system in **case 2** was handling the entire cooling load of the residential space, a larger unit was entailed. Thus, similarly to the sizing of the DPIEC unit in **case 1**, the unit of **case 2** was sized based on the month of July. It was found that the needed unit size increased: the length and width of the channels increased to 2 m. The number of channels as well as each channel height were similarly taken as in **case 1** (230 channels and 3.5×10^{-3} m respectively).

Fig. 10 shows the monthly water consumption reduction between **cases 1** and **2**. An average of 44.2% of water consumption reduction was achieved during the entire cooling season, with a maximum of 100% in the month of March when no DPIEC operation was needed, followed by 64.36% in September and a minimum of 12.25% in July. It was observed that high percentages were reached during March, April, May, September and October. This emphasizes the RC panel's sole operation role, as it managed to meet the cooling requirements without the DPIEC unit's operation for large amounts of time (refer to Fig. 8), which greatly reduced the overall water consumption. On the other hand, lower reduction percentages were attained during June, July and August. This is mainly because of the higher operating hours of the DPIEC unit in **case 1**. Moreover, the amount of fresh air needed to be cooled in **case 2** is higher than that in **case 1** due to pre-cooling of the air using the RC system, which affects the amount of water consumed by the DPIEC unit. Since higher water consumption levels were found in **case 2**, a larger AWH system would be needed, increasing thereby the thermal energy needed for desorption.

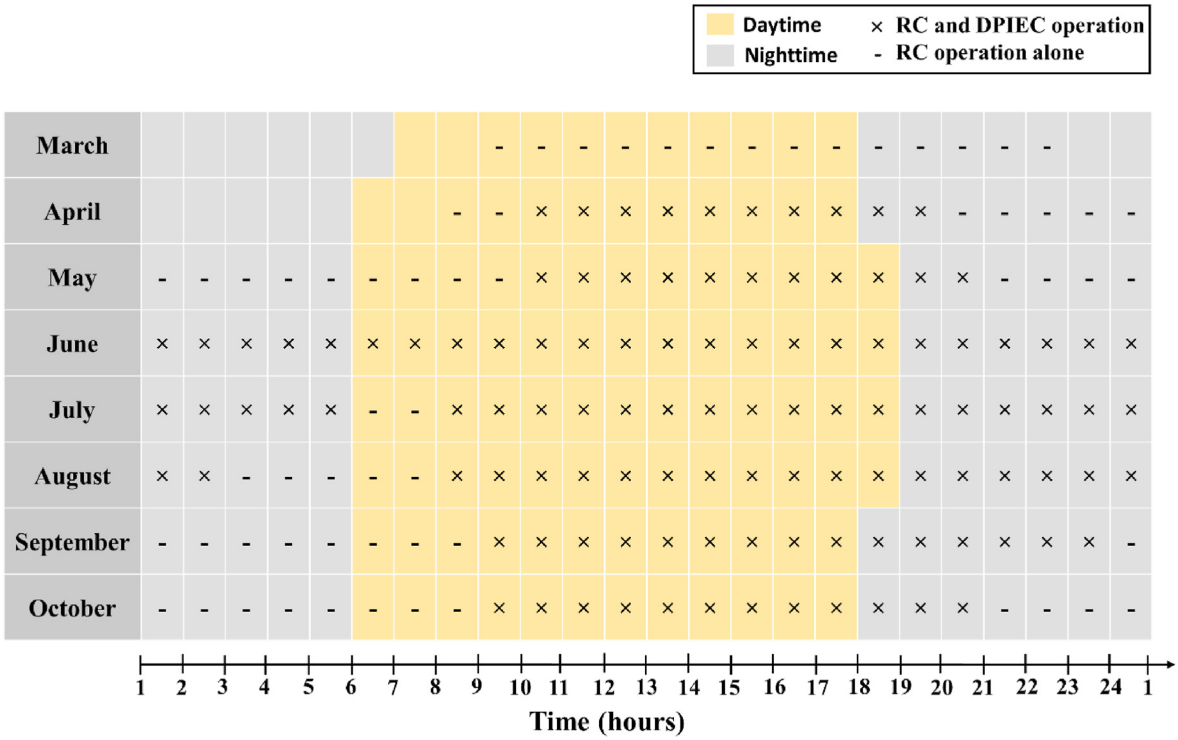

Fig. 8. Hourly schedule of RC + DPIEC operation and RC operation alone for the different considered months.

