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Experimental analysis of air-multiple pcm heat exchanger in evaporative cooling systems for supply air temperature stabilization

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ABSTRACT

The free cooling system is a highly efficient solution that effectively regulates indoor temperature when the ambient air temperature fluctuates within the thermal comfort range. Compared to traditional cooling systems, the evaporative cooling system excels in cost-effectiveness and has exceptional efficiency in hot and dry climates. However, the system's performance is significantly influenced by the environment, leading to fluctuations in the outlet temperatures of the evaporative cooler. A novel approach to integrating thermal energy storage with an evaporative cooling system has been studied to achieve free cooling and stabilize the system's supply air temperature to address this challenge. The evaporative cooler's design, construction, and experimental testing have been carried out in highly challenging hot and dry environments. The utilization of phase change materials (RT21HC and RT25HC) as a thermal energy storage system has been implemented. Incorporating phase change materials has notably improved the stability of the outlet air temperature from the evaporative cooling system. Furthermore, the outlet air temperature from the system exhibited consistent fluctuations within the range of 21–25 °C, requiring a significant amount of energy absorption and release to exceed these temperature thresholds. The findings demonstrate that the proposed system effectively reduces and shifts peak load to off-peak hours. Moreover, thermal energy storage can deliver free cooling during the spring and autumn. However, integrating the PAHX into an evaporative cooling system becomes crucial in regions characterized by extremely hot summer seasons. The maximum deviation between numerical and experimental results is 4 %.

Nomenclature

H	Height (m)
L	Length (m)
T	Temperature (°C)
W	Width (m)
m_a	Air mass flow rate (kg/s)

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m_w	Water mass flow rate (kg/s)
p	Panel (–)
c	Channel (–)
o	Outdoor (–)
s	Supply (–)

Abbreviations

ASHRAE	American society of heating, refrigerating, and air-conditioning engineers
CFD	Computational fluid dynamics
COP	Coefficient of performance
CT	Cooling tower
DEC	Direct Evaporative Cooler
EC	Evaporative cooling
HTF	Heat transfer fluid
HVAC	Heating, ventilation and air conditioning
IEC	Indirect Evaporative Cooler
PAHX	PCM to air heat exchanger
PCM	Phase change material
TES	Thermal energy storage
ε-NTU	Effectiveness-Number of Transfer Units

1. Introduction

The rising energy consumption and increased greenhouse gas emissions are pressing concerns today, with power plants using 15 % of the world's fresh water [1]. Heating, Ventilation, and Air Conditioning (HVAC) systems alone account for approximately 35 % of the total energy consumption in residential and commercial sectors [2]. The cooling load demand in Asian countries was 0.8 EJ in 2010 and is expected to increase to 5.8 EJ in 2050 [3]. Air conditioning units are significant sources of greenhouse gas emissions and large power consumers., necessitating converting traditional air conditioning systems to passive and efficient systems [4]. Peak loads must be moved to peak off-hours to reestablish the ideal balance between energy production and consumption [5]. Up to 14 times more energy could be stored in latent energy storage than in sensible energy storage [6]. Phase Change Materials (PCMs) can store and release substantial thermal energy as they transition between solid, liquid, and gas states [7]. Recently, PCMs have been widely used as latent energy storage [8]. PCMs categorized as eutectic, inorganic, and organic. Paraffin is an organic PCMs, and it is commonly utilized for its good thermal, chemical, and mechanical properties. Organic PCM's primary flaw is their poor thermal conductivity, which causes PCMs to take longer to melt and solidify [9]. Free cooling can be achieved by utilizing PCMs, which effectively store heat energy during the daytime and release it during the nighttime [10]. PCM is applied in many applications since it is widely available in different melting temperatures. Integrating PCM with refrigerator houseware has been studied numerically by Transys. The results show a reduction in operating hours and electricity costs of 34.73 % and 11.99 %, respectively [11]. Paraffin has been employed in a shell-and-tube heat exchanger as part of an experimental study. Additionally, fins were incorporated into the design to enhance the melting rate. The results indicated that introducing 40 mm long fins to the heat exchanger tubes substantially increased melting rates, with a boost of 72.8 % observed [12]. Conduction heat transfer is the primary mode of heat transfer in PCMs when they are in the solid phase. However, when the PCM transitions to the liquid phase, free convection also plays a role in influencing the heat transfer rates. This effect becomes significant when the heights of the PCM panels exceed 5 cm [13]. Different geometry has been used to encapsulate PCMs. However, a flat plate is the most commonly used since it has symmetric melting and solidifying, minimal resistance to airflow, higher surface area per volume, and simplicity in design and construction [14]. An experimental investigation was conducted on a flat plate PAHX, and the findings demonstrated that various factors influence the performance of the heat exchanger. These factors include the inlet air temperature, inlet airflow rates, encapsulation thickness of the PCM panels, and the temperature differential between the PCM and the Heat Transfer Fluid (HTF). The study highlights the importance of these parameters in optimizing the performance of the PAHX [15]. An experimental investigation has been conducted on inorganic PCM in a flat plate PAHX. The study revealed several factors that contribute to increase melting and solidification rate in PCMs. These factors include increasing airflow rates, lowering the inlet air temperature, incorporating multiple PCMs with different melting temperatures, and increasing the potential temperature difference between the HTF and the melting temperatures of the PCMs [16]. Graphene nanoplatelets (GNP) have been incorporated into paraffin RT70HC to improve the heat transfer rate in Thermal Energy Storage (TES). The results showed that adding GNP to paraffin can increase PCM's thermal conductivity by 21.6 % and reduce PCM's latent heat capacity by 10.5 % [17]. Multiple PCM panels have been employed in the TES system to enhance heat transfer. The heat capacity method was utilized in this study to analyze the system's performance numerically. The influence of the PCM panel's length, width, and height of the air channel was investigated. The system achieved an overall coefficient of performance of 7 [18]. PAHX has been studied to absorb free cooling at night through sky cooling. A 2D model was developed using the heat capacity method to assess the system's performance. The results indicated that nighttime sky radiation plays a significant role in free cooling [19]. The enthalpy method has been utilized to develop a 2D numerical model for analyzing the performance of the PAHX. Various parameters have been investigated, including inlet air temperature, flow rates, the height of PCM panels and air channels, length-to-width ratio of the

