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Energy performance assessment of a passive solar wall with phase change materials

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Abstract—

This study investigates the incorporation of Phase Change Materials (PCMs) to enhance the thermal efficiency of Trombe walls in Tunisia. A numerical model was developed using TRNSYS simulation software to evaluate the thermal performance of a test room equipped with a PCM-integrated Trombe wall. This study aimed to quantify potential improvements in thermal regulation and energy conservation achieved through the integration of PCM in classic Trombe wall systems.

The results demonstrated significant benefits of PCM integration, including increased indoor temperatures, improved thermal retention, and substantial energy savings. The PCM Trombe wall showed a 1.14°C increase in daytime temperatures compared to the conventional system and provided an average overall reduction in heating loads of 60%. The study also examined the phase transitions of the PCM during heating periods and discussed the implications for optimal PCM volume and surface area.

This research contributes to efforts to improve building energy efficiency and thermal comfort through innovative passive solar technologies.

***Keywords*— Phase change material PCM, passive solar energy, building, TRNSYS, Trombe wall**

I. INTRODUCTION

In recent decades, the rising energy consumption in buildings has become a major concern, prompting research into innovative energy-efficient technologies [1]. Among these, passive solar-heating systems have emerged as a promising solution. Thermal storage walls, also known as Trombe walls or solar walls, are a passive solar-heating technology typically consisting of a black-painted massive wall positioned behind glazing, with an air gap between the wall and the exterior. The design includes vents at the top and bottom of the wall to facilitate air circulation.
Recent advancements in passive solar technology have focused on various innovative modifications of Trombe walls to enhance their thermal efficiency ([2] [3]). These modifications include Composite Trombe Walls [4], Ventilated Trombe Walls [5], Trombe Walls with Selective Surfaces, and Hybrid Trombe walls ([6] [7]). However, the most extensively studied types are the Photovoltaic Trombe Wall [8], which integrates solar panels into the wall's surface to generate electricity [9], and the Phase Change Material (PCM) Trombe Wall, which incorporates PCMs to enhance thermal storage capacity and improve temperature regulation [10].

The integration of phase change materials (PCMs) in Trombe wall systems has demonstrated significant improvements in thermal performance and energy efficiency. Numerical simulations by Tlili and Alharbi [11] revealed enhanced airflow in rooms with PCM Trombe walls, while Li et al. [12] reported a 30.12% increase in heat release-to-storage ratio in PCM solar walls with embedded evaporators. Alqaed et al. [13]

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emphasized PCM's crucial role in Trombe wall design, noting that 50% of PCM underwent phase change in 40 cm thick walls. Yang et al. [14] observed significant energy savings, with PCM-integrated Trombe walls reducing winter energy consumption by 26.5% and annual energy use by 18%. Innovative designs, such as double-layer

PCM Trombe walls (Kong et al. [15]**;** Askari and Jahangir [16]), demonstrated improved thermal regulation and energy efficiency. The integration of PCMs in photovoltaic Trombe walls also showed promise, with Abdullah et al. [17] reporting increased electrical and thermal efficiencies. Furthermore, experimental investigations by Duan et al. [18] on small-scale integrated PCM Trombe walls demonstrated significant improvements in indoor air temperature regulation.

The integration PCMs in Trombe walls presents a promising path for enhancing building energy efficiency and thermal comfort. This study conducts a comprehensive investigation into the performance of PCM- integrated Trombe wall. The research employs a validated numerical model using TRNSYS software to simulate and compare PCM Trombe wall to classic configuration, for winter heating.

