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Analysis of the Thermal Response of a Floor Heating System Incorporating a Phase Change Material

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KEYWORDS

Floor heating system; Latent storage; Phase Change Materials (PCM); Parametric analysis, Energy storage.

ABSTRACT

The rapid urbanization and the increasing demand for indoor comfort have resulted in a rise in energy consumption and a negative impact on the environment within the building sector. A promising approach to improving energy efficiency is the integration of phase change materials (PCM) into underfloor heating systems. This study aims to assess the impact of PCM integration on the thermal and energy performance of a hydronic floor heating system. To achieve this objective, a two-dimensional numerical model was developed using COMSOL Multiphysics software. The finite element method, combined with the effective heat capacity approach, was employed to accurately simulate the thermal behavior of the system.

The influence of several parameters, such as PCM type, thickness, and position within the floor structure, was analyzed to optimize system performance. The results reveal that integrating a 3 cm thick salt hydrate-based PCM, with a water supply temperature of 40 °C, significantly improves the thermal inertia of the floor. This configuration ensures a comfortable temperature (~27 °C) even after the heating system is turned off, with a time lag of 17 hours compared to a floor heating system without PCM. These findings highlight the potential of PCM in underfloor heating systems, offering an effective solution to reduce energy consumption in buildings while maintaining optimal thermal comfort.

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تحليل الأداء الحراري لنظام التدفئة الأرضية المدمج بمادة متغيرة الطور

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ملخص: أدى التحضر السريع وزيادة الطلب على الراحة الداخلية إلى ارتفاع استهلاك الطاقة وتأثير سلبي على البيئة في قطاع البناء. وتعدّ إحدى المقاربات الواعدة لتحسين كفاءة الطاقة دمج المواد متغيرة الطور في أنظمة التدفئة الأرضية. تهدف هذه الدراسة إلى تقييم تأثير دمج هذه المواد على الأداء الحراري والطاقي لنظام التدفئة الأرضية المائية. ولتحقيق هذا الهدف، تم تطوير نموذج عددي ثنائي الأبعاد باستخدام برنامج كومسول متعدد الفيزياء وقد تم اعتماد طريقة العناصر المحدودة جنبًا إلى جنب مع نهج السعة الحرارية الفعالة لمحاكاة السلوك الحراري للنظام بدقة. تم تحليل تأثير عدة عوامل، مثل نوع المادة متغيرة الطور وسمكها وموقعها داخل هيكل الأرضية، من أجل تحسين أداء النظام. أظهرت النتائج أن دمج مادة متغيرة الطور قائمة على هيدرات الملح بسماكة 3 سنتيمترات ومع درجة حرارة تغذية المياه عند 40 درجة مئوية يُحسن بشكل كبير القصور الذاتي الحراري للأرضية. يضمن هذا التكوين الحفاظ على درجة حرارة مريحة تقارب 27 درجة مئوية حتى بعد إيقاف تشغيل نظام التدفئة، مع تأخير زمني يصل إلى 17 ساعة مقارنةً بنظام تدفئة أرضية بدون مادة متغيرة الطور. تؤكد هذه النتائج الإمكانيات الكبيرة لاستخدام المواد متغيرة الطور في أنظمة التدفئة الأرضية، حيث توفر حلاً فعالًا لتقليل استهلاك الطاقة في المباني مع ضمان راحة حرارية مثالية.

الكلمات المفتاحية – نظام التدفئة الأرضية؛ التخزين الكامن؛ مواد متغيرة الطور؛ التحليل البارامتري؛ تخزين الطاقة.

1. INTRODUCTION

The building sector accounts for approximately 40% of global energy consumption [1]. One of the most effective passive methods to enhance the thermal performance of buildings and reduce their energy consumption is the integration of phase change materials (PCMs) into structural elements such as walls, roofs, floors, and ceilings [2]. Incorporating PCMs specifically into underfloor heating systems represents a significant technological, as it allows for efficient thermal energy storage and improves indoor thermal comfort [3]. This strategy uses the PCM's ability to capture, store, and release heat during phase changes, which reduces energy consumption and stabilizes internal temperatures.

