Phase Change Materials for Applications in Building Thermal Energy Storage

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ABSTRACT

Phase change materials (PCMs) have excellent thermal energy storage (TES) potential to provide thermal comfort in buildings by lowering the cooling and heating energy demands. The primary grid benefit of thermal energy storage is load shifting and shedding by replacing heating, ventilation, and air conditioning system operation during peak times and recharging the storage system during off-peak times. Additional efficiency benefits come from shifting HVAC system operations to periods when the system can operate more efficiently and at a lower cost. This paper discusses the present state-of-the-art PCMs for thermal energy storage systems for buildings applications and some limitations to phase change materials that negatively impact the performance. Results for two available and environmentally friendly PCMs (BioPCM and DuPont Energain) with different melting ranges applied inside the exterior walls and the roof are analyzed and presented.

Keywords: Thermal energy storage, Buildings applications, Phase change material, Thermal comfort, Energy performance.

1 INTRODUCTION

Energy is the backbone of human activity. Consumption of energy in buildings accounts for 40% of the total energy in the world and the United States [1, 2]. The demand for energy increases because of the increasing trend of population and the industrial sector. Thermal energy storage is an efficient technique to reduce the energy consumption rate in domestic and industrial sectors [3]. Thermal energy storage systems are gaining more attention in recent years, emphasizing sustainable and renewable energy sources. Using phase change materials (PCMs) for thermal energy storage provides an elegant and realistic solution to decrease the energy consumption rate in domestic and industrial sectors [4]. The application of PCMs for thermal energy storage reduces the mismatch between electricity supply and demand, improves electricity distribution network performance and reliability, and plays a vital role in conserving energy [5].

This study discusses the present state-of-the-art of PCMs for thermal energy storage systems for building applications. A case study based on two available and environmentally friendly PCMs (BioPCM and DuPont Energain) with different melting ranges applied inside the exterior walls and the roof was analyzed using the dynamic simulation software EnergyPlus. The analyses compared the energy performance of a residential building with and without the application of a layer with two PCMs.

Passive heating and cooling systems perform by utilizing thermal energy via natural convection or directly via solar energy. A prospective passive system uses phase change materials by encapsulating the material into the building structure, such as ceiling, floor, concrete, or gypsum wallboard [6]. One benefit of this is that by adding phase change materials increases the thermal energy storage capacity. Research has shown that passive systems can directly enhance the occupant comfort level by up to 32%, reducing the temperature fluctuations, leading to the indoor air temperature at the desired level for a more extended time [7]. In active systems, solar collectors can capture solar energy during the daytime by storing the energy using the latent heat of PCMs [8]. The stored heat is then utilized during peak electrical load times to supply the additional electricity required by the household's occupants.

2 SOME LIMITATIONS OF PHASE CHANGE MATERIALS

2.1 Supercooling

Supercooling is defined as the state when a liquid solidifies below its usual freezing point [9] and thus experiences a delay in starting its solidification process [10]. Most salt hydrates tend to supercool before the freezing point during the extraction of stored heat after prolonged use [11]. This causes a decrease in the performance of the phase change material and will eventually lead to slower heat recovery from the phase change material. It is more common for inorganic phase change materials to suffer from this limitation. Research has identified that performance degradation happened in organic phase change materials encapsulated in microcapsules due to the lack of nuclei in small spaces [12].

Research has found that by adding a nucleating agent, supercooling can be reduced [13]. Fan et al. [14] have shown that supercooling can be prevented by adding around 9 wt% of 1-octadecanol in the phase change material. However, the results from the research were found that the thermal performance of the phase change material was affected due to a decrease in latent heat of fusion because of the addition of relatively large amounts of additive [15].

2.2 Low thermal conductivity

Low thermal conductivity can limit the prospects of phase change materials in thermal energy storage applications as it causes a reduction in the rate of heat-releasing/absorbing during the solid-liquid phase change [16]. Many research projects have been performed to enhance the thermal conductivities of phase change materials by using additives and composites [17]. For example, carbon-based additives can be included in stearic acid in a nanocomposite form [18]. This study found that a graphite additive of 5 wt % can enhance the thermal conductivity of the phase change material by up to 12 times. In residential building applications, low thermal conductivities could severely affect many performance factors with phase change material systems.

