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Advances in phase change materials and their application in buildings

Faz değiştiren malzemeler ve bina uygulamalarındaki gelişmeler

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ABSTRACT

Due to increasing environmental concerns, efficient energy use has become very important. Therefore, energy storage, saving, and efficiency issues have become increasingly important, especially in engineering studies. Two different methods are used in thermal energy storage systems, which are the subheadings of energy storage technologies: latent heat and sensible heat. Phase change materials (PCMs), which allow thermal energy to be stored and used later, have been increasingly used in construction, automotive, air conditioning, textile, logistics, electronics, health, and many other areas. These materials, divided into organic, inorganic, and eutectic, must have high latent heat storage capacity and appropriate phase change temperature. This study reviews literature, considering types of phase change materials, application methods, and application areas. In this study, where the effects of PCMs on the amount of energy consumed, especially in meeting the heating and cooling demands of buildings, were investigated, it was seen that the use of PCM contributed to both the energy used in heating and cooling processes and the indoor temperature changes. In addition, it was explained in detail which methods and parameters are prominent in the use of PCM in both buildings and other areas.

ÖZET

Günümüzde artan çevresel kaygılardan dolayı enerji kullanımının verimli bir şekilde gerçekleştirilmesi oldukça önem kazanmıştır. Bundan dolayı özellikle mühendislik çalışmalarında enerji depolanması, tasarrufu ve verimi konuları giderek önemli hale gelmiştir. Enerji depolama teknolojilerinin alt başlığı olan ısıl enerji depolama sistemlerinde gizli ısı ve duyulur ısı olmak üzere iki farklı yöntem kullanıldığı bilinmektedir. Isıl enerjinin depolanarak gereksinim anında kullanılmasını sağlayan faz değiştiren malzemelerin (FDM) son yıllarda kullanımı inşaat, otomotiv, iklimlendirme, tekstil, lojistik, elektronik, sağlık ve daha birçok farklı alanda kullanımı giderek artmaktadır. Organik, inorganik ve ötektik olmak üzere temelde üçe ayrılan bu malzemelerin yüksek gizli ısı depolama kapasitesi ve uygun faz değişim sıcaklığına sahip olması önemli unsurlardandır. Bu çalışmada, faz değiştiren malzemelerin çeşitleri, uygulama yöntemleri ve uygulama alanlarının incelendiği bir literatür taraması gerçekleştirilmiştir. FDM'lerin özellikle binaların ısıtma ve soğutma ihtiyaçlarının karşılanmasında tüketilen enerji miktarına olan etkilerinin araştırıldığı bu çalışmada FDM kullanımının hem ısıtma ve soğutma işlemlerinde harcanan enerji kullanımına hem de iç ortam sıcaklık değişimlerine katkı sağladığı görülmüştür. Ayrıca FDM kullanımının hem binalarda hem de diğer alanlarda hangi yöntemler ile ve hangi parametrelerin ön plana çıktığı detaylı bir şekilde açıklanmıştır.

1. Introduction

Considering the increasing environmental concerns today, efficient use of energy is gaining importance [1]. The amount of energy used in heating and cooling buildings to provide thermal comfort conditions has a significant proportion of all energy consumption [2]. Different applications are carried out to use energy efficiently in both existing buildings and newly constructed buildings. In this context, first, if the existing buildings are insufficient, heat loss is tried to be prevented by insulation [3]. While carrying out this insulation process, many parameters such as the geography where the building is located, the climatic characteristics of this geography, and the directions in which the buildings are constructed are considered [4]. At the same time, insulation is also applied to newly constructed buildings, aiming to consume less energy for the same heating or cooling process. In addition, energy efficiency can be achieved by making improvements to the existing heating or cooling systems in buildings. Different applications such as the use of air conditioning systems with higher COP values can be implemented for cooling. For heating, improvements can be made by adding fans to panel radiators, which are also widely used in our country. Thanks to panel radiators with added fans, indoor heating demands can be achieved with lower inlet temperature values. Or, similarly, panel radiators can be evaluated in the low-temperature heating system category by using ventilated-fan radiator systems [5-7].

The two most important methodologies for storing thermal energy directly as heat are the use of PCMs to utilize the large amounts of thermal energy absorbed/released by state changes such as "sensible" heat media or melting/freezing. These idealized enthalpy changes with temperature can be shown in Figure 1 [8].

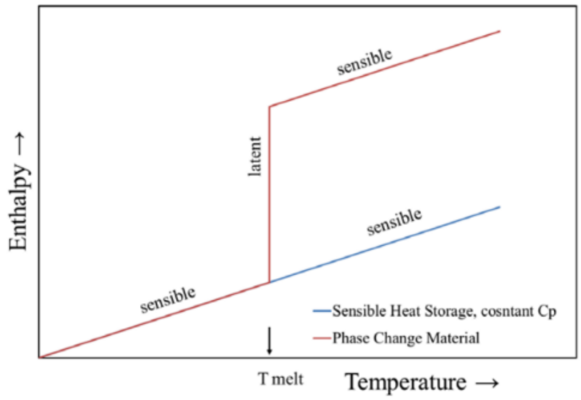


Figure 1. Heat-temperature relationship of latent and sensible heat storage methods [8]

Solid-liquid PCMs are basically divided into three groups: organic, inorganic and eutectic (Figure 2).