II. Methodology

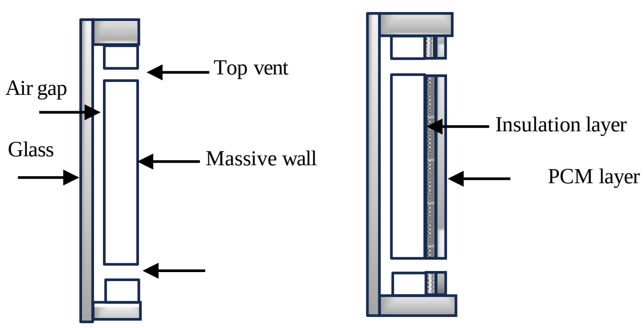
A. *Building envelope description*

In this study, a numerical model of a test room, with dimensions of 4 m in length, 4 m in width, and 3 m in height. The research concentrated on a modified Trombe wall situated on the south-facing façade. This design incorporated a phase-change material (PCM) layer applied to the inner surface of the substantial Trombe wall. The system was implemented to assess its thermal performance and energy efficiency under controlled conditions. The exterior facades of the room were constructed in accordance with Tunisian building guidelines. This study employs the commercial paraffin PCMs known as Rubitherm PCM RT-line, which possess a high latent heat capacity and a melting point range of 27°C to 29°C. The PCM layer was assumed to be 30 mm thick, with its thermo-physical characteristics listed in Table I.

TABLE I
Table 1: Rubitherm RT-HC properties

	Melting area (°C)	**Congealing area (°C)**	**Latent Heat (kJ/kg)**	**Specific heat capacity (kJ/kgK)**	**Solid density (kg/l)**	**Liquid density (kg/l)**	**Heat conductivity (W/mK)**
RT28HC	27-29	29-27	250	2	0.88	0.77	0.2

Dynamic energy simulations were conducted using TRNSYS software, with the phase change material (PCM) represented by Type 1270. To evaluate the impact of the PCM, a reference Trombe wall room was developed and compared to a PCM Trombe wall. Fig. 1(a) depicts the composite structure of the Trombe wall incorporating the PCM, while Fig. 1(b) illustrates conventional Trombe wall.



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Bottom vent

(a) Classic Trombe wall (b) PCM Trombe wall

Fig. 1 Trombe wall structure

B. Climatic conditions data

The study was conducted in Tunis a site characterized by a mild Mediterranean climate with cold, sunny winters and hot summers. To ensure the reliability of the simulation, location-specific meteorological data were, derived for Tunis from TRNSYS software database. The mean ambient temperature ranges from approximately 11°C in winter, with lower extremes at night, to a peak of 26.8°C in August. Relative humidity varies seasonally, from 75% in winter to 63% in summer. Solar radiation on a horizontal surface reaches up to 527 W/m² in summer and exceeds 290 W/m² in winter, offering significant potential for passive solar heating. The average annual wind speed is around 4.57 m/s.

III. RESULTS AND DISCUSSION

A. Impact of PCM on indoor temperature

Fig. 2 demonstrated a significant positive impact on indoor temperature profiles, particularly during afternoon hours. Comparative analysis revealed that the PCM-enhanced Trombe wall configuration resulted in a notable increase in daytime temperatures, elevating them by 1.4°C compared to the conventional Trombe wall design. This improvement in thermal performance can be attributed to the superior heat retention capabilities of the PCM-integrated system. The PCM Trombe wall exhibited an ability to maintain elevated indoor temperatures for extended periods, effectively delaying the start of heating requirements. Specifically, the PCM-enhanced design assures a reduction in heating time by 3 to 5 hours relative to the conventional Trombe wall configuration. This prolonged thermal comfort period demonstrates the PCM's capacity to absorb, store, and gradually release heat, thereby smoothing temperature fluctuations and reducing the reliance on active heating systems.