Research investigating ways of increasing the thermal conductivity of phase change materials can generally be split into two categories [19]; expanding the heat exchanger area with fins or inventing new phase change material composites with additives to enhance the thermal performance. Potential additives to materials are exfoliated graphite nanoplatelets [20, 21], metal foams [22], and carbon-fiber insertion [23]. An investigation of heat transfer enhancement using the triplex tube heat exchanger and normal annular fins has been reported in [24].

2.3 Corrosion

Compatibility is the most important aspect while designing latent heat thermal energy storage systems for building applications. If the PCM material is not compatible with the base material, it will result in corrosion and some changes of PCM properties will happen. The ultimate result is the poor performance of the heat storage system. So, before designing a latent heat thermal energy storage system for building applications, the phase change material and containment compatibility should be checked [25].

3 CASE STUDY OF APPLICATION OF PCM

A case study based on two available environmentally friendly PCMs (BioPCM and DuPont Energain) with different melting ranges applied inside the exterior walls and the roof was analyzed using the dynamic simulation software EnergyPlus. This analysis compared the energy performance of a residential building with and without the application of a layer with two PCMs. The technical characteristics of these PCM materials are presented in Table 1.

Table 1. PCM Properties

Properties	BioPCM	DuPont Energain
Conductivity (W/m k)	0.20	0.16
Thickness (m)	0.01	0.01
Density (kg/m^3)	860	855
Specific heat (J/kg k)	1970	2500
Latent heat (kJ/kg)	219	130
Melting point (°C)	29	21.6

The studied building is a Department of Energy (DOE) [26] midrise apartment building model. It was selected from the U.S. Department of Energy Commercial Reference Building Models from the National Building Stock as of the base case model for this energy simulation. The exterior wall of this building consists of 25 mm stucco, 5/8 in gypsum board, typical insulation R-13.45, and 5/8 in gypsum board from outside to inside. The PCM layer was assumed to be installed between the typical insulation R-13.45 and the 5/8 gypsum board of the four-sided exterior wall. The roof consists of the roof deck, typical insulation R-19.72, and plasterboard from outside to inside. The PCM layer was assumed to be installed between the typical insulation R-19.72 and the plasterboard.

The weather data for Wichita, Kansas in energy plus weather (EPW) file format was used for simulation. The simulation run period was one year, and annual results were obtained from the simulation.

Figure 1 presents the heating energy needs without PCM and with the applications of the PCMs from the simulation.

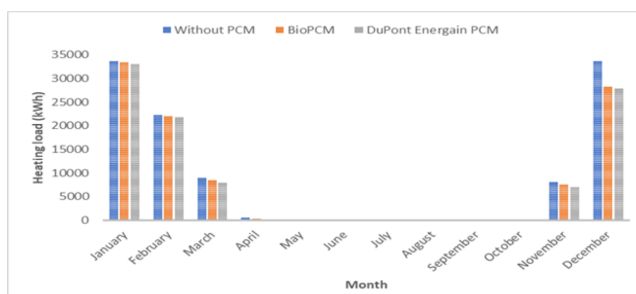

Figure 1. Heating energy needs for reference solution and with PCMs

In Wichita, Kansas, due to the weather, the heating needs of buildings are usually much higher from December to February. By analyzing the heating energy requirements, it was possible to verify that all PCMs analyzed allowed to reduce the heating needs. The PCM that presented better results for heating energy needs was the DuPoint Energain

PCM because the application of this material permitted to reduce the heating needs by 4,440 kWh in a year, which corresponds to a decrease of 4.34% from the reference solution without the application of any PCM.

Figure 2 presents the case study of cooling energy needs without PCM and with the applications of the phase change materials. Figure 2 shows that the cooling loads of the building was 105,049 kWh in a year, and the application of phase change materials reduced the cooling load significantly. There were more significant benefits with the application of the BioPCM. The utilization of this type of material reduced the cooling load by 3.74% compared to the reference solution without any PCM.

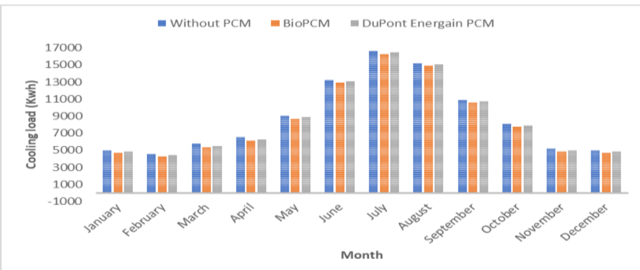

Figure 2. Cooling energy needs for reference solution and with PCMs.