7.4. Electrical energy savings analysis

To underline the proposed hybrid system's worthwhile energy performance, its electrical energy consumption is assessed and compared to that of a typical AC system. For the hybrid cooling system (**case 1**), the electrical energy consumption consisted of that of the fans and pumps used in the system, including the supply/exhaust fans to the space as well as the fans needed for the AWH system operation [45]. The hourly electrical energy consumption of fans can be estimated using equation [5]:

$$E_{fan}(kW) = \frac{\dot{m}_a v_a \, \Delta P_{fan}}{\eta_{fan} \times 10^3} \tag{5}$$

Where $\dot{m}_a$ is the fan mass flowrate, v_a is the specific volume of air, ΔP_{fan} is the pressure increase in the fan and η_{fan} is the fan efficiency which has a typical value of 0.8 [46]. It was found that the supply and exhaust fans of the space consumed 1 kWh. The fan used in the adsorption bed of the AWH system operated at the flow rate of the working air exiting the DPIEC unit, consuming between 0.3 and 2.9 kWh throughout the considered months. As for the desorption bed, the fan consumed a power of 0.4 kWh per desorption cycle.

The pump energy consumption was obtained using equation [6]:

$$E_{pump}(kW) = \frac{\dot{m}_w \, g \, H}{\eta_{pump} \times 10^3} \tag{6}$$

where $\dot{m}_w$ is the pump mass flowrate, g is the acceleration of gravity (i.e. 9.81 m/s^2), H is the differential head and η_{pump} is the pump efficiency taken to be 0.8 [47]. A power of 0.1 kWh was consumed by the RC panel's pump. On the other hand, the power consumption of the DPIEC pump was extremely small (0.002 kWh) and therefore was neglected.

As for the AC system (**case 3**), a standard coefficient of performance (COP) value of 2.35 for typical DX units was considered [41]. Fig. 11 presents the monthly electrical energy consumption from March to October for **cases 1** and **3**. When the AC system was used, the total energy consumption during the entire cooling season was 45.7 MWh. On the other hand, when the hybrid system was implemented, this energy consumption dropped by 53.4% to 21.3 MWh. The highest energy consumption for both cases occurred during the peak cooling needs of the month of July. Accordingly, the hybrid passive system was able to meet the residential house's cooling load while offering substantial levels of energy savings. The highest energy savings were reached during the months of October (64.5%), May (62.7%) and September (60%), followed by April (53.5%), March (52.7%), August (52.2%), July (47.9%) and finally June (42.4%). This is expected since during the months of April, May, September and October, the number of DPIEC unit operating hours is lower than that in the months of June, July and August. Thus, more adsorption/desorption cycles are required during such months (June through August), yielding higher electricity levels consumed by the AWH batch system.

7.5. Life cycle cost assessment

An economic feasibility study of the proposed system (**case 1**) is crucial to highlight its advantage over the traditional AC system (**case 3**). Therefore, a life cycle cost (LCC) assessment considering the initial investment and yearly costs of the considered systems was conducted based on equation [7]:

$$LCC(\$) = C_0 + \sum_{i=1}^{N} \frac{C_i^E + C_i^M}{(1+a)^i} \tag{7}$$

where C_0 is the initial cost of the system ($), C_i^E and C_i^M are the yearly electric and maintenance costs of the system ($), N is the holding

