Comprehensive Review on the Enhancement of Air Conditioning Systems Using Phase Change Materials (PCMs): Applications, Performance, and Challenges

Seyed Amirabbas Tabatabaeemanesh [1], Mohammad Erfan [1], Mohammadreza Safarpoor Khaledi [1] *, Ali Rezaei Niyazkandi [2],
1- ST.C., Islamic Azad University, Tehran , IRAN
2- Iranian Construction Engineering Organization (IRCEO)
***Corresponding Author:** ab.tabatabaee@gmail.com

ABSTRACT
Increasing the efficiency of the air conditioning system can be achieved by injecting fresh air into the building. However, this increases energy consumption. As a proposal, the present study addresses the use of phase change materials (PCM), a heat exchanger, as an alternative to the heating, ventilation and air conditioning (HVAC) system, to extract thermal energy from fresh air and thus reduce energy demand. Calcium chloride hexahydrate ($CaCl_2 \cdot 6H_2O$) is used as the PCM, which is selected by the TOPSIS method based on entropy weights. The energy saved in the increased PCM thickness (from 20 mm to 100 mm) and added longitudinal fins (5 mm wide and 50 mm long) is evaluated in comparison to standard HVAC systems using R134a. For summers in mixed climates, the HVAC system equipped with a heat exchanger with a PCM configuration of 100 mm thickness and 48 fins achieved maximum and average energy savings of 12% and 9%, respectively, when the system was operated for 6 hours. For PCM thicknesses of 75 mm, 50 mm, and 20 mm, the maximum energy savings were 6.64% with 48 fins, 5.22% with 24 fins, and 3.22% with 12 fins, respectively. This study provides policymakers with energy-efficient and sustainable solutions for HVAC systems that can reduce energy demand and help combat climate change.
Keywords:Energy Savings, , Air-phase change material heat exchanger, Retrofitting techniques

1. INTRODUCTION

Cooling affects economic growth and is defined as a catalyst for a healthy life, well-being, and improved productivity for residents of hot climate zones [1]. High ambient temperatures and heat waves, accom- panied by the heat island effect, are identified as the primary causes for an increase in cooling demand in the major cities located in the tropical climate, where almost 60 % of the total energy is exhausted to maintain the thermal comfort of a building [2–5]. Further, by 2040, with 70 % of new constructions in urban areas, the building space in developing nations will double as per the forecast by the International Energy Agency (IEA) [6]. This will increase the energy demand for cooling by 47 Mtoe as the air conditioners (AC) per household unit are expected to increase to 1.6 by 2040 compared to 0.6 in 2019 [6].

In a conventional Heating Ventilation and Air-Conditioning (HVAC) system, a portion of recirculated air is mixed with the fresh air from the ambient to dilute the air in indoor spaces and hence, maintain the quality of air in indoor spaces [7]. Further, the deteriorating indoor air quality in urban spaces and air-borne diseases such as COVID-19 have affected various aspects of human life. Hence, air conditioning societies and state health departments such as ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers),ISHRAE (Indian Society of Heating, Refrigerating and Air Conditioning Engineers) and Washington State Health Department have suggested incorporating fresh air into the recirculated air [8,9]. The fresh air supplement dilutes the air concentration in the closed spaces, thereby reducing further transmission and contamination. The air is incorporated into the system from the ambient at a relatively higher temperature and can reach up to 48 ◦C [10]. This results in a further increase in the energy consumed by a building. Hence, energy-efficient cooling systems are required to make the buildings sustainable.

Phase change materials (PCM) are well known for accumulating thermal energy for the temperature exceeding the phase transition temperature and releasing it when it is below the phase transition temperature, as well as providing a nearly constant temperature oper- ation [11]. These characteristics make them appropriate for a wide range of applications, including solar thermal systems[12,13], the agricultural industry [14], developing integrated photovoltaic thermal systems [15], and regulating indoor temperature in buildings [2,16–20]. PCM can regulate the building temperature using a passive or active system. The integration of phase change materials (PCMs) into construction materials offers various benefits for temperature regulation in buildings. The arrangement of PCM within a wall also affects a building's thermal performance [21,22]. Direct mixing of PCM sim- plifies the process and can yield a temperature difference of 2 ◦C in hot climates like Spain [23]. Studies show that using PCM with a transition temperature of 24 ◦C in reinforced concrete cement can lead to a building temperature reduction of 1.7 ◦C and a peak load shift of 2 h [24]. However, this method has drawbacks, such as impregnation into the building, potentially compromising structural strength and posing hazards in the case of flammable PCMs [25,26]. For cold countries, thermal energy can be stored in the building and district heating net- works, thereby reducing the energy required by the central heating system to 14.8 % [27]. Incorporating a PCM-based heat accumulator increases the heat storage by 69 % as well as improves the overall effi- ciency of the system by 22 % [28]. In addition to building materials, heat exchangers containing PCM are used to cool the air in a building and hence can be used to reduce the energy consumption of a building

[29,30]. It has been experimentally and numerically demonstrated that when a heat exchanger with PCM (melting point 26 ◦C) is used with air at a temperature of 44 ◦C, it can aid in reducing a building's peak de- mand by up to 12 % [31].

Experimental studies have shown that when a PCM-based heat exchanger with single and dual PCMs (melting points 24 ◦C and 26 ◦C) is used to cool the condenser of an AC system, it increases the performance

of the system by 8.8 % and 9.7 %, respectively [32]. Chaiyat [33] used an RT 20 PCM encapsulated bed to experimentally enhance the perfor- mance of a 2 tons of refrigeration (TR) AC system by cooling the air coming from the room and feeding it back to the cooling unit. The modified arrangement led to an energy saving of 9.1 % with a payback period of 4.15 years [33]. A numerical study by modifying the shape, size and arrangement of the PCM configurations concluded that for 2 h of operation, the staggered cylindrical configuration saved energy by 12.5 % compared to conventional AC units [34]. A Simulink-based mathematical model for a modified heat pump system with RT 18 HC PCM observed a maximum energy savings of 8.6 % for summers, while the same was reduced to 1.4 % in winters [35].

