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PCM thermal storage design in buildings: Experimental studies and applications to solaria in cold climates

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HIGHLIGHTS

- This paper analyzes the performance of a building-integrated thermal storage system.
- A wall opposing a glazed surface serves as phase change materials thermal storage.
- The study is based on both experimental and simulation studies.
- Heat is stored and released up to 6–8 h after solar irradiation.
- Yearly heating requirements are reduced by 17% in a cold climate.

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ABSTRACT

As energy availability and demand often do not match, thermal energy storage plays a crucial role to take advantage of solar radiation in buildings: in particular, latent heat storage via phase-change material is particularly attractive due to its ability to provide high energy storage density. This paper analyzes the performance of a building-integrated thermal storage system to increase the energy performances of solaria in a cold climate. A wall opposing a highly glazed façade (south oriented) is used as thermal storage with phase change materials embedded in the wall. The study is based on both experimental and simulation studies. The concept considered is particularly suited to retrofits in a solarium since the PCM can be added as layers facing the large window on the vertical wall directly opposite.

Results indicate that this PCM thermal storage system is effective during the whole year in a cold climate. The thermal storage allows solar radiation to be stored and released up to 6–8 h after solar irradiation: this has effects on both the reduction of daily temperature swings (up to 10 °C) and heating requirements (more than 17% on a yearly base). Coupling of the thermal storage system with natural ventilation is important during mid-seasons and summer to improve the PCM charge-discharge cycles and to reduce overheating.

Results also show that cooling is less important than heating, reaching up to 20% of the overall annual energy requirements for the city of Montreal, Canada. Moreover, the phase change temperature range of the material used (18–24 °C) is below typical summer temperature levels in solaria, but the increase in thermal capacity of the room alone can reduce annual cooling requirements by up to 50%.

1. Introduction

Energy storage is expected to play a key role in moving to a low-carbon electricity system. It can supply more flexibility and balancing to the grid, providing a backup to intermittent renewable energy; locally, it can improve the management of distribution networks, reducing costs and improving efficiency. In this way, it can ease the market introduction of renewables, accelerate the decarbonisation of the electricity grid, improve the efficiency of electricity transmission and distribution (reduce unplanned loop flows, grid congestion, voltage and frequency variations), stabilise market prices for electricity, while also ensuring a higher security of energy supply [1–7].

As solar accessibility and demand often do not match, thermal energy storage plays a crucial role to take advantage of solar radiation in buildings. Building-integrated thermal energy storage

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Nomenclature

i	node being modeled
i + 1	adjacent node to interior of construction
i − 1	adjacent node to exterior of construction
j + 1	new time step
j	time step
Δt	calculation time step
Δx	finite difference layer thickness (always less than construction layer thickness)
C_p	specific heat of material
k_w	thermal conductivity for interface between i node and i + 1 node
k_e	thermal conductivity for interface between i node and i − 1 node
ρ	density of material
CV(RMSE)	coefficient of variation of the root mean square error
MBE	mean bias error
n	number of measures
$T_{m,i}$	monitored temperature
$\overline{T_{m,i}}$	mean monitored temperature
$T_{s,i}$	simulated temperature

systems [8,9] cover a wide range of materials, techniques and designs depending on the applications and aims. They however all have in common this underlining concept: being able to store excess energy for later use in order to reduce the time mismatch between energy availability and demand. Effective utilization of thermal energy storage for ambient renewable energy (e.g. solar heat for heating and cool outdoor air for free cooling) with proper design and control has proven promising in reducing peak demand and energy costs associated with space conditioning. Building-integrated thermal energy storage systems have recently attracted significant research interest. Savings in room space and material is achievable in comparison with conventional centralized and thermally isolated storage systems (e.g. water/ice tanks). One unique characteristic of building-integrated thermal energy storage systems is their thermal coupling with thermal zones due to large exposed surface areas.

