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ENHANCING BUILDING THERMAL INERTIA: IMPACT OF SURFACE-TO-VOLUME RATIO ON MULTI-LAYERED PCM-INTEGRATED BRICK WALLS

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Abstract

In this paper, a numerical study is conducted to investigate the effect of using Phase Change Materials (PCMs) in building bricks to improve the thermal inertia of buildings in hot and dry regions. A numerical model is developed to simulate the heat transfer in a brick with cylindrical holes filled with PCM. The effects of the number, type, and arrangement of PCMs on the thermal performance of the brick are investigated. The results show that the use of PCMs can significantly reduce the heat flux through the brick. The optimal number of PCMs is found to be three layers. The optimal type of PCM for the first layer is n-Eicosane, for the second layer is Paraffin Wax, and for the third layer is n-Octadecane. The enhanced brick configuration, with specific PCM arrangements, reduced total heat flux by up to 71.53% in the simulation period, compared to a brick without PCM.

1. Introduction

In specific climatic zones of southern Algeria, prolonged periods of high temperatures occur each year for several months (refer to Fig. 1), resulting in significantly increased energy demand compared to other regions. This rise in energy consumption is primarily attributed to the extensive use of air conditioning systems (HVAC), as shown in Table 1 [1]. Moreover, the national electricity demand has been consistently rising, exhibiting a substantial 10.26% increase in peak electricity consumption between 2019 and 2021 (refer to Fig. 2) [2].

Enhancing the thermal capacity of the building envelope can minimize reliance on air conditioning, leading to a shift in peak loads, energy preservation, decreased peak demand for utility companies, reduced electricity usage, and cost savings for residential customers.

Table 1. Average Electricity Usage per Customer by Geographic Region

	Electricity Usage (kWh/customer) by Geographic Region	
Year	2008	2009
North	2545	2511
High plateau	2438	2463
South	3612	3799
Overall Average Electricity Consumption (kWh/customer)	2611	2623

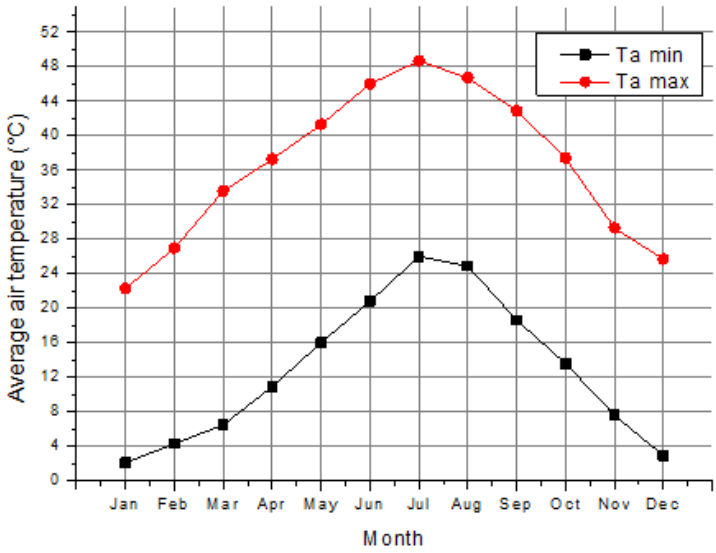


Figure 1. Average maximum (Ta max) and minimum (Ta min) monthly ambient air temperatures in the Ouargla region, Algeria (source: Meteonorm 7)

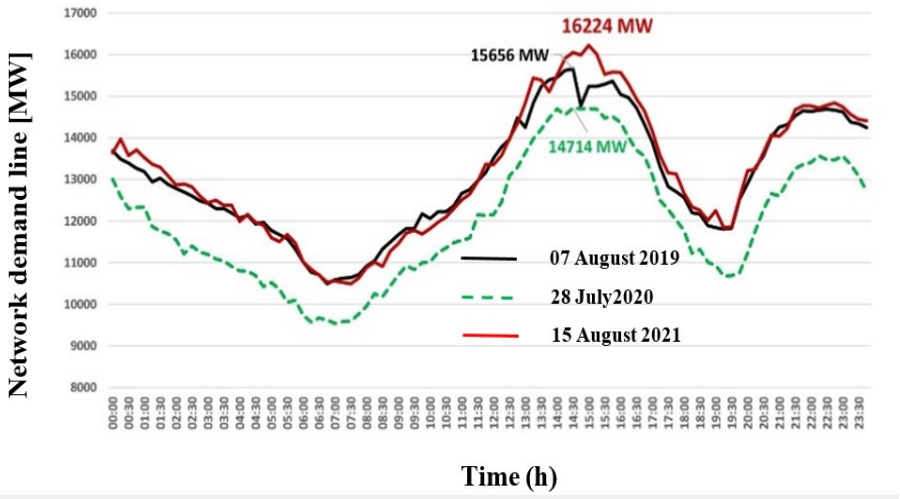


Figure 2. Comparison between maximum demand load of three days

Increasing the thermal mass of the building envelope is a passive method that showed significant reduction of the heating and cooling energy requirement. Thermal mass of the building envelope can be increased without significantly increasing the actual mass by employing latent storage. This method uses Phase Change Material (PCM) encapsulated in concrete, gypsum wallboard, ceiling and floor [3-7].