PAHX, total volume of PCM, number of PCM panels, and the integration of multiple PCMs with different melting temperatures. The findings revealed a decrease of 1 h in the solidification period when employing multiple PCM rather than a single PCM, with the melting time remaining unchanged [20]. The evaporative cooling system has shown superior effectiveness in terms of cost-effectiveness, reduction in carbon emissions, and energy efficiency compared to vapor compression refrigeration systems [21,22]. Evaporative coolers exhibit a remarkable 68 % reduction in annual power consumption compared to refrigeration systems [23]. Also, 70 % of the electricity consumption rate can be reduced by evaporative coolers compared to vapor compression systems [24]. Integrating PCMs into a direct evaporative cooler was studied experimentally to enhance free cooling in unfavorable climate conditions. PCMs with melting temperatures 27-29 °C have been used for free cooling in India during April. The results showed that the PCM could not solidify by ambient air after 8 h. However, the PCMs solidified at all parts of the TES tank after integrating a direct evaporative cooler. Solidification time was reduced after adding a direct evaporative cooler due to the increased temperature differential between the air and PCM's melting temperatures [25]. The industrial evaporative cooling system uses PCMs to produce chilled water at night and shorten working hours during peak times. The system's performance with and without PCM has been investigated using a Matlab-Simulink model. According to the findings, the chiller's working hours were cut by 67 % during peak hours [26]. PCMs in the indirect evaporative cooler and storage unit have been studied numerically for one year. The optimized system size has the potential to save up to 80 % of annual cooling energy in Jordan, with a calculated payback period of 7.8 years [27]. In hot climates, the ambient air temperature remains consistently high throughout both the day and night, preventing the use of a free cooling system. This research provides innovative solutions by investigating the implementation of a free cooling system in challenging conditions and the solidification of PCM-RT21. The outlet air temperature of the evaporative cooling system is subject to variations in the outdoor air temperature, resulting in discomfort within the conditioned space. However, the inclusion of TES within the evaporative cooling system helps reduce temperature fluctuations. In this study, the PAHX comprises a series connection of 8 PCM panels filled with RT21HC and another 8 PCM panels filled with RT25HC. The present study investigates the impact of incorporating a PAHX into an evaporative cooling system to ensure a consistent outlet temperature in hot and dry climates (see Table 1).

2. Methodology

The primary objective of the current research is to design, construct, and develop a free cooling and ventilation system by integrating a PAHX into an evaporative cooling system. Additionally, the study employs multiple PCMs with various melting temperatures to enhance the melting and solidification rates within the PCM materials. The energy equation was employed in the development of the mathematical model for the proposed PAHX and evaporative cooling system, which was conducted using the Engineering Equation Solver (EES). This system has the potential to enhance indoor air quality by offering ventilation and extending the duration of thermal comfort. The model assesses the parameters influencing the system's performance across different climate conditions. To improve the system's efficiency and stabilize the outlet air temperature, a PCMs was integrated into the EC system as a TES. The outlet temperature of the evaporative cooling system is greatly affected by the outside air temperature, which may deviate from the desired thermal comfort range. The presence of PCMs plays a crucial role in absorbing or releasing substantial amounts of heat energy during the phase transition between the liquid and solid states. When the ambient air temperature is either excessively low or high, the system may deliver a supply temperature that falls below or exceeds the desired thermal comfort range. This fluctuation in the outlet air temperature can lead to discomfort in indoor air quality. By incorporating PCMs into the system, the instability in the outlet air temperature can be effectively minimized. Whenever the inlet air temperature of the PAHX unit falls below the melting temperature of the PCM, the PCM undergoes solidification. Conversely, if the inlet air temperature exceeds the melting temperature of the PCM, it triggers the melting process. The proposed system comprised the PAHX, Direct Evaporative Cooler (DEC), Indirect Evaporative Cooler (IEC), and Cooling Tower (CT), as depicted in Fig. (1) and (2).

The system comprises a cooling tower, a slab heat exchanger facilitating heat exchange between the air and PCM, and an indirect compact heat exchanger enabling heat transfer between the air and water. The cooling tower produces chilled water by evaporating water by spraying it into unsaturated air. The combination of an indirect-direct evaporative cooler, a cooling tower, and PAHX have

Table 1
Optimizing the dimensions and configuration of both the evaporative cooling system and the PAHX.

PCM panel height	1 cm
Air channel height	3 cm
Steel (PCM's encapsulation wall)	0.3 cm
Air mass flow rate of HTF	0.4 kg/s
Water mass flow rate	0.1 kg/s
PCM panel length (two sets of PCM panels in series)	0.6 m for each PCM type
PCM's melting temperature	RT21HC (21 °C) and RT25HC (25°C)
A sequence of PCMs in series	The first is RT21HC, and second is RT25HC
Width of the PCM panels and air channels	0.5 m
Length to width ratio of the PCM panels	1.2 m
Wood insulation thickness	0.02 m
Total PAHX size (Length, Width, Height)	(1.5 * 0.5 * 0.35) m
Dimension of indirect evaporative cooler	(0.8 * 0.6 * 0.15) m
Dimension of direct evaporative cooler	(0.6 * 0.4 * 0.2) m
Dimension of cooling tower	(0.5 * 0.5 * 1) m