Numerous studies have examined this technology, highlighting its potential to store and release heat more efficiently, particularly during periods of energy shortages [4]. For instance, S. Lu et al [5] integrated a composite PCM consisting of capric acid and hexadecyl alcohol into a floor heating system, resulting in a 5.87% reduction in energy usage. According to H. Ju et al [6], adding PCM to a standard heating floor lowers overall running costs by 13.8%, boosts load flexibility by 18.1%, and enhances indoor temperature stability by 8.6%. In this experimental study, B.Y. Yun et al [7] integrated macro-encapsulated PCMs into a radiant floor heating system to analyze their effects on thermal comfort and energy savings. The results showed that n-docosane achieved the greatest power reduction, while n-eicosane demonstrated the highest efficiency in terms of energy consumption and maintaining the floor's comfort temperature. W. Cheng et al [8] introduced PCM panels, known as HCE-SSMCP, composed of (solid paraffin + liquid paraffin) / high-density polyethylene / expanded graphite into a test room with a floor heating system in a house during winter. The findings demonstrated that enhancing the thermal conductivity of the PCM within a certain range could significantly improve the energy efficiency of the heating system. In the other hand, the feasibility of incorporating PCM into the heating floor is the subject of multiple research streams that focus on experimental and numerical analysis. K. Huang et al [9] conducted a study on a new PCM floor consisting of two layers of heating tubes and a macro-encapsulated PCM layer. They experimentally and numerically analyzed the heat storage and release processes. The results revealed that the new floor with PCM is capable of releasing 37677.6 kJ of heat over 16 hours during the pumping period in an 11 m^2 room, representing 47.7% of the energy supplied by the solar-heated water. The dynamic thermal performance of a floor heating system using phase change material for thermal storage has been investigated experimentally and numerically by Q. Zhang et al [10]. According to the findings, PCM with a phase change temperature of 313 K was suggested because it could reduce the indoor temperature fluctuation range by 2.2 K, and boost the thermal energy storage rate by 12%. In addition, the radiant floor heating condenser's heat transfer performance using composite phase change material was investigated experimentally and numerically by T. Jiang et al [11].

Using numerical and experimental research, B. Larwa et al [12] investigated the effects of wet and dry sand, as well as the positioning of PCM containers above and below the pipes, in a radiant floor system with macro-encapsulated PCM. The study found that the advantageous effects of wet sand were further enhanced when PCM capsules were placed beneath the pipes. Moreover, the thermal behavior of floor heating systems incorporating PCMs has been extensively studied through numerical simulations by various researchers. M. T. Plytaria et al [13] investigated the efficiency of a heating system incorporating PCM.

They demonstrated that using a Bio PCM (Q29/M91) with a melting point of 29 °C, placed beneath the tube, optimizes the system's performance. This configuration reduced the auxiliary heating load by 65%, increased indoor temperature by 0.8 °C, and minimized both energy consumption and overall costs. Furthermore, B. González and M. M. Prieto [14] developed 2D models to analyze the performance of radiant floor heating systems integrated with PCM. Their findings revealed that the incorporation of PCM significantly increased thermal energy storage (TES) by over 155%, while heat transfer decreased by roughly 18%, resulting in a more consistent indoor temperature and reduced energy consumption.

In a recent work, Z. Kang et al [15] used Fluent software to numerically create a two-dimensional model of a heated floor that included the PCM layer.

CFD simulations were used to examine the temperature distributions and heat charging and discharging behaviors of three low-temperature PCMs. Furthermore, Q. Yu et al [16] studied the behavior of a floor heating system incorporating two distinct layers of PCM. A coupled numerical heat transfer model was developed to examine the heat charging and release processes.

The findings reveal that the thermal energy storage floor heating system prevents overheating while reducing energy consumption by more than 19% during the thermal charging process.

The numerical analysis of the thermal behavior of a floor heating system incorporating two distinct types of PCM to evaluate their heat storage capacity at the ground level during the intermittent period and under certain conditions remains relatively unexplored in the literature, particularly with the use of COMSOL software. Existing studies exhibit certain limitations, highlighting the need for a more in-depth investigation.

In this context, our work provides an original contribution by addressing these gaps and offering a detailed evaluation of the system's thermal performance under various scenarios. More specifically, we analyzed the impact of PCM placement and quantity variations on the thermal efficiency of the floor heating system to optimize its energy performance.