Organic PCMs are classified as paraffin and non-paraffin PCMs. Since paraffins have a straight chain structure, their melting temperatures and phase change enthalpies increase as the length of the carbon chain increases. When the number of carbon atoms in their molecular structures is between 13 and 28, their melting temperatures are between -5 and 60°C. Non-paraffin PCMs do not have similar properties to paraffins, and each phase change substance exhibits its own unique properties [9]. Organic PCMs are not corrosive, are chemically stable and do not have excessive cooling behavior. On the other hand, they have low thermal conductivity and can be high cost. To overcome this deficiency of thermal conductivity, the charge and discharge times should be reduced by using together with metal foam, nanoparticles, or geometrical improvements with fins [10-12].

Inorganic PCMs are classified as alloys, metals, salts and salt hydrates. Salt hydrates constitute an important part of heat storage materials due to their high heat storage density. The advantages of inorganic PCMs can be listed as low cost and easy availability, non-flammability, high latent heat of fusion and high thermal conductivity. Their disadvantages can be summarized as phase deterioration and decrease in the number of hydrates, excessive cooling and corrosiveness.

Eutectic PCMs can be a combination of two or more materials. The two most important factors when combining these materials are high latent heat and appropriate phase change temperature. By mixing in the required proportions, melting temperatures can be adjusted and high quality PCMs are formed. Among all the PCMs investigated, the most advantageous feature is high proportion fatty acids. A eutectic mixture with a lower phase change temperature can be created by mixing two or more fatty acids.

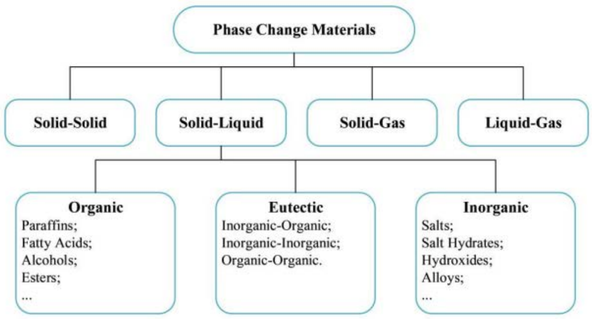


Figure 2. Classification of PCMs [13]

The advantages and disadvantages of these materials according to their types are given in Table 1.

Table 1. Advantages and disadvantages of Solid-liquid PCMs [14, 15]

PCMs	Advantages	Disadvantages
Organic PCMs	High specific heat Small volume change during phase transition Chemical and thermal stability Non-corrosives Compatibility with other materials Recyclable	Low thermal conductivity Lower phase change enthalpy Non compatible with plastic containers Flammability
Inorganic PCMs	High latent heat of fusion High thermal conductivity Low volume change Non-flammable Low cost Wide temperature range Compatible with plastic containers	High volume change High vapor pressure Corrosive and irritant Lack of thermal stability
Eutectic PCMs	Wide temperature range	Extreme cooling High cost

PCMs basically contribute to the heating or cooling load of the building by releasing the energy it stores during the day or night according to the heating or cooling mode later on [16]. PCM can be applied to both existing buildings and newly constructed buildings with different methods such as cement, brick, ceiling, floor, window [17].

In this paper, a comprehensive review on the research area of the phase change materials was performed considering the classification entitled as: i) Application methods of the PCMs ii) Application areas of the PCMs.

2. Application Methods of The PCMs

FDMs can be used in a stable structure by being encapsulated in macro/micro/nano size in practice or by creating a composite structure. The thermal capacity, strength and service life of the materials can be increased by applying different technologies [18]. Salt hydrates, one of the phase change materials, flow in humid regions and there may be changes in the number of hydrates with the change in humidity. When hydrocarbons melt, their viscosity may decrease and thus they may flow into the environment where they are applied. As a result of evaporation, they may increase the volatile organic composition of the air above the limit values. For this reason, phase change materials should be used in a micro-capsule that surrounds them. This method protects the material from external effects for a long time in the core-shell structure (Figure 3).

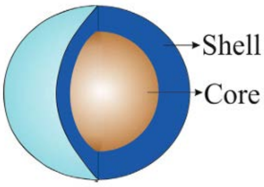


Figure 3. Encapsulated phase change material [19]

When the micro-encapsulation method is considered among these methods, chemical and mechanical methods come to the fore in obtaining PCMs, as seen in Table 2.

Table 2. Micro-encapsulation methods [20]

Chemical Methods	Mechanical Methods
1.Interfacial Polymerization	1.Spray Drying
	2.Centrifuge Method
2.In-situ Polymerization	3.Rotational Method
3.Complex Coacervation	4.Fluidized Bed Method
4.Simple Coacervation	5.Electrostatic Method
5.Super Critical Fluid Method	6. Cooling Drying
	7. Hot Melt Method

These materials, which are manufactured in addition to the basic production methods of PCMs, also have different application methods in buildings. The basic methods of adding PCMs to the building materials in buildings are explained in items below [21].

Direct incorporation method: In this method, liquid or powder PCM building material is added directly to the wet mixture during production (Figure 4). Although it is a simple method, it has disadvantages such as leakage and incompatibility with materials.