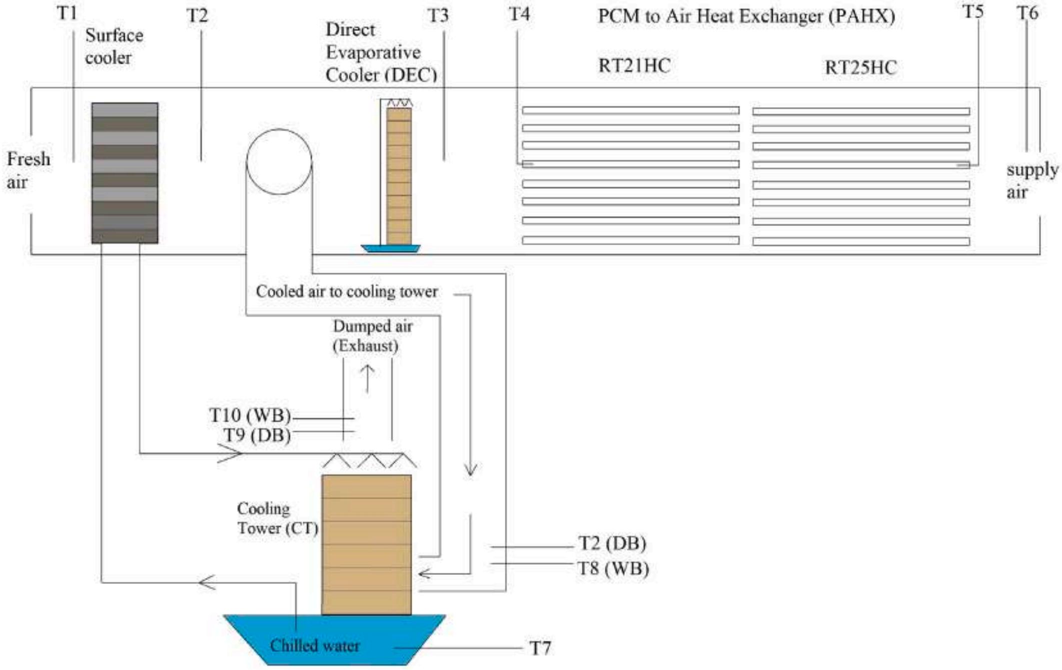


Fig. 1. Proposed cooling and ventilation system with TES.

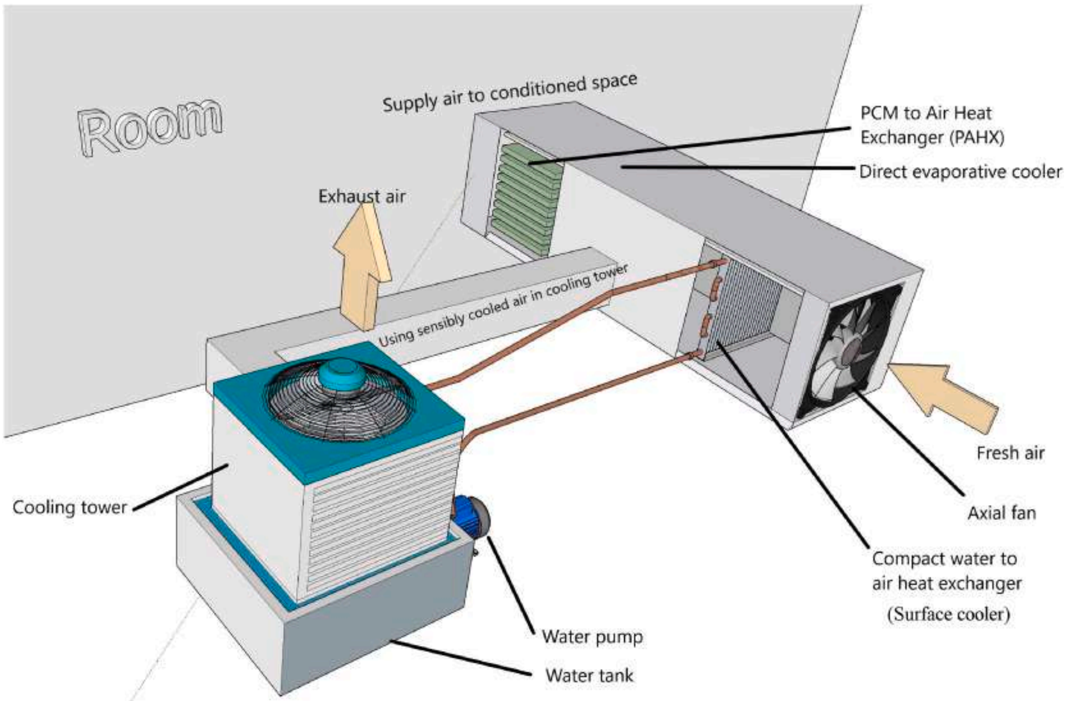


Fig. 2. Design of the proposed system.

been investigated in Erbil, Iraq. This study involves the utilization of 15 kg of paraffin RT-21HC and an additional 15 kg of paraffin RT-25HC, both provided by Rubitherm Technologies (GmbH). The energy equation is calculated using the Engineering Equation Solver (EES) software to evaluate the system's overall performance accurately. The model examines the factors influencing the system's performance across different climate conditions. The system has enhanced indoor air quality by offering ventilation and prolonging the duration of thermal comfort. The system's performance relies on the efficiency of the cooling tower, the indirect-direct evaporative cooler, the PAHX, and the air-to-water compact heat exchanger. The incoming fresh air is sensibly cooled through a compact heat exchanger. This heat exchanger employs chilled water flowing inside tubes while fresh air circulates over the tubes and fins, enabling the sensible cooling of the air. The PAHX was incorporated into the system to stabilize the supply air temperature. This addition was necessary as the supply air temperature from the EC system tends to fluctuate in response to changes in ambient air temperature. The PCM undergoes solidification at night when the ambient air temperature drops below the PCM's melting point. Conversely, it melts during the daytime when the ambient air temperature surpasses the PCM's melting temperature. A decrease in air temperature was observed as the air traversed through the PAHX during the PCM melting process. The latent heat required for the phase change of PCM RT21HC is approximately 190 kJ/kg, while for PCM RT25HC, it is around 230 kJ/kg. The cooling tower will consistently produce chilled water through the evaporation process. The system incorporates organic PCMs, specifically paraffin RT21HC and RT25HC, to ensure a consistent and comfortable thermal environment. The system effectively delivers sufficient cooling to maintain the room temperature within the desired thermal comfort range. The Effectiveness-Number of Transfer Units (ε-NTU) has been utilized in previous research to assess the efficiency of heat exchangers [28]. The effectiveness of the heat exchangers has been examined experimentally before use in the EES model, as explained in Appendix (1).