Phase change materials (PCMs) offer a promising solution to reduce the energy consumption of buildings and minimize their environmental impact. PCMs have the ability to absorb and release large amounts of thermal energy at a specific temperature, known as the phase change temperature [8]. This unique property allows PCMs to be used for thermal energy storage, which can be utilized to regulate the indoor temperature of buildings and reduce the need for conventional cooling and heating systems. Despite the potential benefits of PCMs, there are also challenges associated with their integration into building envelopes. These challenges include the leakage of PCMs, their compatibility with building materials, and their long-term stability [9, 10]. However, the advantages of PCMs, such as their high energy storage capacity, low environmental impact, and potential for cost savings, outweigh these challenges.

In this context many research works have been conducted. Atiq Ur Rehman et al [11] studied the efficacy of dual layer of PCMs, with different melting temperature ranges (28 °C and 21 °C), embedded in building walls to improve the thermal comfort of the inhabitants of these buildings. They concluded that the application of the dual layer of PCMs (RT28HC–RT21HC) combination provided up to a 54.3% reduction in indoor temperatures. In a study conducted by Waqar A et al [12], the influence of incorporating PCM in building materials was evaluated from the perspective of electricity demand. The researchers found that the energy conservation benefits depend on the minimum and maximum temperatures experienced within a 24-hour period. Additionally, the use of PCM in building materials and its potential for reducing electrical energy consumption for air conditioning during the summer were identified as areas for future investigation and assessment. Tareq Saeed studied the impact of using two types of PCM in bricks on a summer day in Medina, Saudi Arabia, through numerical simulations. Bricks with square holes filled with PCMs P116 and n-Eicosane were used to determine their effect on the heat flux passing through the wall. Results showed that the usage of PCM, particularly n-Eicosane, minimized the heat flux passing through the wall [13]. T.A. Mukram and J. Daniel conducted a study on the integration of microencapsulated phase change material (mPCM) into cement bricks to

enhance energy efficiency in buildings. Their research aimed to analyze heat flux reduction and inner wall temperature variation for different mPCM locations within the brick. Findings revealed that bricks incorporating mPCM exhibited lower peak inner wall temperatures and delayed maximum temperatures compared to conventional bricks without PCM. Specifically, the mPCM75 brick demonstrated the lowest peak inner wall temperature and the longest delay in reaching the peak temperature. Experimental validation confirmed the numerical results, showing a maximum inner wall temperature difference of 4.5 °C between solid brick and mPCM30 brick [14]. The thermal behavior of hollow clay bricks (HCBs) incorporating phase change material (PCM) in a hot climate has been studied by Said Hamdaoui et al. [15] This research investigates the effects of micro-encapsulation, where PCM is integrated into the solid parts of HCBs, as opposed to macro-encapsulation. The study examines four types of HCBs with different dimensions and alveoli numbers. Numerical simulations using Fluent software are employed to evaluate the thermal response, thermal storage capacity, and thermal insulation capacity of the PCM-embedded bricks. The findings indicate that the type of HCB significantly impacts thermal performance, resulting in varying phase shifts. Furthermore, the incorporation of PCM in bricks improves their thermal behavior, with specific HCB-PCM combinations exhibiting equivalent performance to larger-sized HCBs without PCM. The introduction of PCM in bricks also leads to notable reductions in volume, material usage, and energy consumption, with potential volume reductions of up to 30% and estimated material savings of approximately 35%. This research contributes to the development of energy-efficient building materials and addresses the need for sustainable resource utilization in the construction sector. . Meng et al. [16]. optimized double-layer shaped phase change wallboards (DLSPCWs) for energy conservation in buildings, finding significant reductions in heating and cooling loads in two contrasting climates. This study optimized DLSPCW structures for energy savings in Xining (severe cold) and Haikou (hot summer/warm winter) cities, China. 54 DLSPCWs with varying PCMs and thermal storage layer thicknesses were simulated using COMSOL Multiphysics. Compared to ordinary walls, optimal DLSPCWs significantly reduced heating load in Xining and cooling load in Haikou. The optimized DLSPCWs achieved remarkable energy savings, conserving 14,198.96 kWh and 18,816.62 kWh of electric energy during heating and cooling periods, respectively. Yang et al. [17]. explored the use of double-layer phase change walls incorporating expanded graphite (EG) to enhance indoor temperature regulation and optimize energy efficiency in buildings. The investigation focused on assessing the efficacy of these walls in mitigating