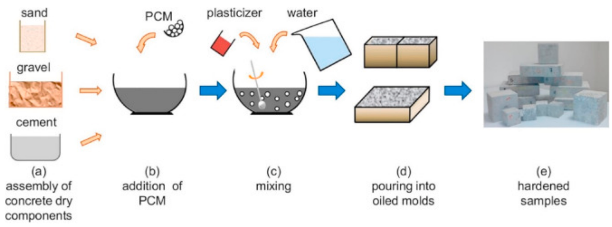


Figure 4. Direct compounding method [22]

Immersion method: In this method, porous building materials are immersed in liquid PCM, and the material absorbs the PCM. Leakage and incompatibility with building materials have also been reported in this method (Figure 5).

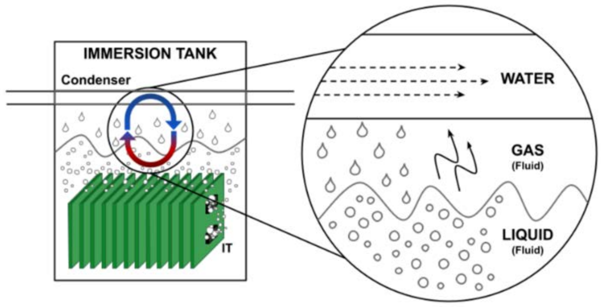


Figure 5. Immersion method [23]

Vacuum impregnation method: In this method, air is drawn from porous aggregates with a vacuum pump and FDM is placed in its place (Figure 6).

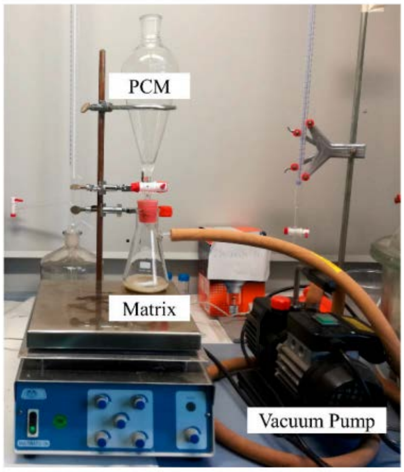


Figure 6. Vacuum impregnation method [24]

Encapsulation method: This method is divided into two as micro and macro (Figure 7). In microencapsulation, PCM of 1-1000 µm size is placed in thin solid capsules made of natural or synthetic polymers and added directly to the building material. This method is both expensive and can affect the mechanical properties of concrete. In macroencapsulation, PCM is packaged in a tube, sphere or panel and combined with the building material in a suitable manner. Although the possibility of leakage is prevented with this method, they can be damaged during use. In addition, the heat transfer area is limited.

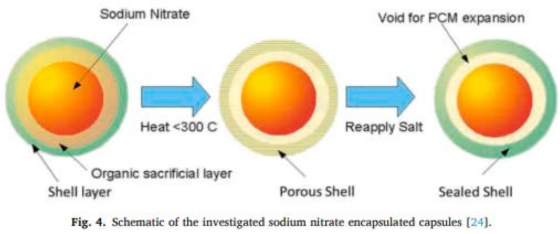


Figure 7. Encapsulation method [25]

Shape-stabilization method: PCM is melted and mixed with an additive material at high temperature. The mixture is then cooled to become solid (Figure 8).

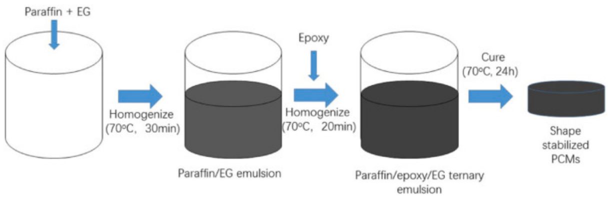


Figure 8. Steady state method [26]

Form stable composites method: This method does not require additional material. FDM is melted at high temperature and cooled after mixing with the building material (Figure 9).

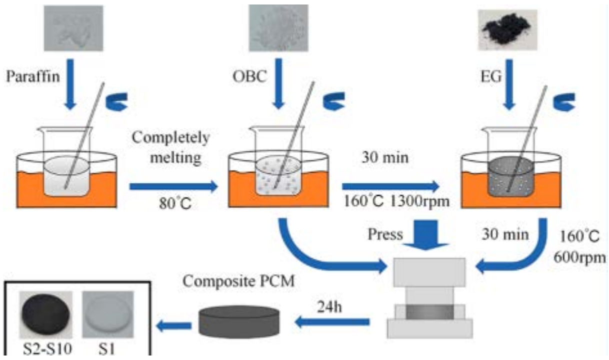


Figure 9. Stable composite method [27]

3. Application Areas of The PCMs

Nowadays, it is aimed to make phase change materials useful in various application areas by using their thermal energy storage properties. In this context, as seen in Figure 10, they have applications in different fields such as environmental science, physics, chemistry and material science, especially in engineering applications [10, 14].