3. Experimental work

PCMs such as RT21HC and RT25HC are employed as TES units encased within a steel container, while air is utilized as the Heat Transfer Fluid (HTF). The properties of PCM RT21HC and RT25HC were obtained from the manufacturer's data sheet provided by Rubitherm company [29]. The PAHX has been used in this study contained 16 PCM panels, the first 8 PCM panels filled with PCM–RT21HC and another 8 PCM panels filled with PCM–RT25HC, and air passages surrounded the PCM panels, as shown in Fig. (3).

A flat plate PAHX has been constructed and examined experimentally. The length, width and height of the PAHX are denoted by L_{panel}, W_{panel}, and H_{panel}, as shown in Fig. (4 a & b). The length and width of both the PCM and the air channel are identical. The height of the PCM panel is indicated as H_{panel}, while the height of the air channel is referred to as $H_{channel}$. The dimension of the PAHX has been investigated, and the affected parameters have been optimized using the CFD model in the earlier study [20]. The optimization was done using the analyzed CFD results before building the heat exchanger. The optimized dimensions and boundary conditions of the PAHX are provided in Table (1) [20]. Wood was used as insulation for PAHX because it has a low thermal conductivity, which prevents heat gain or loss, and was covered with a 2 cm layer.

The melting and solidification time of the PCM serves as a crucial parameter that directly impacts the overall performance of the PAHX. However, incorporating multiple PCMs with varying melting temperatures in a heat exchanger introduces additional complexities to the melting and solidification time. In such cases, the PCM with the lowest melting temperature will undergo melting first, followed by the PCM with the next highest melting temperature, and so forth. This sequential melting process among the PCM can enhance the overall melting and solidification rate in PCMs, compared to utilizing a single PCM by managing the temperature difference between HTF and PCM's temperature among the PAHX. The impact of integrating multiple PCM with various melting temperatures on the melting and solidification time within a PAHX can be intricate, primarily due to the heat transfer between PCMs with different melting temperatures. Integrating multiple PCM within the PAHX makes it feasible to maintain a consistent temperature difference between the HTF and the temperatures of the PCMs along the length of the PAHX. This approach effectively improves the rate of both

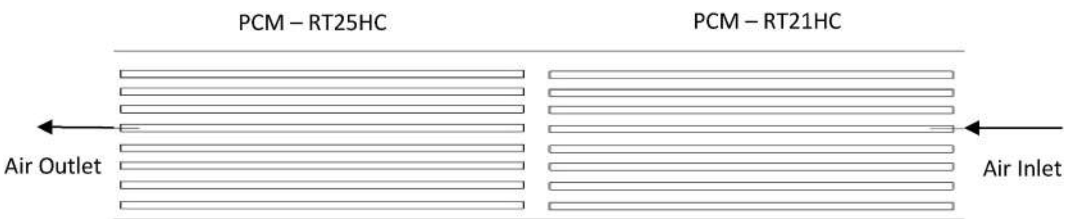


Fig. 3. Schematic of PAHX

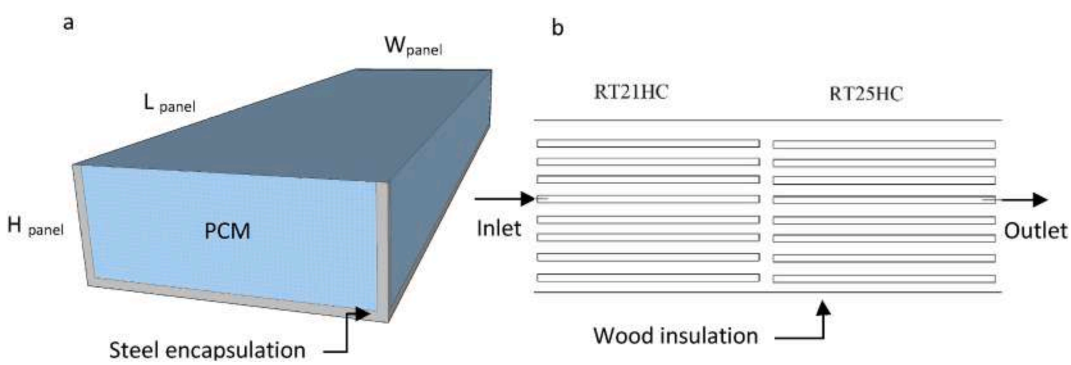


Fig. 4. Dimensions of PAHX (a) a single PCM panel and (b) the configuration with PCM panels and air channels.

melting and solidifying the PCMs. The performance of the PAHX can be enhanced by carefully monitoring the melting and solidification processes in the PCMs. This optimization can be achieved by evaluating multiple factors, including the melting fraction within the PCM panels, the temperature of the PCMs within the PCM panels, and the air temperature within the air channels. The system's total mass comprises 15 kg of RT21HC and an additional 15 kg of RT25HC. Each PCM panel has an internal volume of 0.0025 m^3. The airflow rate in air channels is 0.4 kg/s. The panels were filled with PCM in the liquid phase to prevent overflow since the paraffin used has 12.5 % volume expansion. The variable airflow rates have been tested experimentally using axial fans, airflow measurement (vane anemometer), thermocouple type (K) temperature measurements, and a data logger. Figures (2) and (5) shows the experimental setup from a photographic view.

