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Analysis of the use of phase change materials to improve building energy efficiency and thermal energy storage

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Abstract. The growing demand for energy-efficient buildings and the need to reduce greenhouse gas emissions necessitate the adoption of innovative approaches to thermal energy management in buildings. One such approach involves the use of phase change materials, which enable thermal energy storage and increase the thermal inertia of building structures. This makes them an effective solution for optimising energy efficiency under varying climatic conditions. This article aimed to analyse existing methods of employing phase change materials to enhance the energy efficiency of buildings through thermal energy storage. In particular, the study focused on techniques for incorporating these materials into building envelopes and their application in thermal storage systems. The article applied methods of analysis and synthesis of scientific literature, with particular attention given to studies on the impact of phase change materials on the thermal inertia of building components, their effectiveness in thermal energy storage units, and their influence on overall building energy performance. It has been established that the use of phase change materials significantly increases the thermal inertia of buildings and reduces heat loss. Various methods of incorporating phase change materials into building envelopes and their application in thermal storage systems have been analysed. The main advantages and drawbacks of each method have been identified, along with examples of their practical implementation. Potential uses of thermal storage units for enhancing building energy efficiency have been outlined, particularly their integration into heating and domestic hot water systems. The findings of the study may be applied in the design of energy-efficient buildings and heating and hot water supply systems that utilise phase change materials for thermal energy storage. This contributes to lower energy consumption and improved living comfort

Keywords: phase change materials; paraffin; building envelope; thermal inertia; latent heat

Introduction

High energy consumption in buildings, particularly due to cooling and heating demands, has become one of the most pressing challenges in the field of energy supply over recent decades. Statistics show that energy use in buildings and the associated emissions continue to rise steadily each year (The International Energy Agency, n.d.). As of 2022, building operations accounted for 30% of global energy consumption and 26% of global emissions. In that year alone, energy use in the building sector increased by approximately 1%, and this trend is expected to persist for the foreseeable future. Scientific and technological advancements in energy efficiency are key to accelerating progress in decoupling energy consumption from the rapid growth in total building floor area. It is projected that by 2030 the

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global residential floor area will increase by around 15%, with approximately 80% of this growth occurring in developing countries, including Ukraine.

A substantial body of research has focused on the integration of phase change materials (PCMs) into building walls, aiming to improve energy efficiency and enhance indoor comfort for occupants. In their study, F.S. Bayraktar & R. Köse (2025) demonstrated that, under the climatic conditions of Turkey, placing PCM blocks on the internal surface of walls reduced electricity consumption by 16.6% during the cold season. F. Carlucci *et al.* (2021) conducted simulations of heat exchange processes involving the incorporation of PCM microcapsules into plasterboard mounted on interior wall surfaces, considering the climatic conditions of various European countries. The simulations were carried out for both office and residential buildings. The results indicated an overall reduction in building energy demand of between 2.5% and 5% for active PCM application strategies, as well as a general decrease in discomfort hours of up to 9% for passive strategies. Another study by M. Özdemir & A. Gülten (2024) focused on the impact of PCM integration on the energy loads of heating and cooling systems in buildings. Particular attention was given to the performance of PCM in various wall construction configurations under Turkey's climatic conditions. The authors aimed to determine how the inclusion of PCM in wall assemblies could reduce energy consumption and improve indoor thermal comfort. The findings showed that insulation alone resulted in a substantial 25% reduction in energy use, while the application of PCM by itself led to approximately a 9% decrease. The combined use of both PCMs and insulation materials achieved the most significant results, reducing energy consumption by 30%.

E. Osterman *et al.* (2023) dedicated their study to the application of PCMs for thermal energy storage in the context of "smart" retrofitting of existing buildings. The research forms part of the Horizon 2020 HEART project, which aims to decarbonise the European building sector. The authors explored the integration of PCM-based systems to enhance building energy efficiency and facilitate the use of green energy. As part of the experiment, three thermal storage tanks, each with a volume of 3,000 litres, were used. These tanks were filled with modules in the form of spheres containing liquid PCM. The total PCM volume enabled the accumulation of up to 90 kW of thermal energy. The payback period for the system was estimated at four to five years. A study by M. Jaradat *et al.* (2023) is also worth noting. The authors examined the use of PCM derived from renewable biomass sources, focusing on the effectiveness of its application in building envelopes under the climatic conditions of Romania and Jordan. It was found that the moderate climate of Jordanian cities such as Irbid and Amman is more favourable for PCM use than the colder, more humid climate of Oradea in Romania. The deployment of PCM systems in Amman showed significant benefits, including a potential annual energy saving of 5,476.14 kWh, a possible yearly cost reduction of 1,150 USD, and a decrease in CO_2 emissions equivalent to 2,382.31 kg.

The study by M. Velasco-Carrasco *et al.* (2020) presented an experimental investigation into the potential of integrating PCMs into ceiling panels for thermal energy storage systems under the climatic conditions of Nottingham, United Kingdom. The authors focused on evaluating the effectiveness of such "smart" ceiling panels in regulating indoor temperature and reducing building energy consumption. The research involved measuring the thermal performance of PCMs under conditions simulating real operating scenarios. The results showed that the integration of S23 panels reduced the need for additional heating by increasing the average indoor temperature in the test space. The use of 20 PCM ceiling panels had a significant impact on the indoor microclimate, raising the room temperature by 5°C.

K. Bodarya & V. Kaushal (2025) focused on the future effectiveness of PCM applications in the context of climate change. Their analysis of future climate models demonstrated that PCM efficiency varies considerably by region. In Curitiba (Brazil), which has a mild climate, PCM integration is expected to lead to a marked improvement in energy efficiency, with a projected reduction in annual energy use intensity (EUI) of 8.2% by 2050 and 10% by 2080, compared to the use of resistive insulation alone. In contrast, in the hot climate of Rio de Janeiro, PCM application may have adverse effects, potentially increasing EUI by 12.1% by 2050 and 20.7% by 2080 relative to resistive insulation.

Given the facts, forecasts, and studies presented, it should be noted that the development of innovative solutions in the fields of energy efficiency and energy supply, as well as their optimal practical implementation, are key criteria for achieving a high level of energy performance in buildings. The present study aimed to analyse approaches to improving building energy efficiency through the use of phase change materials capable of storing thermal energy.

The research employed several scientific methods, including analysis, synthesis, classification, and comparison. A total of 40 literature sources, published both in Ukraine and internationally, were reviewed. The selected studies provide a comprehensive overview of the current state of research on the application of PCMs to improve building energy efficiency and develop thermal energy storage systems. The analysed sources include both theoretical materials concerning PCMs, their key properties, and areas of application, as well as the results of various modelling exercises and experimental investigations. The majority of the references consist of academic articles published in specialised scientific journals. This selection enabled a thorough analysis of advances in the application of PCMs in building envelopes and thermal storage units.

