Publications forming the basis of the theses

[S1] Ferencz, M., Németh, B., Gyenis, J., Feczkó, T.: Statistical evaluation of PCM plaster lining impact on indoor temperature fluctuation due to variability of outdoor temperature and solar radiation along a whole spring season. Journal of Building Engineering, 99, 111626, 2025. https://doi.org/10.1016/j.jobe.2024.111626

[S2] Ferencz, M., Nagy, B., Németh, B., Gyenis, J., Feczkó, T.: Quantifying thermal time lag due to PCM plaster in model houses. Buildings, 15(22), 4120, 2025. https://doi.org/10.3390/buildings15224120

[S3] Ferencz, M., Nagy, B., Gyenis, J., Feczkó, T.: An Experimental Study on the Thermal Behavior of PCM Plaster-Lined Model House Walls During a Whole Spring Season Influenced by Their Orientation. Thermo, 6(2), 23, 2026. https://doi.org/10.3390/thermo6020023

Other own publications related to the dissertation

[S4] Németh, B., Ujhidy, A., Tóth, J., Ferencz, M., Kurdi, R., Gyenis, J., Feczkó, T.: Power consumption of model houses with and without PCM plaster lining using different heating methods. Energy and Buildings, 284, 112845, 2023. https://doi.org/10.1016/j.enbuild.2023.112845

[S5] Németh, B., Ferencz, M., Kovács, S., Trif, L., Lendvai, J., Kolay Kovács, Á., Király, K., Feczkó, T.: Fázisváltó hőtároló anyagok előállítása hulladék zsírból és használt növényi olajból. Energiagazdálkodás, 65. évf., különszám, 26–33, 2024.

University of Pannonia

Chemical Engineering and Material Sciences Doctoral School (CEMSDS)

PhD Dissertation theses

Energy-efficiency analysis of phase change thermal storage microcapsules in model houses

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Introduction

Thermal energy storage has become a defining issue in building physics and building energy research. A building's thermal behavior is determined not only by the magnitude of heat losses and heat gains, but also by the extent to which the structure can moderate their time-dependent effects. Thermal storage capacity is therefore not a secondary structural property, but one of the fundamental determinants of dynamic thermal behavior.

In this context, latent heat storage is of particular importance. While sensible heat storage is related to changes in the temperature of the structural material, storage based on phase change allows a significant amount of energy to be absorbed and released within a relatively narrow temperature range. In building physics, this is important because the storage effect does not simply arise from an increase in mass, but appears in a temperature range that is directly connected to indoor conditions and thermal comfort. This explains why phase change materials have become one of the intensively studied areas of building-integrated thermal storage.

Among PCM-based solutions, plaster deserves special attention because it offers a practical possibility for latent heat storage on the inner side of the building wall. Plaster containing microencapsulated PCM is not simply another material layer, but modifies the time-dependent thermal response of the structure. During warmer periods, it absorbs part of the incoming heat and then releases it later, thereby directly influencing the daily course of indoor temperature. For this reason, the effect of PCM cannot be adequately described simply by comparing absolute maxima and minima. Its significance can be captured through daily temperature amplitude, the timing of peak temperatures, and the duration of thermally unfavorable periods.

This issue is particularly important in lightweight buildings. Because of their low thermal mass, these structures react rapidly to changing outdoor conditions. Under solar radiation, the outer surfaces may heat up significantly within a short time, and the resulting thermal load may also appear rapidly indoors. In lightweight spaces with small indoor volume, this may result in greater daily indoor temperature fluctuation and sharper temperature peaks. Under such conditions, dynamic behavior is more important than average values, because a daily average temperature may seem acceptable even if short but significant overheating periods occur.

