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Thermal performance of PCM-to-air heat exchangers in hot desert climate

MOHAMED DARDIR^{1,2}, FARIBORZ HAGHIGHAT^{1*}, and MOHAMED EL MANKIBI³

¹*Energy and Environment Group, Department of Building, Civil, and Environmental Engineering, Concordia University, Montreal, QC H3G 1M8, Canada*

²*Department of Architectural Engineering, Ain Shams University, Cairo, Egypt*

³*ENTPE-Université de Lyon, 3 rue Maurice Audin, 69518 Vaulx en Velin, France*

Utilization of PCM-to-Air Heat Exchangers (PAHXs) in building free cooling applications has been reporting the insufficient cooling charging energy during the PCM solidification, which affects the overall system performance. This study reports the improvements in the cooling potential of the PAHX considering the climatic characteristics of the hot desert climate by taking the advantage of thermal radiation losses to the sky during nighttime. Parametric studies were conducted for the developed PAHX unit with respect to the location, airflow rate, and the PCM type. The improved PAHX unit was integrated into the mechanical ventilation system of an office space under hot desert climatic conditions considering various operational conditions. It was concluded that the PAHX unit outlet air could be directly supplied to the indoor space through a direct free cooling application to satisfy the cooling demand; also, it could be introduced to the mechanical cooling unit to minimize the energy consumption. The results showed that the thermal comfort levels were enhanced by up to 18%, and the cooling system energy consumption was reduced by 18.5% saving an amount of energy up to 10.8 kWh/week.

Highlights

- Thermal performance of a developed PCM-Air HX was analyzed in hot desert climate.
- Radiative cooling was utilized to increase the system free cooling potential.
- Parametric analysis was performed to study system's stand-alone thermal performance.
- Integrated system promoted enhanced thermal comfort levels and energy savings.

Introduction

Utilization of Phase Change Materials (PCMs) in building thermal energy storage has gained much interest lately due to their capability to store high amount of energy during their phase change. The energy storage happens within a relatively constant temperature range called Phase Change

Temperature (PCT) range. In free cooling applications, charging process/solidification of PCM is carried out during nighttime when the ambient air temperature is lower than the PCT. Hence, the PCM can be charged and discharged using a PCM-to-air Heat Exchangers (PAHXs). The applications of PAHX free cooling are highly related to the local climatic conditions (Dardir, Panchabikesan, et al. 2019).

Generally, it has been reported that the thermal performance of the PAHX units can be enhanced in climates with large daily temperature amplitude (Waqas and Kumar 2011a, 2011b; Borderon, Virgone, and Cantin 2015; Berardi and Soudian 2019). Also, most of the studies construed that larger difference between PCT range and inlet air temperature during PCM solidification is more effective for improving the system performance than providing higher air velocities (Waqas and Kumar 2011a, 2011b; Panchabikesan et al. 2017). El-Sawi, Haghghat, and Akbari (2013, 2014) showed that the thermal performance of the PAHX unit could be enhanced when the temperature difference between PCT range and inlet temperature during the PCM solidification is greater than 10.0°C. Waqas and Kumar (2011a, 2011b) investigated the thermal performance of a PAHX unit utilizing a salt hydrate PCM in the hot dry climate applying various inlet temperatures.

The previously developed PAHX units were proposed to ensure the workability of the system under moderate climates.

Mohamed Dardir, is a Postdoctoral Fellow, an Assistant Lecturer. **Fariborz Haghghat**, Fellow/Life Member ASHRAE, is a Professor. **Mohamed El Mankibi**, is a Professor and a Research Director.

*Corresponding author e-mail: Fariborz.Haghghat@Concordia.ca

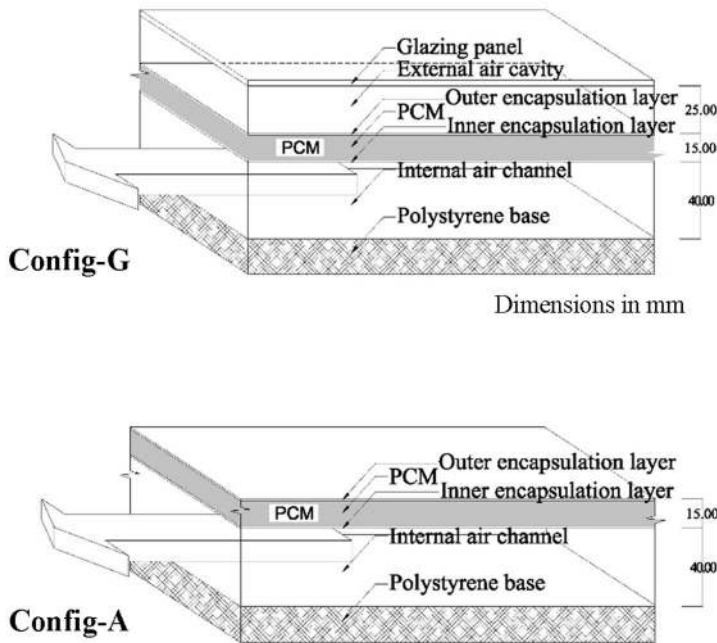


Fig 1. Developed PAHX system design (right), cross-sections of the proposed configurations (left).

Muthuvelan et al. (2018) claimed that the integration of the PAHX unit with other passive cooling techniques such as evaporative or radiative cooling could improve the indoor thermal performance. Soudian and Berardi (2019) proved that integrating the PCM-based systems with well-managed night ventilation strategies (considering operation duration and intensity) could regulate the indoor temperature reducing the energy consumption for cooling under hot summer conditions. The study assured the potential of complete PCM solidification during nighttime in moderate climates. Panchabikesan et al. (2017) studied the integration of a bed packed cylindrical PAHX tank with a direct evaporative cooling unit in a moderate climate. They proved that this integration aided the PCM to be completely solidified at a faster rate by decreasing the PAHX system inlet temperature during PCM solidification. The proposed system showed better thermal performance with higher difference between the inlet air temperature and the PCT range. The approach of using multiple phases of PCM types inside the PAHX system was investigated by Zalba et al. (2004). The system achieved 9.4 times less power consumption compared to a conventional cooling unit. Mosaffa et al. (2013) investigated the multi-PCM approach using a flat plated PAHX. They concluded that a significant difference between PCT of different parts should magnify the system thermal performance. Jaworski (2014) presented a new structure of a ventilated ceiling panel composed of gypsum mortar and 27% of microencapsulated PCM. The developed ceiling system worked as a PAHX free cooling system combined with night ventilation. The results showed that the system achieved a good performance in terms of peak shaving.

However, most of the earlier studies reported the impracticality of PAHXs applications in hot climates in terms of providing sufficient cooling charging energy. This study overcomes this shortcoming by taking advantage of the thermal radiation losses to the nocturnal sky during the PCM

solidification (nighttime and early morning cooling charging). This paper reports the technical feasibility of applying the improved PAHX unit in the hot desert climate. An operational control strategy is proposed to ensure the system workability for cooling application. A parametric analysis is carried out to investigate the influence of design parameters on the system performance. The paper also discusses the influence of integrating the developed PAHX unit into the building ventilation system for enhancing the indoor thermal environment.

Developed PAHX system

The developed PAHX unit consists of PCM panels in contact with an air channel where the air exchanges heat with the PCM. A glazing sheet can be added to the top of the system to create an external air cavity. Accordingly, two configurations are designed, as shown in Figure 1: exposed to ambient environment without glazing layer (config-A), and glazed configuration (config-G). During the cooling charging process, the PCM panel temperature can significantly drop due to the energy exchange by radiation to the sky. The system is mainly designed for free cooling applications by supplying the outlet air to the interior environment or introducing it to a conventional mechanical ventilation system. The numerical model of the proposed PAHX system was developed and experimentally validated (Dardir, El Mankibi, et al. 2019, Dardir et al. 2020).

Operational scenarios

Three different operational scenarios, shown in Figure 2, were defined and investigated:

Scenario 1: The exposed to ambient configuration (without the glazing panel) (config-A),

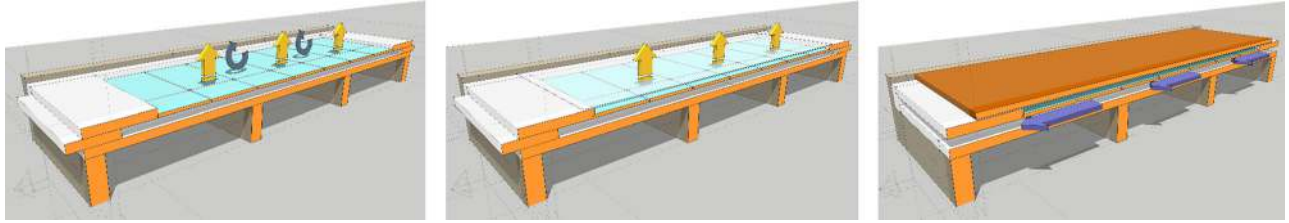


Fig. 2. The operational scenarios: scenario 1 (left), scenario 2 (middle), and scenario 3 (right).

Scenario 2: The configuration with the glazing panel (config-G), and

Scenario 3: The configuration with a thermal insulation sheet, where a 5-mm thick thermal insulation was placed on the top of the system to limit the solar gains during the daytime.