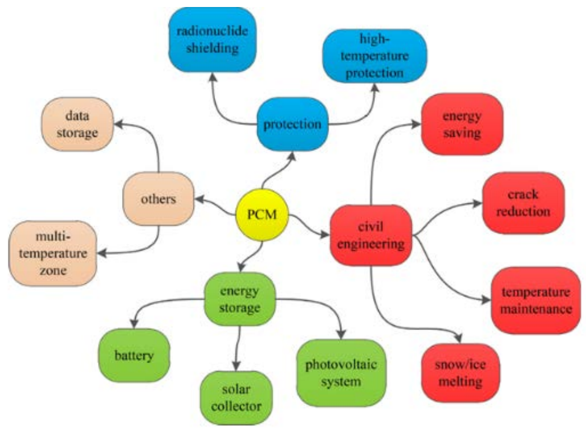


Figure 10. Application areas of using the phase change materials [28]

PCMs are used in different fields in engineering and with tube heat exchangers, which are the most basic heat exchangers. In a study conducted within this scope, a study was conducted by comparing 1, 2 and 4 tube tanks on cold storage applications using tube-in-tank filled with PCM. It was stated that the latent heat energy storage capacity decreased with the increase in the number of tubes. In addition, it was stated that PCM melted more quickly due to the increase in the number of tubes [29].

In another study where tube based storage tank was used, an experimental study was carried out for the heat transfer improvement of this heat exchanger. Two equivalent tanks with tubes inside, one of which had 196 transversal squared fins, were compared. It was concluded that the addition of fins caused an increase in the effectiveness of thermal conductivity between 4.11% and 25.83% depending on the thermal power loaded to the PCM [30].

In a study about the spiral coil tube heat exchanger, the effects of tube diameters, spiral coil diameter and heat transfer fluid parameters were investigated. The results of the study indicated that coil diameter had the most effect and when this value was increased from 50 mm to 70 mm, the total melting time decreased by 71.4%. It was also stated that tube diameter had the least effect [31].

In an experimental study on energy storage in coil in tank heat exchangers, it was stated that the most effective heat transfer mechanisms in charging and discharging processes were natural convection and conduction, respectively. In addition, it was stated that the inlet temperature of the working fluid had more effective than the flow rate [32].

PCMs have also been seen in the automotive field where they store energy and then use this stored energy later in the process. This stored energy is made useful in areas such as vehicle battery cooling systems or during short stops such as traffic lights HVAC systems [33, 34]. In a study examining the application of PCMs in vehicles, the effect of PCM application on heating performance in an innovative heat pump system developed for electric vehicles was experimentally investigated [34]. The flow paths of both the refrigerant and the coolant in this system of the innovative heat pump system developed are given in Figure 11. When the results obtained from the experiments carried out at different ambient temperatures are examined, it is concluded that the stored energy contributes to meeting the heating needs of the vehicle when the heating systems are not in operation. It is also stated that HVAC systems containing PCM can be used to maintain thermal comfort conditions in the vehicle cabin and to prevent temperature fluctuations in the cabin in NEDC and WLTP cycles with stop durations of 23.73% and 13%.

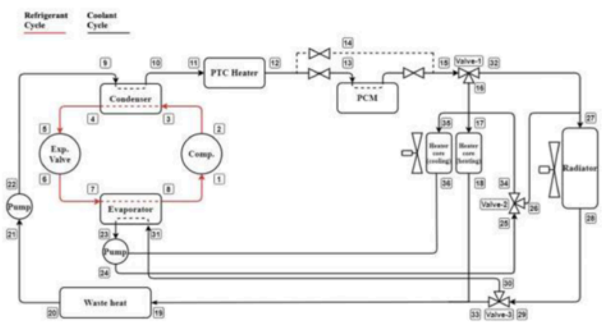


Figure 2. The schematic view of the experimental setup

Table 2. Flow paths of refrigerant and coolant for different working modes

Coolant Circuit 1	Coolant Circuit 2	Refrigerant Circuit
H I- Heating mode I (with PCM)		
10-11-12-13-15-16-17-18-19-20-21-22-9-10	23-24-25-26-27-28-29-30-31-23	1-2-3-4-5-6-7-8-1
H II- Heating mode II (without PCM)		
10-11-12-14-15-16-17-18-19-20-21-22-9-10	23-24-25-26-27-28-29-30-31-23	1-2-3-4-5-6-7-8-1

Figure 11. The schematic view of the experimental setup with the explanations of the flow paths [34]

Latent heat storage using phase change materials can be used for free cooling purposes due to its high storage density (Figure 12). In free cooling using PCM as a storage material, cold air is used to solidify PCM during the night and the collected cold is removed on hot days. A detailed review of the studies conducted by different researchers on PCM-based free cooling is presented. The key challenges in the design of PCM-based free cooling systems; their thermo-physical properties and the geometry of the encapsulation are discussed in detail. The charging and discharging of PCM, phase change temperature and climatic conditions affecting the thermal performance of the free cooling system are also discussed. Additionally, the potential reduction of CO_2 emissions from the application of free cooling systems in residential and commercial buildings is also discussed [35].

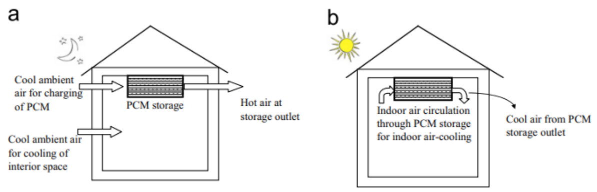


Figure 12. Charging and discharging processes [35]

Osterman et al. investigated the effects of PCMs used in cooling systems on energy consumption and indoor temperature changes. They divided cooling systems into four groups as free cooling applications, encapsulated PCM systems, air conditioning (AC) systems and scorpion cooling systems with integrated PCMs. Paraffin was used as the basis in the study, and in some cases salt hydrates, water and fatty acids were also used. It was stated that PCMs placed in buildings have positive effects on building thermal and energy performance (Figure 13) [36].