2. I quantified the daily temperature attenuation effect of the PCM plaster over the full 105-day measurement period. The average daily indoor temperature amplitude was 6.3 °C in the reference house and 3.6 °C in the PCM-plastered house. This confirmed that, in the investigated lightweight model-house system, the latent heat storage effect of the PCM consistently reduced the daily indoor temperature fluctuation **[S1]**.
3. I demonstrated the heat-trap-like behavior of the reference house through the combined analysis of daily indoor and outdoor maximum temperatures and solar radiation over the full measurement period. Using 3D response surfaces constructed as functions of outdoor temperature and solar radiation, I showed that the daily maximum indoor temperatures in the reference house exceeded the outdoor air temperature to a greater extent than in the PCM-plastered house. Based on the difference between the two response surfaces, the applied PCM plaster reduced indoor overheating relative to the outdoor environment in the investigated experimental system **[S1]**.
4. I quantified the peak-time shifting effect of the PCM plaster on a long measurement time series using a reproducible peak-detection procedure based on curve smoothing. In the PCM-plastered house, the average delay of the temperature peaks was approximately twice the value measured in the reference house. This showed that the effect of the PCM appeared not only in the reduction of peak temperatures, but also in the temporal rearrangement of the daily thermal response **[S2]**.
5. I demonstrated that the peak-time shift caused by the PCM plaster also had a favorable effect from the perspective of thermal comfort. Based on the evaluation relative to the adaptive comfort range, the proportion of time spent within the comfort range increased in the PCM-plastered house. This confirmed that the effect of the PCM appears not only in the modification of daily extrema, but also in the more favorable temporal positioning of temperature peaks and directly contributes to improved thermal comfort in the building **[S2]**.
6. I determined the optimal orientation order for targeted PCM placement from measured surface temperature data, without simulation-based modeling. I calculated a characteristic temperature difference from the daily extrema and then estimated heat flux density from this value using Fourier's law of heat conduction. According to the resulting ranking, in the investigated experimental system, the roof and the western orientation proved to be the most favorable target surfaces, while the role of the northern orientation was substantially smaller **[S3]**.

adjusted to outdoor conditions, and on this basis I evaluated the proportion of time spent within the comfort range and exposure to overheating.

In the orientation-based investigation, the daily extreme values of exterior and interior surface temperatures were compared. To characterize behavior by orientation, I applied trend-based and other statistical indicators. To interpret orientation-dependent thermal differences, I used indicators of characteristic temperature difference and characteristic heat flux density, which made it possible to evaluate the individual surfaces in a comparable way on the basis of measured data.

New scientific results

The new scientific results are derived from the data of a 105-day free-running measurement campaign carried out in 2021. The investigation compared two lightweight model houses with identical geometry and structural design. One of the model houses had a plaster lining containing microencapsulated PCM on the internal vertical wall surfaces, while the reference house had no PCM-containing plaster lining.

The direct validity of the conclusions is limited to this measurement period, the given meteorological conditions, the applied PCM amount, the free-running mode of operation, and the investigated envelope configuration. The generalizable scientific contribution of the thesis statements lies in the fact that they quantify, on the basis of high-resolution measurement time series, the dynamic temperature attenuation, peak-time shifting, thermal comfort-related, and orientation-dependent effects of the PCM plaster. The specific quantitative results are interpreted within these boundary conditions; however, the applied data-processing and evaluation methodology can also be used in other PCM-related building physics studies with similar measurement arrangements.

1. I applied Poincare representation to the long indoor temperature time series recorded at 5-minute resolution in order to compare the dynamic temperature behavior over the full measurement period in an interpretable way. Using this method, the thermal behavior of the model houses could be compared both visually and mathematically through the evaluation of the standard deviations and the extent of the point cloud. Based on this representation, the indoor temperature response of the PCM-plastered house had a lower amplitude and was more balanced than that of the reference house **[S1-S3].**

This is particularly true under free-running measurement conditions, when there is no active heating or cooling system that would mask the building’s natural dynamic response. In such cases, the measured indoor thermal behavior directly reflects the interaction of the structure, solar radiation, outdoor temperature fluctuation, and thermal storage capacity. Free-running measurements are therefore particularly suitable for examining the actual effect of PCM integrated into the structure. At the same time, this also means that interpretation must take natural weather variability into account. The evaluation of PCM performance therefore requires not only measurement data, but also an approach capable of revealing the relationships appearing in long and highly variable time series.

The present work is based on a 105-day measurement campaign carried out in 2021 in two identical lightweight model houses. The geometry and structural design of the two houses were the same. The difference was that one house had plaster containing microencapsulated PCM in its inner wall structure, while the other was a reference house without it. The available dataset consists of a large number of raw sensor data records with 5-minute time resolution. The length and density of the time series make it possible to evaluate the thermal behavior of the two houses not on the basis of a few selected days, but on the basis of the full monitoring period.

