Enhancing Building Energy Efficiency with Innovative Paraffin-based Phase Change Materials

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ABSTRACT

The demand for more energy-efficient and low-carbon buildings and neighborhoods has intensified due to the significant energy consumption associated with the building sector. This, coupled with the expanding global population and rising standards of human comfort, underscores the urgency of addressing this issue. Integrating highly energy-efficient technologies in buildings is key to tackling this challenge. In this context, thermal energy storage (TES) emerges as a recognized and efficient technology for reducing greenhouse gas emissions and energy consumption in buildings and neighborhoods. A solid example of TES is Phase Change Materials (PCMs), which have emerged as promising agents for improving energy efficiency in buildings by mitigating temperature fluctuations. Based on their physical characteristics, PCMs are mainly categorized in Solid-Solid (SS-PCMs) and Solid-Liquid (SL-PCMs). This paper explores the application of PCMs, with a specific focus on organic paraffin-based SL-PCMs solutions, in enhancing thermal performance and reducing energy consumption in buildings. Paraffin-based PCMs offer advantages such as high thermal storage capacity, compatibility with building materials, and cost-effectiveness. This paper shortly reviews recent advancements in the integration of paraffin based PCMs into building components, including roofs, walls, ceilings, windows, and floors, to regulate indoor temperatures and optimize energy usage. The challenge that arises is that, although progress has been made in the use of PCM materials within different categories separately, there has not been a focus on combinations of PCM materials within a building, such as a combination of PCM in walls and ceiling. Therefore, this paper explores a use case example in building design, where paraffin based PCM is employed in various combinations of building materials simulated using OpenStudio/EnergyPlus. The thermal conductivity of paraffin-based PCMs, integrated into building elements such as cement or gypsum boards, was determined using the Hot Disc TPS1500, whereas their solar reflectance was measured using a UV-RIS-NIS spectrophotometer. These laboratory measurements serve as inputs for the OpenStudio/EnergyPlus simulations. Subsequently, energy savings are quantified for each scenario, simulating all samples, with insulated and non-insulated case study building, with two PCM simulation models in EnergyPlus, at different setpoints, allowing for comparative analysis.

KEYWORDS: Phase Change Materials, Paraffin, Energy Efficiency in Buildings, EnergyPlus

INTRODUCTION

In the pursuit of sustainable development and mitigating climate change, enhancing building energy efficiency stands as a paramount goal. In this context, leveraging innovative paraffin-based Phase Change Materials (PCMs) emerges as a promising solution. PCMs possess the unique ability to store and release large amounts of thermal energy during phase transitions, thereby regulating indoor temperatures effectively [1]. This introduction sets the stage for exploring how integrating these advanced materials into building design and construction can revolutionize energy management practices, reduce carbon footprints, and foster environmentally conscious architecture.

Thermal Energy Storage encompasses various methods, including harnessing latent heat, utilizing the sensible heat capacity of materials, or leveraging materials' exothermic and endothermic chemical reactions [2]. However, among these methods, the use of PCMs for storing or releasing thermal energy through latent heat storage has emerged as a particularly promising solution over the past few decades [3]. PCMs possess a significant latent heat capacity, making them highly effective for managing a building's thermal environment. By transitioning between solid and liquid phases, PCMs can effectively absorb and release heat, thereby reducing heating and cooling loads and shifting peak energy demands [4]. During the day, PCMs absorb excess solar energy, minimizing heat penetration into the building. Conversely, at night, when temperatures drop, PCMs release stored heat, maintaining thermal comfort indoors [5].

The application of PCMs in buildings not only enhances energy efficiency but also aligns with broader sustainability goals [6]. Buildings designed with PCMs contribute to reducing overall energy consumption, thereby mitigating environmental impact and promoting resource conservation. Moreover, the integration of PCMs supports the advancement of net-zero energy buildings, offering significant economic and environmental benefits for society [7]. As PCM technology continues to evolve and gain traction, its implementation represents a critical step toward achieving energy-efficient and environmentally sustainable buildings [8]. In a study, integrating PCMs into the outer face of south side brick walls resulted in a 13.4% energy savings [9]. However, a 30-year life cycle analysis revealed that PCM integration into walls may not be cost-effective. Similarly, in another research, it was found that PCM dry walls significantly improved energy efficiency, particularly in a Mediterranean climate like Coimbra, Portugal, with gains of up to 62% [10]. However, the effectiveness varied in other climates, showing energy efficiency improvements ranging from 10% to 46%.