Methods of thermal energy storage using pcms

Modern thermal energy storage technologies are based on three main principles: sensible heat storage, latent heat storage, and the use of thermochemical reactions. Sensible heat is stored through changes in the temperature of a material without a phase change. This method is well-researched and widely applied; however, it has the lowest efficiency due to the low specific heat capacity of materials. The most common storage media include water, metals, rocks, and bricks (Kots *et al.*, 2023). The latent heat storage method relies on the phase transition of a substance, which occurs at a constant temperature. This enables a high energy storage density and allows for the development of compact energy storage systems (Nallusamy *et al.,* 2007). Substances used in this method are known as phase change materials (PCMs). The thermochemical method is based on chemical reactions that absorb or release heat through changes in enthalpy (Pfleger *et al.,* 2015).

The present study focused primarily on the latent heat storage method using PCMs, which is considered a promising approach to improving building energy efficiency due to its high energy storage density and the ability to maintain a constant temperature during heat exchange. Phase transitions can occur in several forms: solid-solid, solid-liquid, solid-gas, liquid-gas, and in the reverse direction for each of these transitions. In the case of a solid-solid phase transition, the crystalline structure of the material changes, accompanied by the absorption or release of thermal energy. This type of phase change is characterised by only a slight change in the material's volume and relatively low heat storage capacity. However, it offers advantages such as reduced requirements for the strength and airtightness of the enclosure, providing greater flexibility in construction design.

Solid-gas and liquid-gas phase transitions can achieve higher thermal energy storage density. Nevertheless, the substantial increase in material volume during these processes complicates their application due to the need for airtight containers and more complex system designs. This significantly limits their practical suitability for thermal energy storage systems. The most balanced and practical option in terms of implementation is the solid-liquid phase transition. Although the amount of thermal energy that can be stored is somewhat limited, this method provides sufficient efficiency while allowing for simple engineering solutions. The volumetric expansion of the material usually does not exceed 10% (Sharma *et al.,* 2009), making it possible to design an optimal PCM enclosure and choose from a wide range of construction materials. The graph of temperature dependence on the amount of stored heat, taking into account the aggregate state of the material, is shown in Figure 1.

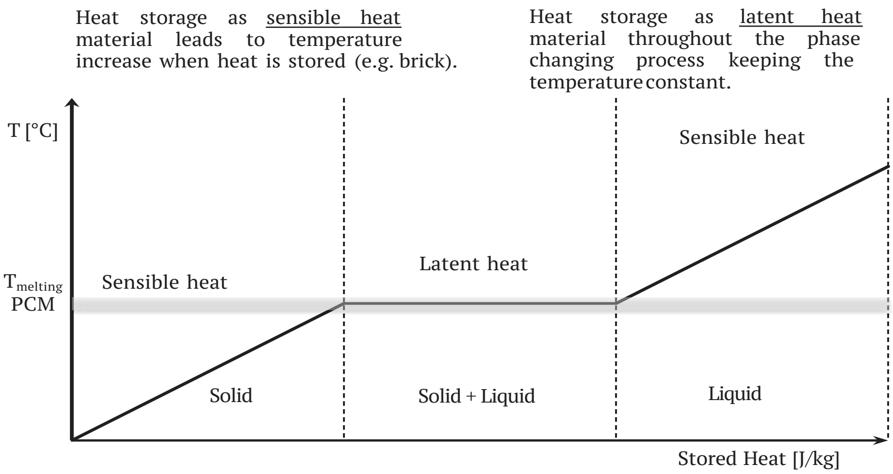


Figure 1. *Phase transition zones of phase change materials*
Source: *developed by the authors based on research by Q. Al-Yasiri & M. Szabó (2021)*

Modern thermal energy storage technologies are based on different physical principles, each with its own advantages and limitations. Among these, the use of phase change materials – which can efficiently store heat during phase transitions – has attracted the greatest practical interest. Of all types of phase transitions, the most common and convenient for building applications is the solid-liquid transition. This approach offers a good balance of energy storage capacity, ease of implementation, and adaptability to various construction systems.

Classification of phase change materials and their properties

Depending on their chemical composition, PCMs are classified into three main groups: organic, inorganic, and eutectic. Each category is characterised by a specific operating temperature range, thermophysical properties, and application features (Kulish *et al.,* 2023). Organic PCMs are divided into paraffins and non-paraffin compounds. They are known for their low corrosiveness, chemical stability, and congruent melting, meaning they can undergo multiple phase changes without decomposing into separate substances or losing their functional properties. These materials also typically crystallise well without supercooling due to active self-nucleation (Sharma *et al.*, 2009). Paraffins are the most widely used organic PCMs due to their availability, low cost, predictable behaviour, and broad melting temperature range. Their main disadvantages are flammability and low thermal conductivity, which reduce heat exchange efficiency and can result in the formation of "dead zones" within the material. Nonparaffin PCMs include complex esters, fatty acids, alcohols, and glycols. These often exhibit higher latent heat values but are also associated with toxicity, low ignition temperatures, flammability, and thermal instability at elevated temperatures.

Inorganic PCMs include metals and salt hydrates. Metals (particularly eutectics and low-melting-point alloys) offer high thermal conductivity, reducing the need for additional methods to enhance heat transfer. However, their considerable mass presents complex engineering challenges in the design of metallic thermal storage systems, which limits their practical use. Salt hydrates are crystalline compounds consisting of salts and water. When heated, they undergo a phase change that results in the formation of lower hydrates or anhydrous salts and water. The main drawback is incongruent melting, where part of the salt settles at the bottom of the storage tank, causing material stratification and gradual degradation of performance. Salt hydrates also exhibit low nucleation ability, leading to supercooling and unstable phase transitions (Al-Yasiri & Szabó, 2021). Eutectic PCMs are mixtures of two or more components that melt and solidify simultaneously and congruently, ensuring a homogeneous phase transition without separation. Based on composition, eutectics can be classified as organic (all components organic), inorganic (all components inorganic), or organic-inorganic mixtures. Among organic eutectics, mixtures of fatty acids are the most studied. In contrast, inorganic combinations are less researched, and their properties require further investigation. The main advantage of eutectic PCMs is the ability to precisely select the phase transition temperature. However, their use is limited by high cost and insufficiently understood thermophysical properties (Kulish *et al.,* 2023).

Considering the advantages and limitations of all PCM types, organic materials – especially paraffins – are the most suitable for thermal energy storage systems and enhancing the energy efficiency of buildings. They are environmentally safe, stable, readily available and exhibit low corrosive activity. The main drawback remains their low thermal conductivity; therefore, a significant proportion of research focuses on enhancing heat transfer within paraffin volumes, particularly in building structures or thermal storage units.

Technologies for the integration of pcms in construction

Thermal inertia refers to a building's envelope ability to slow down internal temperature fluctuations in response to changes in external temperature and solar radiation. In summer, building materials absorb excess heat during the day and release it at night, helping to prevent overheating. In winter, they slow the rate of cooling, helping to retain heat indoors. A building envelope typically consists of multiple layers, each serving a distinct purpose: structural (e.g. concrete, reinforced concrete), thermal insulation, decorative, and so on. The composition and structure of the envelope are determined by national construction standards, which account for climatic conditions, energy consumption requirements, and comfort.