Scenarios 1 and 2 were applied during the cooling charging of the PCM. The inlet and outlet of the air channel were controlled during the operation of the system. Thus, the airflow could be regulated during the charging process (nighttime and early morning periods). The insulated configuration was utilized during the cooling discharging (daytime periods).

Control strategy

This study focuses on the investigation of the thermal performance of the developed PAHX system in the hot desert climate where the high cooling demand prevails, and free cooling is most needed. The hot desert climate (BWh climate according to Köppen classification (Kottke et al. 2006)) is distinguished with hot to exceptionally hot summers with the highest recorded annual average temperatures of 18 °C. It is also featured by dry winters with an accumulated annual precipitation of 250 mm/year and less (Kottke et al. 2006). The main characteristic of the hot desert climate, that promotes the applications of free cooling, is the large diurnal swing between day and night temperatures. However, the high temperature during the nighttime and the seasonal variations in the temperature profile should be considered while designing the free cooling system. Another potential in the hot desert climate is the clear sky conditions, which provides full exposure to the nocturnal sky during the nighttime operations that promotes magnified long-wave radiation losses (Onishi, Nakamura, and Sakai 2009). However, one of the major challenges regarding this climate is the high solar gain during the daytime. Regarding the PCM-based free cooling systems, a control strategy is needed to regulate the system heat gains and losses especially during cooling discharging (the melting of the PCM during daytime).

For the current application of the PAHX system, an operational control strategy was proposed to minimize the heat gains during the daytime application (cooling discharging). During the cooling charging (nighttime and early morning), scenarios 1 and 2 were applied identifying config-A and config-G, respectively. These two scenarios were used to assess the thermal performance of both configurations during the charging process. During the cooling discharging (daytime), scenario 3 was applied by adding the insulation layer to protect the system from the solar gains. Practically, adding the insulation layer could be done mechanically. The air velocity inside

the air channel was initially set to 0.3 m/s during cooling discharging, and the air channel was closed during cooling charging. The control strategy considered the value of the solar radiation as the control parameter that switches between the two operational modes (cooling charging and discharging) with a threshold of 100 W/m² as shown in Figure 3. The threshold was selected to be 100 W/m² to allow the system charging during the early morning to make use of the low ambient air temperature and the low sky temperature during this period.

Thermal performance of the reference case

Table 1 summarizes the system parameters for the reference case of the developed PAHX unit. A parametric investigation was conducted to investigate the impact of location and the type of PCM on the system thermal performance.

Location-based analysis

Several locations within the same climatic region were proposed to investigate the impact of location on the system thermal performance: Six cities were chosen within the hot desert climate with different average ambient air temperature and relative humidity. The locations, exact coordinates of weather stations, and weather data codes are given in Table 2. PCM RT26 was used as a PCM; Table 3 gives its thermal properties. The first week of summer (June 21st–June 27th) was selected to represent the typical weather behavior of the cooling season in these regions.

The thermal performance of the developed PAHX system during cooling discharging was determined in terms of heat exchanger (HX) effectiveness with respect to the ambient air temperature as the system inlet temperature and the sky temperature as the reference temperature of the energy source (the minimum temperature the system can theoretically reach). Both control operational configurations that were defined in “Operational scenarios” and “Control strategy” were compared using the effectiveness criterion. The HX effectiveness (ε) for the specified free cooling application of this study can be defined as:

$$\varepsilon = \frac{T_i - T_o}{T_i - T_r} \times 100 (\%) \quad (1)$$

where $(T_i - T_o)$ is the achieved reduction in the air temperature by the system application (the difference between the ambient air temperature (T_i) and the system outlet air temperature (T_o)), and $(T_i - T_r)$ is the maximum reduction that can theoretically be achieved with respect to the sky

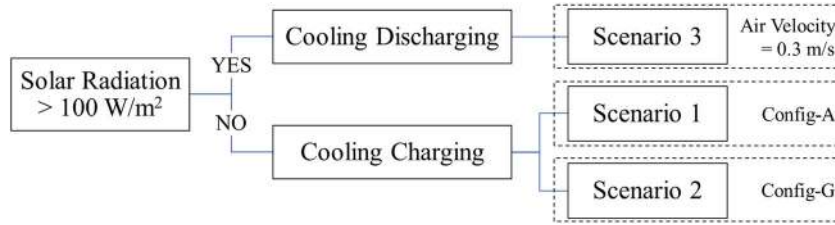


Fig. 3. The operational control strategy of the developed PAHX in respect of solar radiation.

Table 1. System parameters for the reference case.

Variables	Value	Unit
System length	2	m
System width	0.9	m
PCM panel thickness	0.015	m
Air channel height	0.04	m
Air velocity (during discharging)	0.3	m/s

Table 2. The weather data codes of the locations of the study (EnergyPlus 2019).

Location	Coordinates	Weather Data Code
01 Cairo	(N 30° 7') (E 31° 23')	623660 _ ETMY
02 Asyut	(N 27° 2') (E 31° 1')	623930 _ ETMY
03 Aswan	(N 23° 58') (E 32° 46')	624140 _ ETMY
04 Riyadh	(N 24° 42') (E 46° 47')	404380 _ IWEC
05 Kuwait	(N 29° 13') (E 47° 58')	405820 _ KISR
06 Abu Dhabi	(N 24° 25') (E 54° 39')	412170 _ IWEC

Table 3. Thermal properties of RT26 (Rubitherm, GmbH 2019).

Melting range (<i>heating</i>)	25–26 (<i>peak of 26</i>)	°C
Solidification range (<i>cooling</i>)	26–25 (<i>peak of 26</i>)	°C
Thermal storage capacity*	180 ($\pm 7.5\%$)	kJ/kg
Heat capacity	2	kJ/kg.K
Density	880 (<i>solid</i>)	kg/m ³
	750 (<i>liquid</i>)	kg/m ³
Thermal conductivity	0.2	W/m.K
Volume expansion	12.5	%

*Combination of latent and sensible heat in a temperature range of 19 °C to 34 °C

temperature (T_r) as an energy source. Equation 1 was only applied during system operation (cooling discharging of the system). It is worth mentioning that both the ambient air temperature and the sky temperature are functions of the specific location. Figure 4 shows the average values of the ambient air temperature and relative humidity (RH) values during daytime and nighttime for all the locations during the proposed summer weekly application (June 21st–June 27th). The daytime and nighttime periods are referring to the actual periods of charging and discharging of the system. The effectiveness of the PAHX system during cooling discharging was presented by Figure 5. The outlet air temperature, average ambient air temperature and the average sky temperature of the proposed weekly application were calculated

and plotted in the figure. Regarding the difference between the average ambient air temperature and the average outlet air temperature, better performance can be seen in cities with lower RH values and lower ambient air temperature during discharging. In some cities, the extremely high average daytime air temperature affected the performance of the proposed system. In locations with high sky temperature, the system performance was affected due to the reduced available cooling potential of the climate. The application in Cairo and Asyut, which is used for further simulations in this study, achieved the lowest average outlet air temperature promoting higher cooling potential of the system for enhancing the indoor thermal comfort in these locations.

In general, the results show that in most cases config-A achieved a higher HX effectiveness value than config-G, See Figure 5. Only in Riyadh, due to the lowest sky temperature and RH values, the longwave radiation losses were magnified increasing the radiation cooling potential; meanwhile, the relatively high nighttime ambient air temperature affected the thermal losses process discouraging the exposure to the convection heat transfer. Therefore, only in this case, it can be noticed that the HX effectiveness of config-G was 5.6% higher than config-A. However, in all other cases applying the glazing layer to the system during cooling charging (PCM solidification) affected the system performance during the discharging application. Though, applying config-G can be more beneficial in other climates or different duration of the application. Figure 6 shows an example of a 3-days application (June 23rd–June 25th) in the city of Asyut within the proposed summer weekly application. Referring to both configurations, the PCM solidification was maintained with less solidification duration while using config-A allowing the system to reach a lower temperature during charging process. The figure shows that the PCM solidification while applying config-A was limited to 4–7 hours during the whole charging period, which lasted for almost 12 hours. The air temperature inside the channel dropped significantly during charging process, which promoted better system performance during discharging. On the other hand, the duration of the PCM solidification in config-G was almost doubled which slightly affected the outlet air temperature during the cooling discharging. Based on these observations, config-A was used for further investigations in this study.

Selection of PCM

Several commercially available PCM types were selected to evaluate the thermal performance of the system during the

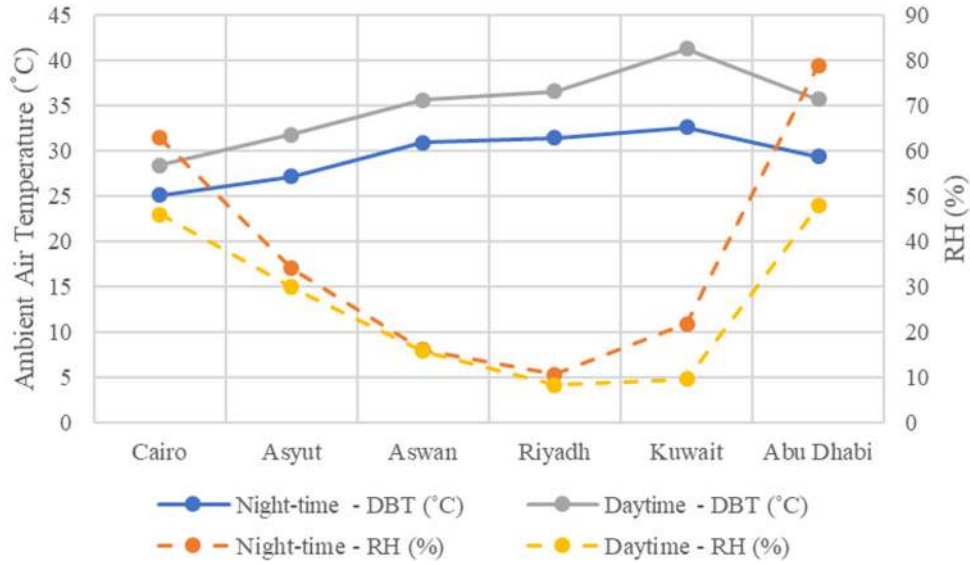


Fig. 4. The average values for ambient air temperature and RH for all the proposed locations during the proposed summer weekly application.