The EES and CFD models have been used to design the experimental rig. Optimization for the models has been done, and based on the numerical findings, the dimension and configuration of the evaporative cooler and PAHX have been modified and constructed [20]. There are preliminary tests and preliminary data to validate the system before being compared with the numerical model. Before taking experimental data from the rig, the calibration for measured instruments and the system's warmup to reach a steady state condition is essential. Before taking the melting test, the PCM must be solidified entirely, and the PCM must be melted thoroughly before taking data for solidification. Based on optimum numerical results, the experimental setup is built. To shorten the solidification time in PCMs, the PCM-RT21HC is first in the PAHX and followed by PCM-RT25HC. The rectangular PCM slab has used a PAHX for symmetry melting and solidification, easy construction and lower pressure drop for HTF. The measuring device has been calibrated, and the system is validated and verified by comparing experimental work with the numerical results. Measurements were calibrated to detect any associated errors, and uncertainty was established before use. The uncertainty of the measured device used in this experiment is calculated as uncertainty error, and the uncertainty of temperature and velocity measurements are ±0.4 % and ±4.7 %, respectively.

4. Results and discussion

This section compares the experimental and numerical results, focusing initially on the empirical study of the performance of the modified evaporative cooling system. The effect of different ambient temperatures, air mass flow rates, and water flow rates have been examined experimentally. In comparison, the previous study examined more factors numerically [28]. Using PAHX as a standalone free cooling system has been studied. Also, the effect of integrating PAHX into the evaporative cooling system has been studied thoroughly for various airflow rates.

4.1. Performance of the PAHX-integrated evaporative cooling system

This section examines the impact of incoming air temperature, airflow rates, and water flow rates on the system's performance through experimental investigation. The system parameters employed for the experiments include an incoming air temperature of 45 °C, an airflow rate of 0.4 kg/s, a relative humidity of 10 %, and the utilization of 15 kg of PCM-RT21HC and 15 kg of PCM-RT25HC. Based on research findings, the efficiency of the compact water-to-air heat exchanger, cooling tower, and PAHX are reported to be 70 %, 80 %, and 20 %, respectively [28].

4.1.1. Influence of outdoor air temperature

The outdoor air temperature influences the system's efficiency, as depicted in Fig. (6). The cooling tower's evaporation process and the performance of the heat exchanger are notably impacted by the outdoor air temperature. As the outdoor air temperature rises, both the supply air temperature and the efficiency of the system increase due to the most efficient evaporation process at higher temperatures. The increased outdoor air temperature reduces relative humidity simultaneously while maintaining the same moisture content, enabling hot air to absorb more water vapor and enhance evaporation. The coefficient of performance (COP) of the system is

Fig. 5. Experimental rig (photo).

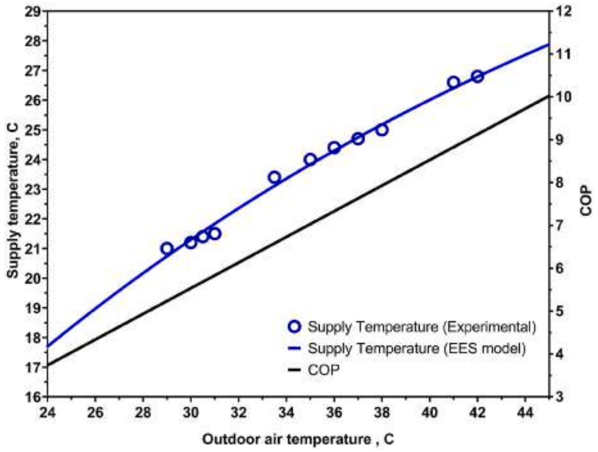


Fig. 6. Influence of the outlet air temperature on both the supply air temperature and the performance of the system.

the ratio between cooling effect and power consumption of the system as described in Appendix 1. The experimental and numerical results are in good agreement.

4.1.2. Influence of the airflow rate

Figure (7) demonstrates the relationship between the air mass flow rate and the system's performance. As the airflow rate increases, the system's COP also increases, primarily due to a higher cooling or heating effect and an improved heat transfer rate. Additionally, it is worth noting that the supply air temperature rises with higher airflow rates, as it reduces the duration of heat transfer contact. The maximum deviation between experimental and numerical results is 2.5 %.

4.1.3. Impact of water flow rate

Figure (8) illustrates the influence of the water flow rate on the system's performance. As the water flow rate increases, the system's COP exhibits a significant increase at low water flow rates, specifically those below 0.2 kg/s. However, for higher water flow rates, the COP does not increase due to an excessive water spray relative to the airflow rate of the cooling tower. The results indicate a preference for a water flow rate of less than 0.2 kg/s. It is worth noting that the water flow rate relies heavily on the airflow rate within the evaporation medium. Justifying the air-to-water ratio becomes crucial in optimizing the performance of the cooling tower. The maximum deviation between experimental and numerical results is 4 %.

4.2. The impact of adding PAHX to the evaporative cooling system on stabilizing the system's supply air temperature

The principal aim of this study is to offer free cooling, ventilation and prolonged indoor thermal comfort. In this section, the cooling system's performance has been tested experimentally. The system combines indirect and direct evaporative cooling, cooling towers and thermal energy storage. The system has been designed and tested in a hot and dry climate in Iraq – Erbil. The evaporative cooling system exhibits remarkable efficiency in regions characterized by hot and arid environments. However, its limitation of use is its high relative humidity and high supply temperature, which usually exceed thermal comfort limits on summer days when ambient temperatures approach 50 °C. ASHRAE standards recommended the thermal comfort range during summer as (23-27 °C) dry bulb

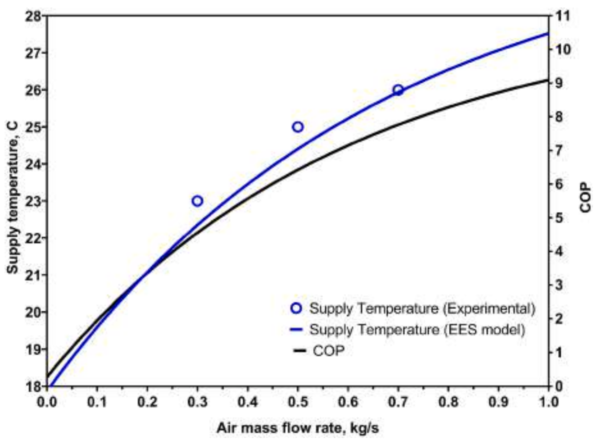


Fig. 7. The influence of the airflow rate on both the supply air temperature and the performance of the system.