2. METHODOLOGY AND APPROACH

2.1. Presentation of the physical model

In the present study, an innovative heated floor model was developed by integrating a PCM layer to enhance energy and thermal performance, as well as to improve thermal comfort. The floor structure, illustrated in figure 1, comprises a base layer of limestone and heavy concrete with respective thicknesses of 300 mm and 100 mm. Directly above, a 50 mm thermal insulation layer is installed to minimize downward heat losses.

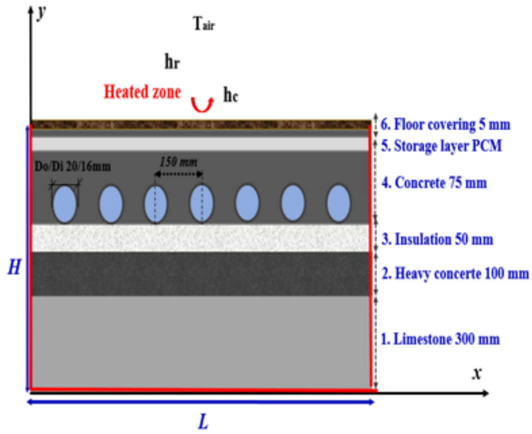

Figure 1. Structure of floor heating system with PCM, 2D View (X, Y) [17].

A network of heating pipes, arranged in a spiral configuration, is placed above the insulation layer to ensure the uniform circulation of hot water. The pipes are encapsulated within a 75 mm thick concrete screed, which serves to distribute heat evenly and provide structural stability. Above the screed, a 5 mm PCM layer is positioned to retain thermal energy as latent heat during periods of excess heat and release it when the temperature decreases, enabling passive temperature regulation. As a final step, A finishing layer made of tiles is applied at the surface, offering a durable and visually appealing finish while facilitating effective heat transfer.

2.2. Numerical model description

The numerical modeling of thermal interactions within the underfloor heating system with and without PCM was carried out using the COMSOL Multiphysics software [18]. This software allows for the simulation of heat transfer processes, as well as the charging and discharging of the PCM layer integrated into the structure of the underfloor heating system. Indeed, the phase change phenomenon was modeled using the effective heat capacity approach [19]. This method effectively replicates the thermal behavior of the PCM during phase transitions, guaranteeing the accuracy and dependability of the simulation outcomes. By adopting this method, the 2D model offers a precise and in-depth analysis of the thermal behavior of the system. It allows for an accurate representation of heat transfer dynamics while significantly reducing computational complexity.

The heat transfer occurs primarily through conduction, successively passing through the wall of the hot water pipes, the concrete layer, the PCM layer, and the finishing layer. Moreover, the finishing layer transfers heat to the ambient air through convection and radiation, ensuring an optimal distribution of heat in the environment. To streamline the calculations, the following assumptions were adopted:

1. The heat transfer through the insulation layer is assumed to be negligible.
2. Heat transfer within solid materials (concrete, finishing layer, etc.) is considered two-dimensional.
3. The PCM's thermophysical characteristics won't alter during the phase transition process.
4. Due to the liquid's high viscosity and moderate velocity, natural convection within the PCM layer is insignificant.

The governing equations used to precisely describe heat transfer across the layers of a heated floor system with PCM are as follows:

-The thermal conduction equation in solid materials (pipe walls, mortar, finishing layer, etc.) is governed by Fourier's equation (1) [20]:

$$\left(\rho c_{\mathrm{p}}\right)_{\mathrm{s}} \frac{\partial T_{\mathrm{s}}}{\partial t} = k_{\mathrm{s}} \nabla^{2} T_{\mathrm{s}} \qquad (1)$$

Where:
$(\rho c_p)_s$ represents the volumetric heat capacity of the solid material (product of density ρ and specific heat capacity c_p.
$(\partial T_s)/\partial t$ is the transient term that describes the rate of temperature change over time.
$k_s \nabla^2 T_s$ represents the heat conduction term, where k_s is the thermal conductivity of the solid material, and $\nabla^2 T_s$ is the Laplacian of temperature, describing the spatial distribution of heat within the solid.
To model the thermal behavior of PCM, which includes phase transitions (melting/ solidification), an effective heat capacity method is used. This approach adjusts the specific heat capacity to represent the latent heat in the thermal conduction equation (2) [19]:

$$\left(\rho c_{\mathrm{p}}\right)_{\mathrm{eff}} \frac{\partial \mathrm{T}}{\partial t} = \left(k_{\mathrm{eff}} \nabla^{2} \mathrm{T}\right) \qquad (2)$$