One way to improve energy efficiency is to increase the building's thermal inertia through the use of PCMs. For instance, paraffin integrated into walls or ceilings accumulates heat during the day (in summer) or while heating systems are in operation (in winter) as it undergoes a phase change. At night in summer, or after the heating is turned off in winter, the stored energy is released as the paraffin solidifies, helping to stabilise indoor temperatures and reduce the demand on cooling or heating systems. PCMs are most commonly integrated into walls and ceilings, which are the main surfaces exposed to high thermal loads. Incorporation into floors is generally less effective due to the stable temperature of the ground. The use of PCMs in windows is limited owing to the risk of leakage and the potential reduction in glazing transparency. Thus, the application of PCMs in building envelopes contributes to temperature stabilisation, improved energy efficiency and enhanced comfort of the residents. The existing methods for incorporating PCMs into the building envelope, along with their advantages and disadvantages, are presented in Table 1.

Table 1. *Methods for incorporating PCMs into the building envelope*

Method	Description	Advantages	Disadvantages
Mixing with construction materials	Impregnation of porous structural materials with liquid PCM.	Simple implementation; low cost.	Leakage during phase change; reduction in structural strength.
Impregnation of porous structural materials with liquid PCM	Based on capillary absorption of liquid PCM into porous materials.	Relatively simple technology.	Leakage during phase change; potential corrosion of reinforcement due to contact between PCM and metal.
Microencapsulation	PCM is divided into microgranules, each coated with a polymer shell.	High efficiency; prevents leakage.	High cost; may be economically unfeasible; requires complex equipment; some granules may be defective due to limitations in the production process.
Macroencapsulation	PCMs are enclosed in containers of various sizes (tubes, plates, bricks, panels).	Relatively low cost; Easy to implement; no special equipment required.	There is a risk of PCM leakage if the container is damaged or loses integrity.

Table 1. Continued

Method	Description	Advantages	Disadvantages
Incorporation into a supporting matrix	PCM is embedded in a polymer or other supporting structure (e.g. polyethylene or butadiene rubber).	Stable retention of material through repeated phase transitions; improved thermal conductivity throughout the PCM volume; low risk of leakage; high number of phase change cycles without significant degradation of properties.	High cost.
Shape-stabilised method	PCM is absorbed into or embedded within a porous or composite structure (e.g. expanded graphite, polymers, foams).	Simple design; material remains sealed; durability; high number of phase change cycles without significant degradation of properties.	High cost.

Source: *developed by the authors based on research S. Lu et al. (2016), K. Cellat et al. (2017), K. Powała et al. (2022)*

One of the simplest and most widely used methods listed in Table 1 is macroencapsulation, due to its significant advantages and the absence of major drawbacks. Examples of this method in application are shown in Figure 2.

a b c

Figure 2. *Various forms of macroencapsulation used in building structures*
Note: *a – plates; b – tubes; c – spheres*
Source: *developed by the authors based on research P.K.S. Rathore & S.K. Shukla (2020), M. Velasco-Carrasco et al. (2020), E. Osterman et al. (2023)*

The effectiveness of a chosen method depends on numerous factors – material type, enclosure design, temperature fluctuations, cost, and more. Therefore, the integration of PCM must be not only reliable but also an economically justified solution for enhancing a building's energy efficiency. A key thermophysical characteristic of PCM is the optimal temperature at which the phase transition occurs. The optimal phase change temperature must be determined based on the climatic conditions of the specific location where the PCM is intended for use in the building envelope. Primarily, the phase transition temperature should ensure full activation of the melting-crystallisation cycle throughout the entire PCM layer (Lei *et al.*, 2016). This enables the material to be used with maximum efficiency and allows the phase change to occur across the full volume of PCM. On the other hand, the phase change temperature should be as close as possible to the indoor thermal comfort range in order to maintain a comfortable environment for occupants. Several studies have shown that the use of PCM is ineffective if the phase transition temperature is poorly selected (Alshuraiaan, 2022).

The location of the PCM layer within the building envelope also affects the material's efficiency. The number of layers in the building envelope and the materials used depend on construction standards and regulations in a given region. There are two boundary options for positioning PCM to enhance building cooling: on the inner or outer surface of the envelope. Experiments by A. de Gracia (2019), P.K.S. Rathore & S.K. Shukla (2020), and A. Khayyaminejad & A. Fartaj (2024) demonstrated that, in terms of effective cooling, placing the phase change material on the external surface allows it to absorb a substantial amount of heat during the day and undergo a full phase transition (with the proportion of melted PCM approaching 100%). At night, the phase change material cools and crystallises, releasing thermal energy into the surrounding environment. This type of PCM application does not require additional heating or cooling mechanisms and is referred to as a passive system. When the phase change material layer is positioned internally, ventilation systems are needed to enhance night-time cooling and ensure the PCM fully solidifies (Khayyaminejad & Fartaj, 2024). This setup is classified as an active system. Compared to passive systems, active ones are more complex, as they require the installation of additional cooling and ventilation equipment within the building.

The use of PCM in building envelope components offers an effective means of improving energy efficiency and stabilising the indoor microclimate. The most suitable methods of integration are considered to be macroencapsulation and stabilised forms, which combine efficiency with technological simplicity. The selection of the phase change temperature must take into account the local climate and ensure full activation of the material.

Assessing the effectiveness of incorporating a pcm layer into the building envelope

A substantial number of studies focus on assessing the effectiveness of incorporating PCM into building envelopes. Most of them (nearly 60%) are based on the use of organic PCM for passive building cooling, with paraffin being the most commonly used organic PCM (46%). This focus can be attributed to its relatively high melting point, broad compatibility with most envelope materials, and chemical stability. This conclusion aligns with the assertion that chemical instability, supercooling, and high corrosiveness are the main disadvantages of inorganic PCMs. The second most commonly used PCM type is the eutectic variety. Although this category of PCM is expensive, its high latent heat of fusion per unit volume and superior thermal conductivity have made it a promising option for cooling applications (Akeiber *et al.*, 2016). The following section presents the results of several studies.

P. Rathore & S. Shukla (2020) investigated the effectiveness of PCM macroencapsulated within the wall of an experimental cubic chamber (Fig. 3) measuring1.12 m × 1.12 m × 1.12 m under the climatic conditions of Mathura, India.