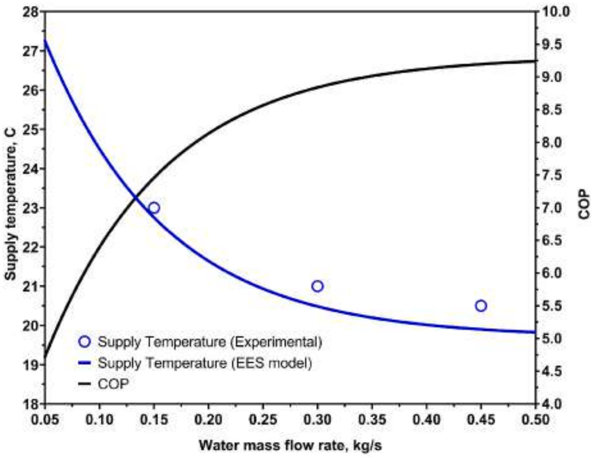


Fig. 8. Water flowrate impact on the system.

temperature and relative humidity as (30–60 %) [30]. Providing free cooling in a scorching climate is a challenge. In this study, PCM as TES has been proposed to shift and reduce peak cooling loads by charging PCMs at night and discharging during hot days. TES system can be an independent solution for delivering free cooling, especially when the ambient temperature during summer days and nights remains slightly above and below the desired thermal comfort range. Unfortunately, using PCM as a free cooling is impractical, primarily due to its incapability to solidify in hot climates, particularly when the nighttime temperature exceeds the thermal comfort limit. The impact of adding the cooling system has been tested experimentally. The performance of using PAHX without the cooling system for free cooling has been investigated, as discussed in the following sections.

4.2.1. Variation of supply air temperature from the system with using PAHX during day and night

In this section, the PAHX has been tested as a stand-alone free cooling without using evaporative cooling, in which the outdoor air simultaneously passes through PAHX to melt and solidify PCM. The results showed the time that the PAHX could provide comfortable air without using air conditioning systems. Figure (9) illustrates the average temperatures of PCMs RT21HC and RT25HC over 6 h, along with the corresponding fluctuations in ambient air temperature. Once the ambient air is introduced into the PAHX, the resultant outlet air temperature from the PAHX is supplied to the conditioned space. The maximum and minimum temperature between day and night is called the daily range temperature, which is 10 °C. The PAHX cools the ambient air only for the first 3 h. After that time, the PCMs entirely melted and could not cool the air anymore, as illustrated in Fig. (9). As the PCMs continued to melt continuously, the outlet air temperature gradually increased. After 4 h, the outlet air temperature reached 28 °C, surpassing the thermal comfort threshold. The PAHX cannot be used for longer than 3 h due to the limited capacity of PCMs. Solidifying PCMs need air with low temperatures as 23 °C and 19 °C or lower for solidifying PCMs RT25HC and RT21HC. The findings indicated that the PAHX is unsuitable for deployment as a free cooling system in hot and dry climates due to the inability of the PCMs to solidify naturally at the temperatures typically experienced during hot summer nights. So combination with evaporative cooling is recommended for enhancing solidifying PCMs in hot climates. In the next section, the PAHX with an evaporative cooling system has been tested experimentally.

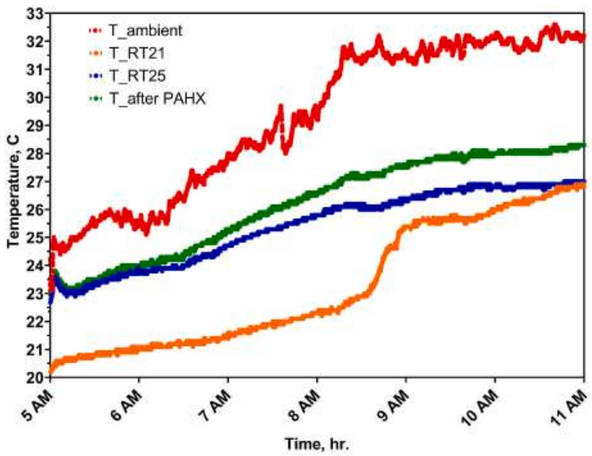


Fig. 9. Using PAHX as a stand-alone free cooling system.

4.2.2. Variation of supply air temperature by using PAHX and cooling system during day and night

The PAHX is integrated with the evaporative cooling system to conduct testing under real operating conditions. The air temperature variations before and after PAHX and the average temperature in PCMs RT21HC and RT25HC have been recorded as shown in Fig. (10). The daily range temperature exceeds 10 °C, the test was done for 24 h, and PCMs solidified well before starting the test. An evaporative cooling system is employed to attain the minimum supply air temperature. Interestingly, the outlet air temperature predominantly falls within the range of temperatures exhibited by PCMs RT21HC and RT25HC. This phenomenon can be attributed to the substantial absorption or release of heat and cold energy required by both PCMs during their phase transitions. The outlet air temperature from PAHX exceeds PCM's temperatures when the PAHX is used without a cooling system. Throughout the conducted experimental tests depicted in Figures (10)–(12), it was observed that the PCM did not melt fully. Instead, the PCMs predominantly remained solid due to the evaporative cooling system's ability to deliver cool air temperatures of 17–18 °C during nighttime. The system is successful in terms of saving energy and achieving thermal comfort. Inlet air temperature and airflow has an impact on melting and solidification rate. Higher airflow rates have been recommended to shorten the solidification time. The solidification process takes significantly more time than the melting process, primarily because of the temperature difference between the melting temperature of the PCM and the inlet temperature of the HTF. Furthermore, the melting process is further facilitated by free convection. Various air mass flow rates were examined to explore the impact of airflow rates on the system's performance, as illustrated in Fig. (10)–(12). Increasing the airflow rates improves the rates of melting and solidification. Conversely, reducing the airflow rates prolongs the duration of contact between the HTF and the PCM, ultimately leading to a consistently lower outlet air temperature from the PAHX.