Where $C_{p_{eff}}$ is calculated using equation (3) [20]:

$$C_{eff}(T) = \begin{cases} C_{p,s}\ , if \quad T < T_m - \delta T \\ \dfrac{C_{p,s} + C_{p,l}}{2} + \dfrac{L}{2\delta T}\ , if\ T = T_m \\ C_{p,l}\ , \quad if \quad T > T_m + \delta T \end{cases} \qquad (3)$$

Where: (L) is the latent heat of fusion of the PCM (J/kg), (T_m) the average melting temperature (K) and (δT) the temperature range over which the phase change occurs. In addition, the liquid fraction of a PCM represents the proportion of the material that has transitioned from the solid state to the liquid state at a given moment, depending on the temperature or the applied thermal energy. This fraction β is calculated using equation (4) that links the PCM's temperature to its melting temperature [20].

$$\beta = \begin{cases} \beta_S = 0\ if\ T < T_m - \dfrac{\Delta T}{2} (solid\ phase) \\ \beta_m = [0,1]\ , if\ \ T = T_m\ (mixed\ phase) \\ \beta_l = 1\, if\ T > T_m + \dfrac{\Delta T}{2} (liquid\ phase) \end{cases} \qquad (4)$$

The following are the initial and boundary conditions:
1. The initial temperature of the heating system with PCM is set at 20°C (t=0).
2. The upper surface of the floor interacts with the indoor environment, exchanging heat through both convection and radiation. with a radiation emissivity factor of 0.9.
3. The lateral boundaries of the heated floor are considered adiabatic.
4. The insulation layer beneath the piping is defined as an adiabatic boundary to minimize heat losses downward.

2.3. Validation

The 2D numerical model of the heated floor, developed using COMSOL software, was validated by comparison with the experimental results obtained by Larwa et al [12]. The analysis of the relative error in the surface temperature of the floor shows a minimal discrepancy of approximately 2.33% between the numerical and experimental data, exhibiting a high level of consistency between the numerical model and the findings reported in the literature.

3. RESULTS AND DISCUSSIONS

3.1. Types of PCM

In this investigation, two types of PCMs were tested under an inlet temperature of 40 °C to assess their performance in terms of thermal storage capacity and thermal regulation.
The studied PCMs have distinct melting temperatures and thermal capacities, which allows for comparing their efficiency in the context of a floor heating system.
The thermo-physical properties of each PCM are detailed in the following Table 1.

Table 1. Thermo-physical properties for the different PCM [12 , 21].

Type of PCM	Salt hydrates	Organic alkanes
	S27	N-octadecane
Density (Kg/m³)	1530	722
Thermal conductivity (W/m. K)	0.54	0.192
Melting temperature Tm (°C)	27	29.95
Latent heat of fusion (kJ/Kg)	185	186.5
Specific heat capacity (kJ/Kg. K)	2.200	2.153

Figure 2 shows the evolution of the floor surface temperature (°C) as time progresses (h) for three scenarios: without PCM, with salt hydrate as an inorganic PCM, and with N-octadecane as an organic PCM.

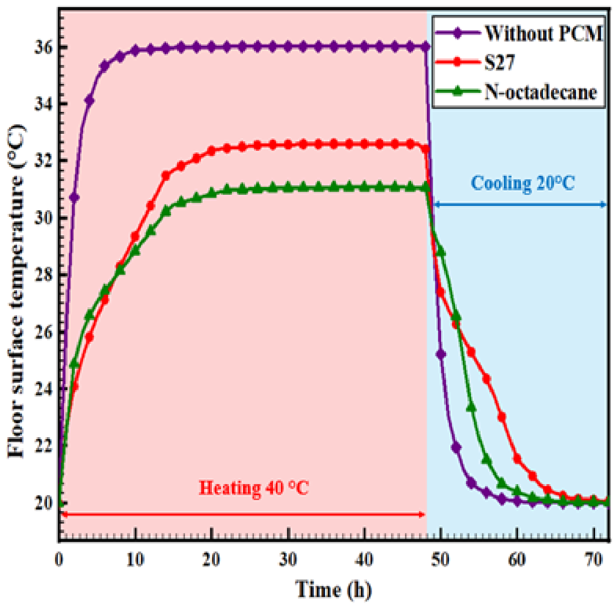

Figure 2. Evolution of floor surface temperature of heating system with and without PCM (salt hydrates and N-octadecane).