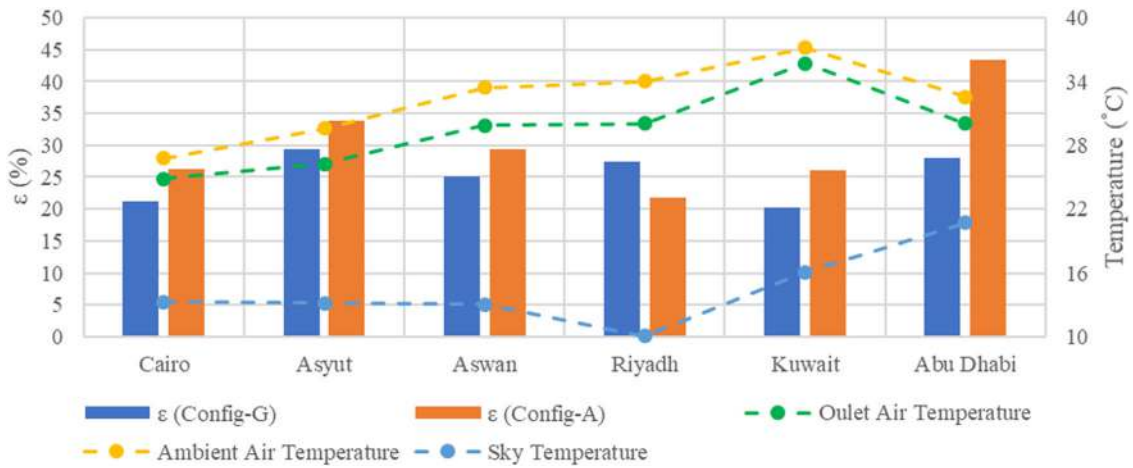


Fig. 5. HX effectiveness and outlet air temperature in all the proposed locations.

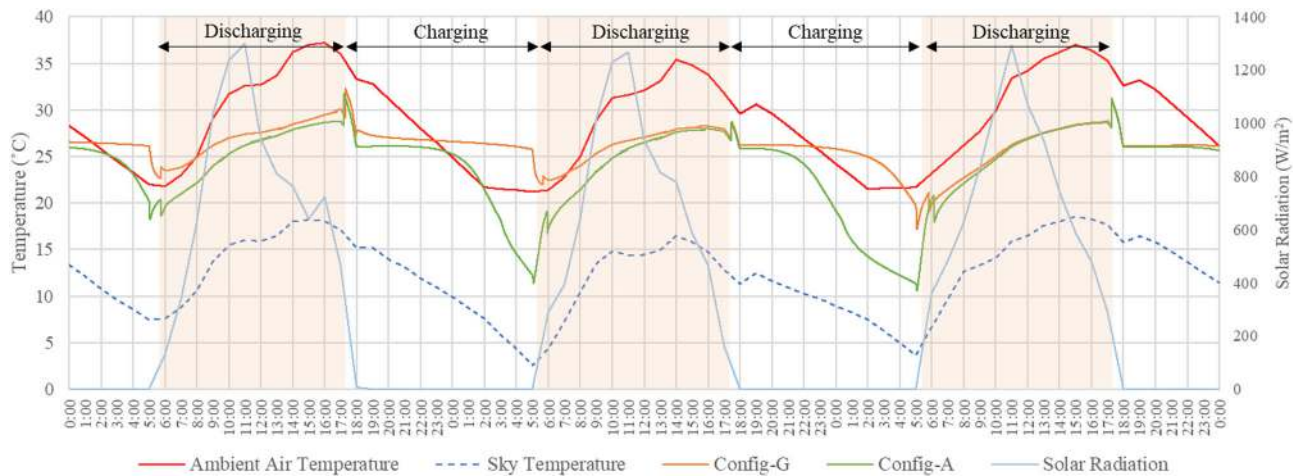


Fig. 6. Outlet air temperature during charging and discharging of the PAHX system.

Table 4. Proposed types of PCMs.

PCM	PCT Range	Storage Capacity
RT18HC	17 °C–19 °C	260 kJ/kg
RT22HC	20 °C–23 °C	190 kJ/kg
RT25HC	22 °C–26 °C	210 kJ/kg
RT26	25 °C–26 °C	180 kJ/kg
RT28HC	27 °C–29 °C	250 kJ/kg
RT31	27 °C–33 °C	165 kJ/kg

typical summer week for a cooling application in Asyut city. Table 4 gives the physical properties of selected PCMs. Config-A was employed applying the control strategy mentioned in “Control strategy” while charging and discharging. Figure 7 shows the outlet air temperature while applying various types of PCMs from June 23rd to June 25th for the selected PCMs, and Figure 8 shows the HX effectiveness. The results showed that choosing the PCM with a proper PCT range is more efficient than applying the PCM with a higher storage capacity. For this specific application, RT25HC had the highest value of the HX effectiveness and the minimum average outlet air temperature during cooling discharging. Overall, RT22HC and RT25HC recorded a considerable thermal performance for this specific application, which supports utilizing this range of PCT in this location. It can be noticed that a PCM with a lower range of PCT does not necessarily assure a better performance for the PAHX application (in this case RT18HC did not show the best performance). Instead, each location has its own proper range of PCT that promotes a better performance, which assures the locality of the PCM-based free cooling applications.

Thermal performance of the stand-alone unit

The outlet air temperature of the system was investigated to assess the thermal performance of the single (stand-alone) unit. The system parameters of the reference case were applied to test the thermal performance of the developed PAHX using PCM RT25HC (see Table 5). The insulated configuration was applied during discharging and config-A was utilized during charging with an open-air channel to simplify the operational conditions and for comparison purposes. Thus, the air velocity was set to 0.3 m/s for the whole periods of charging and discharging. According to ASHRAE standard 55 (2013), the adaptive thermal comfort range was developed based on the provided ambient profile. Figure 9 shows the outlet air temperature of the developed PAHX in terms of the adaptive thermal comfort zone. It can be noticed that during most of the charging and discharging periods, the outlet air temperature was within the comfort range. Only during 8.5% of the total duration of the weekly application, the outlet air temperature was higher than the upper limit of the comfort range. Moreover, during 14.5% of the application, the outlet air temperature was less than the lower limit of the comfort range. Whereas the criterion defines the comfort range of the operative temperatures (not the air temperature), only the cooling potential can be

claimed to be increased by applying the PAHX system. It can also be argued that the improved PAHX unit can supply an outlet air that can enhance the indoor thermal comfort conditions.

Parametric analysis

In this section, the influences of the system parameters on the thermal performance of the single PAHX unit were assessed in terms of HX effectiveness. The parametric analysis was focused on monitoring the influence of the main system variables (the air velocity inside the air channel, the PCM panel thickness, the system length in the direction of airflow, the height of the air channel, and the PCT range of the PCM (using the same type of PCM)). Additionally, the multiple-PCM approach was investigated to assess the influence of including different types of PCM in series within the same volume of the system. The analysis was conducted applying the configurational and climatic conditions of the reference case.

Air velocity

The air velocity is an essential parameter in determining the thermal performance of the system. Air velocity values from 0.1 m/s to 1.1 m/s were applied with a step of 0.2 m/s considering an air channel of 40-mm height of. Figure 10 shows the behavior of air temperature in the air channel (at the channel outlet). The results showed that lower air velocity values provided higher HX effectiveness, where they delivered lower outlet air temperature during cooling discharging.

PCM panel thickness

Further simulations were carried out to investigate the impact of PCM thickness on the system performance. The thickness varied from 7 mm to 22 mm with a step of 3 mm. Figure 11 shows that there was an optimal range of thicknesses (between 10 mm and 13 mm) when the system had the highest thermal performance.

PAHX system length

Simulation was also performed to investigate the impact of system length. The length varied from 1.2 m to 3.2 m with a step of 0.4 m. Figure 12 shows that as the length increases the system performance improves. However, after a specific length value (2 m) the improvements in the effectiveness value were limited. As noticed, the average outlet air temperature was stabilized around the peak of the PCT range of the used PCM (25 °C). This means that within this range (2 m–2.8 m), the latent storage of the PCM mass dominates the heat transfer process. Meanwhile, at the length of 3.2 m (increasing the PCM mass), the performance showed further improvement promoting increased cooling potential for increased system lengths.