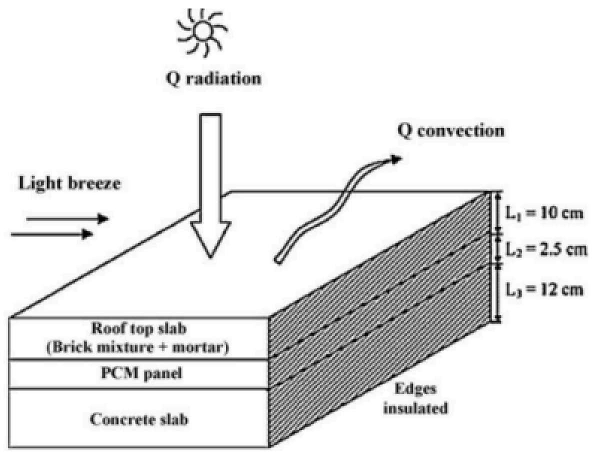
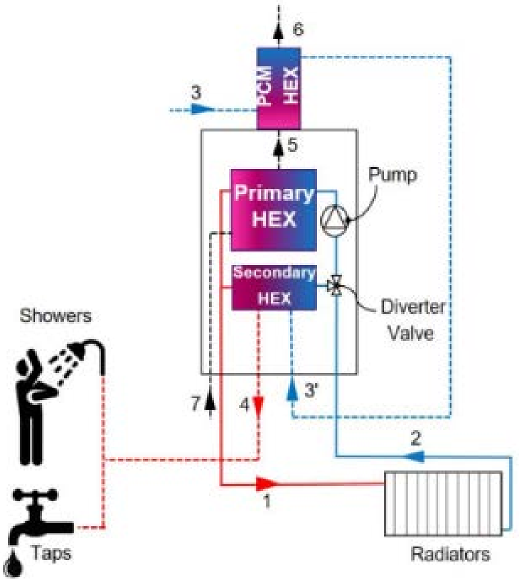


Figure 13. The schematic view of the building roof alignment [36]

In another study, the effect of using PCM materials for insulation purposes on energy consumption was investigated. The thermophysical properties of PCMs used in the study were determined experimentally. The temperature distributions on the walls in the uninsulated and insulated (foam, foam+PCM) cases were investigated in June, July, August and September. It was observed that in the case where the temperature was highest, 39.8 ^{0}C, 33 ^{0}C and 32 ^{0}C values were obtained in the uninsulated, only insulated and both PCM and insulated cases, respectively, and the case with both insulation and PCM was recommended as the best case in terms of cooling load [37].

In another study conducted to benefit from the waste heat generated in the gas combi chimney, a heat exchanger containing PCM was added to the system (Figure 14 and 15). In the three-dimensional numerical study conducted using the ANSYS-Fluent software package program, only the discharge period of the PCM-heat exchanger, that is, the period in which it returns the stored energy, was considered. The effects of the PCM mass, melting temperature and local cold water flow rate were investigated in the study. Four different PCMs were used in the study and their melting temperature values were 40°C, 44°C, 48°C and 54°C. It was observed that the PCM with a high phase change transition temperature provided both higher temperature increases and discharge power. Regarding the discharge power, it was determined that the maximum discharge power varied between 1526 W and 2000 W depending on the PCM melting temperature. It was stated that the amount of solidified PCM at the end of the discharge process also increased with increasing the melting temperature of the material [38].



(1) Central heating inlet, (2) Central heating outlet, (3) Domestic cold water, (3') Preheated domestic cold water, (4) Domestic hot water, (5) Flue gas FDM-heat exchanger inlet, (6) Flue gas PCM-heat exchanger outlet, (7) Gas-air mixture

Figure 14. Schematic of the FDM-heat exchanger gas-fired combi boiler [38]

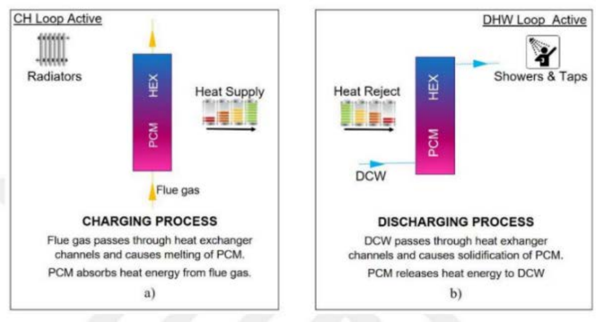


Figure 15. Schematic view of charging and discharging processes [38]

In another study, the effects of using different insulation and phase-changing materials in simultaneously heated and unheated environments in a sample building consisting of a basement, ground floor and two normal floors on energy efficiency and thermal comfort conditions were investigated. Nine different situations were modeled in three types of flooring types, namely uninsulated, insulated and a layer containing PCM in addition to insulation. The effects of the variables on the heat loads of the environments, ambient temperature and energy use were investigated. As a result, it was observed that the heat load of the environments decreased with the use of insulation and PCM in the floor and ceiling. It was concluded that the thermal comfort conditions improved because the ambient temperatures were parallel to the set temperature. It was also stated that the use of insulation and PCM in the floor and ceiling reduced the annual energy use and caused a significant increase in energy efficiency [39].