Latent heat storage via phase-change materials (PCMs) [10–16] is particularly attractive due to its ability to provide high energy storage density. Several studies have demonstrated that the use of PCMs in well-insulated buildings can reduce heating and cooling energy in residential buildings by as much as 25% and obtain similar reductions in the peak power required for air conditioning [17–19]. Such applications are of interest since they can have lower heating and cooling requirements for a given volume than most sensible systems and may be used in contexts where the application of standard solutions would be difficult, such as in renovation of historical buildings. On the other hand, daily charge-discharge cycles must be carefully planned.

PCMs represent a potential solution for reducing peak heating and cooling loads and heating, ventilation, and air conditioning (HVAC) energy consumption in buildings for both new buildings and retrofits. The use of latent energy storage systems may be one of the solutions to the energy mismatches in Net-Zero Energy Buildings [20–29] when renewable energy production and building energy demand are out of phase. A building-integrated and distributed thermal storage could shift and reduce part of the load of residential air conditioners at peak to off-peak periods. As a result, capital investment in peak power generation equipment could be reduced for power utilities and then the savings could be passed on to customers. In areas where power utilities are offering time of day rates, building-integrated thermal storage could enable customers to take advantage of lower utility rates during off peak hours.

Literature published on PCMs over the last two decades covers a broad area. The target of this paper is to study the use of wallboard incorporated PCMs to be used passively in high performance buildings with high window-to-wall ratios in cold climates, particularly in retrofit applications where the PCM is only applied to the surface which receives most of the solar radiation. Some relevant previous experiences on building-integrated PCMs are briefly described below.

Most existing studies focus on the design and optimization of PCM layers into vertical walls or in the roof mostly located on the inside walls in various positions.

In [30], Chen et al. propose the modeling of a simple room, aiming at determining the best positioning of PCM in the envelope for improving all-year performance. At the optimal locations, the peak heat flux reductions were 51.3% and 29.7% for the south wall and the west wall, respectively. The maximum time delays in the peak heat flux were 6.3 h for the south wall and 2.3 h for the west wall. During winter, energy savings in comparison to non-PCM rooms can reach 10%.

In [31] a light envelope test cell was equipped with 25 mm thick PCM on all internal surfaces of a test cell (cubical, around 1 m on all dimensions) to increase the thermal inertia of the envelope and reduce indoor temperature fluctuations. An identical test cell was built and operated on the same weather conditions but without PCM in the envelope. This study showed that PCM allowed a reduction of the indoor temperature range of approximately 20 °C in the test-cell. The influence of the PCM wall thickness was also studied through numerical simulation, from 10 mm to 35 mm. It was found that for a wall thickness higher than 20 mm the indoor temperature variation amplitude would not significantly decrease further.

Kuznik and Virgone [32] carried out an experimental research in a full-scale test cell under controlled thermal and radiative conditions to evaluate the performance of walls with and without PCMs during a summer day. In a subsequent study, authors used the same PCM composite [13] to show that PCM wallboards reduce air temperature fluctuations in a room and overheating. In order to assess the potential of a PCM wallboard with 60% of microencapsulated paraffin within a copolymer (the melting and freezing temperatures are 13.6 °C and 23.5 °C respectively), a renovated office building in Lyon was monitored during one year by Kuznik et al. [18]. A room was equipped with PCM wallboards in the lateral walls and in the ceiling, and another room, identical to the first one, was not equipped with PCM wallboards but also monitored. The results showed that the PCM wallboards enhance the thermal comfort of occupants during the whole year.

Evers et al. [33] evaluated the thermal performance of enhanced cellulose insulation with paraffin and hydrated salts for use in frame walls. The thermally enhanced frame walls were heated and allowed to cool down in a dynamic wall simulator that replicated the sun's exposure in a wall of a building on a typical summer day. The results showed that the paraffin-based PCM-enhanced insulation reduced the average peak heat flux by up to 9.2% and reduced the average total daily heat flow up to 1.2%.

Other studies focused specifically on PCM application to the floor. In [34], authors discuss the application of PCM below