PCMs are categorised in solid-solid and solid-liquid transitions, where in the latter there are the organic, eutectic and inorganic categories [11]. The organic category includes fatty esters, fatty acids, alcohol/polyols and paraffins (Figure 1). Application of paraffin based PCMs in buildings are seen across the floor, bricks, walls, roof, and windows (Figure 1) [12].

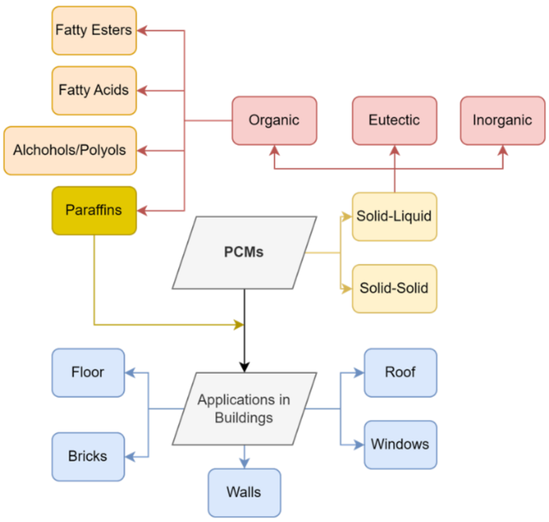

Figure1. *PCM categories focused on paraffin-based one, and their applications in Buildings.*

Extensive research has delved into the utilization of paraffin PCMs within building components, prompting a shift towards emerging alternatives such as biobased PCMs [12]. However, much of this exploration has remained confined to simulation studies or laboratory-scale experiments. The untapped potential lies in implementing PCMs within real-life building environments to evaluate their thermal performance in real-time scenarios. Current studies predominantly emphasize singular applications [13-19]. However, by diversifying integration across multiple building elements—walls, ceilings, and floors—there's a prospect for yielding varied outcomes, ultimately enhancing overall building performance, and aligning with sustainable endeavors to transition conventional

structures into net-zero energy buildings [12].
The objective of this study is to measure the properties of shape stabilized paraffin-based PCM building elements and conduct simulations to determine their energy-saving potential when used as construction materials. Key parameters such as solar reflectance, thermal conductivity, and specific heat will are measured. This data, in conjunction with other relevant factors, serve as inputs for the EnergyPlus simulation tool. By analyzing the performance of PCMs-containing boards in combinations for roof and wall applications, the aim is to quantify the resulting energy savings.

METHODOLOGY

The methodology followed in this work is shown in Figure 2. N-octadecane with a melting point of 28 °C, was used as the phase change material, and a lightweight ceramic/carbon foam [20] was used as the shape stabilizer. The composite PCM/foam materials that were produced were utilized as thermal energy storage additives for cement and gypsum boards. First, their thermal conductivity and specific heat of boards are measured with Hot Disc TPS 1500 and their solar reflectance with UV Carry 5000. The measured characteristics along with the other inputs are used to be simulated as components in roof, external walls, and a combination of them in the case study building. The building simulation takes place in EnergyPlus simulation tool. The different scenarios and their energy savings results are assessed.