5. Conclusion

The PAHX can not be used as a stand-alone cooling system in a hot environment, primarily due to the inability of the PCM to solidify naturally. When the evaporative cooling system is coupled with the PAHX, the system's performance is much better, and outlet air temperature is mostly between PCMs melting temperatures. The arrangement of PCMs in series affects melting and solidifying PCMs.

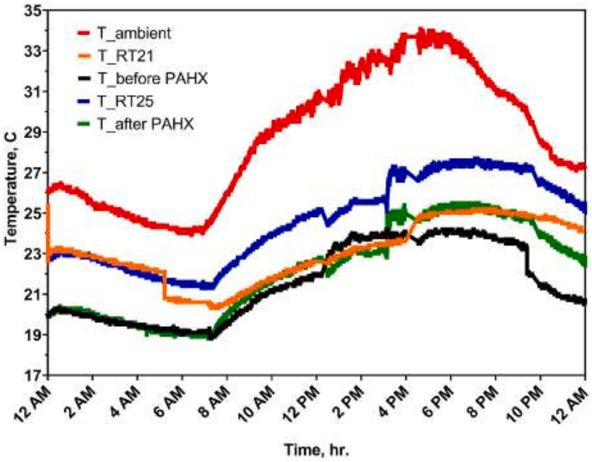


Fig. 10. Stabilizing supply air temperature fluctuations with cooling system and PAHX (The air mass flow rate is 0.6 kg/s).

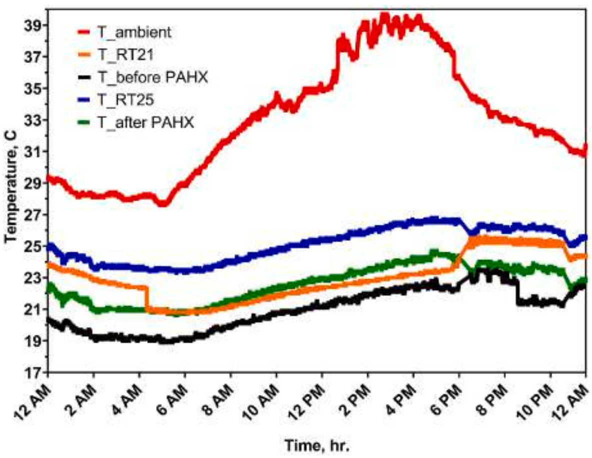


Fig. 11. Stabilizing supply air temperature fluctuations with cooling system and PAHX (The air mass flow rate is 0.4 kg/s).

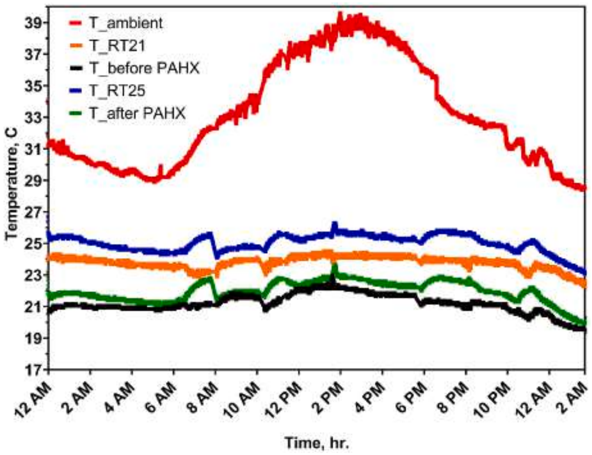


Fig. 12. Stabilizing supply air temperature fluctuations with cooling system and PAHX (The air mass flow rate is 0.2 kg/s).

PCM-RT21HC is used first and followed by PCM-RT25HC, which this arrangement is recommended for a better solidification rate, whereas the opposite arrangement performs better with the melting process. Using PCMs as a TES is a passive system that provides free cooling or heating in buildings by absorbing and releasing heat energy throughout the day and night. The storage systems can reduce and shift peak load to peak off hours. In most climate conditions, PCMs can be solidified only at some time of the year. In hot climates, phase change materials (PCMs) with melting temperatures ranging from 21 to 25 ˚C may solidify when exposed to the cooler night air in the spring and autumn seasons. However, solidification during the summer becomes unfeasible due to the persistently high temperatures. In this study, the modified evaporative cooling system is integrated with PAHX to solidify PCMs RT25HC and RT21HC, which need an air temperature below 19 ˚C to solidify completely. The system has been investigated under actual climate conditions. The results indicated that employing multiple phase change materials (PCMs) can significantly reduce the duration of both melting and solidification processes within the PCMs. Integrating PAHX into an evaporative cooling system increases the temperature difference between the heat transfer fluid (HTF) and the PCM. The PAHX has been investigated to reduce indoor temperature fluctuation with and without cooling systems. The findings revealed that the PAHX, as a stand-alone free cooling system, could not consistently deliver thermal comfort air during summer. Therefore, employing the PAHX with a cooling system is an excellent solution for free cooling and ventilation in hot and arid climates. By using PCMs RT25HC and RT21HC to regulate the supply air temperature within the comfortable range of 21–25 ˚C, the findings demonstrate the challenge faced by the cooling system in surpassing this temperature threshold. The key conclusions drawn from this study are summarized as follows:

- In the literature, the researchers recommended using PCMs with melting temperatures between 27 and 29 ˚C in hot and dry climates for a higher heat transfer rate. However, in this study, RT25 and RT21 have been used to provide thermal comfort air since PCMs with high melting temperatures are unable to provide thermal comfort air during summer months in extremely hot climates.
- The PCM-RT25HC solidified quickly, which needed 4 h to solidify entirely, but PCM-RT21HC required more than 12 h.
- The PCM-RT21HC demonstrated a higher rate of melting when compared to the PCM-RT25HC. This higher melting rate can be attributed to the substantial temperature difference between the heat transfer fluid (HTF) and the melting temperature of the PCM. It is important to note that both PCMs fully melted within 4 h.
- The system's performance is enhanced by several factors, including higher outlet air temperature, lower relative humidity, increased water flow rates, and improved wet-bulb effectiveness of IEC, DEC, PAHX, and CT.
- Experiments have been conducted to assess the influence of various flow rates of the HTF on the melting and solidification times. However, it has been observed that the impact of a temperature difference between the HTF and the melting temperature of the PCM carries greater significance than the impact of the high flow rates of the HTF.
- Experimental studies have successfully employed PCM units to enhance the heat transfer rate between air and PCMs. The findings indicated a notable decrease in solidification and melting time when multiple PCMs were utilized instead of a single PCM.
- The system can offer cost-free cooling and ventilation to the conditioned area, even with an extended duration of thermal comfort within the building. The supplied air temperature to the conditioned space typically ranges from 21 to 25 ˚C. For the outlet air temperature to remain below 21 ˚C, the PCM-RT21HC must release significant heat energy. Similarly, to surpass 25 ˚C, the PCM-RT25HC must absorb substantial heat energy to raise the system's supply air temperature.
- The system alone cannot provide thermal comfort air for a long time, but with evaporative cooling, the PCMs can solidify, and the system can work effectively continually.

Declaration of competing interest

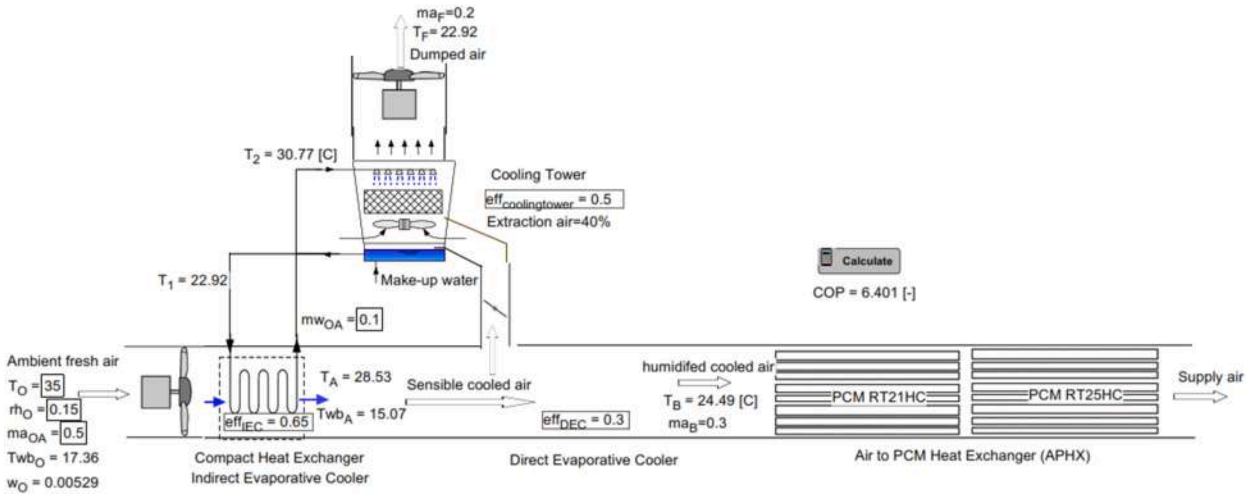
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix 1. ((EES code for PAHX and evaporative cooling system)

```
Procedure system.
(ma_OA,mw_OA,P,rh_O,T_O,T_1:eff_IEC,eff_coolingtower, eff_DEC,Twb_O,w_O,cpa,cpw,cmin,T_A,T_2,Twb_A).
If (T_O > 40) Then
eff_IEC = 0.8
eff_coolingtower = 0.6
eff_DEC = 0.4.
Else.
If (T_O > 35) and (T_O ≤ 40) Then
eff_IEC = 0.75
eff_coolingtower = 0.55
eff_DEC = 0.35.
Else.
If (T_O ≥ 30) and (T_O ≤ 35) Then
eff_IEC = 0.65
eff_coolingtower = 0.5
eff_DEC = 0.3.
Else
eff_IEC = 0.55
eff_coolingtower = 0.4
eff_DEC = 0.25.
Endif.
Endif.
Endif.
Twb_O = wetbulb(AirH2O,T = T_O,R = rh_O,P=P).
w_O = humrat(AirH2O,T = T_O,R = rh_O,P=P).
cpa = cp(AirH2O,T = T_O,w = w_O,P=P).
cpw = cp(Water,T = T_1,x = 0).
cmin = min((cpa*ma_OA),(cpw*mw_OA))
If (cmin=(cpa*ma_OA)) Then.
T_A = T_O-(eff_IEC*(cmin*(T_O-T_1)))/(cpa*ma_OA).
T_2 = T_1+((ma_OA*cpa*(T_O-T_A))/(cpw*mw_OA))
Else.
T_2 = T_1+(eff_IEC*(cmin*(T_O-T_1)))/(cpw*mw_OA).
T_A = T_O-((mw_OA*cpw*(T_2-T_1))/(ma_OA*cpa))
endif.
Twb_A = wetbulb(AirH2O,T = T_A,w = w_O,P=P).
End.
T_1 = T_2-eff_coolingtower*(T_2-Twb_A).
Call system (ma_OA,mw_OA,P,rh_O,T_O,T_1:
eff_IEC,eff_coolingtower, eff_DEC,Twb_O,w_O,cpa,cpw,cmin,T_A,T_2,Twb_A).
T_B = T_A-eff_DEC*(T_A-Twb_A).
COP=(0.6*ma_OA*cpa*1000*(T_O-T_B))/(500).
P = 100.1
power = 500.
```



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