From the literature mentioned above, it can be observed that most of the studies have selected PCM on their melting point and latent heat only, and the effect of using a PCM-air heat exchanger in the fresh air inlet on the performance of an HVAC system is yet to study and analyzed. Hence, the authors propose a modified HVAC system with a PCM-based heat exchanger to cool the fresh air before entering the system. The PCM for the heat exchanger is selected using the Multi- Attribute Decision Making (MADM) method. Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) is a MADM method used to select suitable PCM while considering other thermophysical properties. Further, the effect of radial fins on the performance of heat exchangers is studied, followed by the analysis of incorporating modified heat exchangers on the energy savings by an HVAC system.

2. METHODOLOGY

The methodologies used for solving statements are described in the present section and will follow the flow as stated in Fig. 1.

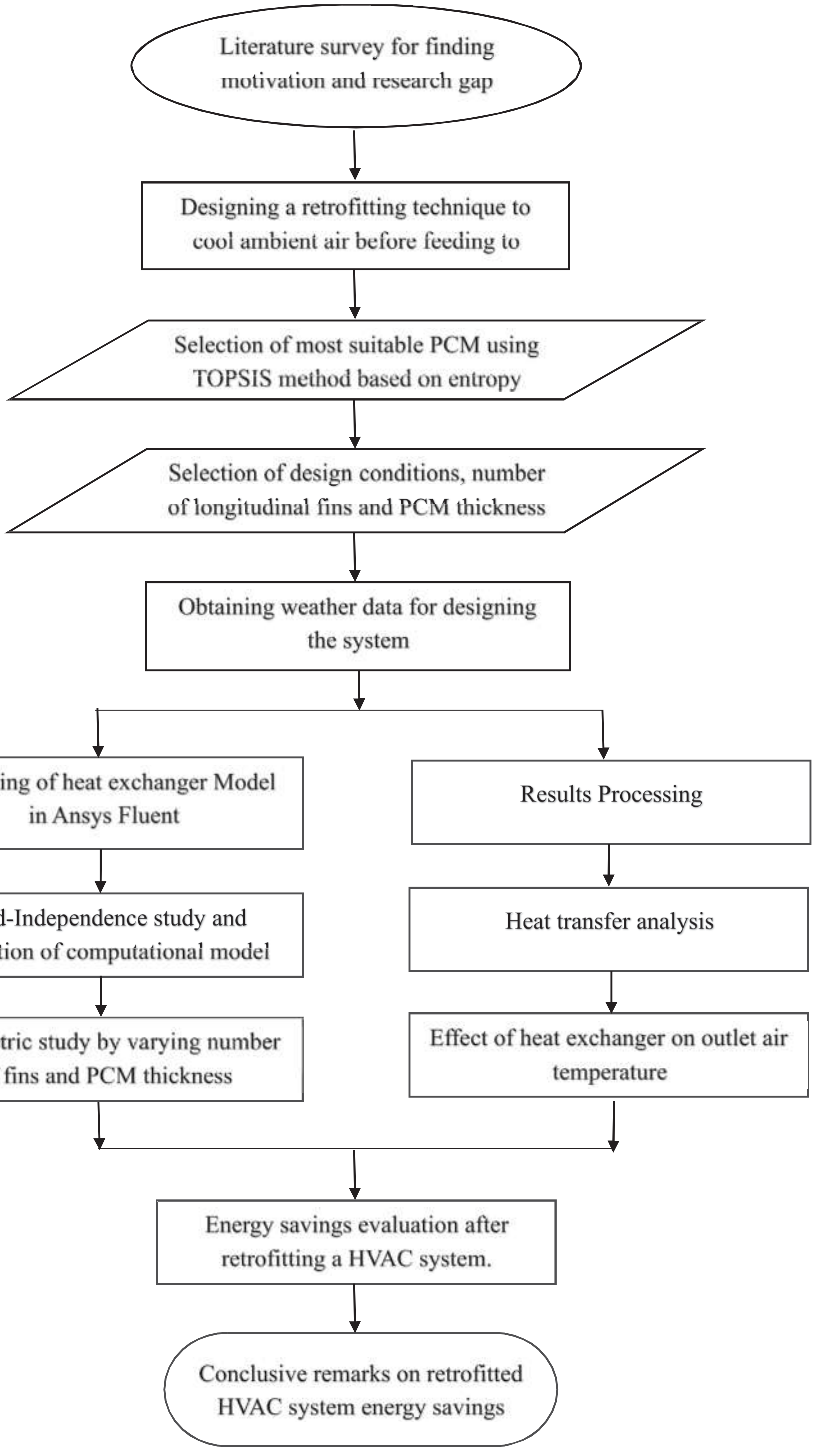


Fig. 1. Flow chart for the study.

3. MATERIAL SELECTION

Researchers have reported various commercial PCMs for numerical as well as experimental studies, but validating the thermo-physical properties of each of them theoretically and experimentally is tire- some and challenging. For research and analysis purposes, the selection is restrained by the experimental data available in the literature and the experience and opinions of the researchers and experts. However, this can lead to an inappropriate selection, which can affect the performance and operation of such a facility [36]. MADM is used for selecting the most suitable among the available options based on the attributes [37], i.e. thermo-physical properties of PCM. TOPSIS is a simple MADM methodology where the best option is nearest to the positive ideal so- lution and farthest from the negative ideal solution [38].

In the domain of data science, entropy denotes the degree of un- certainty related to distinct distributions of probability. In a standard- ized evaluation matrix, the amount of diversity of the data within each attribute determines the weight of the respective attribute, obviating the need for human opinion. Das et. al. [39] performed a comparative evaluation of different MADM methods and found the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method based on entropy-based weights the most appropriate method for making de- cisions. Therefore, this study uses TOPSIS with an entropy-based weight to identify the optimal PCM for the present study. For maintaining human thermal comfort, the first criterion for selecting PCM is that their phase transformation must occur between 27 ◦C and 32 ◦C. Further other thermophysical properties that affect the thermal performance of a PCM-based heat exchanger are the phase change temperature, the latent heat of fusion, the specific heat capacity, thermal conductivity in solid and liquid states and the density in solid and liquid form. Hence, among the documented PCMs in the fore-mentioned temperature range, a few with thermal properties are mentioned in Table 1.