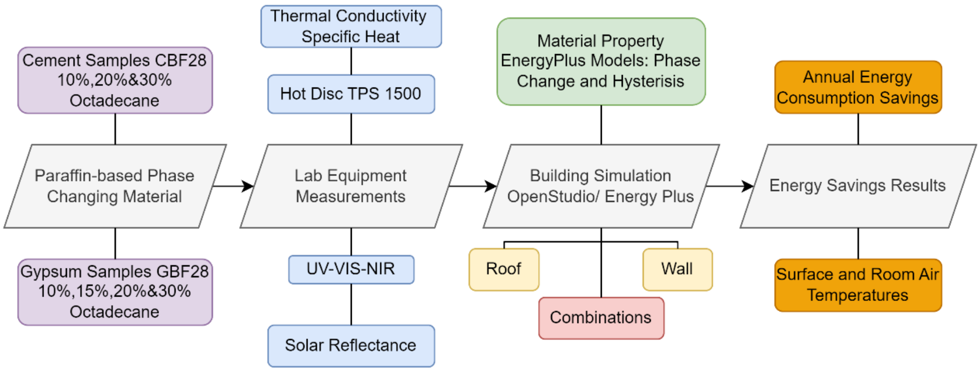

Figure 2. *Methodology.*

The samples measured encompassed various compositions, including cement/perlite boards samples containing 0%, 10%, 20%, and 30% v/v PCM/foam, alongside gypsum boards containing 0%, 10%, 15%, 20% and 30% octadecane mixtures w/w PCM/foam.
The case study two-storey building is located in Chania, Greece, has 214m^2 area, with no insulation and comprised of simple construction materials. Its annual energy consumption is 45.469 kWh.
The energy simulation of the building takes place in EnergyPlus tool. The PCM materials are simulated under MaterialPropert:PhaseChanging and MaterialPropert:PhaseChangingHysterisis types. When these types are included the need of another algorithm is required. The Conduction Transfer Function (CTF) transformation is the default method for computing conduction heat transfer in building cooling/heating loads and energy calculations in EnergyPlus. Its efficiency lies in the streamlined computation of surface heat fluxes, facilitating simple and linear calculations of building loads and surface temperatures in a time-efficient manner. By eliminating the need for knowing temperatures and fluxes within the surface, it simplifies the process while assuming constant properties. However, its limitations include an inability to handle dynamic thermal behavior associated with phase-changing phenomena and a lack of results for the interior of the surface. In contrast, the Conduction Finite Difference (CondFD) solution algorithm is tailored for more complex constructions, such as those involving PCMs. This algorithm complements the CTF method by accommodating variable thermal conductivity cases and property variations. It determines the number of nodes in each layer of the surface based on Fourier stability criteria and is particularly useful for short zone time steps. MaterialProperty:PhaseChange defines material properties for phase changes without considering hysteresis, assuming a constant phase change

temperature. MaterialProperty:PhaseChangeHysteresis, however, incorporates hysteresis effects, allowing for different temperatures for melting and solidification to capture the material's non-linear behavior during phase transitions.

RESULTS AND DESCUSSION

The measurements were used as inputs for the EnergyPlus simulations, as shown in Tables 1, 2 and 3. The simulations tested scenarios regarding all 9 samples, with MaterialProperty:PhaseChange and hysteresis models, adding a PCM layer in the case study building with or without insulation, tested at cooling setpoint of 26C and heating setpoint of 20C, as well as a heating and cooling setpoint that were close to the melting and freezing point of the samples. The setpoints were tested because in PCM modelling in buildings, the cooling setpoint should be slightly below melting point, and the heating setpoint slightly above freezing point.

Table 1. *PCM Properties Inputs in EnergyPlus.*

Field	Units	Samples						
Name		**CBF28_30**	**CBF28_20**	**CBF28_10**	**GBF28_30**	**GBF28_20**	**GBF28_15**	**GBF28_10**
Roughness		Smooth	Smooth	Smooth	Smooth	Smooth	Smooth	Smooth
Thickness	m	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Conductivity	W/mK	0.086	0.086	0.063	0.173	0.170	0.175	0.164
Density	Kg/m^3	650	630	540	950	940	960	870
Specific Heat	J/kgK	125	160	106	118	105	101	103
Thermal Absorptance		0.9	0.9	0.9	0.9	0.9	0.9	0.9
Solar Absorptance		0.57	0.55	0.55	0.51	0.44	0.32	0.30
Visible Absorptance		0.58	0.55	0..58	0.54	0.48	0.35	0.33