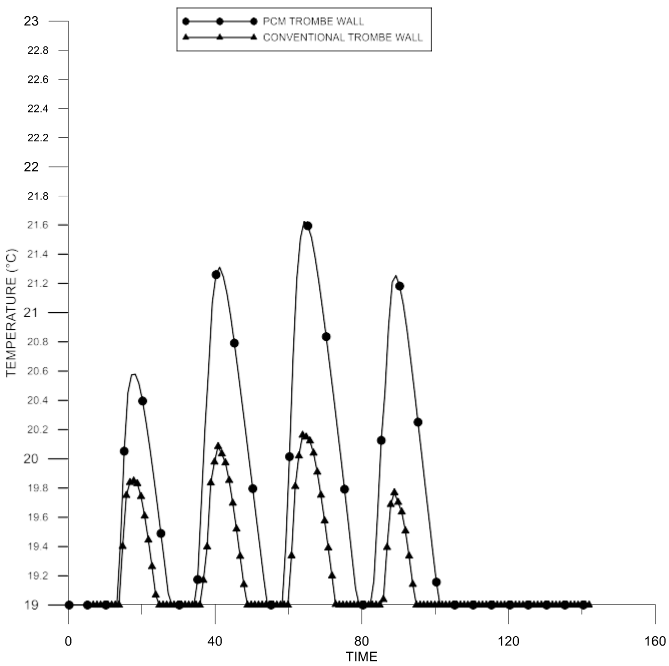

Fig. 2 Evolution of indoor temperature for classic and PCM Trombe wall

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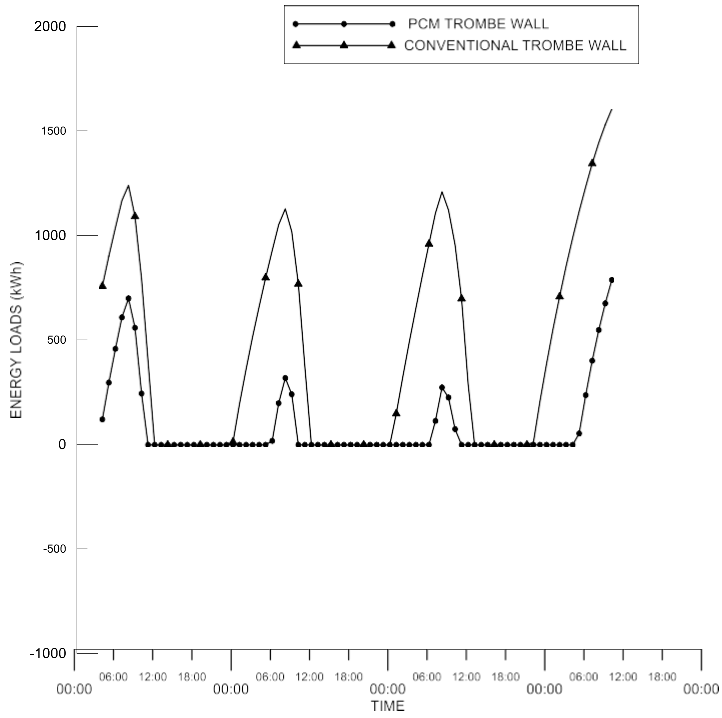

Fig. 3 Evolution of energy loads for classic and PCM Trombe wall

B. Energy Performance Analysis

Fig. 4 illustrated substantial reductions in heating energy demands for the PCM-integrated Trombe wall configuration. The monthly heating requirements are 183.9 kWh for the PCM Trombe wall, while the conventional Trombe wall necessitates 456.19 kWh. This reduction in heating load translated to shorter heating durations, attributed to the PCM's ability to effectively capture, store, and release solar heat gains. The PCM's phase change properties ensured optimal diurnal cycling, retaining heat during the day and releasing it at night. Comparative assessment of the two configurations revealed that the PCM Trombe walls achieved an impressive average overall reduction in heating loads by 60%. These findings underscore the substantial energy-saving potential of PCM-integrated Trombe walls, highlighting their efficacy in enhancing building energy efficiency and reducing reliance on active heating systems.

C. Liquid fraction

Furthermore, the study investigated the phase transitions of the PCM (solid, liquid, and phase-changing states) during heating periods and examined the structural characteristics of the PCM Trombe wall.

Fig. 4 depicts the percentage of time that the PCM was in the solid, liquid, or changing phase during the heating periods, as determined by the hourly fraction values generated by the simulation. Because of the increased solar energy on bright days, the liquid percentage can exceed one and the PCM is entirely melted. In January, February, and March, the PCM remained solid for approximately 20% of the time, whereas in December, it was solid for approximately 12% of the time, liquid for 35% of the time, and changing phase for the rest of the time. It can be observed that when the PCM is melted and solidified for a longer period, it becomes more efficient during hot days to achieve full or partial daytime cycling. To ensure that the mass is completely melted or solidified, the volume of the PCM should be appropriately selected throughout each phase-change-day cycle. If the PCM volume is sufficiently large, complete melting may not occur due to the limited duration of solar radiation, which fails to provide the thermal energy necessary for the phase change of the PCM. Furthermore, increasing the surface area of the PCM improved the heat transfer between this area

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and PCM. The thickness decreased when the surface area of the PCM layer increased while maintaining the same volume. As a result, the melting and solidification processes are becoming more effective. A reduction in the PCM layer thickness and an increase in the surface area to optimum levels will result in energy savings and, hence, greater efficiency for a given amount of PCM.