Considering the summer climate conditions of Elazığ province, instead of insulation material, paraffin-based RT-27, which melts in the range of 28-30 °C in summer conditions, was used on the external walls of buildings facing different directions, and cooling loads were numerically examined in a two-dimensional and time-dependent manner with the ANSYS Fluent program. It was seen that the use of phase-change material on the outside was more efficient and 20 °C lower temperature was obtained on the inner surface compared to the uninsulated wall (Figure 16). It was observed that the heat storage capacity of the wall increased because of the maximum phase shift and minimum damping ratio in places where PCM was applied [40].

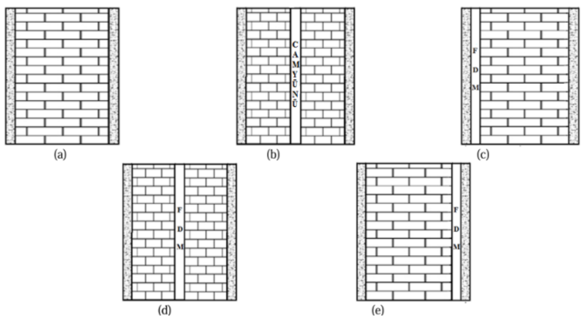


Figure 16. Wall models: (a) Uninsulated wall (b) Wall with glass wool in the middle (c) Wall with PCM on the outside (d) Wall with PCM in the middle (f) Wall with PCM on the inside [40]

Recently, the use of lightweight building walls (LBW) has been increasing due to their easy construction and sustainability in structural terms. In these types of buildings, thermal storage capacities are also low due to the low thermal mass compared to traditional brick buildings. To eliminate this deficiency, PCM applications are carried out in these types of buildings [41-43]. In one of these studies, it was stated that a 25 mm thick PCM wall can store heat equivalent to a 420 mm thick concrete wall [44].

In the study conducted on LBWs, three different wall models with PCM and placed in different locations and a reference wall model without PCM were examined in terms of thermal performance. In the results of the study, it was mentioned that the phase transition temperature parameter was a more effective parameter than the PCM location. It was also stated that for the conditions implemented in this study, the most suitable situation was to position the PCM in the middle of the wall [45]. In another study conducted on LBWs, the effects of the outdoor thermal environment of the wall in different directions were investigated. In this study, where meteorological parameters were examined, it was stated that there were different optimal locations for PCM due to different directions ow the wall [46].

4. Conclusions

In this paper, a detailed literature review about the PCM and its applications is performed. While reviewing the available published extensive studies, we focus on the basic details of the PCM and its applications on heating and cooling process of buildings. According to this study, the main conclusions considering PCM applications on the buildings are listed below.

• Phase change materials are widely used in heating and cooling applications of buildings due to their ability to heat store and then release it again.

• It has been observed that less energy is consumed, and energy is saved in the heating and cooling processes of buildings thanks to phase-changing materials.

• It has been observed that fluctuations in temperature values inside buildings can be prevented thanks to PCMs.

• It has also been determined that by using it in the automotive industry during short stops such as traffic lights, the sustainability of the cabin interior temperature value can be ensured and fluctuations in this value can be prevented.

• It has been observed that the use of PCM in new generation buildings with low thermal masses such as LBW is quite effective in terms of thermal performance.

• It has been observed that PCM thickness, melting temperature and other thermophysical properties of PCM are effective in PCM application on the walls of buildings. In addition, it has been reported that the geographical characteristics of the building where PCM is applied and the direction in which the building is built are also very important.

• It has been stated that PCMs can be easily applied to both existing buildings and newly constructed buildings.

• Thanks to the use of organic PCMs, thermal improvements can be made in the area used without harming the environment.

• Although the amount to be encapsulated in the polymeric structure in microencapsulation is generally not predictable in advance, literature studies have reported that PCMs can be obtained at encapsulation rates of up to 85%.

• It has been seen that different types of heat exchangers such as tubular heat exchangers and plate type heat exchangers can be used in PCM applications, as well as being applied directly as a layer or filling material as in building walls.

The results obtained with this article show that phase change materials can be integrated into different application areas for better understanding and development of thermal management and energy efficiency. After these comprehensive studies, it is anticipated that more experimental and numerical studies can be conducted to clearly reveal the thermal and mechanical behavior of phase change materials.

Conflict of Interest Statement: The authors declare no conflicts of interest.

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Data Availability Statement: The data generated and/or analyzed during this study are not publicly available but can be provided by the corresponding author upon reasonable request.

References

[1]. Kishore, R. A., Bianchi, M. V., Booten, C., Vidal, J., and Jackson, R. (2020) *Modulating thermal load through lightweight residential building walls using thermal energy storage and controlled precooling strategy,* Applied thermal engineering, 180, 115870.

[2]. Chen, S., Yang, Y., Olomi, C., and Zhu, L. (2020, April) *Numerical study on the winter thermal performance and energy saving potential of thermo-activated PCM composite wall in existing buildings,* In Building simulation (Vol. 13, pp. 237-256). Tsinghua University Press

[3]. Iffa, E., Hun, D., Salonvaara, M., Shrestha, S., and Lapsa, M. (2022) *Performance evaluation of a dynamic wall integrated with active insulation and thermal energy storage systems,* Journal of Energy Storage, 46, 103815.