The methodology consists of m assessment criteria “D1, D2, ⋯ Dm”, and n evaluation indices - “X1, X2, ⋯ Xn” for each criterion. The solution was obtained by following the procedure mentioned in Annexure I.

The weights of the attributes obtained for TOPSIS using entropy- based weight [41] to determine the suitable PCM are shown in Fig. 2. It can be observed that different thermo-physical properties play an essential role in the selection of PCM, unlike the conventional approach, where the selection is solely based on melting temperature and the latent heat of fusion. A maximum weight of 0.37 is assigned to the PCM’s latent heat capacity, followed by the material’s density in solid and liquid states with a value of 0.16. In the analysis, the minimum weight is assigned to the phase change temperature, as in the present study, it lies in a very narrow range of 27–C — 32 ◦C. Further, the material’s thermal conductivity and specific heat are considered while selecting the appropriate PCM for the application, as they play an important role in the heat transfer through the material in both solid and liquid states.

Thus, based on the weights obtained by the entropy method, a weight-standardized decision matrix is prepared, and the PCMs are ranked as per their proximity to the ideal and anti-ideal solutions. The ideal solution provides maximum benefits, while anti-ideal is the solu- tion with minimum benefits within a defined set of options. The weight- standardized decision matrix is illustrated in Table 2, along with the rankings of PCM considered for the analysis. It is evident from the standardized decision matrix and proximity to the ideal solution and farthest from the non-ideal solution that calcium chloride hexahydrate is the suitable PCM. Hence, for the study from here onwards, the term ’PCM’ is used for calcium chloride hexahydrate.

The latent heat of fusion and melting temperature of the selected PCM is further determined using a differential scanning calorimeter (DSC). This is because of the inconsistency observed in the latent heat of fusion and melting temperature of calcium chloride hexahydrate in the existing literature.

DSC-Q2000 (TA, New Castle, USA) is used to perform the charac- terization of the selected PCM, i.e., calcium chloride hexahydrate. The instrument is illustrated in Fig. 3 (I)(a) and has a thermal accuracy of ±
0.01 ◦C with a high precision of ± 0.05 %. A microbalance (GR-202,
A&D, Japan) (Fig. 3 (I)(b)) (accuracy – 0.1 mg) is used to weigh the PCM sample placed within the pan and lid. The variance in the heat trans- mission of the sample and a reference is used to evaluate the amount of heat captivated or emitted by the sample of PCM contained in the pan and lid. The furnace is supplied with 50 ml/min of pure nitrogen, and RCS90 (refrigerated cooling system) is used to control the heating and
cooling rate. The PCM is tested for a temperature range of —10 ◦C to 60 ◦C, with a ramp rate of 1 ◦C /min, and Fig. 3(II) shows that the complete melting of PCM occurs at 30.02 ◦C with a latent heat of 171.06 J/g. For uncertainty analysis, characterization is performed three times
for the PCM with an accuracy of 1.1 % in enthalpy of fusion and phase change temperature accuracy of 0.16 ◦C. Hence, in the numerical analysis, the melting point of PCM is considered as 30 ◦C, and the latent heat is 171 kJ/kg.

4. PHYSICAL DOMAIN

The physical domain of the latent heat energy storage system (LHESS), i.e. in shell and tube configuration of 1500 mm length, is represented in Fig. 4. The LHESS is placed vertically with gravity acting along the longitudinal axis of the LHESS, with the heat transfer fluid (air) flowing through the tube along the gravity. The inner and outer tubes are made of an aluminium alloy with a thickness of 5 mm having an inner of 200 mm, while the outer diameter is 250 mm. The annulus is filled with the selected PCM, i.e., $CaCl2·6H2O$, and the thermophysical properties of the selected PCM and air are mentioned in Table 3. Further, the thickness of PCM in the annulus is varied to observe the effect on the performance of the heat exchanger and the air conditioning unit attached to it. The PCM thickness is varied as 20 mm, 50 mm, 75 mm and 100 mm, increasing the corresponding outer diameter to 250 mm, 310 mm, 360 mm and 410 mm, respectively.

From table 3, it can be inferred that the heat transmission through the air will be minimal due to a low degree of thermal conductivity. Extended surfaces(Fins) are known for enhancing the heat transfer rate in fluids with low thermal conductivity [43]. Hence, longitudinal fins are extruded radially, running through the heat exchanger length, and are used on the air side. For the analysis, four different fin configurations are deployed where the number of fins is varied to 6, 12, 24 and 48. The maximum number of fins in a heat exchanger is limited to 48 because they will begin to intersect with one another and adversely impact the flow rate after a certain number of fins. The dimension of the fin is kept constant and has a width of 5 mm and a height of 50 mm.

The analysis of a three-dimensional model of the designed system will be a cumbersome task and will need considerable computational resources. Hence, to save computational time and make it tedious, a section of geometry is used, simplifying the flow problem and repli- cating the designed system, as observed in Fig. 5. For a heat exchanger with 6 fins, the one-sixth axisymmetric three-dimensional domain is taken, which reduces to a one-twelfth three-dimensional for 12 fins, one- twenty-fourth axisymmetric for 24 fins and one-forty-eighth axisym- metric three-dimensional numerical domain for 48 fins, with an assumption of uniform heat transfer in the radial direction and imposing symmetry boundary condition on the selected domain.

The transient flow and heat transfer of the LHESS is analyzed by developing the axisymmetric three-dimensional model for 6, 12, 24 and 48 finned configurations, as illustrated in Fig. 5. To study the melting of the PCM in the melted form, it is considered as an incompressible, laminar and Newtonian fluid. Further, the heat transmission due to ra- diation, change in the volume of PCM during the transition and energy dissipation due to viscosity are neglected. The thermophysical

Table 1. Selected PCMs with thermal properties [39,40].