Table 3 presents the heating and cooling energy savings as well as the total annual energy savings for both PCMs considered in this investigation. It can be observed that the application of this type of material leads to a significant reduction of all these indices. Observing the PCM that produced fewer effects (BioPCM), it is possible to highlight that the total annual energy needs decreased from the reference value without PCM by 2.94%. The PCM that allowed a more significant reduction of the energetic necessities was the application of DuPont Energain PCM. This material reduced the energy needs by 6,563 kWh in a year, corresponding to a percentage decrease of 3.2%.

Table 3. Annual HVAC system energy loads and savings

PCM	Without PCM	BioPCM	DuPont Energain PCM
Heating load (kWh)	102,352	100,177	97,912
Savings (%)	-	2.13	4.34
Cooling load (kWh)	105,049	101,125	102,926
Savings (%)	-	3.74	2.02
Total energy load (kWh)	207,401	201,302	200,838
Savings (%)	-	2.94	3.2

4 CONCLUSION

This study has identified that although using PCMs in buildings can improve the energy efficiency of buildings and lead to improved occupant comfort, some limitations of PCMs should be overcome to get their full potential. The challaenges include supercooling, low thermal conductivity, phase segregation, fire safety, corrosion, and cost. This study discussed how some of these issues can be limited or entirely eliminated. Lack of public awareness of PCMs and high implementation costs mean that final solutions are still under investigation towards becoming recognized solutions. Along with raising public awareness of PCMs, several other factors were discussed that require further studies. The application of phase change materials has been demonstrated as a solution to decrease the high-energy consumption of an apartment building. Simulations have been performed with and without the application of PCM materials. It can be concluded that PCM is able to store heat energy from solar radiation, thus reducing energy consumption for heating and cooling. It was found that the phase change materials studied led to a reduction of maximum 4.34% in energy requirements for heating, maximum 3.74% of energy requirements for cooling and maximum 3.2% of total energy requirements.

REFERENCES

[1] Z.X. Li, A.A.A.A. Al-Rashed, M. Rostamzadeh, R. Kalbasi, A. Shahsavar, and M. Afrand, "Heat Transfer Reduction in Buildings by Embedding Phase Change Material in Multi-layer Walls: Effects of Repositioning, Thermophysical Properties, and Thickness of PCM," Energy Conversion and Management, Volume 195, Pages 43-56, 2019.

[2] J. Paige, C. McMillan, D. Steinberg, M. Muratori, L. Vimmerstedt, and T. Mai, "Electrification Futures Study: End-Use Electric Technology Cost and Performance Projections through 2050," National Renewable Energy Laboratory, Golden, CO. NREL/TP-6A20-70485.

[3] Y. Sun, S. Wang, F. Xiao, and D Gao, "Peak load shifting control using different cold thermal energy storage facilities in commercial buildings: A review," Energy Conversion and Management, Volume 71, Pages 101-114, 2013.

[4] M. Kenisarin and K. Mahkamov, "Solar energy storage using phase change materials," Renewable and Sustainable Energy Reviews, Volume 11, Issue 9, Pages 1913-1965, 2007.

[5] Y. Zhang, G. Zhou, K. Lin, Q. Zhang, and H. Di, "Application of latent heat thermal energy storage in buildings: State-of-the-art and outlook," Building and Environment, Volume 42, Issue 6, Pages 2197-2209, 2007.