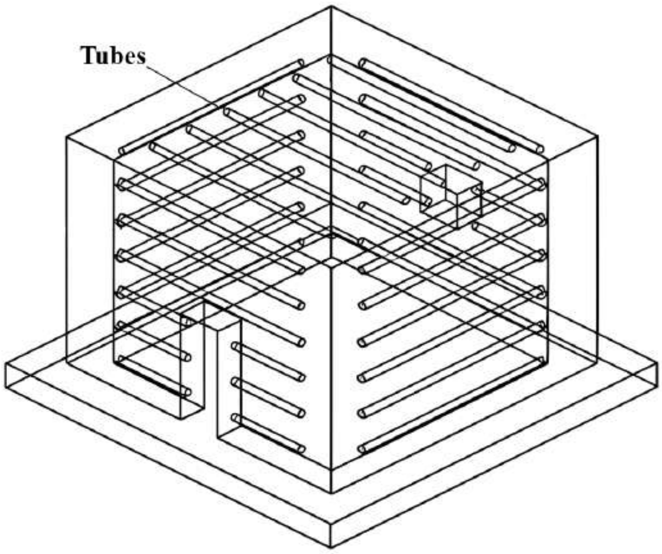


Figure 3. *Schematic diagram of the experimental chamber with macroencapsulated PCM*
Source: *developed by the authors based on research by P.K.S. Rathore & S.K. Shukla (2020)*

Tubes of varying lengths with a diameter of 16.7 mm were used as capsules, positioned horizontally within the building envelope. During the experiment, two identical chambers were constructed: a baseline model and a PCM-enhanced model. The results showed that the incorporation of PCM reduced the heat flux through the envelope wall by 19.41%-41.31% for different components of the structure. Additionally, a 27.32% reduction in overall peak heat flux was achieved. The peak temperature of the PCM-enhanced model was 7.41%-8.08% lower compared to the baseline version. The authors concluded that macroencapsulated PCM integrated into the walls of a building could reduce the cooling load by up to 38.76%.

A. Khayyaminejad & A. Fartaj (2024) examined the effectiveness of placing a PCM layer in three different locations within the envelope of a residential building (Fig. 4) under the climatic conditions of Las Vegas, USA. The baseline wall assembly consisted of brick, wooden siding, insulation, and plasterboard. In the first scenario, the PCM layer was positioned close to the exterior surface of the wall, behind the brick layer and in front of the wooden siding. In the second scenario, the PCM was placed between the wooden siding and the insulation layer. In the third and final scenario, the PCM layer was located near the interior surface of the wall. The results of the study by A. Khayyaminejad & A. Fartaj (2024) demonstrated that integrating a PCM layer into the walls led to a reduction in peak indoor temperature by 1.5 K in scenarios 1 and 2, whereas in scenario 3 the reduction was only 0.5 K. Regarding the percentage of liquid PCM after discharge, in scenarios 1 and 2 the PCM completely melted, with a time difference of 42 minutes (melting occurred earlier in scenario 1). In contrast, in scenario 3, the PCM melted only by 70%. This is due to the greater influence of the indoor temperature. The results indicate that placing the PCM layer near the internal surface of the envelope reduces its effectiveness during summer cooling. Overall, integrating PCM into the building envelope in the most efficient configuration resulted in an additional energy saving of 3.5% over 24 hours and 5% during peak temperature periods.

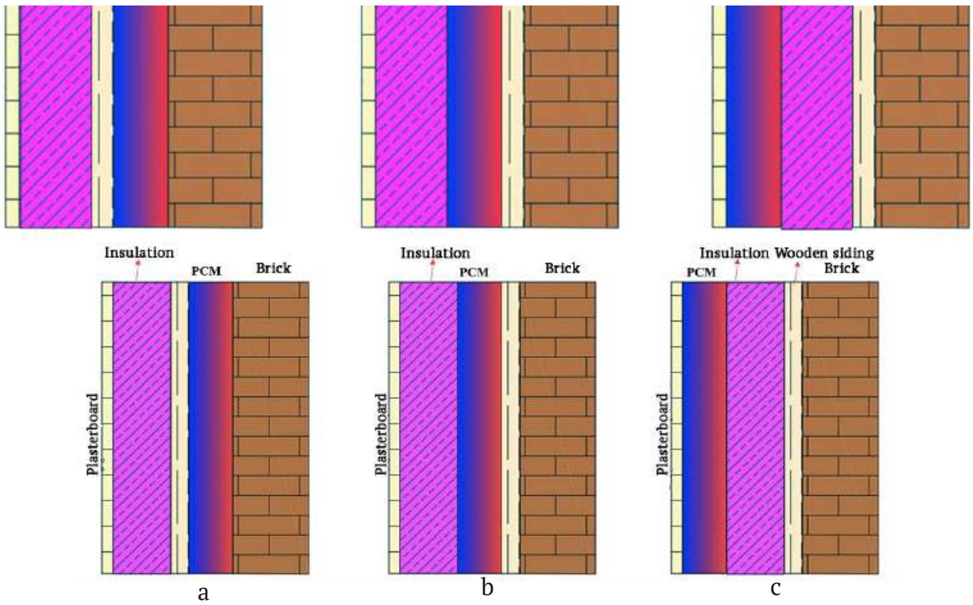


Figure 4. *Investigated configurations of PCM layer placement within the building envelope*
Note: *a – scenario one; b –scenario two; c –scenario three*
Source: *developed by the authors based on research by A. Khayyaminejad & A. Fartaj (2024)*

The study by J. Lei *et al.* (2016) investigated the effectiveness of incorporating a PCM layer into a building envelope under the climatic conditions of Singapore. A simplified cubic model measuring 3 × 3 × 2.8 m was developed, with a 10 mm thick PCM layer applied to the external walls. A reference model without PCM was also simulated as the baseline. A reduction in the peak temperature of the concrete surface located behind the PCM layer reached 3-4°C. Furthermore, the phase-change material contributed to a 21-32% annual reduction in monthly heat gain through the envelope. In the study by K. Powała *et al.* (2022), the authors used a specialised technique to produce gypsum granules containing PCM, which were coated with a protective polymer layer. This encapsulation method was then applied by adding the granules in large quantities to a gypsum mixture, which was subsequently used to manufacture plasterboard panels. After placing the granules into dedicated moulds for testing, they were filled with gypsum as a binding material. Two identical panels were prepared: one incorporating PCM elements and the other without (Fig. 5). Several thermocouples were embedded into the fabricated panels, which were then exposed to artificial light with a power output of 1,000 W to simulate sunlight.

Figure 5. *Appearance of the experimental setup*
Note: *a – plasterboard panels attached to the measurement station; b – 1,000 W lamps*
Source: *developed by the authors based on research by K. Powała et al. (2022)*

The results of the experiment by K. Powała *et al.* (2022) demonstrated that the panel containing PCM granules with a polymer coating exhibited superior thermal performance. Notably, a phase transition occurred after 3 hours of heating at a temperature of approximately 22°C (Fig. 6). It was also observed that the time at which peak temperature was reached was delayed. This is most evident at 25°C, where the delay in reaching this temperature was about one hour compared to plasterboard without PCM. The peak temperature was also reduced by approximately 3°C.