It can observe that the heated floor system without PCM shows no ability to store thermal energy, resulting in significant fluctuations and a rapid decrease in temperature.

In contrast, the temperature of the floor heating, incorporating a layer of hydrated salt with a thickness of 1 cm, gradually increases to stabilize around 32 °C during an extended heating period. This thermal behavior exceeds that of N-octadecane, whose temperature stabilizes between 28 °C and 30 °C. After the heating is stopped, the salt hydrate stands out for its superior ability to release heat, maintaining high temperatures for a longer duration compared to the reference case. On the other hand, n-octadecane releases heat over a narrower temperature range, stabilizing around t= 3h before rapidly decreasing to reach thermal equilibrium.

These results highlight that the choice of salt hydrates as PCM is particularly advantageous due to their specific thermal properties, including high thermal conductivity, significant specific heat capacity, substantial latent heat of fusion, and superior thermal storage capacity.

This ensures effective thermal storage within the comfort temperature range for an extended period.

3.2. Impact of thickness

Figure 3 shows the effect of the thickness of the salt hydrate-based PCM layer embedded in the soil on the surface temperature of the floor heating, comparing different PCM thicknesses of 1 cm, 2 cm, and 3 cm with the reference case (without PCM).

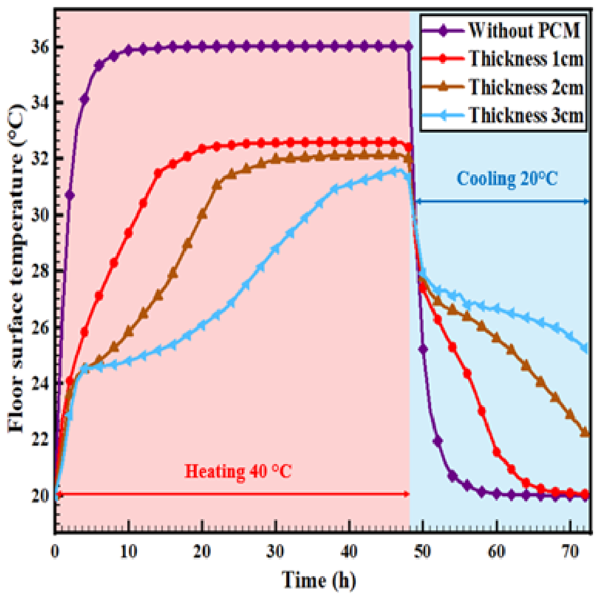

Figure 3. Evolution of floor surface temperature for difference thickness of PCM (salt hydrate)

During the heating period, the increase in the thickness of the PCM layer based on salt hydrate slightly slows the initial temperature rise compared to the reference case, due to the greater mass of PCM, which introduces higher thermal inertia.

After the heating is stopped, it is evident that heat dissipation with a 3 cm thick layer is very gradual, reducing thermal fluctuations and ensuring prolonged heat release for 17 hours. This layer maintains a temperature of 27 °C, with a divergence of 6.98 °C, 6.85 °C, and 1.18 °C when compared with the floor heating without PCM and the 1 cm and 2 cm layers, respectively.

3.3. Impact of position

Figure 4 illustrates the various possible positions of a 3 cm PCM layer within the coating layer.

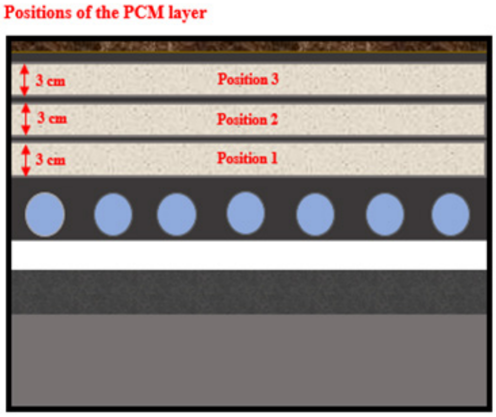

Figure 4. Positions of PCM salt hydrate with a thickness of 3 cm (2D view).

Figure 5 demonstrates the effect of varying the position of the salt hydrate PCM layer on the floor surface temperature, highlighting the differences compared with the reference case without PCM.