Table 2. *PCM Properties Inputs in EnergyPlus for MaterialProperty:PhaseChange model.*

Field	Units	Samples						
Name		**CBF28_30**	**CBF28_20**	**CBF28_10**	**GBF28_30**	**GBF28_20**	**GBF28_15**	**GBF28_10**
Temperature 1	C	10	10	10	10	10	10	10
Enthalpy 1	J/kg	2500	2500	2500	2500	2500	2500	2500
Temperature 2	C	26	26	26	28	27.5	26.5	25
Enthalpy 2	J/kg	9875	8284	4883	14313	8931	5038	3378
Temperature 3	C	26.7	26.6	26.4	28.3	28.1	27.2	25.7
Enthalpy 3	J/kg	17250	14470	8530	25000	15600	8800	5900

Table 3. *PCM Properties Inputs in EnergyPlus for MaterialProperty:PhaseChangeHysterisis model.*

Field	Units	Samples						
Name		**CBF28_30**	**CBF28_20**	**CBF28_10**	**GBF28_30**	**GBF28_20**	**GBF28_15**	**GBF28_10**
Latent Heat during the Entire Phase Change Process	J/kg	14750	22500	6030	22500	13100	6300	3400
Liquid State Thermal Conductivity	W/mK	0.086	0.086	0.063	0.173	0.170	0.175	0.164
Liquid State Density	Kg/m^3	650	630	540	950	940	960	870
Liquid State Specific Heat	J/kgK	125	160	106	118	105	101	103
High Temperature Difference of Melting Curve	deltaC	6.7	5.6	6.4	3.3	3.1	2.2	1
Peak Melting Temperature	C	26.7	26.6	26.4	28.3	28.1	27.2	25.7
Low Temperature Difference of Melting Curve	deltaC	2.3	2.4	1.6	2.7	2.4	1.8	1
Solid State Thermal Conductivity	W/mK	0.086	0.086	0.063	0.173	0.170	0.175	0.164
Solid State Density	Kg/m^3	650	630	540	950	940	960	870

Solid State Specific Heat	J/lgK	125	160	106	118	105	101	103
High Temperature Difference of Freezing Curve	deltaC	3.4	7.8	7.7	4.5	3.3	2.04	2.2
Peak Freezing Temperature	C	23.4	22.8	22.7	24.5	24.3	24.04	22.2
Low Temperature Difference of Freezing Curve	deltaC	1.1	1.2	1.3	1.5	1.7	1.96	1.8

The simulation results show that from the 72 scenarios, CBF28_20 (20% v/v PCM/foam in cement board) resulted in the lowest annual energy consumption, in a scenario were the PCM layer was added in combination with insulation at the external walls and roof, with heating and cooling setpoint at 20-26^{o}C respectively and the sample was modeled with hysteresis effect. The annual energy consumption with this scenario is 31550kWh and 147kWh/m^2, with 45.5% savings from the scenarios with the non-insulated case study building and 4.7% savings from the scenario with the insulated case study building. It should be noted that MaterialProperty:PhaseChange results for annual energy consumption were higher than hysteresis , as expected, due to the latter modelling the change between solid and liquid phases of the material. In addition, even though the optimum annual energy consumption was achieved with heating and cooling setpoint at 20C-26C, there was higher percentage (8.8% from the insulated case study building) of energy savings when the hysteresis model ran at melting and freezing points temperatures as setpoints. This can state that PCMs with melting and freezing points close to 26C and 20C respectively, could result in an even lower annual energy consumption. In Figures 3 and 4, the room air temperature of 1st and ground floor respectively are shown for the optimum scenario (S16), its equivalent scenario ran without hysteresis (S15) and the insulation baseline scenario (S4). There is a notable change in room air temperature in the 1st floor room between S4 and S15-S16, with the latter differentiating on a smaller scale, at hourly level. In ground floor, the change in air temperature is obvious during the summer period.

