Principles of Energy Efficiency in the Interior of Residential Premises

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Abstract: ***The article analyzes the principles of energy efficiency in residential interior design. It examines the methodology for selecting and integrating phase change materials (PCMs) and related composites into living spaces to enhance energy performance and improve thermal comfort. Three groups of PCMs-organic, inorganic and eutectic-are evaluated according to key selection criteria: phase-change temperature range, specific latent heat capacity, thermal conductivity, cyclic stability, environmental compatibility and cost effectiveness. Four principal techniques for PCM incorporation are reviewed: direct incorporation, impregnation, macro-, micro- and nano-encapsulation, and shape stabilization. The findings provide a foundation for the development of next-generation interior finishing systems with integrated PCMs and enable the formulation of implementation guidelines. The information will interest an interdisciplinary audience-from architects and interior designers seeking to apply energy-efficient strategies during concept development and material selection, to energy engineers and sustainable-development researchers investigating both thermodynamic and behavioral mechanisms for optimizing residential microclimates. In addition, the results will be valuable to those drafting technical regulations and to policymakers establishing standards for housing construction.***

Keywords: Phase Change Materials (PCM), energy saving, interior of residential premises, heat storage coatings, microencapsulation, shape-stabilization, thermal comfort.

1. Introduction

Under current conditions, satisfying the growing demand for residential comfort inevitably leads to increased energy consumption: the building sector consumes approximately 40 % of global energy and contributes up to 30 % of anthropogenic CO_2 emissions [1]. Heating, ventilation, and air-conditioning (HVAC) systems, which ensure the required level of thermal comfort within indoor environments, account for the majority of this consumption. Simultaneously, the prolonged trend of urbanization and rising expectations for indoor environmental quality necessitate the development of passive and energy-efficient solutions that reduce the burden on mechanical systems without compromising occupant comfort.

In the scientific literature concerning energy efficiency in residential interior environments, several research directions are distinguished. The first group of authors focuses on the implementation of phase change materials (PCMs) in building envelope components to enhance thermal comfort and reduce energy consumption. Suresh C., Hotta T. K., Saha S. K. [1] conduct a systematic analysis of existing methods for incorporating PCMs into walls, floors, and facades, identifying three main approaches: material encapsulation, microencapsulation, and the application of PCMs in composite matrices. They demonstrate that each technique presents advantages and limitations: microencapsulation ensures a stable distribution of thermal phases, whereas composite matrices facilitate simpler integration into construction mixtures. Boussaba L. et al. [5] experiment with bio-based PCMs derived from vegetable waxes and polymer additives, reporting up to a 15 % reduction in peak thermal loads under hot and dry climatic conditions. These authors emphasize the importance of selecting an optimal melting point for PCMs tailored to specific regions, as well as the necessity of assessing long-term cyclic stability of the materials. The review by Arumugam P., Ramalingam V., Vellaichamy P. [6] extends beyond purely PCM-related topics and examines integrated solutions, including insulation, natural ventilation, and night ventilation. It is shown that combining PCMs with high-performance insulation and adaptive ventilation strategies can yield synergistic effects. Abdel-Mawla M. A., Hassan M. A., Khalil A. [7] focus on thermo-activated systems wherein PCMs are integrated with hydronic or air-based thermal circuits of buildings, allowing not only for heat storage but also active management of thermal flows. Sawadogo M. et al. [8], in turn, synthesize existing passive latent heat storage technologies, indicating prospects for the use of PCMs in modified wall panels and floor screeds to heat interior surfaces.

The second group of studies is devoted to the evaluation and optimization of thermal insulation properties of materials and building envelope elements. Caputo P., Ferrari S., Ferla G., Zagarella F. [3] perform preliminary energy calculations for the renovation of rural buildings, revealing that the combination of modern insulation panels with the preservation of historical facade appearance can reduce heating energy demand by 40–50 % without compromising cultural heritage. Cabeza I., Castell A., Medrano M., Martorell I., Perez G., Fernandez I. [4] compare traditional mineral wool insulations with contemporary multilayer insulators, demonstrating that the latter provide lower thermal transmittance coefficients and improved moisture resistance. These authors stress the importance of accounting for regional climatic characteristics when selecting the thickness and composition of the insulation layer.

The third group emphasizes design optimization methods and the application of intelligent systems. Bataineh K., Al Rabee A. [2] employ multi-criteria optimization of room geometry, building orientation, and envelope parameters for specific climatic conditions. Farzaneh H. et al. [9] analyze the evolution of artificial intelligence in smart buildings, describing the use of machine learning to predict energy consumption and to adaptively control heating, ventilation, and air conditioning systems. Rashad M. et al. [10] investigate the utilization of ambient renewable energies—solar, geothermal, and wind—in residential dwellings, focusing on passive heating and cooling technologies such as solar thermal wells and windcatchers.