temperature fluctuations and decreasing overall energy consumption. Experimental results affirmed the capacity of EG-enhanced walls to stabilize indoor temperatures. Additionally, simulations conducted under Shanghai's climate conditions indicated notable reductions exceeding 15% in both cooling and heating loads, particularly during winter heating. Remarkably, the simulated outcomes closely aligned with the experimental data, showcasing a minimal temperature deviation of less than 1°C. In their 2023 study, Zhang et al. [18] conducted experiments on the integration of thermal insulation material (TIM) and phase change material (PCM) in concrete masonry unit (CMU) block walls. They examined eight placement modes with varying volumes of TIM and PCM under different thermal conditions, focusing on evaluating stationary and transient thermal performances and considering factors such as wall patterns. The findings highlighted the impact of thermal bridging on the effectiveness of functional materials within wall cavities. Multi-layer walls, compared to cavity walls, demonstrated superior thermal performance, suggesting potential cost savings. The thermal performance ranking, with the same material quantities, was "multi-layer walls with PCM" > "cavity walls with PCM" > "multi-layer walls with TIM" > "cavity walls with TIM." The study provided insights into optimal locations and volumes for TIM and PCM. The TIM-layer's location in a common wall had minimal effect, with slightly better performance in the exterior and middle regions. PCM showed an optimal location in the middle area of the wall for outdoor temperatures below 40°C, shifting towards the interior region otherwise. The distribution pattern of PCM had a minor effect on thermal performance.

The objective of this research is to enhance the thermal inertia of buildings in hot and arid regions by optimizing and conducting thermal analysis of a brick integrated with phase change material. Two-dimensional numerical simulations were performed using the Fluent commercial software to determine the ideal number, type, surface-to-volume (S/V) ratio of cylindrical cavities, and arrangement of PCM within the brick. For this study, the PCM is incorporated into the brick using cylindrical holes rather than square holes. Previous research conducted by Necib.H et al [19] has demonstrated the superiority of cylindrical holes over square-shaped ones. Moreover, in comparison to square holes, cylindrical holes provide a larger surface area per unit volume. This facilitates more efficient heat exchange between the PCM and the brick, resulting in improved thermal performance.

2. Model and analysis

The enhanced brick used in our work has dimensions of 48x30x30 cm, and its final geometry is shown in Fig. 3. The diameters of the cylindrical holes containing the PCM vary depending on the surface-to-volume ratio. The PCM can be inserted in its solid form, embedded in a transparent plastic film in the cavities of the brick. The exterior surface of the wall experiences time-varying solar radiation and a forced convection boundary condition (hout = 20 W/m²°C). The total heat transfer rate between the air and the outer wall of the brick is determined by combining the convection and solar radiation components [20]. The interior wall is subjected to a steady-state free convection boundary condition (hin = 10 W/m²°C), and the air temperature at the inner face of the brick is set to ensure thermal comfort. It should be noted that, according to the adaptive thermal comfort principle, occupants in dry and hot climates may feel comfortable at higher temperatures, up to 30°C [21, 22]. For this study, an internal temperature of 27°C was imposed.

In each analyzed case, only a section of the wall is considered due to the symmetry of the problem.

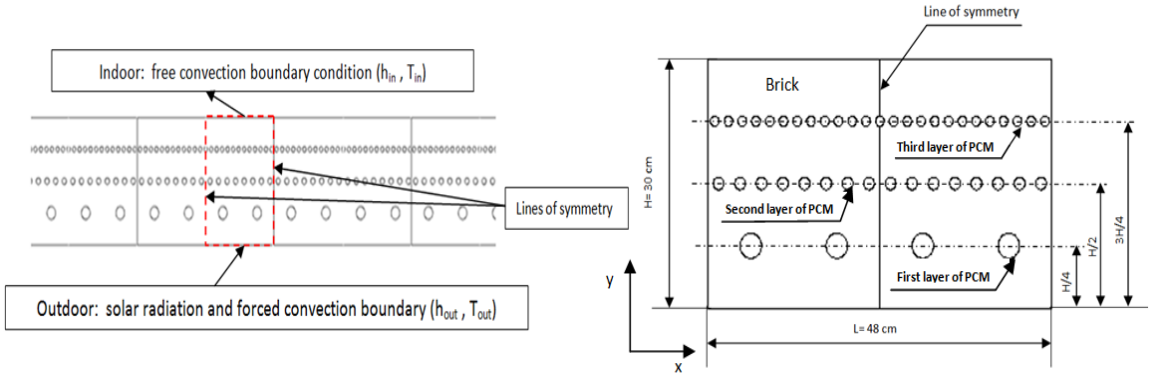


Figure 3. Boundary conditions and final geometry of the enhanced brick

2. 1. Numerical method analysis

The numerical simulation analysis was conducted using the commercial software Fluent. A grid cell size of 0.1cm for quadrilateral cells was determined to be adequate for accurately capturing the temperature distribution, as evidenced by comparing the liquid fraction for different grid densities. The Second Order Upwind differencing scheme was employed to solve the energy equations. To introduce the boundary condition for the outer wall of the brick, which involves time-dependent solar radiation and forced convection, a User Defined Function (UDF) was utilized.

The thermal characteristics of the phase change materials (PCMs) and brick utilized in this study are presented in Table 2.