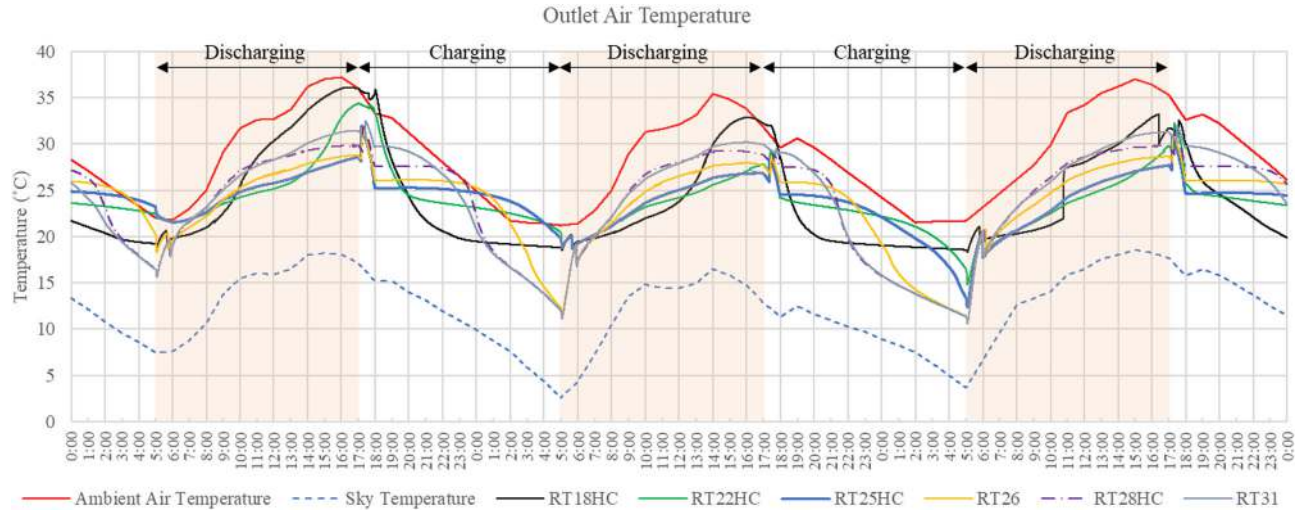


Fig. 7. Outlet air temperature while applying various types of PCMs.

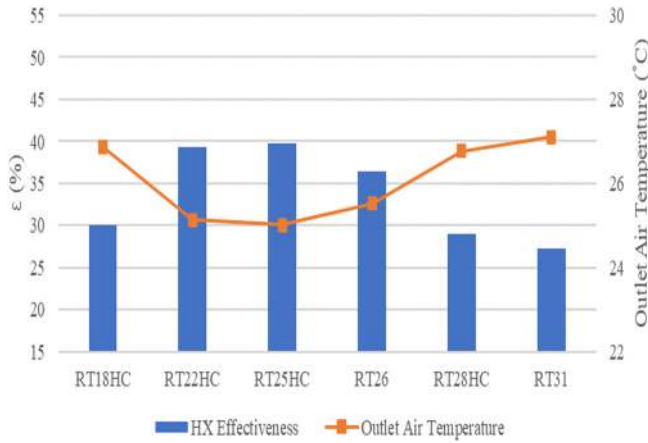


Fig. 8. HX effectiveness of applying various types of PCMs.

Table 5. Thermal properties of RT25HC (Rubitherm, GmbH 2019).

Melting range (<i>heating</i>)	22–26 (<i>peak of 25</i>)	°C
Solidification range (<i>cooling</i>)	26–22 (<i>peak of 25</i>)	°C
Thermal storage capacity*	210 ($\pm 7.5\%$)	kJ/kg
Heat capacity	2	kJ/kg.K
Density	880 (<i>solid</i>)	kg/m ³
	770 (<i>liquid</i>)	kg/m ³
Thermal conductivity	0.2	W/m.K
Volume expansion	12.5	%

*Combination of latent and sensible heat in a temperature range of 19 °C to 34 °C

Air channel height

The impact of air channel on the system performance was studied by varying the gap height from 10 mm to 60 mm with a step of 10 mm, for the case with an air velocity of 0.3 m/s. Figure 13 shows that a higher thermal performance can be achieved by a smaller air channel height. However, the changes occurred in the flow regimes from turbulent to

laminar (starting at the thickness 40 mm) enhanced the thermal performance of the system.

PCT range

The same thermophysical properties of the PCM RT25HC were utilized applying different PCT ranges. A factor of temperature was added to the upper and lower limits of the PCT range of the PCM (22 °C–26 °C) to assess the effect of changing only the PCT range applying the same thermal storage capacity (210 kJ/kg). The temperature factor ranged between -4 °C and $+6$ °C with a step of 2 °C. The results supported the above-mentioned results of PCM selection in “Selection of PCM” that the PCT range is a location-based variable that is related to the local climatic conditions. As shown in Figure 14, a better thermal performance was observed around the PCT range of the reference case. Higher and lower values than ± 2 °C for the added factor to the PCT range lead to lower values of the system effectiveness.

Multi-PCM approach

It has been reported that the system performance can be improved by application of multiple PCM (Mosaffa et al. 2013). Most of the earlier investigation applied a fixed inlet air temperature to investigate the thermal performance of the PAHX unit (Mosaffa et al. 2013; Zalba et al. 2004). With respect to the system length (in the flow direction), the system was equally divided into three consecutive parts (inlet, middle and outlet parts), where the PCM with a higher PCT range was applied to the inlet part. Four different options, presented in Table 6, were designed and compared to the reference case with only one type of PCM (RT25HC). Figure 15 shows that the HX effectiveness of the reference case was higher than all the different compositions of the multi-PCM applications. The lowest performance was observed in *Opt. 01* for PCMs with higher PCT ranges. However, applying PCMs with lower PCT ranges achieved

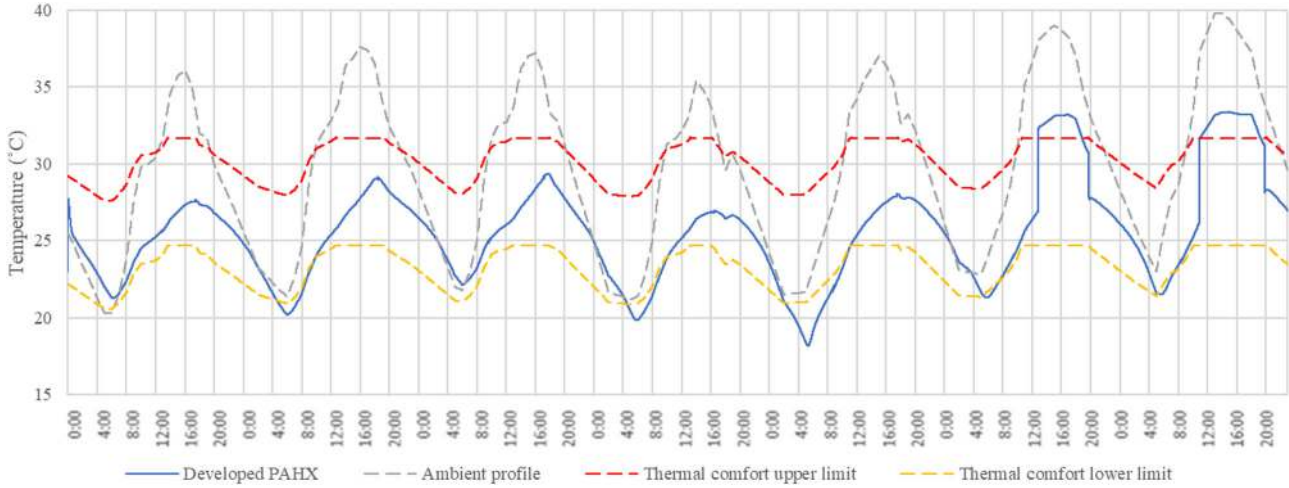


Fig. 9. Outlet air temperature in respect of the thermal comfort range.

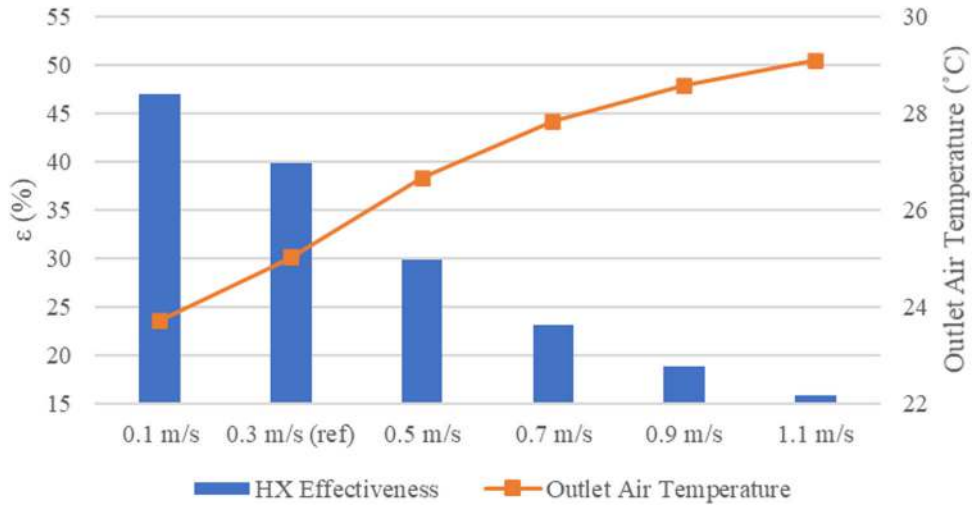


Fig. 10. HX effectiveness of applying various air velocity values inside the air channel.