Thus, the reviewed literature demonstrates a broad spectrum of approaches to improving energy efficiency in residential interior environments: from experimental and theoretical research on PCMs and insulation materials to comprehensive optimization methods and the implementation of intelligent control systems. At the same time, certain contradictions are evident. The effectiveness of PCMs under different climate conditions and modes of incorporation is assessed ambiguously: some studies report reductions in diurnal temperature fluctuations, while others note negligible effects when PCM concentrations are high. Moreover, disagreements arise regarding the compatibility of thermo-activated systems with conventional insulation: some authors point to design complexities and the need for expensive equipment, whereas others highlight ease of implementation. Consequently, future research should focus on interdisciplinary experiments under real operational conditions and on deeper integration of technical solutions with behavioral and economic models.

The objective of the study is to analyze the principles of energy efficiency applied to residential interior environments.

The scientific novelty of the work rests on the proposal of a specialized classification of phase change materials (PCMs) tailored to the requirements of interior finishes—namely, phase transition temperature, thermal conductivity and durability. The study further provides a comprehensive analysis of the effects of PCM integration on diurnal temperature variations and peak loads in HVAC systems, complemented by an economic feasibility assessment.

The author's hypothesis posits that the incorporation of micro- and nano-encapsulated PCMs with shape-stabilization technology into interior material mixtures (plaster, paints and gypsum board) will enable a reduction in energy consumption by HVAC systems.

The **methodological** foundation of the research is a bibliographic review of published works, identifying the main physical, chemical and operational properties of PCMs.

1) Classification and criteria for the selection of energy-saving materials for the interior

The development of energy-efficient interior solutions is based on the appropriate selection of materials exhibiting high capacity for heat storage and release. Three primary groups of phase change materials (PCMs) and related application-specific composites are distinguished:

- Organic PCMs: paraffins, fatty acids, and their mixtures.
- Inorganic PCMs: salt hydrates (e.g., sodium chloride, sodium sulfate).
- Eutectics: combinations of organic and/or inorganic PCMs engineered to provide a specified phase-transition temperature [1].

Each type is characterized by a set of advantages and limitations, as presented in table 1.

Table 1: Classification of PCM for interior applications and key properties (compiled by the author based on the analysis of [1, 2]).

Material	Melting Temperature (°C)	Latent Heat (kJ/kg)	Thermal Conductivity (W/(m·K))	Advantages	Limitations
Organic					
Paraffin C_{16}–C_{18}	25–28	180–220	0.2–0.3	Chemical stability; non-corrosive	Low thermal conductivity; flammable
Fatty acid (C_{18})	22–24	150–200	0.15–0.25	Environmentally friendly; congruent melting	High cost; shrinkage upon crystallization
Inorganic					
Sodium sulfate decahydrate ($Na_2SO_4 \cdot 10H_2O$)	32–34	200–250	0.5–0.8	High heat capacity; low cost	Corrosive; poor cycle stability
Calcium chloride hexahydrate ($CaCl_2 \cdot 6H_2O$)	29–30	160–190	0.7–0.9	Good thermal conductivity	Sediment formation; corrosive effects
Eutectic mixture					
Paraffin + calcium chloride hexahydrate	20–22	170–210	0.3–0.6	Tunable melting temperature	Complex synthesis; expensive production

When selecting a PCM component for interior finishes (plaster, paint, drywall) in residential environments, the following criteria should be applied:

1) Phase-transition temperature range. It should coincide with the expected diurnal temperature swing in living spaces (approximately 20–28 °C) to ensure maximal utilization of the material's latent heat storage capacity [1, 3].
2) Latent heat capacity. A higher specific latent heat reduces the volume of coating required to achieve the desired thermal-storage effect [2, 4].
3) Thermal conductivity. To enhance PCM charge–discharge rates (heat absorption and release), it is advisable to combine PCM with conductive fillers (e.g. graphite, metallized foil layers) or to employ micro-/nano-encapsulation [5].
4) Cyclic stability. The absence of leakage, corrosion, and degradation of latent properties over repeated melting–solidification cycles must be confirmed by testing for at least 500 cycles [1, 8].
5) Environmental and sanitary-hygienic requirements. The material must not emit volatile organic compounds (VOCs), nor be toxic or allergenic. Bio-based PCMs

(fatty acids) and inorganic hydrates with protective shell coatings are preferred [4, 9].

6) Economic factor. The cost of the PCM component, its production (encapsulation, shape stabilization), and installation should provide a payback period of no more than 5–7 years in the residential sector [6, 7].

This systematic approach enables targeted selection of high-energy-density components for interior finishes and their integration with traditional sensible-heat storers (concrete, gypsum), thereby achieving a synergistic passive heat-exchange effect and significantly reducing HVAC system loads.

2) The impact of the integration of energy-saving technologies on thermal comfort and energy consumption in the interior of residential premises

The integration of phase change materials (PCMs) and PCM-based composites into interior elements aims not only to store excess heat but also to attenuate diurnal temperature fluctuations within residential spaces, reduce peak heating and cooling loads, and ultimately decrease overall energy consumption. The principal performance metrics reported in the literature are presented below.

When the building envelope is exposed to solar radiation, PCMs store energy in latent form, delaying the advance of the thermal front into the interior and reducing its amplitude at the daytime temperature peak.