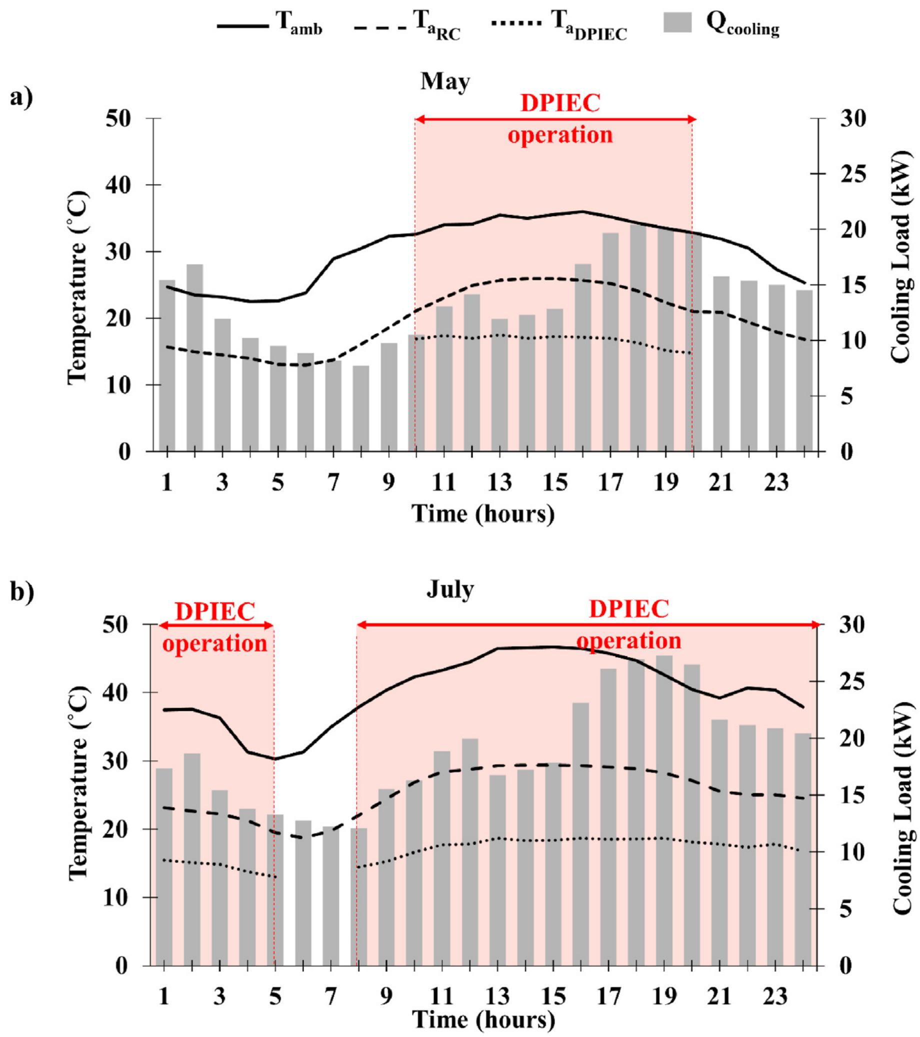

Fig. 9. Hourly variation of the ambient air temperature T_{amb}, the air temperature leaving the RC system $T_{a_{RC}}$, the air temperature exiting the DPIEC unit and the cooling load $Q_{cooling}$ for a) the month of May and b) the month of July.

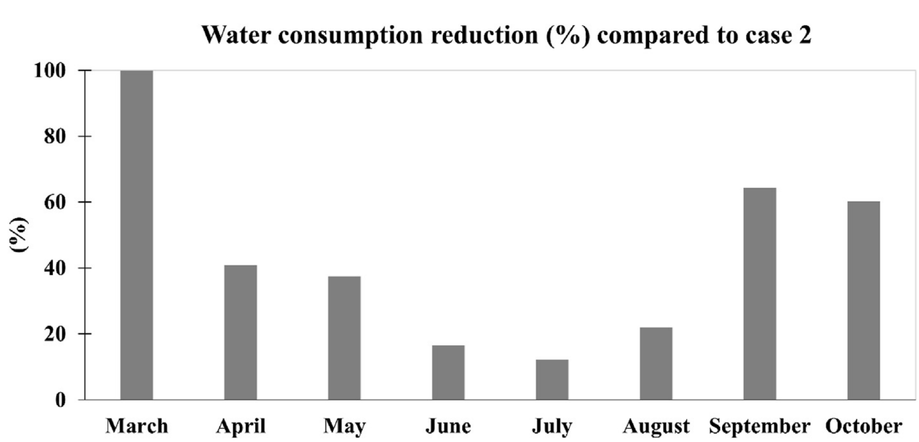

Fig. 10. Water consumption reduction percentage of **case 1** compared to **case 2.**

period of the system and a is the discount rate that reflects the change in local currency value over the holding period. This discount rate usually ranges between 0 and 10%, however a typical value of 8% was considered in this work [48].