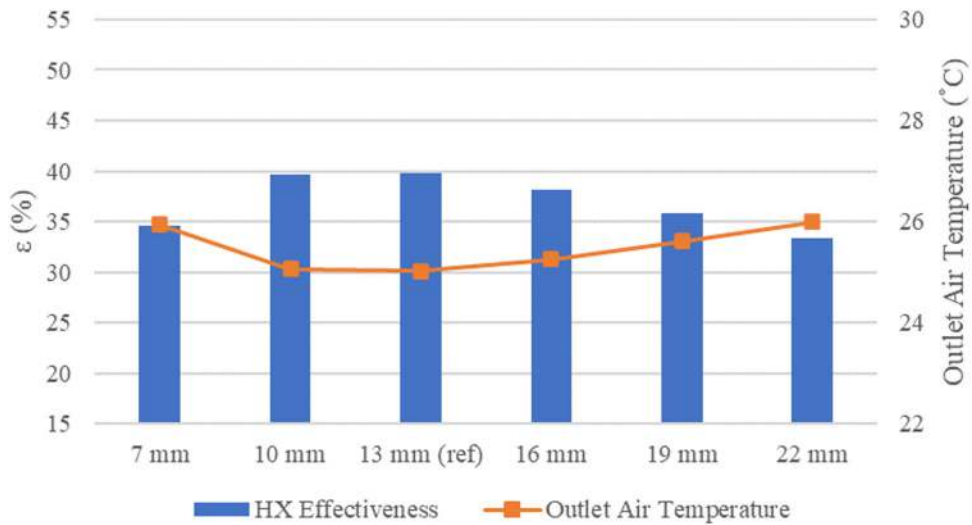


Fig. 11. HX effectiveness of applying various thicknesses for the PCM panel.

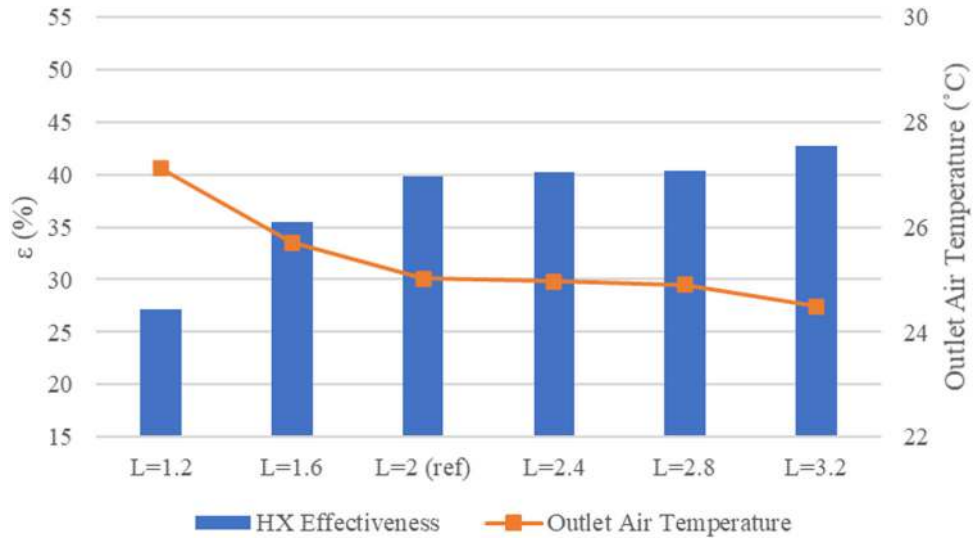


Fig. 12. HX effectiveness of applying various values for system length.

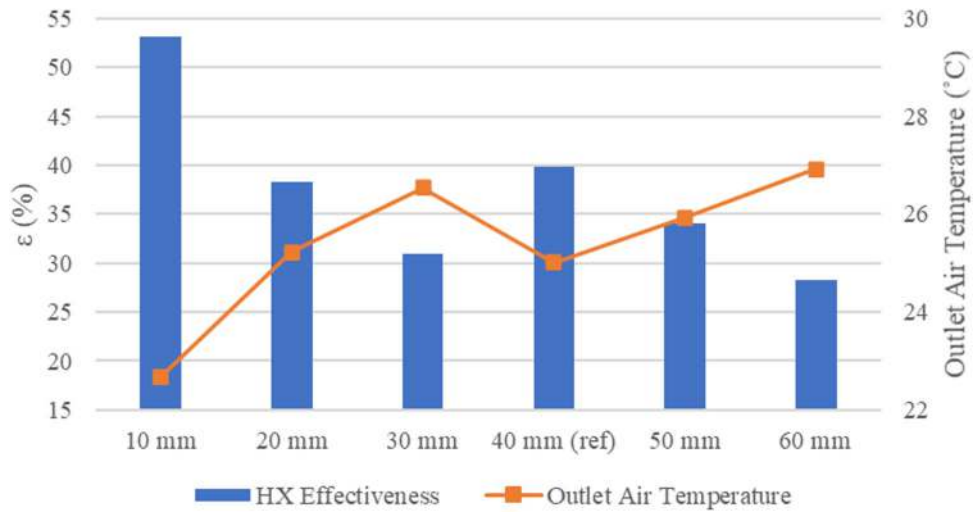


Fig. 13. HX effectiveness of applying various values for air channel height.

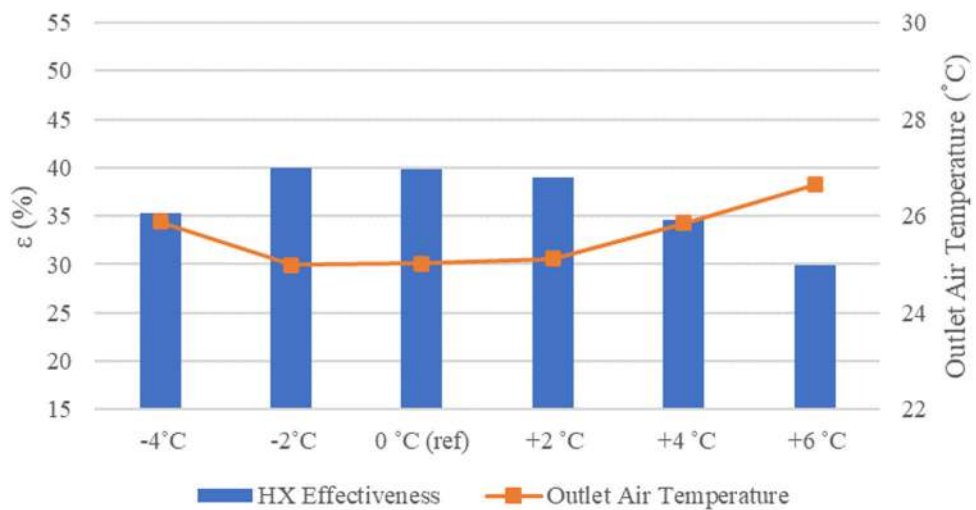


Fig. 14. HX effectiveness of applying various PCT ranges.

better thermal performance. It can be concluded that applying single type of PCM while utilizing the radiative cooling during PCM solidification is more efficient than applying the multi-PCM approach.

Discussion

It was noted that the most influential parameters on the thermal performance of the PAHX unit are the air velocity and the height of the air channel. It can be observed that small air channel heights have significantly increased the HX effectiveness. Meanwhile, the air velocity dramatically affected the HX effectiveness value. This ensures the importance of the convection heat transfer inside the heat exchanger, which most significantly determines the thermal behavior of the PAHX unit. Essentially, the power consumption of the supply fan should be considered in terms of the air velocity, the air channel height, and the system length due to the pressure drop along the system. Generally, the stand-alone performance is an indicator for the real-case system performance when the single unit is integrated to the building ventilation system. The analyses of PCT ranges and multi-PCM approach support the location-based nature of the PAHX system. It is obvious that each location has its own optimum PCT range that achieves a better performance.

Indoor thermal performance

The developed PAHX unit was integrated with a mechanical ventilation system of an occupied space, as shown in Figure

Table 6. Options of multi-PCM approach investigation.