S. No.	Material	Melting Temperature (°C)	Latent Heat (kJ kg^{-1})	Density (kg m^{-3})		Thermal Conductivity (W m^{-1} K^{-1})		Specific Heat (kJ kg^{-1}K^{-1})	
				Solid	Liquid	Solid	Liquid	Solid	Liquid
1	Bio-PCMQ27	27	251.30	235.00	225.00	0.21	0.19	1.77	0.99
2	RT28HC	28	250.00	880.00	770.00	0.20	0.20	2.00	2.00
3	$CaCl_2.6H_2O$	30	187.00	1710.00	1530.00	1.09	0.54	2.20	1.40
4	OM29	29	229.00	868.00	770.00	0.29	0.17	4.80	3.90
5	Bio-PCMQ29	29	260.70	235.00	225.00	0.21	0.19	2.22	0.27
6	Paraffin wax	32	251.00	830.00	830.00	0.51	0.22	1.92	3.26
7	Capric acid	32	152.70	878.00	878.00	0.37	0.14	0.47	0.47
8	RT31	31	165.00	880.00	760.00	0.20	0.20	2.00	2.00
9	n-Octadecane	27	243.50	865.00	860.00	0.19	0.15	2.14	2.66

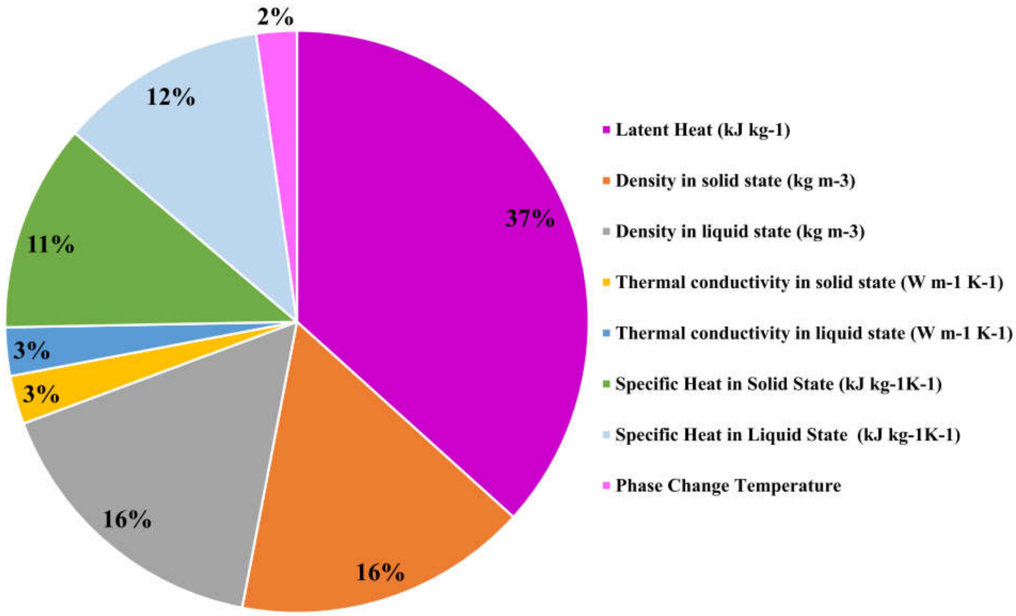
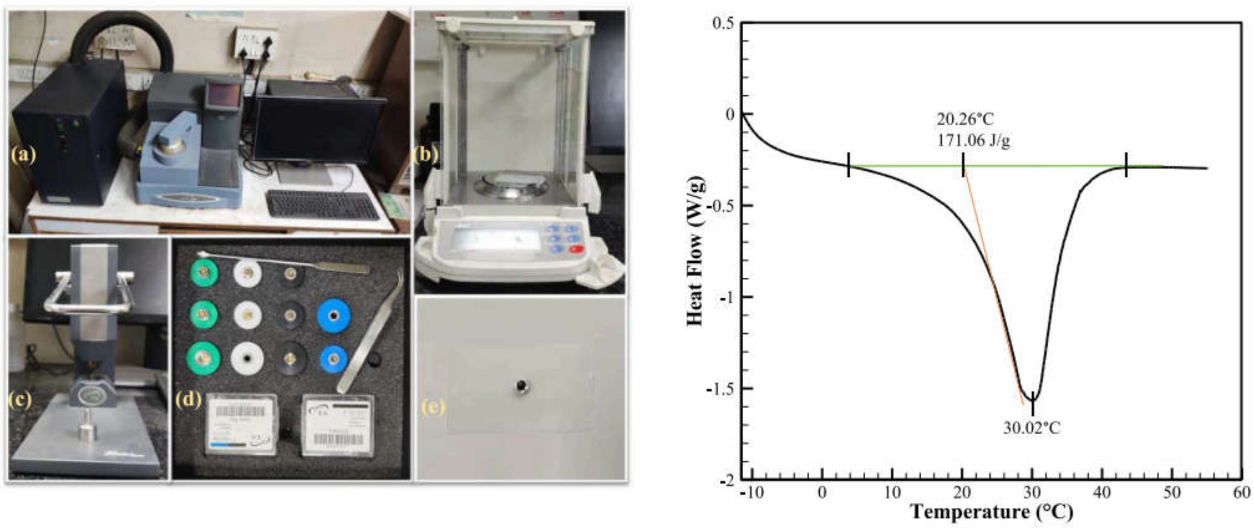


Fig. 2. Weight of attributes obtained by using TOPSIS entropy-based methodology.

Table 2. Weight standardized decision matrix and ranking of PCM using TOPSIS.