Table 2. Thermal Characteristics of PCMs and Bricks

Compound	**References**	**Melting temp, T_m (°C)**	**Heat of fusion, L_{fus} (kJ kg^{-1})**	**Specific heat capacity, C_p (kJ kg^{-1} K^{-1})**	**Thermal conductivity, k (Wm^{-1} K^{-1})**	**Density, ρ(kg m^{-3})**
Brick	[23]	-	-	0.84	0.7	1600
P116-Wax	[23]	47	225.0	2.4 (solid), 1.9 (liquid)	0.24 (solid), 0.24 (liquid)	830 (solid), 773 (liquid)
n-Eicosane	[23]	37	241.0	2.01 (solid), 2.04 (liquid)	0.15 (solid), 0.15 (liquid)	778 (solid), 856 (liquid)
Paraffin wax	[24]	32	251	1.92(solid) 3.26(liquid)	0.514 (solid) 0.224 (liquid)	830
$CaCl_2.6H_2O$	[24]	29.9	187	1.4 (solid) 2.2 (liquid)	1.09 (solid) 0.53 (liquid)	1710 (solid) 1530 (liquid)
n-Octadecane	[23]	27.7	243.5	2.14 (solid) 2.66 (liquid)	0.190 (solid) 0.148 (liquid)	865 (solid) 785 (liquid)

The enthalpy-porosity model employed in Fluent to address solidification and melting phenomena has been previously validated in multiple studies [25-28]. The mathematical equation that governs the melting and solidification processes in the PCM is represented as follows:

$$\frac{\partial(\rho h)}{\partial t} + \frac{\partial(\rho u_i h)}{\partial x_i} = \frac{\partial}{\partial x_i}\left(k\frac{\partial T}{\partial x_i}\right) + S \quad (1)$$

In the equation, h represents the enthalpy, T denotes the temperature, ρ signifies the density, u_i represents the component of fluid velocity, and x_i represents a Cartesian coordinate. The term S corresponds to the source term.

The material's enthalpy is calculated as the combined value of the sensible enthalpy and the latent heat:

$$\mathrm{h} = \mathrm{h_{ref}} + \int_{\mathrm{T_{ref}}}^{\mathrm{T}} \mathrm{C_p dT} + \beta \mathrm{L_{fus}} \quad (2)$$

Where h_{ref} is the reference enthalpy at the reference temperature T_{ref} and C_p is the specific heat, L_{fus} is the latent-heat of fusion.

The liquid fraction,β, can be defined as:

$\beta = 0$ if $T < T_{solidus}$

$\beta = 1$ if $T > T_{liquidus}$

$$\beta = \frac{T - T_{solidus}}{T_{liquidus} - T_{solidus}} \quad \text{if} \quad T_{solidus} < T < T_{liquidus} \tag{3}$$

The following assumptions are made for the CFD *(Computational fluid dynamics*) analysis:

(i) No heat generation occurs (S = 0).

(ii) For both the solid and liquid phases of the PCM, the density and thermal conductivity are assumed to remain constant. During the phase change process, an average value is considered [28]. The mass of PCM is conserved in brick, and for simplicity, the thermal expansion of PCM is not considered [29]. This factor has great importance for mechanical problems, and it must be considered in another study of rigidity of enhanced brick

(iii) The computations do not take into account the natural convection of the liquid PCM. Nevertheless, all particles are assumed to have a constant zero velocity ($u_i = 0$). Consequently, Equation (1) can be simplified as follows:

$$\left[\rho C_p + \frac{\rho L_{fus}}{T_{liquidus} - T_{solidus}}\right] \frac{\partial T}{\partial t} = \frac{\partial}{\partial x_i}\left(k \frac{\partial T}{\partial x_i}\right) \tag{4}$$

2.2. Computational procedure

The heat transfer is influenced by a high surface area to volume ratio, which leads to increased heat exchange [30]. As a result, the surface-to-volume ratio plays a crucial role in determining the duration of the melting or solidification process. A larger surface contact area between the PCM and brick facilitates heat transfer, thereby reducing the phase change time. If the phase change from solid to liquid occurs rapidly during the hot hours of the day, the PCM remains inactive for a significant portion of the time and cannot effectively mitigate solar heat gain (as the PCM is already in a liquid state early in the day, despite the increasing external temperature). Conversely, if the phase change time is prolonged due to a reduced contact surface, the PCM may never fully melt, resulting in a quantity of inactive PCM remaining.

To see the effect of this ratio on the heat storage of building envelope, we began to simulate a brick with a single cylindrical hole of 6 cm in diameter and of which the report surface/volume is equal to 0.67 cm^{-1}. To keep the same volume (i.e. the same quantity of

PCM) we decrease the diameter and consequently we increase the number of holes by line. Table 3 illustrates the studied cases.

Table 3. Surface-to-volume ratio of cylindrical holes for studied cases

Diameter (cm)	Number of PCM by line	surface-to-volume ratio (cm^{-1})
6	1	0.67
4.242	2	0.94
3	4	1.33
2	9	2.00
1.5	16	2.67
1.2	25	3.33
0.948	40	4.22

To reach maximum reduction of solar heat gain, multiple layers of PCM in parallel cylindrical holes of various diameters in the brick have been placed. Using multiple layers of PCM versus using a single layer was studied previously. It was shown that multilayered PCM demonstrated more realistic thermal benefit than single layer PCM in some cases [31-33]. In this study we suggest an introduction of three layers of PCM in brick. The first one situated at H/4, the second at H/2 and the third at 3H/4. A parametric study would be required in order to find the better number and location of layers. The procedure of calculation is detailed in the following steps:

(1) To begin, an unsteady numerical simulation was conducted on the brick without Phase Change Material (PCM) using the weather conditions representative of a typical day in the Ouargla region. The primary objective of this simulation was to calculate the total heat flux through the brick over a 24-hour period and analyze the temperature variation along the H/4 line, where the first PCM is positioned.