Configuration	Inlet part	Middle part	Outlet part
Reference case	RT25HC	RT25HC	RT25HC
Opt. 01	RT31	RT28HC	RT25HC
Opt. 02	RT31	RT26	RT22HC
Opt. 03	RT28HC	RT25HC	RT22HC
Opt. 04	RT26	RT22HC	RT18HC

16, to assess the effect of this integration on the indoor thermal comfort (in case of direct supply) and the energy consumption. The room under investigation, shown in Figure 17, was assumed to be an office space with a volume of $3 \times 3 \times 2.8 \text{ m}^3$. TRNSYS simulation was used to model the office space utilizing the building type 56 with the assumptions mentioned in Table 7. The investigation was conducted during the typical summer week (June 21st–June 27th) and applying the climatic data shown in reference case analysis. The study was focused on (Room_B) as a typical intermediate space. The outlet air of the PAHX unit can be directly supplied to Room_B to satisfy the indoor cooling loads in direct free cooling applications. Also, it can be introduced to the mechanical cooling unit before supplying the air to the space to reduce the cooling energy consumption of the mechanical system (energy saving strategy). Number of assumptions were made for the simulations. The supply airflow rate and the air temperature of the building ventilation system were considered to be equal to the outlet airflow rate and the outlet air temperature of the PAHX system. Accordingly, the mass flow rate was initially set to 44.58 kg/h. Although, in practical applications, the RH value of the outlet air of the PAHX unit would change due to cooling effect, however, for simplifying the comparison process of the different analysis modes, the RH of the supply air was assumed to be equal to the ambient RH. Four parameters were analyzed: the indoor air temperature, the cooling loads, the thermal comfort level, and the energy consumption of the cooling unit. The indoor thermal comfort defined by ASHRAE standard 55 (2013) is represented by the Predicted Percentage of Dissatisfaction (PPD) index which quantitatively predicts the percentage of thermally dissatisfied people. All the convective and radiative gains to the indoor environment were considered by type 56 in the calculations of thermal comfort. The indoor air, mean radiant, and operative temperatures were calculated considering indoor thermal gains. The space air velocity was calculated using balanced airflow approach considering supply mass flowrate and infiltration. The indoor RH was calculated considering the

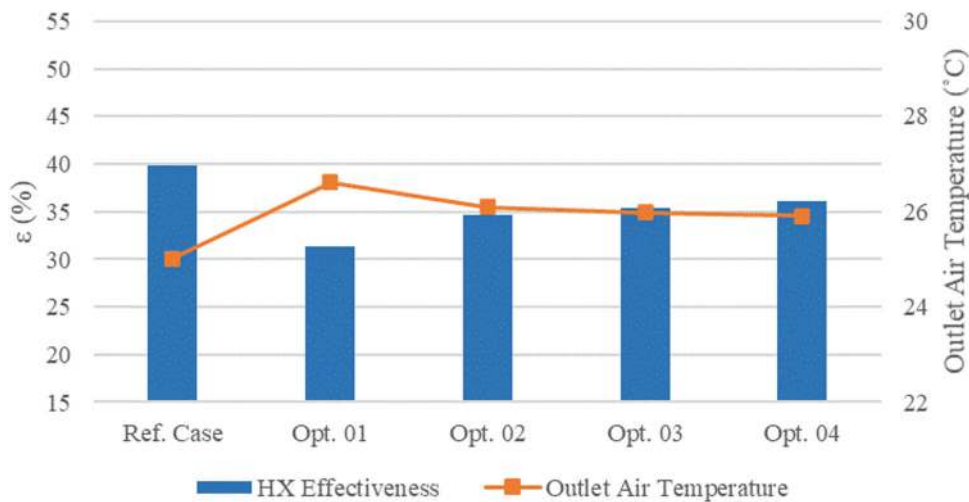


Fig. 15. HX effectiveness of applying various types of PCMs.

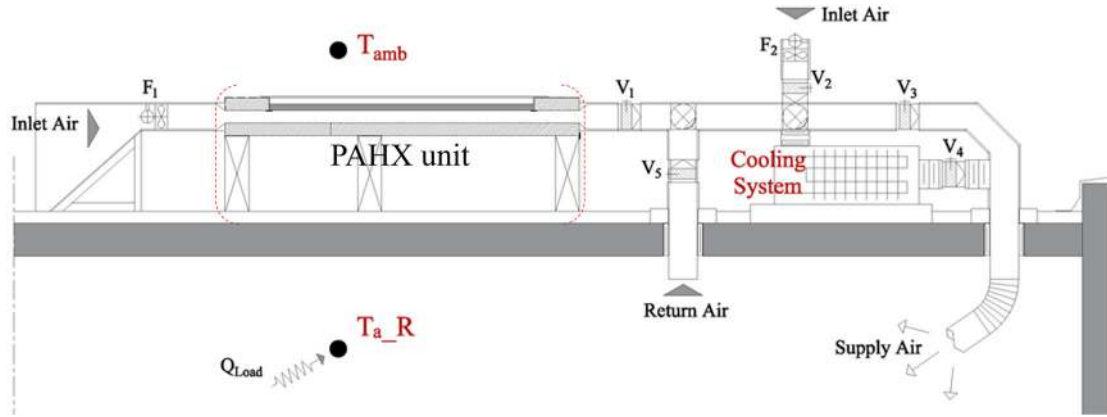


Fig. 16. The integrated PAHX system with the building ventilation system and the cooling unit.

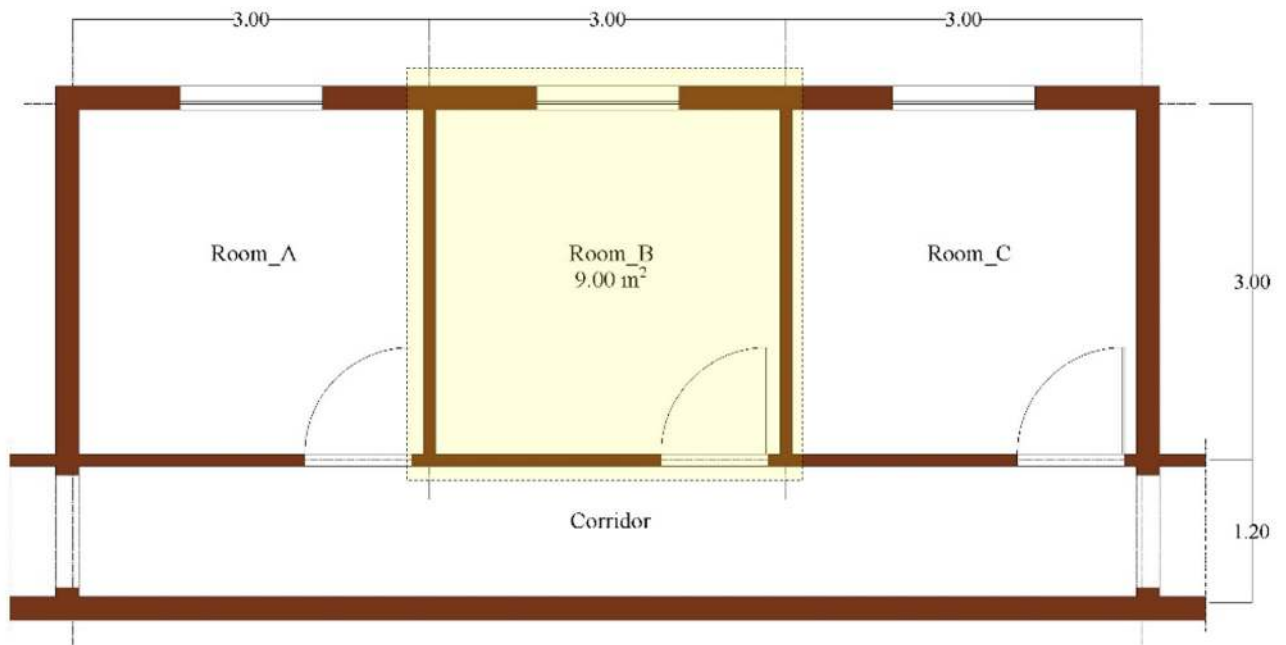


Fig. 17. The proposed office space of the study.

Table 7. Construction and operational assumptions of the office space.

Window to wall ratio	14% (North)
Infiltration	0.2 ACH
Occupation	2 persons / room
Internal gains	14 W/m ²
Clothing factor	0.6 clo
Metabolic rate	1 met
Artificial lighting gains	10 W/m ²
Lighting control	Lower Threshold 120 Lux
(Daylighting plan)	Upper Threshold 200 Lux
Window shading	Fixed horizontal shading (0.4 m in depth)

internal gains, the ambient RH, and the supply air RH of the ventilation system. It is worth mentioning that the air temperature and velocity are critical factors in determining the

indoor thermal comfort. During free cooling applications, the cooling loads were calculated by the energy required to cool down the space air temperature ($T_{a,R}$) to a set-point temperature of 22 °C.

Operational modes

The proposed integrated ventilation system was designed to assess several operational modes. In most of the operational modes, 100% fresh supply air was maintained (no return air was mixed to the supply air). However, in other scenarios, the return air was introduced to the space during PAHX charging periods in order to study its contributions to the required cooling loads and energy consumption. As shown in Figure 16, two fans (F1 and F2) were installed to control the supply airflow: F1 was installed at the inlet of the PAHX unit, and F2 was installed at the inlet of the active cooling unit. Five control valves were installed to manipulate the different modes of operation. Table 8 summarizes

Table 8. Operational modes of integrating the proposed PAHX unit with the ventilation system.

Operational Mode	Fans		Valves				
	F1	F2	V1	V2	V3	V4	V5
Mode 1 (Free running)	OFF	ON	OFF	ON	ON	OFF	OFF
Mode 2 (Free cooling)	ON	OFF	ON	OFF	ON	OFF	OFF
Mode 3 (Free cooling)-Return	ON/OFF	OFF	ON/OFF	OFF	ON	OFF	OFF/ON
Mode 4 (conventional cooling)	OFF	ON	OFF	ON	OFF	ON	OFF
Mode 5 (Energy saving)	ON	OFF	ON	OFF	OFF	ON	OFF
Mode 6 (Energy saving)-Return	ON/OFF	OFF	ON/OFF	OFF	OFF	ON	OFF/ON
Mode 7 (Energy saving)-Ambient	ON/OFF	OFF/ON	ON/OFF	OFF/ON	OFF	ON	OFF

all the designed operational modes utilizing the proposed fans and control valves. **Modes 1, 2, and 3** represent the free operational conditions of the system without the operation of the mechanical cooling unit. While **modes 4, 5, 6, and 7** represent the active cooling operation of the ventilation system operating the mechanical cooling unit.