S. No.	Material	Melting temperature	Latent Heat	Density		Thermal conductivity		Specific Heat		Si+	Si-	N$^+$	Rank
				Solid	Liquid	Solid	Liquid	Solid	Liquid				
1	Bio-PCMQ27	0.0006	0.0067	0.0121	0.0119	0.0367	0.0284	0.0304	0.0340	0.0067	0.0121	0.644	8
2	RT28HC	0.0006	0.0067	0.0454	0.0408	0.0350	0.0299	0.0343	0.0687	0.0067	0.0454	0.871	6
3	$CaCl_2 \cdot .6H_2O$	0.0006	0.0050	0.0882	0.0810	0.1905	0.0806	0.0377	0.0481	0.0050	0.0882	0.946	1
4	OM29	0.0006	0.0061	0.0448	0.0408	0.0512	0.0257	0.0823	0.1340	0.0061	0.0448	0.88	4
5	Bio-PCMQ29	0.0006	0.0070	0.0121	0.0119	0.0367	0.0284	0.0381	0.0093	0.0070	0.0121	0.634	9
6	paraffin wax	0.0007	0.0067	0.0428	0.0440	0.0898	0.0334	0.0329	0.1120	0.0067	0.0428	0.865	7
7	Capric acid	0.0007	0.0041	0.0453	0.0465	0.0650	0.0210	0.0082	0.0163	0.0041	0.0453	0.917	2
8	RT31	0.0007	0.0044	0.0454	0.0402	0.0350	0.0299	0.0343	0.0687	0.0044	0.0454	0.912	3
9	n-Octadecane	0.0006	0.0065	0.0446	0.0455	0.0332	0.0221	0.0367	0.0914	0.0065	0.0446	0.873	5
	V+	0.0007	0.0070	0.0882	0.0810	0.1905	0.0806	0.0823	0.1340				
	V-	0.0006	0.0041	0.0121	0.0119	0.0332	0.0210	0.0082	0.0093				

Properties of air, tube material and PCM are assumed to be constant, except for the density of PCM, which is approximated using the Bous- sinesq approximation, which considers the buoyancy forces (FB).



I II

Fig. 3. I. (a) Differential scanning calorimeter (b) Microbalance (c) Pressing machine (d) Pans, lids and press (accessories of DSC) (e) PCM encapsulated in pan and lid II. Melting of calcium chloride hexahydrate obtained using DSC.

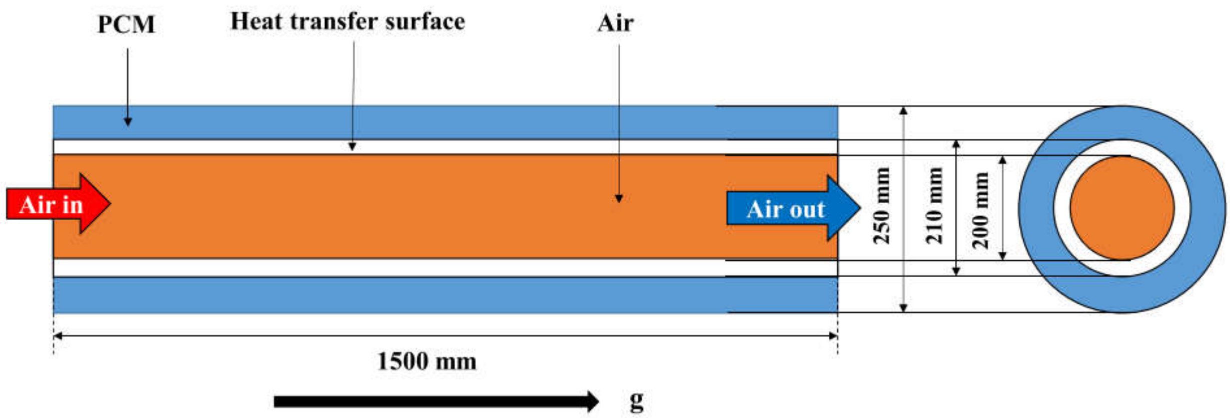


Fig. 4. Schematic layout of the physical domain of the designed LHESS.

Table 3. Thermophysical properties of CaCl2·6H2O and air [39,42].

Property	$CaCl_2{\cdot}6H_2O$	Air
$\rho(kg/m^3)$	1538	1.225
k(W/m K)	0.546	0.0242
c_p(J/kg K)	2230	1006.43
μ(Pa.s)	0.01	1.789×10^{-5}
$T_{solidus}$(°C)	30	–
$T_{solidus}$(°C)	30	–
L_{latent}(kJ/kg)	171	–

5. METHOD OF SOLUTION

The numerical modelling to study the flow and the heat transfer is performed using the finite volume method and ANSYS FLUENT 2021. The SIMPLE algorithm is used for the velocity–pressure coupling, while the PRESTO scheme is used to spatially discretize the pressure equation. The change in pressure from one iteration to other to control the change due to the non-linearity of equations is limited to 0.3; for the momentum, it is limited to 0.7, and for the change in melt fraction, it is limited to 0.7. The convergence criteria in the study for continuity is 10- 3, for momentum is 10-3, and for energy, it is 10-6.