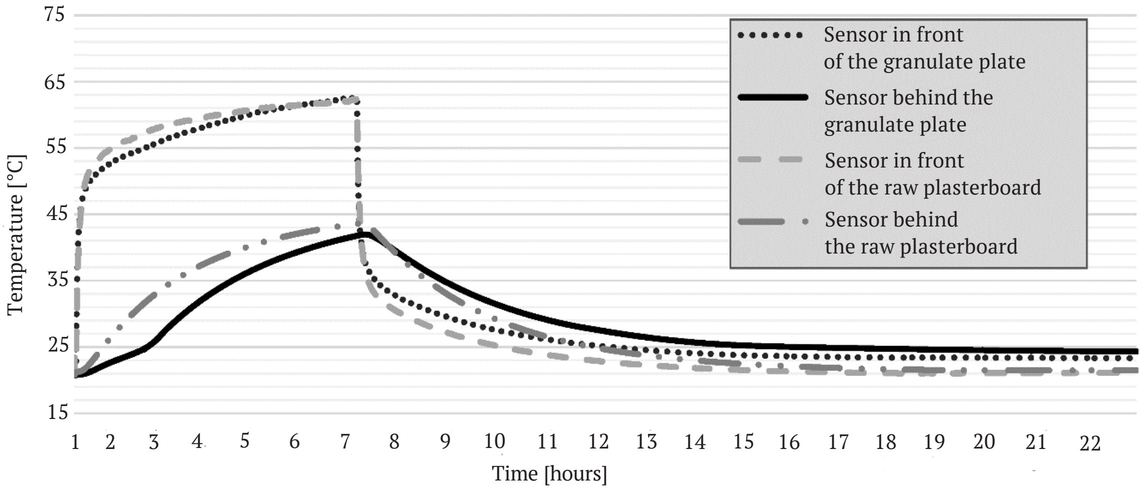


Figure 6. *Temperature variation as a function of time for plasterboard with and without PCM*
Source: *developed by the authors based on research by K. Powała et al. (2022)*

The study by Y. Gao *et al.* (2020) focused on the thermal performance of hollow bricks into which PCM was integrated within the cavities. The aim of the research was to enhance the thermal inertia of lightweight construction materials, which are commonly used in high-rise buildings and can lead to considerable indoor temperature fluctuations. The authors developed a numerical model to simulate the melting-solidification processes of PCM within bricks and validated its accuracy through a full-scale experiment. The results indicated that filling bricks with PCM significantly improved their thermal performance by reducing the rate of heat flux attenuation and increasing the time delay in heat transfer. Specifically, it was found that, with an appropriate phase change temperature, PCM could reduce the attenuation rate from 13.07% to 0.92%-1.93% and extend the delay time from 3.83 hours to 8.83-9.83 hours. In addition, the use of PCM contributed to a reduction in peak heat flux.

The study by M. Saffari *et al.* (2022) focused on exploring methods to enhance the energy flexibility of buildings by integrating PCM into their envelope structures. The authors investigated how PCM could help buildings respond more effectively to variations in energy availability and cost, particularly in the context of an increasing share of renewable sources. The research employed modelling and analysis of the thermal behaviour of buildings with PCM-integrated envelopes. The aim was to demonstrate how such systems can smooth peak loads on the energy grid by storing thermal energy when it is cheap or abundant and releasing it when needed. The results showed that the maximum flexibility efficiency in energy consumption reached 356% in a scenario involving short-term preheating of the building for 30 minutes followed by a long demand response period of four hours.

The study by R. Vanaga *et al.* (2023) focused on a comparative analysis of the effectiveness of two different PCMs – RT21HC and RT28HC – for integration into building envelopes with the aim of thermal energy storage. The research combined experimental and numerical methods, allowing for a comprehensive assessment of their performance. Laboratory tests simulated the conditions of all four seasons using a specialised PASLINK test facility to replicate both indoor and outdoor environments. Based on the experimental data, a numerical model was developed to further explore PCM behaviour under various climatic conditions. The experimental findings demonstrated that RT21HC was more effective at storing and releasing thermal energy into indoor spaces, while numerical simulations indicated that RT28HC performed better in the climate of Southern Europe, where it more effectively prevented indoor overheating.

In summary, the findings confirm that integrating PCM into building envelope structures effectively reduces peak temperatures, heat flux, and energy consumption for cooling. The best outcomes are achieved through the appropriate selection of PCM type, encapsulation method, and placement within the structure. These studies highlight the potential of PCM as a means of enhancing building energy efficiency and flexibility, particularly in the context of increasing reliance on renewable energy sources.

Thermal accumulators based on PCM

A thermal accumulator is a device designed for the accumulation, storage, and gradual release of thermal energy. This article considers the potential application of thermal accumulators based on PCM, taking into account the advantages offered by this type of material. In the context of improving a building's energy efficiency, a thermal accumulator can be integrated into heating systems (Antypov *et al*., 2022), domestic hot water (DHW) supply, or cooling systems (Bejarano *et al.,* 2018). The charge-discharge cycle is implemented through the circulation of a heat transfer fluid. Depending on the method of heat exchange between the heat transfer fluid and the PCM, accumulators are classified as either contact or non-contact.

In contact-type thermal accumulators, the heat transfer fluid comes into direct contact with the phase change material. Oil is most commonly used as the heat carrier, with water or gas used less frequently. Direct contact enables intense heat exchange, with a heat transfer coefficient ranging from 100 to 1,000 W/m^2·K. The heat carrier is typically injected through nozzles, transferring heat to the PCM primarily via convection, and then exits the accumulator under the influence of gravity. However, contact accumulators present several drawbacks, including the risk of nozzle blockage due to PCM crystallisation (Liu *et al*., 2024), mixing of the heat carrier with the PCM – which is unacceptable for domestic systems – chemical degradation of PCM from prolonged contact with the fluid, and the complexity of the design required to ensure uniform heat transfer, which increases cost and complicates installation. These factors make the use of contact-type accumulators in buildings impractical for enhancing energy efficiency.

Non-contact accumulators separate the heat transfer fluid and the PCM by means of a tubular wall, preventing direct interaction between them. The phase change material is housed within a sealed casing, while one or more tubes of various shapes pass through the accumulator, facilitating heat exchange between the storage medium and the heat carrier. The heat transfer coefficient through the tube walls can reach 50-500 W/m^2·K. Water is most commonly used as the heat transfer fluid due to its affordability, versatility, availability, and high specific heat capacity. This makes such accumulators easy to integrate into even the simplest heating or DHW systems in buildings. Technical-grade paraffins are the most widely used storage materials owing to their physical and chemical stability, low corrosive activity, low cost, and ready availability. During the charging process, hot fluid transfers heat to the PCM through the walls of the tubes, causing it to melt. During discharging, cooler fluid absorbs the stored heat, leading to the crystallisation of the PCM.

The primary function of a thermal accumulator is to store surplus heat and release it during periods of increased demand. When integrated with renewable energy sources (RES), PCM can store excess energy – for instance, from solar panels during daylight hours – and subsequently supply it for heating or DHW at the required time. In systems connected to the traditional electricity grid, night-time charging of the accumulator at reduced tariffs is a viable option.