[4]. Sun, X., Jovanovic, J., Zhang, Y., Fan, S., Chu, Y., Mo, Y., and Liao, S. (2019) *Use of encapsulated phase change materials in lightweight building walls for annual thermal regulation*, Energy, 180, 858-872.

[5]. Hesaraki, A., Ploskic, A., and Holmberg, S. (2015) *Integrating low-temperature heating systems into energy efficient buildings*, Energy Procedia, 78, 3043-3048.

[6]. Johansson, P. O., and Wollerstrand, J. (2010, September) *Improved temperature performance of radiator heating system connected to district heating by using add-on-fan blowers*. In Proceedings of The 12th International Symposium on District Heating and Cooling.

[7]. Bayram, H., and Koc, N. (2023) *Experimental investigation of the effects of add-on fan radiators on heat output and indoor air temperature*, Case Studies In Thermal Engineering, 50, 103432.

[8]. Sugo, H., Kisi, E., Bradley, J.,Fiedler, T., and Luzin,V. (2017) *In situ neutron diffraction studies of operating MGA thermal storage materials*, Renewable Energy and Environmental Sustainability. 2. 34. 10.1051/rees/2017023.

[9]. Mert, M. S., Sert, M., ve Mert, H. H. (2018). *Isıl enerji depolama sistemleri için organik faz değiştiren maddelerin mevcut durumu üzerine bir inceleme*, *Mühendislik Bilimleri ve Tasarım Dergisi*, *6*(1), 161-174.

[10]. Kurşun, B. and Balta, M. (2023). *Effect of inner channel geometry on solidification performance of phase change material (PCM) in double-pipe thermal energy storage*, International Journal of Pioneering Technology and Engineering, 2(02), 165-169.

[11]. Choure, B. K., Alam, T., and Kumar, R. (2023). *A review on heat transfer enhancement techniques for PCM based thermal energy storage system,* Journal of Energy Storage, 72, 108161.

[12]. Wu, S., Yan, T., Kuai, Z., and Pan, W. (2020). *Thermal conductivity enhancement on phase change materials for thermal energy storage: A review,* Energy Storage Materials, 25, 251-295.

[13]. Liu, L., Niu, J. and Wu, J. (2021*) Preparation of Stable Phase Change Material Emulsions for Thermal Energy Storage and Thermal Management Applications: A Review,* Materials. 15. 121. 10.3390/ma15010121.)

[14]. Kıraylar, K. (2020) *Yenilenebilir kaynaklardan potansiyel faz değiştirici maddelerin etkin sentez yöntemleri*, Yüksek Lisans Tezi, Bursa Uludağ Üniversitesi Fen Bilimleri Enstitüsü, Bursa.

[15] Socaciu, L., Pleşa, A., Ungureşan, P., and Giurgiu, O. (2014). *Review on phase change materials for building applications*, Leonardo Electronic Journal of Practices and Technologies, *25*, 179-194.

[16]. Mukram, T. A., and Daniel, J. (2022) *A review of novel methods and current developments of phase change materials in the building walls for cooling applications,* Sustainable Energy Technologies and Assessments, 49, 101709.

[17]. Reddy, V. J., Ghazali, M. F., and Kumarasamy, S. (2024) *Advancements in phase change materials for energy-efficient building construction: A comprehensive review,* Journal of Energy Storage, 81, 110494.

[18]. Yaldız, S. (2023*) Düşük sıcaklık uygulamaları için faz değiştiren malzemelerin hazırlanması ve ısıl özelliklerinin incelenmesi,* Yüksek Lisans Tezi, Yalova Üniversitesi Lisansüstü Eğitim Enstitüsü, Yalova.

[19]. Milián,Y.E.,Gutiérrez, A.,Grágeda, M. and Ushak, S. (2017) *A review on encapsulation techniques for inorganic phase change materials and the influence on their thermophysical properties*, Renewable and Sustainable Energy Reviews,Volume 73,Pages 983-999,ISSN 1364-0321.

[20]. Gül, R. (2024) *Akıllı tekstil ürünlerde kullanılmak üzere Halfeti gül (R. ODORATA 'LOUIS IV') yağı içeren mikrokapsüllerin geliştirilmesi,* International Journal of Health and Applied Science, 2(2), 9-30.

[21]. İkbal, F. M. (2018) *Radyatör ve beton kolon ile ısıtılan oda içerisindeki termal konforun sayısal incelenmesi*, Yüksek Lisans Tezi, Erciyes Üniversitesi Fen Bilimleri Enstitüsü, Kayseri.

[22]. Al-Yasiri, Q., and Szabó, M. (2021*) Incorporation of phase change materials into building envelope for thermal comfort and energy saving: A comprehensive analysis,* Journal of Building engineering, 36, 102122.

[23]. Arroba, P., Buyya, R., Cárdenas, R., Risco-Martín, J. L., and Moya, J. M. (2024) *Sustainable edge computing: Challenges and future directions,* Software: Practice and Experience.

[24]. Frigione, M., Lettieri, M., and Sarcinella, A. (2019*) Phase change materials for energy efficiency in buildings and their use in mortars,* Materials, 12(8), 1260.