Mode 1 was designed to identify the free running condition of the building where the ambient air was directly driven to the space for ventilation purposes with no mechanical cooling. The free cooling condition was applied using **mode 2** where the outlet air of the PAHX unit was directed to the space (scenario 1 with an open air channel during charging and scenario 3 during discharging, as discussed in “Control strategy”). **Mode 3** applied the free cooling concept during only discharging. During charging period, the air channel of the PAHX unit was closed, and the return air was circulated to the space. **Mode 4** simulated the conventional cooling scenario where the ambient air was actively cooled before it was supplied to the space. To assess the energy saving potential of the PAHX system, **mode 5** was proposed in which the outlet air of the PAHX unit was directed to the cooling unit to reduce its energy consumption before introducing the air to the space. **Mode 5** assumed that the air was directed through the PAHX unit during both charging and discharging at the same air velocity. **Modes 6 and 7** followed the previous energy saving concept while the airflow was only allowed during the discharging periods. During charging periods with a closed PAHX air channel, the return air and the ambient air were delivered to the cooling unit to be resupplied to the space in **modes 6 and 7**, respectively. **Modes 1, 2, and 3** were used to assess the system performance in terms of the thermal comfort levels (percentage of PPD) and the cooling loads, while **modes 4, 5, 6, and 7** were investigated to evaluate the energy consumption of the cooling unit.

Building envelope characteristics

Two different characteristics were defined for the proposed building envelope: heavyweight and lightweight construction types. Usually, the heavyweight construction defines the conventional buildings in the hot desert region; while the lightweight envelopes are one of the main features of the contemporary construction style, see Table 9. The roof

construction and the glazing type were assumed to be similar in both types.

Direct free cooling

The three free operational **modes (1, 2, and 3)** for the integrated ventilation system were tested without the operation of the mechanical cooling. The airflow rate was the same in all modes, which was similar to the reference case (44.58 kg/h). The analysis utilized the weekly average values of the room air temperature, PPD, and cooling loads to evaluate the thermal performance of the building during the typical summer week application.

- **Heavyweight Building Type**

Figure 18 shows the simulation results of the passive modes for the heavyweight building type. It shows that **mode 2** (direct free cooling) achieved the lowest average values of the room air temperature (30.77 °C) and the PPD (57.01%). Thus, **mode 2** accomplished an enhancement of 16.4% in the PPD level than the free running condition of the building (**mode 1**); this also indicates a reduction of 10.4% in cooling loads. However, **mode 3** achieved the least required amount of energy for satisfying cooling loads (81.38 kWh) with a reduction of 14.5% than **mode 1** (due to the return air strategy), but with a reduction of only 2.8% in PPD levels. Based on the results, **mode 2** maintained better indoor thermal comfort conditions.

- **Lightweight Building Type**

Figure 19 shows the analysis of the average values of room air temperature, PPD, and cooling loads for the lightweight building type during the typical summer week. It can be inferred that applying **mode 2** (direct free cooling) enhanced the thermal comfort levels than the free running case (**mode 1**) by 10.1% with a reduction of 10.5% in the cooling loads. Meanwhile, utilizing the return air during PAHX charging time in **mode 3** achieved a reduction of 14.6% in the cooling loads but without any enhancements in the PPD levels. It can be noticed that, in general, the thermal comfort levels were enhanced in heavyweight building type than the lightweight type for all the modes. Comparing the two building types in case of direct free cooling mode (**mode 2**), the analysis shows an enhancement of about 17% in PPD levels when heavyweight construction was utilized.

Table 9. Envelope characteristics for the used building types.

		Layer	Thickness (m)
Roof <i>U-value (0.324 W/m²K)</i>		Plaster (innermost layer)	0.02
		Concrete slab	0.25
		Insulation	0.1
		Flooring tiles	0.02
Glazing <i>U-value (5.68 W/m²K)</i>		Single glazing	0.004
Heavyweight <i>U-value (1.012 W/m²K)</i>	Exterior walls	Plaster (innermost layer)	0.01
		Limestone	0.4
	Interior walls <i>U-value (1.711 W/m²K)</i>	Plaster (outermost layer)	0.015
		Plaster (innermost layer)	0.01
		Limestone	0.2
Lightweight <i>U-value (0.342 W/m²K)</i>	Exterior walls <i>U-value (0.342 W/m²K)</i>	Plaster (outermost layer)	0.01
		Plaster (innermost layer)	0.01
		Gypsum boards	0.05
	Interior walls <i>U-value (0.652 W/m²K)</i>	Insulation	0.1
		Plaster (outermost layer)	0.015
	Gypsum boards (innermost layer)	0.012	
	Insulation	0.05	
	Gypsum boards (outermost layer)	0.012	

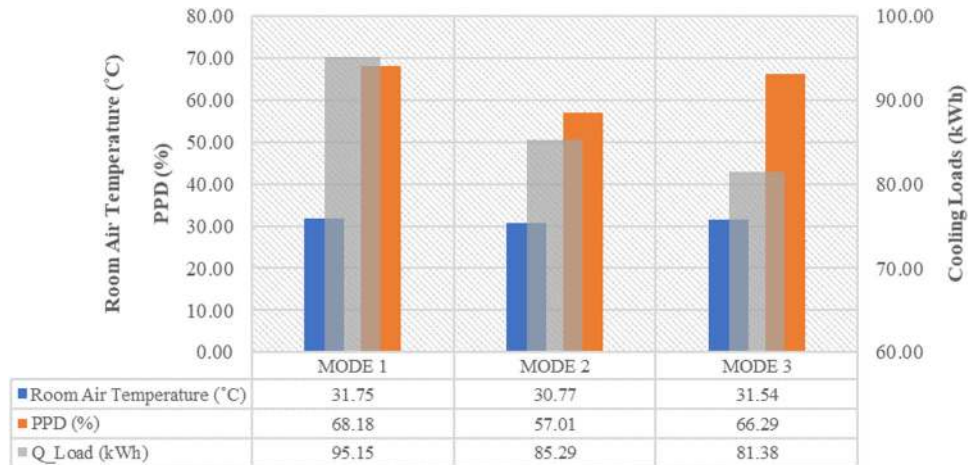


Fig. 18. Results of free cooling investigation for heavyweight building.

Energy saving strategy

Energy saving modes (*modes 4, 5, 6, and 7*) aimed at the conservation of the cooling energy consumed by the mechanical ventilation system by introducing the PAHX outlet air to the active cooling unit. For all the modes, the mass air-flow rate was maintained to be 44.58 kg/h, and the set-point temperature of the cooling unit was set to 6 °C with no specified set-point temperature for the space. The average values of the room air temperature and the PPD were assessed for the typical summer week application. Regardless the applied mode, the average room air temperature recorded 25.7 °C and 26.3 °C for heavyweight and lightweight building types, respectively. The average PPD recorded 9.1% and 13.7% for heavyweight and lightweight building types, respectively.

Figure 20 shows the energy consumption of the cooling system for the four modes during the typical summer week

application. It can be inferred that the continuous supply of the PAHX outlet air to the cooling system (*mode 5*) instead of the ambient air (*mode 4*) reduced the energy consumption of the cooling unit by 16.9% consuming an amount of energy of 4.5 kWh/m² in respect to the room area. However, introducing the return air to the cooling system during PAHX charging periods in *mode 6* did not attain more reduction in energy consumption. Meanwhile, as expected, introducing the ambient air during PAHX charging (*mode 7*) decreased the overall energy consumption by only 11.2%.

Influence of airflow rate on the indoor thermal performance

Further simulation was conducted to study the influence of airflow rates on the indoor thermal comfort levels and the energy consumption of the mechanical ventilation system in case of

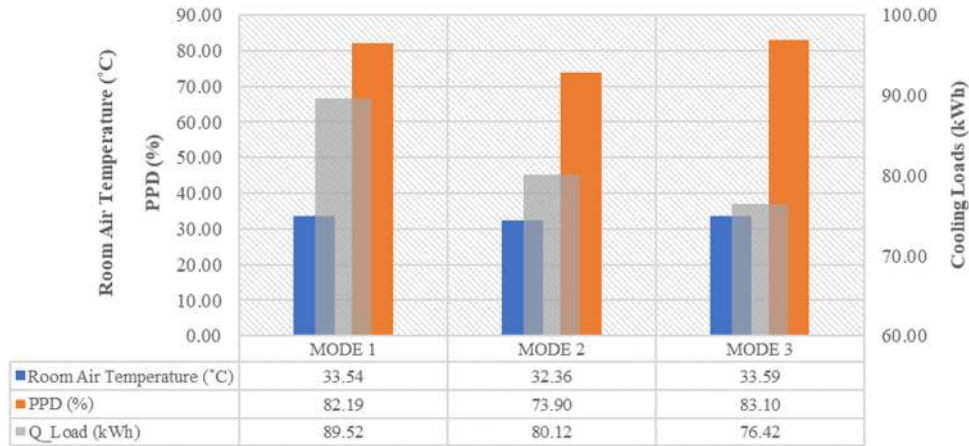


Fig. 19. Results of free cooling investigation for lightweight building.