Enhancing heat transfer in thermal accumulators

The primary drawback of thermal accumulators using paraffins as PCM lies in the inherently low thermal conductivity of paraffins. This significantly prolongs the charging and discharging times and leads to the formation of zones where the storage material does not undergo a phase change and thus does not participate in the heat accumulation process. Another consequence of low thermal conductivity is the emergence of a high temperature gradient, with certain areas containing overheated liquid-phase material and others remaining in a low-temperature solid state. This uneven temperature distribution within the PCM reduces the efficiency of the accumulator and may result in local degradation of the material or a decline in its thermal activity. A substantial body of experimental and theoretical research has focused on addressing this issue through optimisation of the thermal accumulator design and enhancement of heat transfer between the PCM and the heat transfer fluid.

Ye.O. Antipov (2016) proposed an optimised thermal accumulator design featuring a wavy bottom configuration and the addition of electric heating wires as internal heat sources. The temperature fields before and after optimisation are shown in Figure 7. An analysis of the performance of the modified accumulator in comparison to the original model demonstrated that the temperature of the PCM near the lower part of the casing wall was 7%-15% higher than in the previous flat-bottomed design. The introduction of additional electric heating elements enabled an 8%-10% increase in heat removal efficiency, a 10%-15% reduction in the device's mass and overall dimensions, a 36% improvement in the useful mass utilisation coefficient of the storage medium, and an 86% extension of discharge duration (heat release mode), assuming the same thermal output as the baseline model.

In the article by A. Dmitruk *et al.* (2020a), the authors proposed the use of metallic inclusions in the form of honeycomb frameworks (Fig. 8) to optimise heat transfer in paraffin-based thermal accumulators using RT-82. The proposed metal structures present a promising solution for enhancing heat exchange due to their large heat transfer surface area, high thermal conductivity, and compact shape. The aluminium alloy used, containing 13% silicon, has a thermal conductivity of 158 W/m·K, which intensifies heat flow within the PCM during the charging process. An additional design using perforated honeycomb structures was also developed and cast (Fig. 8). Compared to the solid element, this approach allowed for an 18% mass reduction, promoted more active convection, and improved thermal conductivity, while maintaining thermal performance similar to the solid variant.

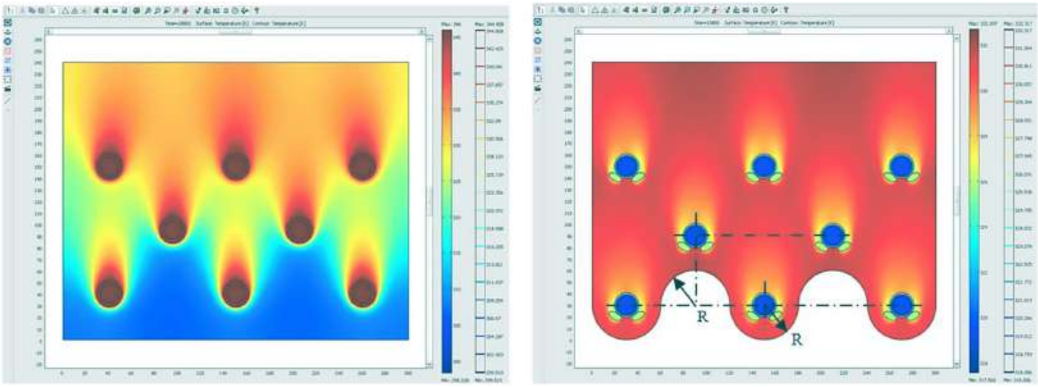
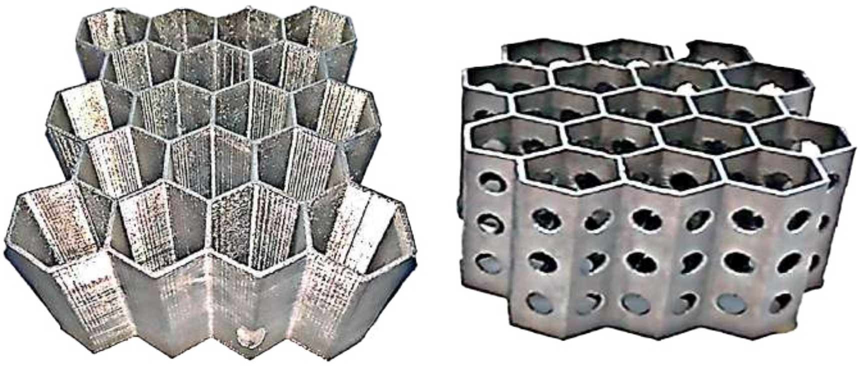


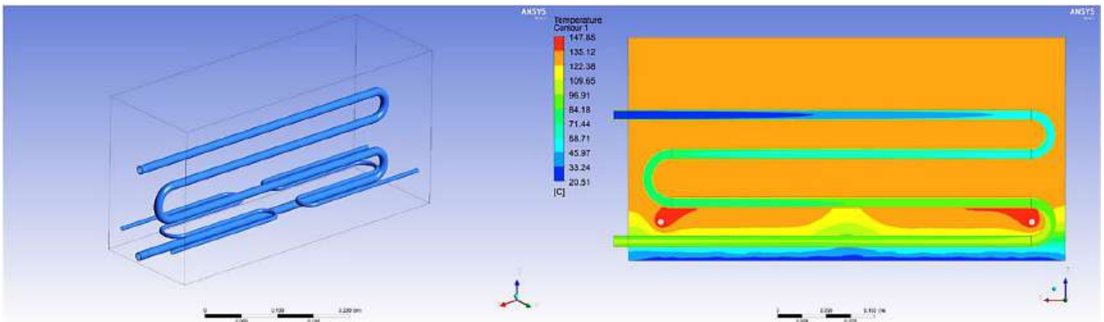
Figure 7. *Temperature fields of the cross-section in the original and optimised accumulator designs*
Source: *developed by the authors based on research by Ye.O. Antipov (2016)*



a b

Figure 8. *Cast Al-Si honeycomb structures*
Note: *a – solid honeycomb structures; b – perforated honeycomb structures*
Source:*developed by the authors based on research by A. Dmitruk et al. (2020a)*

Y.O. Hlek (2024), in her study, developed two new paraffin-based thermal storage materials: paraffin/fullerene C_{60} and paraffin/thermally expanded graphite. These materials were produced by introducing carbon-based additives into pure paraffin using nanotechnology. As a result of this combination, the thermal conductivity of the paraffin/thermally expanded graphite composite increased by a factor of 8.9 to 9.6 at 25°C and 8.8 to 10.9 at 65°C, compared to pure paraffin. The findings indicate that the addition of even a small amount of fullerene C_{60} (0.0746 wt%) can enhance the thermal conductivity of the liquid phase from 0.256 to 0.506 $W{\cdot}m^{-1}{\cdot}K^{-1}$. L. Constantin *et al*. (2015) based their investigation on a standard PCMbased thermal storage unit incorporating a coil embedded within the PCM volume (Fig. 9), through which the heat transfer fluid (water) circulates. Experimental results showed that a layer of semi-solidified paraffin, approximately 50 mm thick, remained in the lower part of the accumulator.



a b

Figure 9. *Reference thermal accumulator model*
Note: *a – base model of the accumulator; b – temperature distribution within the PCM and heat transfer fluid*
Source: *developed by the authors based on research by L. Constantin et al. (2015)*

To improve thermal performance and eliminate heat exchange issues, the original model underwent modernisation. The first optimisation version aimed to homogenise the temperature of the molten paraffin by installing two pipes on either side of the accumulator casing (Fig. 10). The pipes connect the upper and lower parts of the casing, thereby promoting the circulation of paraffin between different layers of the accumulator due to differences in its density.