The initial cost of the RC covering 60% of the roof was 2100 $ [10]. As for the DPIEC unit used, an initial investment of 1680$ was estimated [49]. Moreover, an initial cost of 11,520$ was allocated for the AWH system that included the Silica gel adsorbent [50]. Thus, a total amount C_0 of 15,300$ was initially paid in **case 1** at year 0. As for case 3, the cost and installation of the AC system was estimated

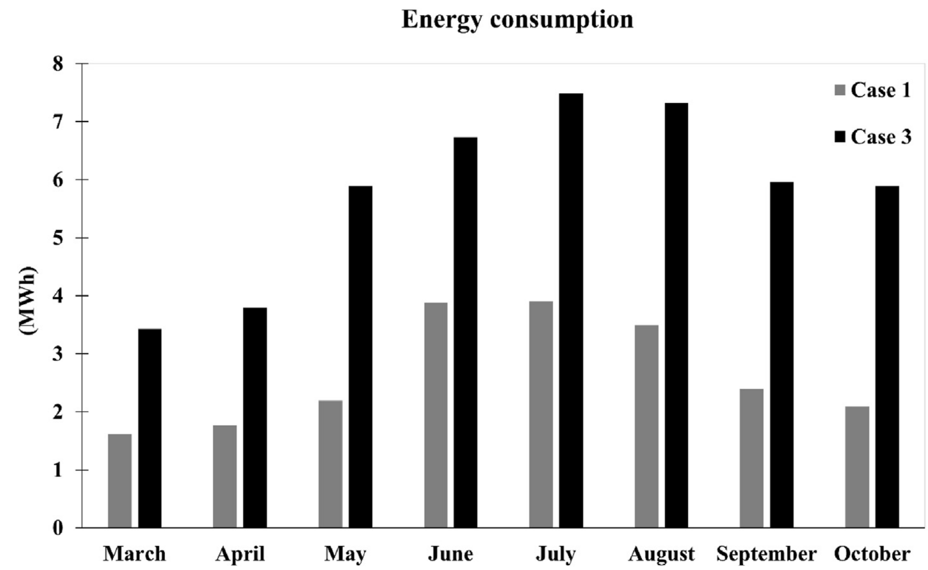

Fig. 11. Electrical energy consumption of the proposed hybrid system (**case 1**) and the conventional AC system (**case 3**) for the considered months.

to be 10,000$ [51]. The yearly electric cost C_i^E consisted of the annual spending on the electric power consumption (KWh) of each system (presented in Fig. 11). Note that the electricity tariff in Kuwait is 0.026$/KWh [52]. As for the annual maintenance cost C_i^M, it included the maintenance of the RC, DPIEC and AWH systems for **case 1** and the maintenance of the AC system considered in **case 3**. It is noteworthy to mention that some literature studies emphasized on the low maintenance cost of the passive radiative sky cooling [53], mainly consisting of cleaning of the panel.

Assuming a holding period of 50 years, the yearly variation of the LCC for each considered case was calculated and illustrated in Fig. 12. It can be noticed that for the first 5.1 years, the typical AC system was more economically profitable than the proposed hybrid passive system. However, throughout the remaining holding period (around 45 years), the proposed passive system was found to be more economically beneficial to meet the cooling load of the residential house during the entire cooling season. Thus, it can be concluded that the system in **case 1** outperforms the AC system in **case 3** while providing similar indoor conditions.

8. Limitations and applicability

The proposed hybrid cooling system in this study was implemented in the hot and dry Kuwaiti weather, yielding high performance levels and meeting the cooling load of the residential house. However, such worthwhile operation cannot be reached under any climate conditions: The proposed system cannot be implemented in humid climates, as it would negatively affect the performance of both the RC and DPIEC systems [3,13] where it was observed when comparing performance of current system in different months that during periods where the RH reached 60% (during the month of October), the maximum cooling power of the RC panel was not attained. This is because the spectral transmittance of the atmosphere is largely affected by the humidity of the air: higher RH levels cause lower atmospheric transmittance towards the outer