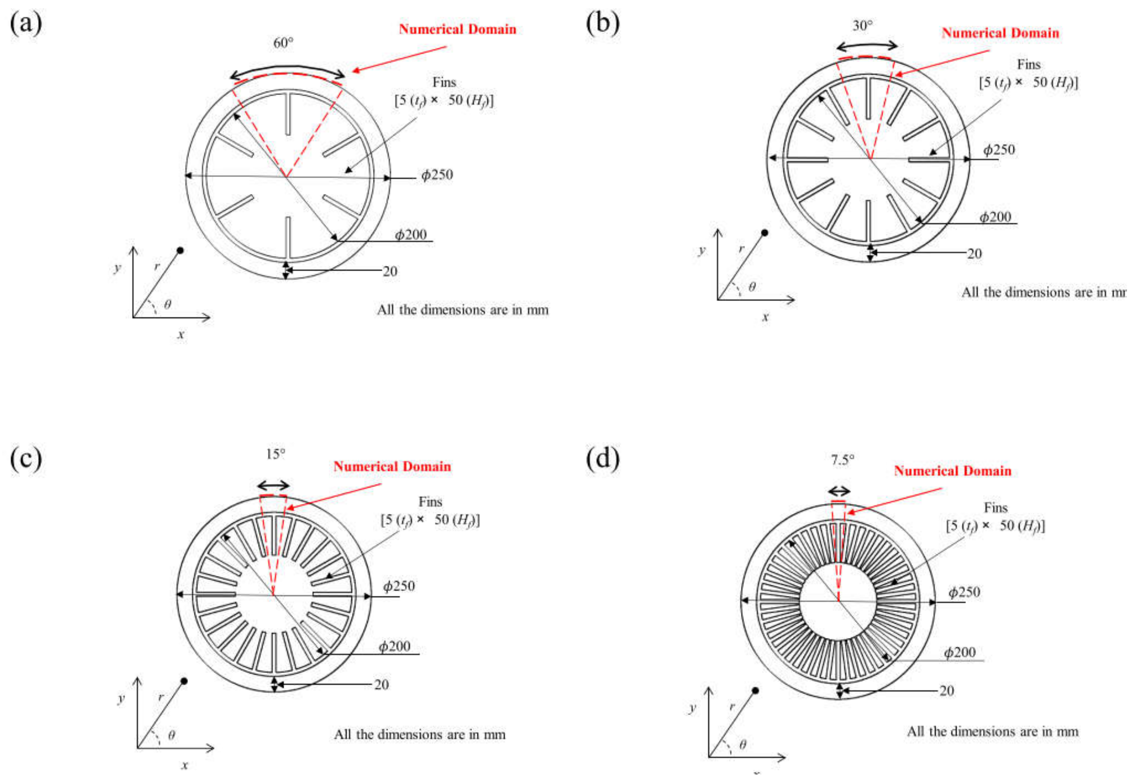
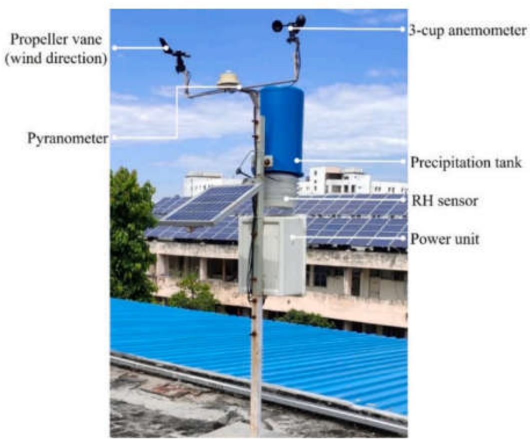
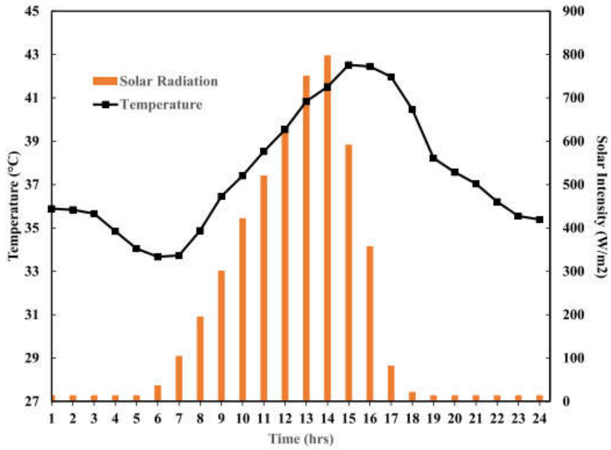


Fig. 5. The physical and numerical domains of the heat exchanger with extended surfaces (fins) (a) 6 fins, (b) 12 fins, (c) 24 fins, and (d) 48 fins.



(a)



(b)

Fig. 6. (a)Weather station for ambient air conditions in Delhi (b) Ambient conditions for 9th June 2022.

6. CONCLUSION

The present study proposes a technique to reduce the energy consumption in conventional HVAC systems by retrofitting them with a PCM-based heat exchanger. The heat exchanger reduces the temperature of fresh air from the ambient before entering the air-cooling unit. The PCM for the application is having melting point within the human thermal comfort range. The following conclusions have been drawn from the analysis: 1. Along with the melting point and latent heat, thermal conductivity, density, and specific heat in both solid and liquid phases affect the thermal performance of a PCM. Calcium Chloride Hexahydrate ($CaCl_2 \cdot 6H_2O$) is most suitable for application as per the TOPSIS method using entropy weights.

2. Longitudinal fins are extruded in air, and a parametric study is done to analyze the effect of the number of fins and the thickness of PCM on the energy savings of the HVAC system. It was observed that the combinations providing lower stable air outlet temperature for a longer duration could achieve more energy savings. 3. When the HVAC system is retrofitted with a heat exchanger with a PCM thickness of 20 mm, the 12-finned version yields the highest energy savings at 3.22 %. For a PCM thickness of 50 mm, the 24- finned variant offers peak savings of 5.22 %. As the PCM thickness increases to 75 mm and 100 mm, the energy savings rise to 6.64 % and 9.06 %, respectively, when using the 48-finned heat exchanger.

4. The study concluded that the heat exchanger with 48 fins and 100 mm of PCM thickness provides a peak energy saving of 12 % and an average energy savings of 9.06 % when operated for 6 h during the daytime.

REFERENCES

N.H. Abu-Hamdeh, A.A. Melaibari, T.S. Alquthami, A. Khoshaim, H.F. Oztop, A. Karimipour, Efficacy of incorporating PCM into the building envelope on the energy saving and AHU power usage in winter, Sustain. Energy Technol. Assessments. 43 (2021), 100969, https://doi.org/10.1016/J.SETA.2020.100969.

M. The, E. Efficiency, P. For, INDIA ' S ROOM AC SECTOR.

R. Verma, S. Kumar, D. Rakshit, B. Premachandran, Design and Optimization of Energy Consumption for a Low-Rise Building With Seasonal Variations Under Composite Climate of India, J. Sol. Energy Eng. 145 (2023), https://doi.org/ 10.1115/1.4054831.

India Energy Outlook 2021 – Analysis - IEA. https://www.iea.org/reports/india- energy-outlook-2021 (accessed September 6, 2022).

S. Vashisht, D. Rakshit, Recent advances and sustainable solutions in automobile air conditioning systems, J. Clean. Prod. 329 (2021), 129754, https://doi.org/ 10.1016/J.JCLEPRO.2021.129754.