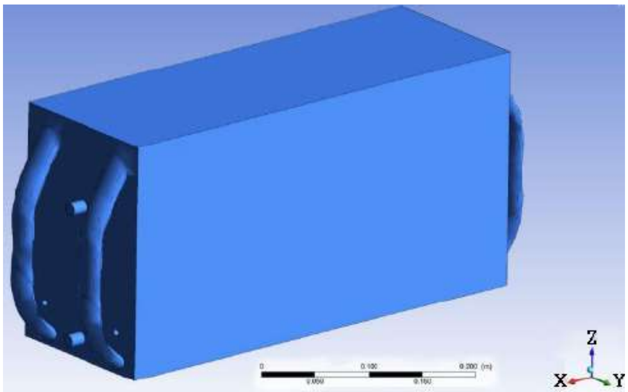
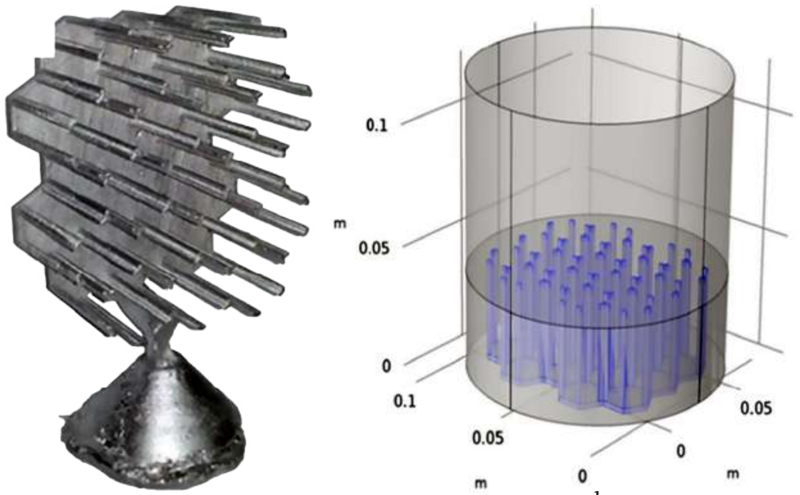


Figure 10. *Thermal accumulator with external pipes*
Source: *developed by the authors based on research by L. Constantin et al. (2015)*

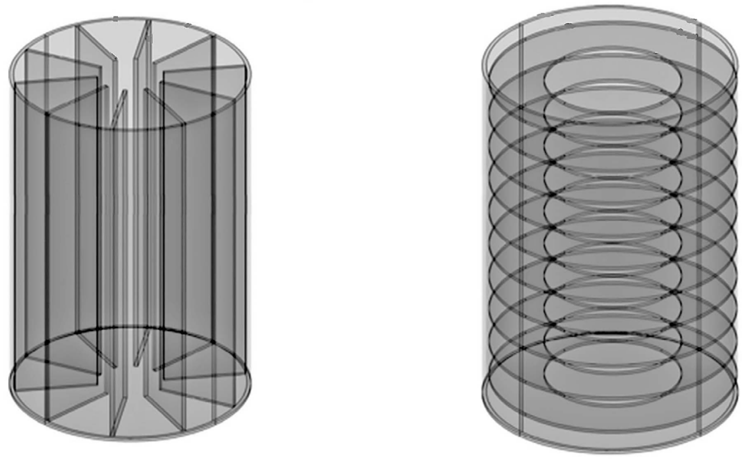
Another modification involved changing the direction of fluid flow to downward, which helps to maintain a high temperature of the heat transfer fluid in the lower part of the PCM volume. As a result of the implementation of these optimisation methods, the thickness of the semi-solidified PCM layer at the bottom of the unit was reduced from 50 mm to 20 mm, thereby increasing the accumulator's storage capacity. A. Dmitruk *et al*. (2020b) investigated the effectiveness of integrating a pin-fin element into the accumulator casing. This element acts as a heat exchange insert in the form of one or several thin rods or pins inserted into the PCM volume to improve heat transfer and stabilise the temperature gradient (Fig. 11). During the experiment, the authors measured temperatures at three points located along the central axis of the accumulator: 1 mm, 18 mm, and 38 mm above the metal base, comparing two accumulator configurations – one with the pin-fin structure and one without it. The results showed that the temperature difference between the measured points was more than twice as low in the PCM with the metallic pin-fin structure compared to the configuration without it. This helped to significantly reduce the temperature drop across the height of the heat accumulator, reduce its recharging time and generally increase the efficiency of the heat storage system.



a b

Figure 11. *Pin-fin heat exchange insert*
Note: *a – cast element made from Al-Si AC 44200 alloy;b – pin-fin structure as a separate metal element in a laboratory-scale thermal accumulator model*
Source: *developed by the authors based on research by A. Dmitruk et al. (2020b)*

In the study by Y. Bai *et al*. (2023), the authors examined the effectiveness of using fins to enhance heat transfer between the heat transfer fluid and the PCM, as well as to reduce the charging time of the thermal accumulator. The main aim of this modification was to test fins of different configurations (longitudinal and annular) and to determine their optimal parameters, such as fin length, thickness, and number. The results showed that under heat accumulation conditions, a built-in longitudinal fin was more effective than an annular one (Fig. 12). The length of the fin played a dominant role in the charging/discharging rate of the accumulator. An analysis of the phase change behaviour of the PCM with and without embedded longitudinal fins revealed that in the model with fins measuring 45 mm in length, the PCM fully solidified in 3,200 s, whereas in the model without fins, it solidified in 19,500 s – a difference of 610%. This result indicates that the embedded fins significantly enhanced heat transfer between the heat transfer fluid and the PCM.



a b

Figure 12. *Configuration of longitudinal and annular fins*

Note: *a – longitudinal fin; b – annular fin*

Source: *developed by the authors based on research by Y. Bai et al. (2023)*

The study by G. Liu *et al.* (2022) focuses on investigating the effect of the position of the internal heating tube on the efficiency of the phase change (melting) process in a shell-andtube type thermal energy storage system. The authors developed a two-dimensional numerical model to simulate the thermal energy accumulation process. The primary objective was to determine the optimal position of the internal tube to minimise the total melting time of the material. The simulation results indicated that displacing the internal tube from the central axis significantly affects the rate of the phase change. In particular, it was found that positioning the tube 12 mm off-centre reduced the total melting time by 13.4% compared to a centrally placed tube. This demonstrates the potential of geometric optimisation to enhance heat transfer efficiency and accelerate energy storage processes in such systems.