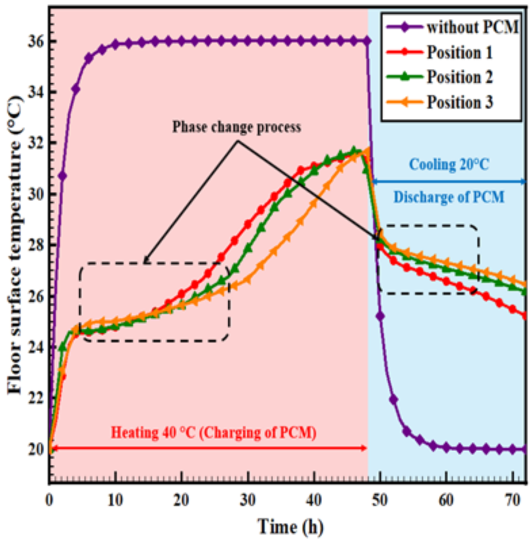

Figure 5. Different positions of PCM salt hydrate with a thickness of 3 cm

The incorporation of a 3 cm thick salt hydrate-based PCM layer significantly improves the thermal performance of the floor heating. Placing the PCM closer to the floor surface (below the finishing layer, i.e., position 3) guarantees more gradual heat dissipation, while ensuring a gradual decrease in floor temperature over a long discharge period. This is suitable for ensuring optimal thermal comfort above 28 °C.

In contrast, positioning it closer to the heat source (position 1) provides faster heating during the heating period. Therefore, placing the PCM at position 3 guarantees temperature stability for a long time, with a 7 °C difference compared to the reference case.

O. Babaharra et al [21] also tested the two types of PCM proposed in this study under different conditions. Their results indicate that using a hydrated salt-based PCM allows the floor temperature to reach approximately 26.4 °C, with a phase shift of 5.5 hours compared to the reference case. However, in our study, further performance improvements are achieved when the supply water temperature is increased while increasing the thickness of the MCP layer from 1 to 3 cm, placed close to the floor surface, which extends the heat release duration to 17 hours while keeping the floor temperature stabilized at (~27 °C). In comparison, our model provides a significant

improvement, increasing the heat release duration by 67.64% compared to the previous study. The choice of hydrated salt in this study offers several advantages, including a higher thermal storage capacity compared to organic PCMs, as well as high energy density and thermal conductivity. Despite the challenges related to its degradation over time, this type of PCM remains an ecological, non-toxic, and more cost-effective solution than its organic counterparts [22,23]. In this context, the use of hydrated salts represents a promising alternative to enhance energy efficiency and reduce heating costs in the long term.
Thanks to its thermal properties, it is particularly suitable for this type of heating application.

4. CONCLUSION

This study highlights the thermal effectiveness of heated floors incorporating phase change materials, testing two types of PCM (organic: N-octadecane; inorganic: salt hydrate) along with the reference case without PCM, as well as the impact of the thickness and positioning of the salt hydrate. The results demonstrate that both types of PCM enhance thermal regulation compared to the case without PCM. However, the salt hydrate, due to its specific thermal properties, proved to be more effective than N-octadecane, maintaining higher surface temperatures for an extended duration. Furthermore, increasing the thickness of the salt hydrate to 3 cm was found to be optimal, allowing surface temperatures to remain within the comfort zone (~27 °C) for more than 17 hours after the heating was turned off. Regarding positioning, the salt hydrate placed near the surface (under the finishing layer, position 3) provided a more gradual heat dissipation, extending the duration of thermal comfort compared to other positions.

Authors contribution: Afaf Charraou: conceptualization, methodology, data curation, writing original draft, formal analysis, visualization, supervision, writing review and editing. Mohamed Errebii: investigation, conceptualization, methodology, supervision, and editing.
Amina Mourid: conceptualization, data curation, supervision.
Rachid Saadani: conceptualization, data curation, supervision.
Miloud Rahmoune: conceptualization, data curation, supervision.
Mustapha El Alami: supervision and conceptualization.
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Symbol	Designation	Unity
k_{eff}	The effective thermal conductivity	W/(m·K)
$C_{p,s}$	The specific heat capacity of the solid phase	J/(kg·K)
$C_{p,l}$	The specific heat capacity of the liquid phase	J/(kg·K)
h_r	Heat transfer coefficient for radiation	W/(m²·K)
h_c	Heat transfer coefficient for convection	W/(m²·K)
T_{air}	Air temperature	°C