V. Kapur, B. Agarwal, G. Baliga, J.M. Bhambure, V. Garg, J. Mathur, R. Mittal, V. Murthy, S. Rajasekaran, Y. Shukla, A. Sur, ISHRAE COVID-19 Guidance Document for Air Conditioning and Ventilation, Indian Soc. Heating, Refrig. Air Cond. Eng. (2020) 15.

Washington State Department of Health, Ventilation and Air Quality for Reducing Transmission of COVID-19, 19 (2020) 1–4.

A. Sharma, S.K. Sharma, T.K.M. Rohtash, Influence of ozone precursors and particulate matter on the variation of surface ozone at an urban site of Delhi, India, Sustain. Environ. Res. 26 (2016) 76–83, https://doi.org/10.1016/J. SERJ.2015.10.001.

A. Kumar, S.K. Saha, Latent heat thermal storage with variable porosity metal matrix: A numerical study, Renew. Energy. 125 (2018) 962–973, https://doi.org/ 10.1016/J.RENENE.2018.03.030.

V. Goel, A. Saxena, M. Kumar, A. Thakur, A. Sharma, V. Bianco, Potential of phase change materials and their effective use in solar thermal applications: A critical review, Appl. Therm. Eng. 219 (2023), 119417, https://doi.org/10.1016/J. APPLTHERMALENG.2022.119417.

C. Li, B. Zhang, B. Xie, X. Zhao, J. Chen, Z. Chen, Y. Long, Stearic acid/expanded graphite as a composite phase change thermal energy storage material for tankless solar water heater, Sustain. Cities Soc. 44 (2019) 458–464, https://doi.org/ 10.1016/J.SCS.2018.10.041.

S.M. Shalaby, M.A. Bek, A.A. El-Sebaii, Solar dryers with PCM as energy storage medium: A review, Renew. Sustain. Energy Rev. 33 (2014) 110–116, https://doi. org/10.1016/J.RSER.2014.01.073.

S. Kumar Verma, R. Kumar, M. Barthwal, D. Rakshit, A review on futuristic aspects of hybrid photo-voltaic thermal systems (PV/T) in solar energy utilization: Engineering and Technological approaches, Sustain. Energy Technol. Assessments. 53 (2022), 102463, https://doi.org/10.1016/J.SETA.2022.102463.

A. Sharma, V.V. Tyagi, C.R. Chen, D. Buddhi, Review on thermal energy storage with phase change materials and applications, Renew. Sustain. Energy Rev. 13 (2009) 318–345, https://doi.org/10.1016/j.rser.2007.10.005.

C. Croitoru, I. Nastase, F. Bode, A. Meslem, A. Dogeanu, Thermal comfort models for indoor spaces and vehicles - Current capabilities and future perspectives, Renew. Sustain. Energy Rev. 44 (2015) 304–318, https://doi.org/10.1016/j. rser.2014.10.105.

J. KoS´ny, K. Biswas, W. Miller, S. Kriner, Field thermal performance of naturally ventilated solar roof with PCM heat sink, Sol. Energy. 86 (2012) 2504–2514, https://doi.org/10.1016/j.solener.2012.05.020.

R. Saxena, D. Rakshit, S.C. Kaushik, Experimental Assessment of Characterised PCMs for Thermal Management of Buildings in Tropical Composite Climate, in: MCM2018, Avestia, Madrid, Spain, 2018. https://doi.org/10.11159/htff18.170.

Z. Cao, G. Zhang, Y. Liu, X. Zhao, C. Li, Influence of backfilling phase change material on thermal performance of precast high-strength concrete energy pile, Renew. Energy. 184 (2022) 374–390, https://doi.org/10.1016/J. RENENE.2021.11.100.

L. Zhu, Y. Yang, S. Chen, Y. Sun, Numerical study on the thermal performance of lightweight temporary building integrated with phase change materials, Appl. Therm. Eng. 138 (2018) 35–47, https://doi.org/10.1016/J. APPLTHERMALENG.2018.03.103.

M. Arıcı, F. Bilgin, S. Niˇzeti´c, H. Karabay, PCM integrated to external building walls: An optimization study on maximum activation of latent heat, Appl. Therm. Eng. 165 (2020), https://doi.org/10.1016/j.applthermaleng.2019.114560.

L.F. Cabeza, C. Castello´n, M. Nogu´es, M. Medrano, R. Leppers, O. Zubillaga, Use of microencapsulated PCM in concrete walls for energy savings, Energy Build. 39 (2007) 113–119, https://doi.org/10.1016/J.ENBUILD.2006.03.030.

M. Bahrar, Z.I. Djamai, M. EL Mankibi, A. Si Larbi, M. Salvia, Numerical and experimental study on the use of microencapsulated phase change materials (PCMs) in textile reinforced concrete panels for energy storage, Sustain. Cities Soc. 41 (2018) 455–468,https://doi.org/10.1016/J.SCS.2018.06.014.

Y. Cui, J. Xie, J. Liu, S. Pan, Review of Phase Change Materials Integrated in Building Walls for Energy Saving, Procedia Eng. 121 (2015) 763–770, https://doi. org/10.1016/J.PROENG.2015.09.027.

M. Xiao, B. Feng, K. Gong, Preparation and performance of shape stabilized phase change thermal storage materials with high thermal conductivity, Energy Convers. Manag. 43 (2002) 103–108, https://doi.org/10.1016/S0196-8904(01)00010-3.

M. Turski, R. Sekret, Buildings and a district heating network as thermal energy storages in the district heating system, Energy Build. 179 (2018) 49–56, https://doi.org/10.1016/J.ENBUILD.2018.09.015.

M. Turski, K. Nogaj, R. Sekret, The use of a PCM heat accumulator to improve the efficiency of the district heating substation, Energy 187 (2019), 115885, https://doi.org/10.1016/J.ENERGY.2019.115885.

A. Lazaro, P. Dolado, J.M. Marín, B. Zalba, PCM–air heat exchangers for free- cooling applications in buildings: Experimental results of two real-scale prototypes, Energy Convers. Manag. 50 (2009) 439–443, https://doi.org/10.1016/J. ENCONMAN.2008.11.002.