The study by C. Liu *et al.* (2020) was dedicated to the experimental investigation of the effectiveness of oscillating heat pipes (OHPs) in improving heat transfer in PCM-based thermal energy storage systems. The article focuses on integrating OHPs into a reservoir containing PCM to accelerate the charging and discharging of thermal energy. During the experiments, the influence of various parameters – such as the working fluid inside the OHP and the heat flux – on the melting and solidification rates of the PCM was measured. The results showed that the thermal energy storage time for a paraffin-based unit combined with OHPs (Dinr = 3 mm, Dout = 4 mm, 4 loops) was 38.45% shorter compared to a unit without such pipes. This makes the use of OHPs effective for enhancing heat transfer, which in turn leads to a reduction in the time required for storing and releasing thermal energy.

In the study by H. Yang *et al.* (2021), an experimental investigation was conducted into the mechanisms of control and improvement of heat transfer efficiency in composite phase change materials (CPCMs). The authors focused on developing and testing innovative approaches to improve thermal energy charging and discharging using CPCMs. The research included an analysis of the impact of various structural components and methods of their integration on the thermophysical properties of the materials. The experimental results demonstrated that copper foam significantly improved the thermal conductivity of CPCMs. The thermal conductivity of the composite material (copper foam/PCM) with 95% porosity and a pore density of 50 pores per inch was 1.34 W/m·K, while for a foam with 85% porosity and the same pore density, it reached 4.35 W/m·K – approximately 20 times higher than the thermal conductivity of PCM without copper foam.

The study by B. Lu *et al.* (2023) was devoted to improving the melting efficiency of PCM in latent heat thermal energy storage systems. The authors focused on the development and analysis of new configurations to enhance heat transfer during the phase change process of PCM. The study examined the impact of fin geometry and the use of additional thermally conductive elements on the melting rate of phase change materials. Numerical methods were applied to assess system performance. The results showed that the total melting time for nonuniformly distributed longitudinal fins was reduced by 31% compared to a traditional fin arrangement. A correlation was found between the PCM melting rate and both the intensity and distribution of natural convection throughout the melting process.

In the study by S.K. Singh *et al.* (2022), an experimental investigation was carried out on a latent heat thermal energy storage system using encapsulated PCM. The authors focused on the integration of multiple types of PCM within a single storage unit to improve overall system efficiency. This research aimed to analyse the thermal characteristics and behaviour of the system under various operating conditions. The findings confirmed that using multiple PCMs with different melting points in a single unit enhances the system's heat storage capacity. As the heat transfer fluid (HTF) flow rate increased from 1 to 5 litres per minute, the melting time decreased by 10%-30%, while the solidification time was reduced by 14%-28%.

Research has shown that the efficiency of PCM-based thermal energy storage systems depends on design geometry, thermal conductivity enhancers, and material type. Optimising the arrangement of heating elements, using heat pipes, copper foam, and multiple PCMs improves heat transfer and shortens the phase transition time. Such approaches hold considerable potential for enhancing the energy efficiency of thermal energy storage systems.

Conclusions

As a result of the analysis of scientific research and experimental findings, it has been established that the use of phase change materials holds significant potential for enhancing the energy efficiency of buildings and ensuring effective thermal energy storage. Incorporating PCM into building envelope structures can considerably increase their thermal inertia, reduce indoor temperature fluctuations, and lower energy consumption for heating and cooling. Various types of energy storage and phase transitions that underpin PCM operation have been reviewed, along with a classification of PCM by composition and methods of integration into construction materials. It has been identified that the correct selection of the material's phase change temperature, as well as its optimal placement within the building envelope, are critical factors in achieving maximum energy-saving effects. Particular attention has been given to the potential integration of PCM in thermal storage units for heating and hot water supply systems, as well as to methods of enhancing heat transfer in such systems to maximise their efficiency. The results indicated that the choice of PCM type should be based on the building's operating temperature conditions and the required level of thermal stability of the indoor environment. The use of encapsulation technologies and shape-stabilised methods significantly enhances the reliability and durability of PCMs when integrated into building structures. Furthermore, PCM-based thermal storage units offer additional opportunities for controlled heat supply, particularly in the context of the widespread adoption of renewable energy sources, thereby contributing to the overall improvement of building energy efficiency.

Future research should focus on conducting experimental and numerical studies on the long-term performance of PCM in building applications under real operating conditions, particularly considering the effects of cyclic phase transitions and material degradation. A key area of development involves the creation of new PCM-based composite materials with improved thermal conductivity, chemical stability and resistance to leakage. Further research is also required to optimise heat transfer processes in PCM thermal storage systems through the use of specialised inserts, fins and other structural elements. Another promising direction is the study of PCM integration in combination with other energy-efficient technologies for buildings, such as heat recovery ventilation systems, solar collectors and heat pumps. Additionally, it is important to analyse the effectiveness of PCM use in construction across different climate zones of Ukraine, taking into account projected climate change over the coming decades. In summary, continued research in this area offers wide-ranging opportunities for the development of innovative building solutions that enhance energy independence, indoor comfort and the reduction of greenhouse gas emissions.

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Conflict of Interest

None.

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Аналіз використання фазоперехідних матеріалів для підвищення рівня енергоефективності будівель та акумуляції теплової енергії

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Анотація. Зростання попиту на енергоефективні будівлі та прагнення до зниження викидів парникових газів вимагають впровадження інноваційних підходів до управління тепловою енергією в будівлях. Одним із таких підходів є використання фазоперехідних матеріалів, які забезпечують акумуляцію теплової енергії та підвищують теплову інерційність будівельних конструкцій, що робить їх ефективним рішенням для оптимізації енергоефективності будівель у різних кліматичних умовах. Метою статті був аналіз існуючих методів використання фазоперехідних матеріалів для підвищення енергоефективності будівель шляхом акумуляції теплової енергії. Зокрема, досліджувалися методи включення таких матеріалів в оболонку будівель та застосування їх у теплових акумуляторах. У статті застосовано методи аналізу та систематизації наукової літератури, зокрема розглянуто результати досліджень щодо впливу фазоперехідних матеріалів на теплову інерційність будівельних конструкцій, ефективність їх використання в теплових акумуляторах та вплив на енергоефективність будівель. Встановлено, що застосування фазоперехідних матеріалів сприяє значному підвищенню теплової інерційності будівель та зниженню втрат теплової енергії. Проаналізовано різні методи включення фазоперехідних матеріалів в оболонку будівель та їх використання у теплових акумуляторах. Виявлено основні переваги та недоліки кожного з методів, а також наведено приклади їх практичного застосування. Висвітлено можливі способи використання теплових акумуляторів з метою підвищення енергоефективності будівель, зокрема їх включення в системи опалення та гарячого водопостачання. Результати дослідження можуть бути використані при проєктуванні енергоефективних будівель, систем опалення та гарячого водопостачання, які використовують фазоперехідні матеріали для акумуляції теплової енергії, що сприятиме зниженню енергоспоживання та підвищенню комфорту проживання

Ключові слова: фазоперехідні матеріали; парафін; огороджувальні конструкції; теплова інерційність; прихована теплота