The total heat flux through the brick during the 24-hour simulation can be calculated as follows:

$$Q_{T-without\ PCM} = \sum_{i=1}^{i=24} Q_{i-without\ PCM} \quad (5)$$

Where:

$Q_{T-without\ PCM}$: Total heat flux through the brick during the 24-hour period

$Q_{i-without\ PCM}$: Heat flux through the brick for each hour

i: Time of simulation in hours (in this case, representing a typical 24-hour day)

(2) Based on the temperature range observed along the H/4 line, two or three Phase Change Materials (PCMs) were selected from the existing literature (refer to Table 2). These

PCMs were chosen based on their melting points, which are within the range of temperatures recorded along the H/4 line.

(3) Numerical simulations were performed for the brick using each of the selected Phase Change Materials (PCMs), taking into account various surface-to-volume ratios of cylindrical holes (as indicated in Table 2). For each ratio, the total heat flux through the brick with PCM over a 24-hour period was calculated ($Q_{T-with\ PCM}$). Consequently, a total of 14 unsteady simulations were conducted, considering the seven ratios and the two chosen PCMs for this step. It is worth noting that these simulations required significant computation time. For each unsteady simulation case, the reduction in total heat flux was calculated using the following equation :

$$Q_{T-reduction} = \frac{Q_{T-without\ PCM} - Q_{T-with\ PCM}}{Q_{T-without\ PCM}} \times 100 \quad (6)$$

In this equation, $Q_{T-reduction}$ represents the percentage reduction in total heat flux achieved by incorporating PCM, compared to the scenario without PCM.

It is crucial to emphasize that the total quantity of PCM remained constant across all surface-to-volume ratios by adjusting the number of cylindrical holes. This ensured that the amount of PCM within the system was consistent, allowing for a fair comparison of the different surface-to-volume ratios and their impact on heat flux and thermal performance.

(4) Select the most suitable PCM and the optimal surface-to-volume ratio for the first position, H/4, which corresponds to the maximum percentage reduction in total heat flux through the internal surface of the brick. If the reduction in total heat flux for two ratios is nearly identical, prioritize the configuration of the brick containing the PCM with fewer holes to maintain an acceptable level of rigidity for the brick.

(5) Repeat steps 1 to 4 for the positions H/2 and 3H/4.

3. Results and discussion

3. 1. First layer of PCM

The unsteady numerical simulation of the brick without PCM indicates an average temperature ranging from 30 to 49.38°C along the H/4 line. Based on this temperature range, the following PCMs were selected: P116 with a melting point of 47°C and n-Eicosane with a melting point of 37°C. These chosen PCMs align with the temperature range of the H/4 line,

ensuring the successful melting and solidification of the PCMs. As a result, it guarantees the cycle of heat storage and release.

Fig 4 illustrates the relationship between the reduction in total heat flux, as described by equation (6), and the surface-to-volume ratio. It is observed that n-Eicosane achieves a greater reduction in total heat flux compared to P116 across all surface-to-volume ratios. Specifically, a surface-to-volume ratio of 1.33 cm^{-1} for n-Eicosane results in a maximum reduction of 25.33% in the heat flux transmitted through the brick, in comparison to the scenario without PCM. This reduction in heat flux directly contributes to a lower cooling load, leading to reduced energy consumption by HVAC systems.

To maintain the same volume of the selected PCM (n-Eicosane) within the brick, while considering the chosen surface-to-volume ratio of 1.33 cm^{-1}, a configuration is proposed. This configuration involves four containers, each with a diameter of 3cm, for the specific line mentioned (see Table 3).

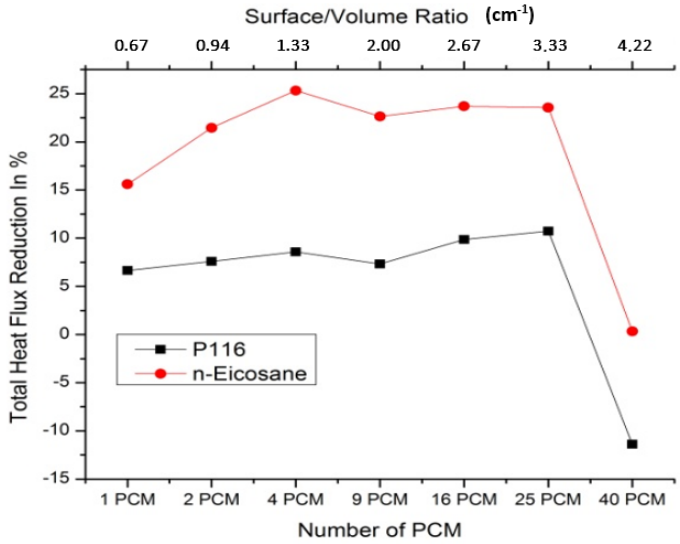


Figure 4. Total heat flux reduction for different Surface/Volume ratio in first layer

3. 2. Second layer of PCM

For the second layer of PCM positioned at the H/2 line, an average temperature range of 29.82 to 37.025°C was observed. Considering this temperature range, two PCM options were compared: n-Eicosane and Paraffin Wax, with respective melting temperatures of 37°C and 32°C. Fig 5 illustrates the variation in total heat flux reduction as a function of the surface-to-volume ratio. It is clearly observed that the n-Eicosane - Paraffin Wax double layer exhibits the highest rates of heat flux reduction for all surface-to-volume ratios. Furthermore, the ratio of 3.33 cm^{-1} achieves the most significant reduction of 38.46%.