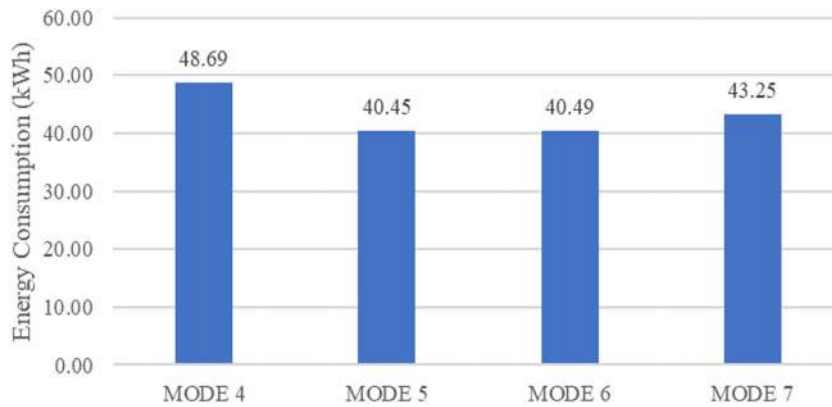


Fig. 20. Energy consumption of the energy saving modes during the typical summer week.

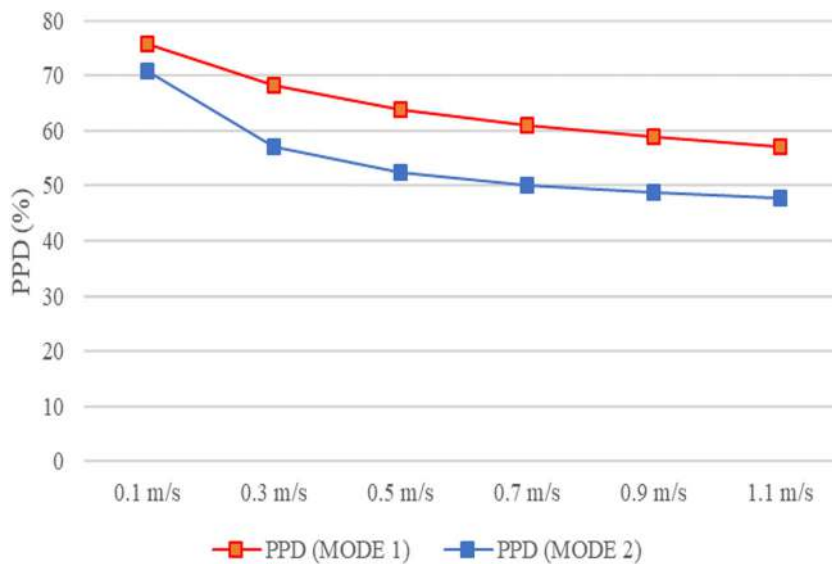


Fig. 21. Thermal comfort levels of direct free cooling for elevated air velocities.

heavyweight construction. The range of airflow rates was similar to those investigated earlier in “Air velocity” for the PAHX parametric analysis. Meanwhile, the airflow rate of the ventilation system was considered to equal the airflow rate of

the PAHX system. The PPD levels and the energy consumption were assessed for direct free cooling (*mode 2*) and energy saving strategy (*mode 5*), respectively. Regarding the direct free cooling application, the weekly average PPD value for

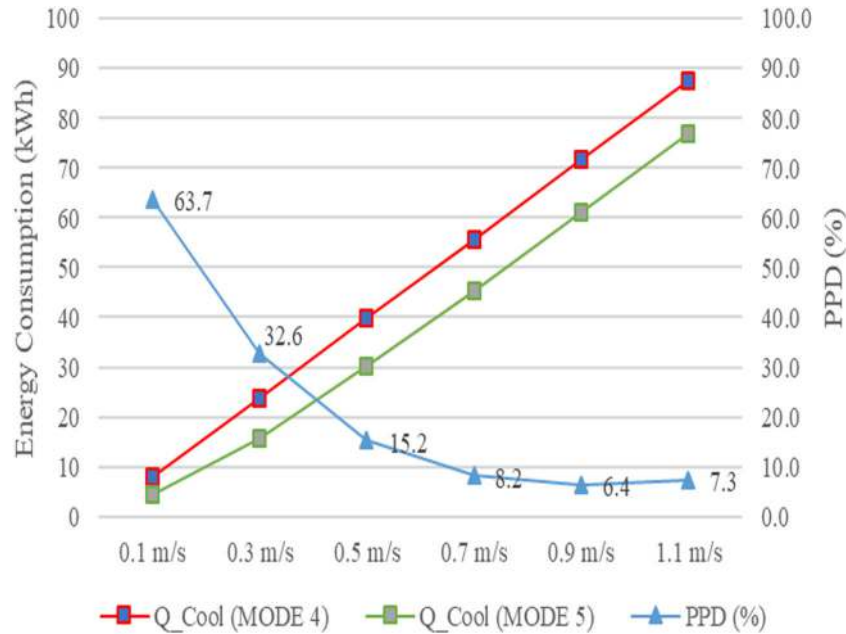


Fig. 22. Energy consumption and thermal comfort levels of energy saving mode for elevated air velocities.

mode 2 was compared to the free running condition (*mode 1*). Figure 21 shows that higher air velocities provided lower PPD values. The application recorded a PPD value of 47.9% with direct free cooling and an air velocity of 1.1 m/s. Overall, *mode 2* achieved an enhancement in the PPD levels up to 17.9% than the free running condition (*mode 1*).

The accumulated energy consumption during the typical summer week was evaluated for the energy saving mode (*mode 5*) and the conventional cooling application (*mode 4*). The set-point temperature of the cooling unit was reset to 18°C to avoid over cooling by the higher air velocities. Figure 22 shows that lower values of airflow rates achieved lower energy consumption values (with lower provided PAHX outlet air temperature), however, they achieved higher values for PPD levels. The PPD levels were maintained below 9% for air velocity values of 0.7 m/s and higher. For the air velocity of 0.7 m/s, the application recorded an average PPD of 8.2% with a reduction of the energy consumption of the cooling system of 10.3 kWh, which represented 18.4% of the weekly energy consumption. The reduction in the accumulative energy consumption increased with the elevated air velocity values that reached up to 10.8 kWh (1.2 kWh/m²) for an air velocity of 1.1 m/s. The later observation was also supported by Soudian and Berardi (2019) that the cooling energy use decreases with increased airflow rates applying appropriate PCM integrated systems.

Conclusion

An innovative PCM-to-Air Heat Exchanger (PAHX) was developed utilizing the radiative thermal losses to the sky during the PCM solidification (cooling charging) to increase the system cooling performance in the hot desert climate. The location-based analysis of the developed PAHX within

various locations in the hot desert climate assured that the free cooling system parameters should be carefully designed with respect to the location (climate). An operational control plan was proposed to block the solar radiation during the daytime (cooling discharging) and to allow the thermal losses to the clear sky during nighttime. A parametric analysis was conducted to demonstrate the influence of applying various values of the system variables on the system thermal performance. The investigated parameters included: the air velocity within the air channel, the PCM panel thickness, the system length, the height of the air channel, and the PCT range of the PCM. Also, the multi-PCM approach was discussed and evaluated utilizing different compositions of the PCM types.

The outlet air temperature of the single unit was compared with the thermal comfort range of the naturally conditions spaces. It was shown that over 91.5% of the time, the system can provide an outlet air that could satisfy the occupants' thermal comfort indicating the developed PAHX unit as an efficient cooling system.

The single PAHX unit was then integrated to a mechanical ventilation system of an office space, in the hot desert climate, to evaluate its performance in terms of the indoor thermal comfort and energy consumption. Two building types were analyzed: heavyweight and lightweight constructions. In general, under the investigated conditions and assumptions, the heavyweight construction promoted better thermal comfort levels than the lightweight building type during both free running and conventional cooling modes. The thermal comfort levels were assessed utilizing the direct free cooling application of the PAHX unit, and the energy consumption of the cooling system was evaluated during the energy saving operation of the mechanical system. It can be concluded that, during the direct free cooling application, the thermal comfort levels were enhanced by up to 16.4% by supplying the PAHX outlet air directly to the proposed

space. During the energy saving mode, integrating the PAHX unit with the mechanical ventilation system reduced the energy consumption required for cooling by 16.9% saving an amount of energy of 8.24 kWh during a weekly cooling application. The influence of increasing the airflow rate through the ventilation system was assessed. The results showed that higher air velocity values provided better thermal comfort levels. The direct free cooling application provided an enhancement up to 17.9% in thermal comfort levels. For energy saving application, lower airflow rates provided lower outlet air temperatures of the PAHX unit, but with poor indoor thermal comfort conditions. Instead, higher air velocities recorded satisfying performance with respect to the thermal comfort levels achieving a reduction of 18.4% (up to 10.8 kWh/week) for the cooling energy consumption.

In conclusion, the developed PAHX system promoted the energy saving concept when it is integrated with the mechanical ventilation system in the hot desert climate. The study promotes the practical application of the developed PAHX system with respect to the local climatic conditions. However, an optimization study that considers all system parameters and operational conditions of the PAHX unit is highly recommended to reach the optimal thermal performance of the integrated PAHX system, maximizing the indoor comfort levels and minimizing the energy consumption of the mechanical ventilation system. Moreover, the performance analysis should be extended to consider the whole cooling season with respect to the location. It is worth mentioning that the aimed optimization study should be a location-based investigation with respect to the specific climatic characterizations of the location.

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