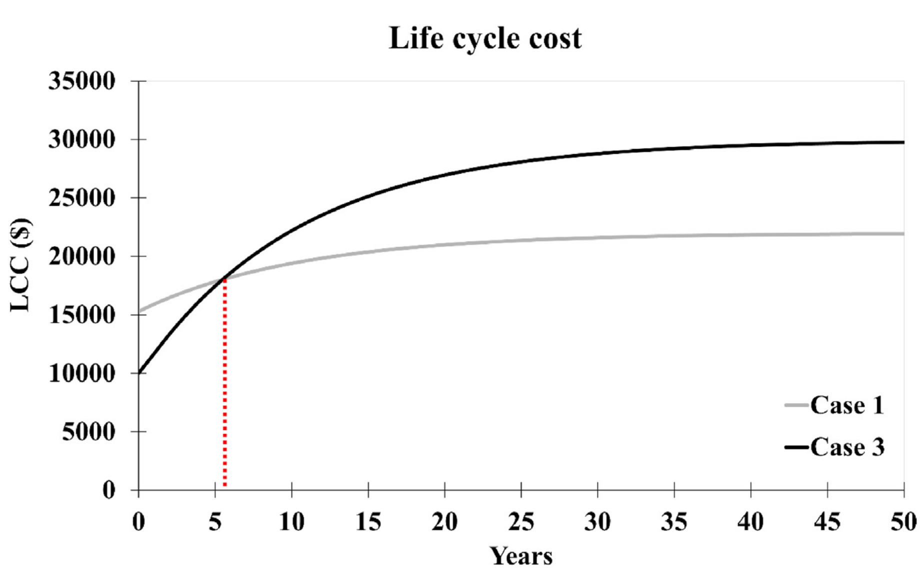

Fig. 12. Comparison of the yearly variation of the LCC for the proposed hybrid system (**case 1**) and the conventional AC system (**case 3**).

space and thus lower radiative cooling potential [8]. Moreover, since the DPIEC system produced cool air at temperatures close to the dew point temperature, it also performed best under dry conditions.

On the other hand, aspects of weather conditions other than RH (%) should be considered when implementing this system. Kuwait is prone to dust and dust storms, which are considered as a hazardous weather condition [54]. In general, the Arabian Peninsula is a hot-spot region that has reported the highest occurrence of dust storms [55]. The latter are even more frequent during the hot seasons (spring and summer) than during the cool seasons (autumn and winter) [56]. With such dusty days comes an increase in the RH (%) and wind speed, which might jeopardize the performance of the RC panel [3]. However, it was reported by Sabbah et al. [56] that the air temperature decreases during dust events due to scattering of sun rays back to space by the suspended particles of dust. An extensive study must therefore be executed to assess whether this ambient temperature reduction may compensate the higher RH (%) levels. Taking this a little further, the fact that dust will cover the RC panel requires a recurrent cleaning method while ensuring the intactness of the panel's nano-materials. Subsequently, the application of this system in climates with less dusty climate possibilities might offer a more guaranteed outcome.

Moreover, the AWH sizing is estimated based on the equilibrium uptake of the water on silica gel [32]. However, a detailed modeling methodology can optimize the bed design, yielding more accurate system sizing.

Finally, the proposed system requires a large space for the RC panel, DPIEC apparatus as well as the AWH beds. This might present a drawback when the system is applied in other case studies where the available free space is limited.

9. Conclusion

The performance of a hydronic RC panel integrated with a DPIEC and AWH system in the hot and dry climate of Kuwait has been evaluated in this work in the aim of providing a typical residential house with the required cooling needs. A set of simulations was conducted based on the representative day of each cooling month. The performance of the proposed cooling system was compared with: i) a cooling system including only a DPIEC system for water consumption reduction comparison, and ii) a typical AC system for energy savings assessment. It was found that the water consumed by the proposed hybrid system was reduced by an average of 44.2% throughout the cooling season compared to the case when the DPIEC was employed alone without the implementation of RC system. In addition, the electrical energy consumption of the proposed system was 53.4% lower than that of the typical HVAC system.

Future work can also address improving the performance of the hybrid system. This can be done using improved characteristics of the RC panel. In addition, a life cycle assessment based on the CO_2 footprint can also be investigated.

Credit author statement

Elvire Katramiz: Software, Validation, and Writing-original draft **Hussein Al Jebaei:** Formal Analysis, Investigation, Writing-original draft. **Sorour Alotaibi:** conceptualization, Writing - Review & Editing, Funding acquisition and Supervision. **Walid Chakroun:** Conceptualization, Writing - Review & Editing, Methodology, and Project administration. **Nesreen Ghaddar**: Conceptualization, Supervision, Project administration, and Writing. **Kamel Ghali:** Conceptualization, Methodology, Reviewing & 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.

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