According to Table 3, this ratio corresponds to a configuration of 25 cylindrical holes with a diameter of 1.2 cm. Very close to this reduction rate, we find a heat flux reduction of 38.32% for the ratio of 2.67 cm^{-1}, which corresponds to a configuration of 16 holes with a diameter of 1.5 cm each. The latter configuration is chosen, prioritizing the rigidity of the brick.

The understanding that the insertion of a second layer of PCM alters the temperature range of the first layer H/4 and consequently influences the selection of PCM for the first layer prompted us to test the Paraffin Wax - Paraffin Wax double layer. This test demonstrated a significant reduction in heat flux, although it remains lower in comparison to the n-Eicosane - Paraffin Wax PCM double layer across all surface-to-volume ratios.

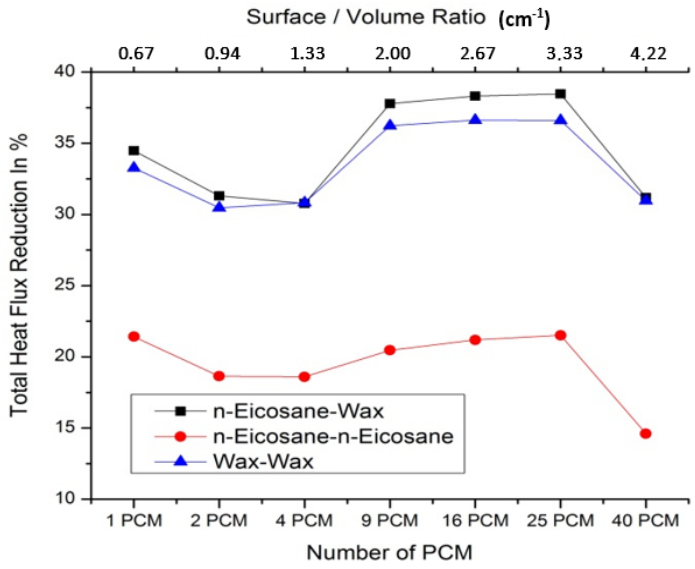


Figure 5. Total heat flux reduction for different surface-to-volume ratio in second layer

3. 3. Third layer of PCM

In a brick structure consisting of four cylindrical holes filled with n-Eicosane in the first layer and sixteen cylindrical holes filled with paraffin wax in the second layer, the average temperature along the line 3H/4, where the third layer of PCM will be placed, was found to range from 28.99°C to 31.19°C. Within this temperature range, we compared three PCM options: Paraffin Wax, CaCl2•6H2O, and n-Octadecane, with melting temperatures of 32°C, 29.9°C, and 27.7°C, respectively.

Fig 6 demonstrates that using n-Octadecane in the third layer (line 3H/4) can lead to a reduction of up to 73.33% in total heat flux during the simulation period, with an optimal surface-to-volume ratio of 4.22 cm^{-1}. This ratio is 1.8% larger than the ratio of 3.33 cm^{-1}. It should be noted that an excessive number of cylindrical holes in the brick structure can

compromise its rigidity. Therefore, we recommend adopting the ratio of 3.33 cm^{-1}, which corresponds to 25 cylindrical holes with a diameter of 1.2 cm filled with n-Octadecane in the third layer.

Additionally, Fig 6 indicates that choosing Paraffin Wax or CaCl2•6H2O in the third layer results in a smaller reduction in heat flux compared to using n-Octadecane.

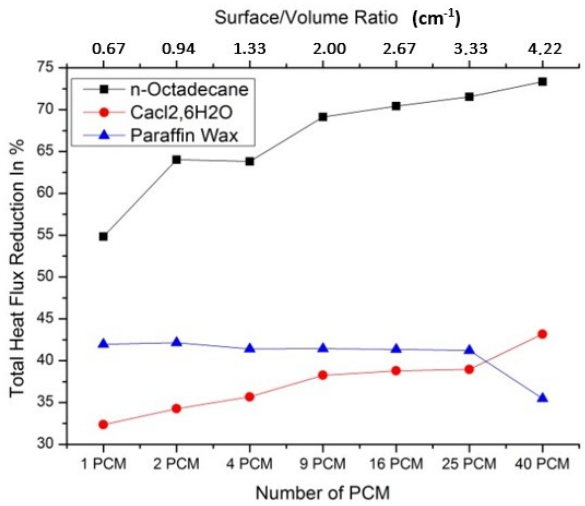


Figure 6. Total heat flux reduction for different surface-to-volume ratio in third layer