The large sensor database was processed and evaluated in a Python-based, reproducible workflow, in several cases using statistical evaluation methods. This is of particular importance because the dissertation does not draw conclusions from a few selected days or individual weather situations, but is based on a dataset containing the natural meteorological variability of the full measurement period. In this sense, handling the large dataset was not merely a technical issue, but one of the conditions for the validity of the conclusions drawn.

The dissertation investigates the effect of PCM plaster within a measurement and evaluation framework that makes it possible to interpret the daily course of indoor temperature, the dynamic thermal response, and the relationships relevant to practical applicability. The aim of the dissertation is therefore not merely to demonstrate that PCM influences thermal behavior, but also to examine how this effect appears in a measured lightweight system and how it can be interpreted in practice.

Objectives

The aim of my research was to determine how plaster containing microencapsulated phase change material modifies the indoor thermal behavior of lightweight model houses under real, naturally varying outdoor conditions. The focus of the investigation was not merely whether the presence of PCM reduces daily temperature extremes, but also how this effect appears in the complete daily temperature profile, how it is related to comfort, and on which surfaces of the structure it is expected to have the greatest practical significance.

The dissertation is organized around three closely interrelated questions:
The first question was aimed at determining to what extent and in what form PCM plaster modifies the indoor temperature response of a lightweight model house under real, naturally varying outdoor conditions. In this context, my aim was to examine whether plaster containing PCM reduces daily indoor temperature amplitude, moderates daily maxima and minima, and to what extent this effect can be regarded as consistent over the full monitoring period. Related to this was the interpretation of the extent to which the heat-trap effect developing in the model houses under solar radiation appears, and how this is influenced by the PCM plaster.

The second question focused on the temporal structure of the dynamic response. At the center of this was peak-time delay, that is, whether PCM modifies not only the magnitude of the indoor temperature peak, but also shifts its timing to a later point. My aim was to quantify the extent of peak-time delay and to examine how this temporal shift is related to thermal comfort. The dissertation therefore also sought to answer how the later occurrence of the daily maximum influences the proportion of time spent within the comfort range and exposure to overheating.

The third question approached the problem from the perspective of practical applicability. If the favorable effect of PCM can be verified, the next step is to determine in the case of which orientations and building elements the greatest benefit may be expected. The aim of the dissertation was therefore not to provide a general, average PCM effect, but to determine on the basis of measurement data which surfaces can be regarded as the most favorable application locations. The engineering significance of this is especially high where the amount of PCM, its location, or the treatable surface area is limited, and therefore the ranking of surfaces becomes a matter of practical decision-making.

To answer the above questions, I set the objective of applying evaluation procedures that make long time series and large amounts of measurement data interpretable from both dynamic and

statistical points of view. The aim was therefore not merely a simple comparison of the two houses, but also to establish a methodological framework that makes it possible to evaluate the effect of PCM plaster while taking into account the natural meteorological variability of the full monitoring period.

Methods used

The processing and evaluation of the measurement data were carried out in a reproducible, Python-based workflow. Time synchronization, checking and cleaning of the raw time series, as well as the generation of additional calculated descriptors, were performed in a programmed environment.

One basis of the evaluation was daily summary indicators. For each day, indoor and outdoor daily maximum and minimum temperatures, as well as the daily amplitudes calculated from them, were determined. These indicators served as the primary basis for characterizing daily indoor temperature fluctuation.

Poincaré representation was applied for the dynamic comparison of the long time series. The method made it possible for the thermal behavior over the full monitoring period to be interpreted not only in the form of time-dependent curves, but also in the form of a unified, comparable geometric representation.

To determine peak-time delay, I identified the timing of daily temperature peaks. Since the raw curves in the peak region could also contain short-term fluctuations and several nearby local maxima, peak positions were identified on smoothed time series. The extent of the delay was calculated as the time difference between the corresponding outdoor and indoor peak points. The evaluation of peak-time delay was based not on a single characteristic day, but on the daily values of the full monitoring period. Statistical characterization of the daily delays made it possible to demonstrate that the phenomenon was not incidental, but a dynamic feature interpretable over the full period.

For comfort evaluation, I applied the adaptive comfort approach of EN 16798-1:2019. The indoor temperature time series were related to the comfort temperature and comfort range