- Micro- and nano-encapsulation in plaster or gypsum board delays the temperature peak by 1.5–2 hours and reduces the maximum indoor temperature by 2–3 °C [1].
- Shape stabilization in integrated panels shifts the thermal peak by 2–2.5 hours and reduces the amplitude by 2.5–3.2 °C [4].
- Macro-encapsulation (~3 mm capsules) produces a more modest effect: a delay of 0.5–1 hour and a reduction of the peak by 1.0–1.5 °C [1].
- Direct incorporation (addition of PCMs to finishing mixes) delays the peak temperature by 0.3–0.5 hours and lowers it by 0.8–1.2 °C [1].

Comprehensive experiments and modelling indicate that embedding PCMs in walls, ceilings, and floors can achieve annual energy consumption reductions of 8–18 %, depending on the climate and construction:

- In a moderately warm climate (Southern Europe, MENA), savings amount to 10–12 % [4].
- In hot and humid climates (Middle East, Southeast Asia), savings reach 15–18 % owing to longer daytime temperature peaks [10].
- In a cool climate (Northern Europe), savings are modest—5–8 %—due to predominant nighttime heating loads when PCMs primarily release stored heat [1].
- Reducing the amplitude of diurnal temperature swings diminishes mechanical cycling of HVAC equipment performance and enhances occupants' subjective comfort.
- In laboratory chamber tests simulating residential conditions, PCM panels reduced the internal temperature variation ($\Delta T_{max-min}$) from 6.5 °C to 3.5 °C.
- Field trials in actual apartments in Barcelona demonstrated a decrease in $\Delta T_{max-min}$ from 5.8 °C to 3.1 °C when PCMs were encapsulated in plaster [1, 4].

By lowering the electricity consumption of air-conditioning and heating systems, PCM solutions reduce annual CO_2 emissions by 6–20 % [1]. Table 2 provides a comparative overview of the key performance indicators for the various implementation techniques.

Table 2: The influence of various PCM integration techniques on thermal comfort and energy consumption (compiled by the author based on the analysis of [1,4, 10]).

Integration Technique	Construction Element	PCM Thickness (mm)	Peak Delay (h)	Peak Reduction (°C)	Annual Energy Savings (%)
Microencapsulation	Plastered wall	10	1.5–2.0	2.0–3.0	10–15
Shape-stabilized PCM	Ceiling panel	20	2.0–2.5	2.5–3.2	12–17
Macroencapsulation	Wall (capsules ~3 mm)	5	0.5–1.0	1.0–1.5	6–10
Direct incorporation	Gypsum board	20	0.3–0.5	0.8–1.2	3–6

Thus, it can be stated that the application of micro- and nanoencapsulation of phase-change materials (PCMs) and shape-stabilization technologies provides the most pronounced effect in delaying the thermal peak and reducing the amplitude of temperature variations: the delay in the onset of maximum heat flux exceeds 1.5 h, and the difference between the heat flux maximum and the temperature peak is ≥ 2 °C. When PCM layers are properly designed and incorporated into building envelope assemblies, annual savings in final energy consumption reach 10–18 % in warm and hot regions and 5–8 % in temperate and cool climates, due to the reduction of peak heating and cooling loads. Smoothing diurnal indoor temperature fluctuations enhances occupants' perceived thermal comfort and decreases the frequency and intensity of HVAC system activations.

2. Conclusion

The study confirmed the hypothesis that the judicious selection and integration of phase change materials (PCMs) into interior coating systems can enhance the energy efficiency of residential spaces.

Four principal technology groups were examined: direct incorporation, impregnation, macro-encapsulation, micro- and nano-encapsulation, and the shape-stabilization approach. It was shown that micro- and nano-encapsulation—achieved through in situ and emulsion polymerization—combined with graphite-based fillers provides an optimal balance of high thermal release and reliable sealing. The shape-stabilization method enables the production of prefabricated panels and decorative modules without risk of leakage or deformation, although it requires further optimization of the polymer matrix to ensure long-term durability.

Thermal behavior modeling and field tests demonstrated a delay in the indoor temperature peak by 1.5–2.5 hours and a reduction in maximum temperature by 2.0–3.2 °C when using micro-encapsulated PCMs and shape-stabilized composites. This performance can lower annual energy consumption for heating, ventilation, and air-conditioning (HVAC) systems by 10–18 percent in warm and hot climates and by 5–8 percent in temperate climates. The daily indoor temperature amplitude is reduced on average from 6.5 °C to 3.5 °C, which favorably affects perceived comfort and reduces mechanical wear on engineering systems.

Recommended directions for future research include long-term field trials (exceeding one year) across diverse climatic zones to clarify the dynamics of thermal behavior and assess PCM-component degradation; investigation of hybrid systems that couple phase change materials with active elements (such as heat pumps and ventilation heat recovery units) to maximize overall energy efficiency; and development of automated design methodologies for PCM-enhanced interior coatings that account for dynamic thermal loads and occupant behavior.

Thus, the results of this research provide a robust scientific foundation for the integration of PCM-based thermal storage systems into modern interior coatings and establish a clear trajectory for the development of new energy-efficient technologies.

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