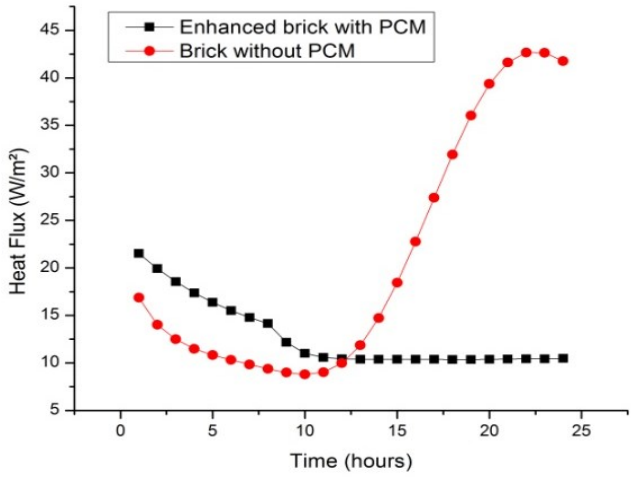


Figure 7. Hourly variation of heat flux at the indoor surface for brick with and without PCM

3. 4. Heat flux and temperature distribution for the enhanced brick

Finally, a brick with four hollow cylinders filled with n-Eicosane in the first layer, sixteen-cylinder of Paraffin Wax in the second layer and twenty five-cylinder of n-Octadecane in the third layer is selected. We see that a large amount of heat flux is reduced compared to a brick without PCM (Fig. 7). The three types of PCM introduced into the brick exhibit lower conductivity compared to the brick itself (refer to Table 2). These PCM types serve as effective insulators, primarily utilizing their sensible heat properties. Fig. 8 shows the

isothermal contours of the enhanced brick during time 1h, 3h, 6h, 9h, 12h, 15h, 18h, 21h and 24h. The left side of the brick is the outside face; it is exposed to solar radiation and convective flux. The right side is in direct contact with air of constant temperature equal to 27°C inside the habitat.

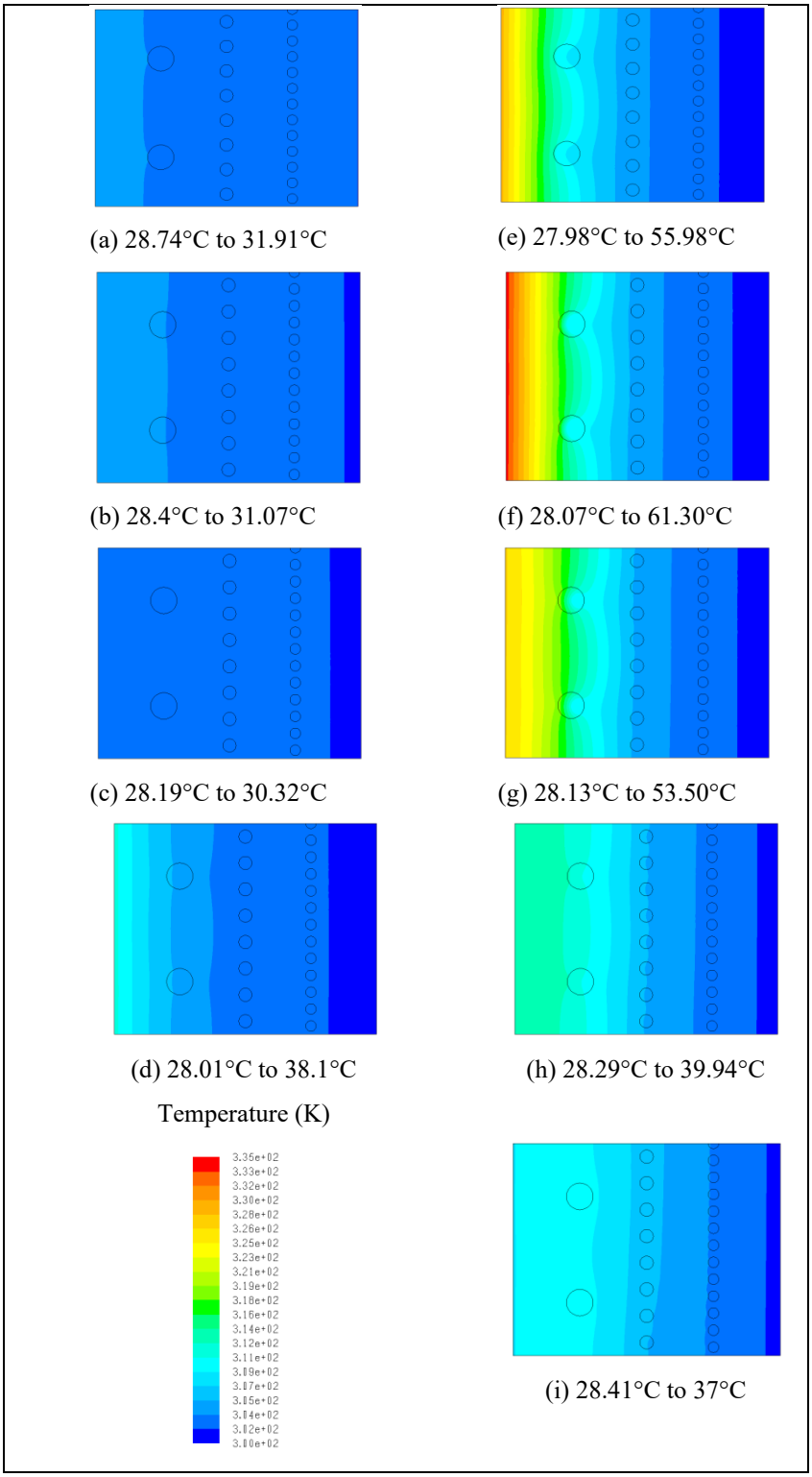


Figure 8. Isothermal contours of the enhanced brick during time (a)1h, (b)3h, (c)6h, (d)9h, (e)12h, (f)15h, (g)18h, (h)21h and (i)24h