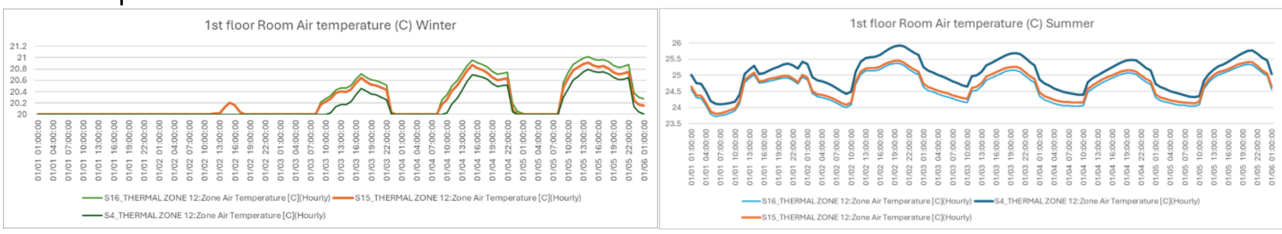

Figure 3. *Case Study Building 1st floor Room Air Temperature for Scenarios with insulation (S4), insulation and CBF28_20 (20% v/v PCM/foam in cement board MaterialProperty:PhaseChange (S15) and MaterialProperty:PhaseChangeHysterisis (S16), at winter (left) and summer (right) .*

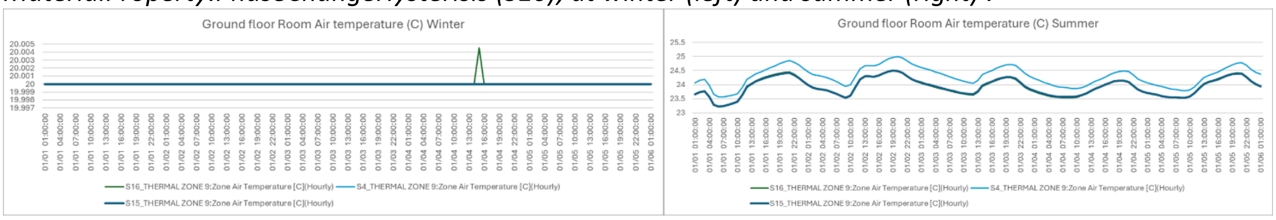

Figure 4. *Case Study Building Ground floor Room Air Temperature for Scenarios with insulation (S4), insulation and CBF28 20 (20% v/v PCM/foam in cement board) MaterialProperty:PhaseChange (S15) and MaterialProperty:PhaseChangeHysterisis (S16), at winter (left) and summer (right) .*

CONCLUSIONS

In conclusion, the utilization of shape stabilized paraffin based PCMs building elements presents a promising avenue for enhancing building energy efficiency and contributing to sustainable development goals. Through the unique ability to store and release thermal energy during phase transitions, PCMs offer effective regulation of indoor temperatures, thereby reducing heating and cooling loads and shifting peak energy demands. The integration of PCMs into building design and construction not only enhances energy management practices but also aligns with broader sustainability objectives by reducing carbon footprints and promoting environmentally conscious architecture.

This study has demonstrated the significant potential of PCM integration in building components (cement and gypsum boards), particularly in improving energy efficiency and reducing overall energy consumption. The simulation results highlight the effectiveness of PCM layers, especially when combined with insulation, in achieving substantial energy savings. The scenario analysis revealed that specific PCM compositions and application methods can lead to optimal energy performance, with notable reductions in annual energy consumption. Furthermore, this investigation underscores the importance of considering hysteresis effects in PCM modeling, as it accurately captures the non-linear behavior during phase transitions, resulting in more realistic simulation outcomes. The comparison between different setpoints for heating and cooling further emphasizes the potential for even greater energy savings with PCMs closely matching melting and freezing point temperatures.

Overall, the findings of this study contribute to the growing body of research on PCM applications in building energy systems and provide valuable insights for practitioners and policymakers in the field of sustainable architecture and construction. Moving forward, continued research and innovation in PCM technology, coupled with real-world implementation and monitoring, will be crucial in realizing the full potential of PCMs in achieving energy-efficient and environmentally sustainable buildings.

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