[6] M. Kenisarin and K. Mahkamov, "Passive thermal control in residential buildings using phase change materials," Renewable and Sustainable Energy Reviews, Volume 55, Pages 371-398, 2016.
[7] S. Ramakrishnan, X. Wang, J. Sanjayan, and J. Wilson, "Thermal performance of buildings integrated with phase change materials to reduce heat stress risks during extreme heatwave events," Applied Energy, Volume 194, Pages 410-421, 2017.
[8] V. V. Tyagi and D. Buddhi, "PCM thermal storage in buildings: A state of art," Renewable and Sustainable Energy Reviews, Volume 11, Issue 6, Pages 1146-1166, 2007.
[9] R. Al-Shannaq, J. Kurdi, S. Al-Muhtaseb, M. Dickinson, and M. Farid, "Supercooling elimination of phase change materials (PCMs) microcapsules," Energy, Volume 87, Pages 654-662, 2015.
[10] A. Safari, R. Saidur, F. A. Sulaiman, Y. Xu, and J. Dong, "A review on supercooling of phase change materials in thermal energy storage systems," Renewable and Sustainable Energy Reviews, Volume 70, Pages 905-919, 2017.
[11] G. A. Lane, "Phase change materials for energy storage nucleation to prevent supercooling," Solar Energy Materials and Solar Cells, Volume 27, Issue 2, Pages 135-160, 1992.
[12] X. Qiu, G. Song, X. Chu, X. Li, and G. Tang, "Microencapsulated n-alkane with p (N-butyl methacrylate-co-methacrylic acid) shell as phase change materials for thermal energy storage," Solar Energy, Volume 91, Pages 212-220, 2013.
[13] Y. Yamagishi, T. Sugeno, and T. Ishige, "An evaluation of microencapsulated PCM for use in cold energy-transportation medium," In Proceedings of the 31st Intersociety Energy Conversion Engineering Conference, Washington, DC, USA, 11-16 August 1996.
[14] Y. F. Fan, X.X Zhang, X.C Wang, J. Li, and Q.B Zhu, "Supercooling prevention of microencapsulated phase change material," Thermochimica Acta, Volume 413, Issues 1–2, Pages 1-6, 2004.
[15] A. Bland, M. Khzouz, T. Statheros, and E. I. Gkanas, "PCMs for residential building applications: A short review focused on disadvantages and proposals for future development," Building, Volume 7(3), 78, 2017.
[16] F. Cao and B. Yang, "Supercooling suppression of microencapsulated phase change materials by optimizing shell composition and structure" Applied Energy, Volume 113, Pages 1512-1518, 2014.
[17] Y. Jin, Q. Wan, and Y. Ding, "PCMs heat transfer performance enhancement with expanded graphite and its thermal stability," Procedia Engineering, Volume 102, Pages 1877-1884, 2015.
[18] L. W. Fan and J. M. Khodadadi, "Thermal conductivity enhancement of phase change materials for thermal energy storage: A review," Renewable and Sustainable Energy Reviews, Volume 15, Pages 24-46, 2011.
[19] T. X. Li, J. Lee, R. Z. Wang, and Y. T. Kang, "Heat transfer characteristics of phase change nanocomposite materials for thermal energy storage application," International Journal of Heat and Mass Transfer, Volume 75, Pages 1-11, 2014.
[20] H. Lee, S. Jeong, S. J. Chang, Y. Kang, S. Wi, and S. Kim, "Thermal performance evaluation of fatty acid ester and paraffin-based mixed SSPCMs using Exfoliated Graphite Nanoplatelets (xGnP)," Applied Science, Volume 6, Issue 4, 106, 2016.
[21] S. Kim and L. T. Drzal, "High latent heat storage and high thermal conductive phase change materials using exfoliated graphite nanoplatelets," Solar Energy Materials and Solar Cells, Volume 93, Issue 1, Pages 136-142, 2009.
[22] C. Y. Zhao, W. Lu, and Y. Tian, "Heat transfer enhancement for thermal energy storage using metal foams embedded within phase change materials (PCMs)," Solar Energy, Volume 84, Issue 8, Pages 1402-1412, 2010.
[23] J. Fukai, Y. Hamada, Y. Morozumi, and O. Miyatake, "Improvement of thermal characteristics of latent heat thermal energy storage units using carbon-fiber brushes: Experiments and modeling," International Journal of Heat and Mass Transfer, Volume 46, Issue 23, Pages 4513-4525, 2003.
[24] M. J. Hosseini, M. Rahimi, and R. Bahrampoury, "Thermal analysis of PCM containing heat exchanger enhanced with normal annular fines," Mechanical Sciences, Volume 6, Pages 221-234, 2015.
[25] K. A. Thakare and A. G. Bhave, "Review on latent heat storage and problems associated with phase change materials," International Journal of Research in Engineering and Technology, Volume 04, Issue 10, Pages 176-182, 2015.
[26] DOE's Commercial Reference Building Models. Available online: https://energy.gov/eere/buildings/commercial-reference-buildings (accessed on 18 April 2021).