All brick is initialized to a temperature of 30°C except for the third layer where the n-Octadecane is initialized at a lower temperature than its melting temperature of one degree Celsius.

We note that the temperature decreases during period 12 AM to 12 PM on the inner face and from 12 AM to 6 AM on the outer face. However, the PCM in both layers H/4 and H/2 remain in solid state. Only n-Octadecane in the third layer (3H/4) starts melting from the first time (see Fig. 9). It reaches a maximum fusion rate of 100% at 6 PM and remains liquid until the last hour of simulation. The PCM selected (i.e. n-Octadecane) is transformed into continuous liquid state, even in the coolest hours overnight. And colder nights will be needed for the PCM turns into solid state. Consequently, study time of one day is not enough to choose the best PCM.

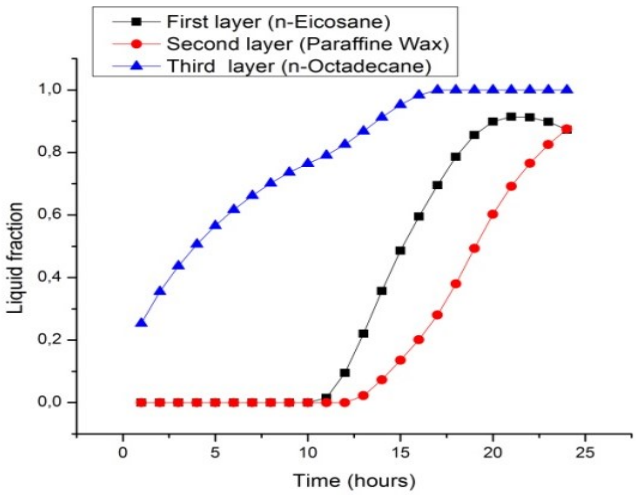


Figure 9. Liquid fraction for the three layer of PCM

4. Conclusion

The comprehensive investigation focused on optimizing an enhanced brick integrated with phase change materials (PCMs) for augmenting the thermal mass of building envelopes in hot and dry regions, particularly in southern Algeria. The research employed two-dimensional numerical simulations using Fluent software to meticulously assess the most efficient number, type, and arrangement of PCM within the brick.

The study's results highlight the substantial impact of the surface-to-volume ratio on the thermal inertia efficiency of the brick. Notably, the enhanced brick configuration, comprising specific PCM arrangements, exhibited an impressive reduction of up to 71.53% in total heat flux during the simulation period compared to a brick without PCM. This optimal

configuration consisted of n-Eicosane in the first layer, Paraffin Wax in the second layer, and n-Octadecane in the third layer.

However, the study underscores a crucial limitation: the results obtained might be confined to the initial day of observation. Thus, it strongly recommends extending the research duration to comprehensively understand the cyclic nature of PCM melting and solidification within the brick over longer periods.

The practical implications of implementing such an enhanced brick are significant. The considerable reduction in solar heat gain not only facilitates a more stable room climate by mitigating temperature fluctuations but also diminishes the necessity for air conditioning. This reduction in energy consumption offers numerous positive impacts, including peak load shifting, energy conservation, and a decrease in peak demand for network line companies. These effects are especially promising in the context of the hot and arid southern Algerian regions, offering potential benefits for the well-being and comfort of Algerian citizens.

The diameter of the cylindrical holes containing the PCMs plays a crucial role in balancing thermal performance and structural integrity. In this study, the optimization of hole diameters is carried out with a focus on thermal comfort objectives only. It is directly related to the optimization of the surface-to-volume ratio. While smaller diameters and, consequently, a greater number of holes in the brick increase the heat transfer surface area, they can also weaken the structural strength of the brick. It is recommended to conduct studies optimizing the number and diameter of the holes based on a compromise between thermal performance and structural integrity.

Finally, the implementation of PCM-integrated bricks presents several considerations and practical implications:

- Integrating PCM into bricks requires careful consideration of construction methods. The PCMs must be securely encapsulated within the brick structure to prevent leakage and ensure their long-term effectiveness. This may necessitate modifications to existing brick manufacturing processes or the development of innovative encapsulation techniques.
- The PCMs chosen must be compatible with the brick material to avoid unwanted reactions or degradation over time. Compatibility testing is essential to ensure the long-term performance and integrity of the enhanced brick.

- The cost of PCMs and their integration into bricks must be carefully evaluated against potential energy savings and other benefits. A comprehensive cost-benefit analysis is crucial to determine the economic feasibility of this technology

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