N. Morovat, A.K. Athienitis, J.A. Candanedo, V. Dermardiros, Simulation and performance analysis of an active PCM-heat exchanger intended for building operation optimization, Energy Build. 199 (2019) 47–61, https://doi.org/ 10.1016/J.ENBUILD.2019.06.022.

N. Stathopoulos, M. El Mankibi, R. Issoglio, P. Michel, F. Haghighat, Air-PCM heat exchanger for peak load management: Experimental and simulation, Sol. Energy. 132 (2016) 453–466, https://doi.org/10.1016/j.solener.2016.03.030.

M. Ismail, W.K. Zahra, H. Hassan, Experimental study of vapor compression refrigeration system enhanced via tubular heat exchanger incorporating single/ dual phase change materials, Case Stud. Therm. Eng. 49 (2023), 103164, https://doi.org/10.1016/J.CSITE.2023.103164.

N. Chaiyat, Energy and economic analysis of a building air-conditioner with a phase change material (PCM), Energy Convers. Manag. 94 (2015) 150–158, https://doi.org/10.1016/J.ENCONMAN.2015.01.068.

M. Ismail, W.K. Zahra, S. Ookawara, H. Hassan, Boosting the air conditioning unit performance using phase change material: Impact of system configuration, J. Energy Storage. 56 (2022), 105864, https://doi.org/10.1016/J. EST.2022.105864.

M.G. Gado, H. Hassan, Energy-saving potential of compression heat pump using thermal energy storage of phase change materials for cooling and heating applications, Energy 263 (2023), 126046, https://doi.org/10.1016/J. ENERGY.2022.126046.

M. Rastogi, A. Chauhan, R. Vaish, A. Kishan, Selection and performance assessment of Phase Change Materials for heating, ventilation and air-conditioning applications, Energy Convers. Manag. 89 (2015) 260–269, https://doi.org/ 10.1016/j.enconman.2014.09.077.

S. Hashemkhani Zolfani, R. Maknoon, E.K. Zavadskas, Multiple attribute decision making (MADM) based scenarios, Vilnius Gedim. Tech. Univ. 20 (2016) 101–111, https://doi.org/10.3846/1648715X.2015.1132487.
S. Chakraborty, TOPSIS and Modified TOPSIS: A comparative analysis, Decis. Anal. J. 2 (2022), 100021, https://doi.org/10.1016/J.DAJOUR.2021.100021.

D. Das, R.K. Sharma, P. Saikia, D. Rakshit, An integrated entropy-based multi- attribute decision-making model for phase change material selection and passive thermal management, Decis. Anal. J. 1 (2021), 100011, https://doi.org/10.1016/ J.DAJOUR.2021.100011.

S.F. Ahmed, N. Rafa, T. Mehnaz, B. Ahmed, N. Islam, M. Mofijur, A.T. Hoang, G. M. Shafiullah, Integration of phase change materials in improving the performance of heating, cooling, and clean energy storage systems: An overview, J. Clean. Prod. 364 (2022), 132639, https://doi.org/10.1016/J.JCLEPRO.2022.132639.

F.H. Lotfi, R. Fallahnejad, Imprecise Shannon's Entropy and Multi Attribute Decision Making, Entropy 2010, Vol. 12, Pages 53-62. 12 (2010) 53–62. https:// doi.org/10.3390/E12010053.

R. Kumar Sharma, A. Kumar, D. Rakshit, Building Energy Efficiency Enhancement Through Load Reduction in the Air Conditioning System, (2022). https://doi.org/ 10.18086/eurosun.2022.01.12.

M. Barthwal, D. Rakshit, No fins attached? Numerical analysis of internal–external fins coupled PCM melting for solar applications, Appl. Therm. Eng. 215 (2022), 118911, https://doi.org/10.1016/J.APPLTHERMALENG.2022.118911.

L.L. Tian, X. Liu, S. Chen, Z.G. Shen, Effect of fin material on PCM melting in a rectangular enclosure, Appl. Therm. Eng. 167 (2020), 114764, https://doi.org/ 10.1016/J.APPLTHERMALENG.2019.114764.

A. Kumar, S.K. Saha, Performance study of a novel funnel shaped shell and tube latent heat thermal energy storage system, Renew. Energy. 165 (2021) 731–747, https://doi.org/10.1016/J.RENENE.2020.11.023.

A.K. Ray, S. Singh, D. Rakshit, Udayraj, Comparative study of cooling performance for portable cold storage box using phase change medium, Therm. Sci. Eng. Prog. 27 (2022), 101146, https://doi.org/10.1016/J.TSEP.2021.101146.

I. Indoor, E. Quality, S. Second, ISHRAE_IEQ_Feb_26_2019_public_draft, (2019) 2018–2019.

Refrigeration and Air Conditioning . https://www.expresslibrary.mheducation. com/pdfreader/refrigeration-air-conditioning50163303 (accessed May 18, 2022).

M. Barthwal, A. Dhar, S. Powar, The techno-economic and environmental analysis of genetic algorithm (GA) optimized cold thermal energy storage (CTES) for air- conditioning applications, Appl. Energy. 283 (2021), 116253, https://doi.org/ 10.1016/J.APENERGY.2020.116253.

C. Gau, R. Viskanta, Melting and solidification of a pure metal on a vertical wall, J. Heat Transfer. 108 (1986) 174–181, https://doi.org/10.1115/1.3246884.
A.D. Brent, V.R. Voller, K.J. Reid, Enthalpy-porosity technique for modeling convection-diffusion phase change: application to the melting of a pure metal, Http://Dx.Doi.Org/10.1080/10407788808913615. 13 (2007) 297–318. https://doi.org/10.1080/10407788808913615.

Rahul Kumar Sharma a, Ashish Kumar b, Dibakar Rakshit a, *A phase change material (PCM) based novel retrofitting approach in the air conditioning system to reduce building energy demand , https://doi.org/10.1016/j.applthermaleng.2023.121872