[25]. Palacios, A., Navarro-Rivero, M. E., Zou, B., Jiang, Z., Harrison, M. T., and Ding, Y. (2023) *A perspective on Phase Change Material encapsulation: Guidance for encapsulation design methodology from low to high-temperature thermal energy storage applications,* Journal of Energy Storage, 72, 108597.

[26]. Chinnasamy, V., Heo, J., Jung, S., Lee, H., and Cho, H. (2023) *Shape stabilized phase change materials based on different support structures for thermal energy storage applications–A review*. Energy, 262, 125463.
[27]. An, Z., Chen, H., Du, X., Shi, T., and Zhang, D. (2022) *Preparation and performance analysis of form-stable composite phase change materials with different EG particle sizes and mass fractions for thermal energy storage,* ACS omega, 7(38), 34436-34448.
[28]. Wang, X., Li, W., Luo, Z., Wang, K., and Shah, S. P. (2022) *A critical review on phase change materials (PCM) for sustainable and energy efficient building: Design, characteristic, performance and application,* Energy and buildings, 260, 111923.
[29]. Tay, N. H. S., Belusko, M., and Bruno, F. (2012) *Experimental investigation of tubes in a phase change thermal energy storage system,* Applied energy, 90(1), 288-297.
[30]. Gil, A., Peiró, G., Oró, E., and Cabeza, L. F. (2018) *Experimental analysis of the effective thermal conductivity enhancement of PCM using finned tubes in high temperature bulk tanks,* Applied thermal engineering, 142, 736-744.
[31]. Ahmadi, R., Hosseini, M. J., Ranjbar, A. A., and Bahrampoury, R. (2018) *Phase change in spiral coil heat storage systems, Sustain*. Cities Soc. 38 145–157.
[32]. Kabbara, M., Groulx, D., and Joseph, A. (2018) *A parametric experimental investigation of the heat transfer in a coil-in-tank latent heat energy storage system,* International Journal of Thermal Sciences, 130, 395-405.
[33]. Kowsky, C., Wolfe, E., Chowdhury, S., Ghosh, D., and Wang, M. (2014) *PCM evaporator with thermosiphon,* SAE Technical Paper, (No. 2014-01-0634).
[34]. Başak, E., Dursun, H., Sevilgen, G., and Bayram, H. (2023) *The experimental investigation of the usage of PCM in the heat pump system for the electric vehicles*. 5. International Ankara Multidisciplinary Studies Congress.
[35]. Waqas, A., and Din, Z. U. (2013) *Phase change material (PCM) storage for free cooling of buildings—A review,* Renewable and sustainable energy reviews, 18, 607-625.
[36]. Osterman, E., Tyagi, V. V., Butala, V., Rahim, N. A., and Stritih, U. (2012) *Review of PCM based cooling technologies for buildings,* Energy and Buildings, 49, 37-49.
[37]. Ismail, K.A. and Castro, J.. (1997) *PCM thermal insulation in buildings,* International Journal of Energy Research.
[38]. Balci, O. M. (2018). *Design of a Heat Exchanger with Phase Change Material,* Master's thesis, Dokuz Eylul University Institute of Science,İzmir.
[39]. Haydaraslan, E., Çuhadaroğlu, B., ve Yaşar, Y. (2020) *Kat ısıtmasında yüzer döşeme ve faz değiştiren malzeme kullanımının enerji verimliliğine ve konfor koşullarına etkisi*, Mühendis ve Makina, 61(700), 180-197.
[40]. Özel, M., ve Çakmak, F. A. (2023). *Farklı yönlendirmeli bina dış duvarlarında faz değiştiren malzeme kullanımının ısı kazancına etkisinin araştırılması,* Fırat Üniversitesi Mühendislik Bilimleri Dergisi, *35*(1), 413-424.
[41]. Liu, Z. A., Hou, J., Chen, Y., Liu, Z., Zhang, T., Zeng, Q., ... and Jiang, G. (2023) *Effectiveness assessment of different kinds/configurations of phase-change materials (PCM) for improving the thermal performance of lightweight building walls in summer and winter,* Renewable Energy, 202, 721-735.
[42]. Evola, G., and Marletta, L. (2014*) The effectiveness of PCM wallboards for the energy refurbishment of lightweight buildings,* Energy Procedia, 62, 13-21.
[43]. Hou, J., Meng, X., and Dewancker, B. J. (2021) *A numerical study on the effect of phase-change material (PCM) parameters on the thermal performance of lightweight building walls,* Case Studies in Construction Materials, 15, e00758.
[44]. Cai, R., Sun, Z., Yu, H., Meng, E., Wang, J., and Dai, M. (2021) *Review on optimization of phase change parameters in phase change material building envelopes,* Journal of Building Engineering, 35, 101979.
[45]. Hou, J., Huang, Y., Zhang, J., Meng, X., and Dewancker, B. J. (2022*) Influence of phase change material (PCM) parameters on the thermal performance of lightweight building walls with different thermal resistances,* Case Studies in Thermal Engineering, 31, 101844.
[46]. Hou, J., Wei, D., Meng, X., and Dewancker, B. J. (2022) *Thermal performance analysis of lightweight building walls in different directions integrated with phase change materials (PCM),* Case Studies in Thermal Engineering, 40, 102536.