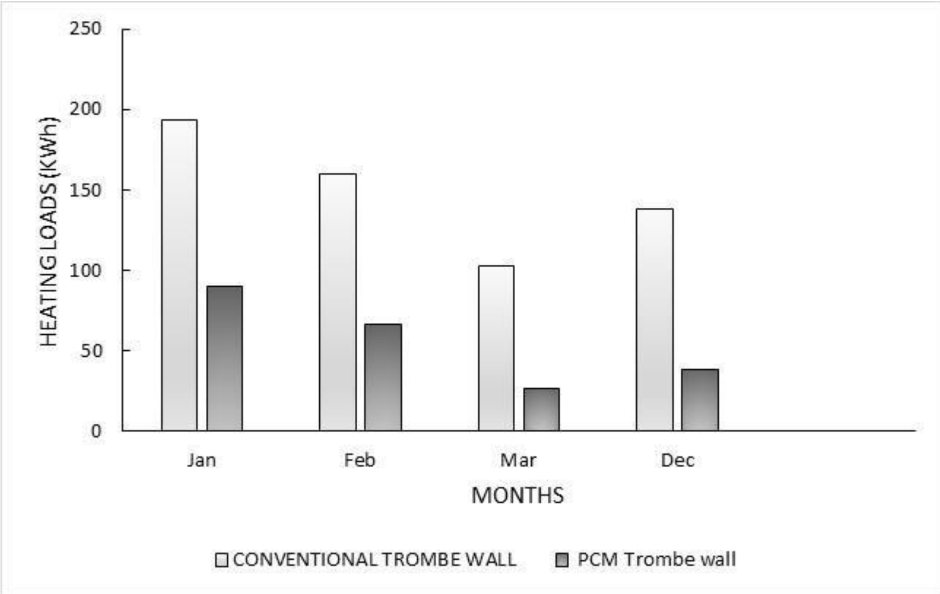

Fig. 3 Monthly heating energy demands

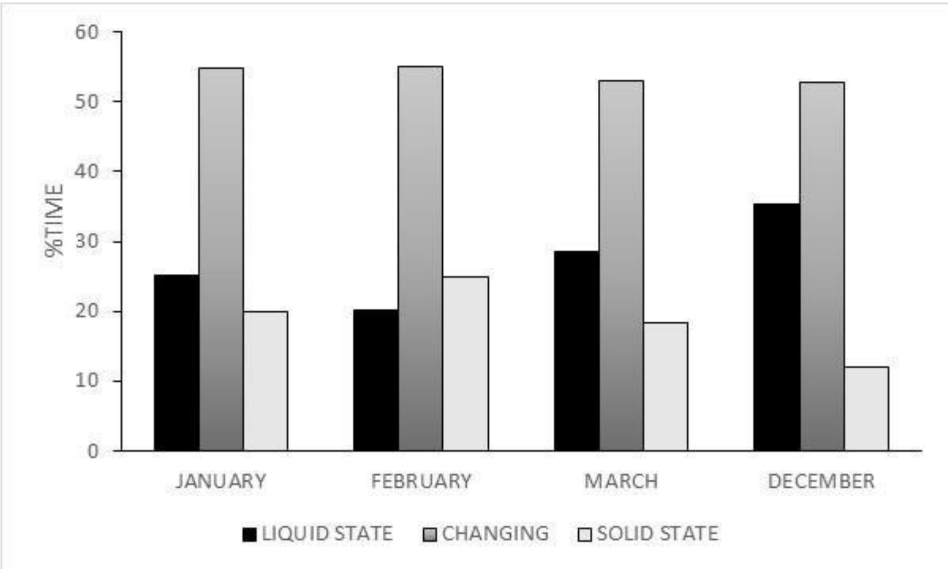

Fig.4 Percentage of time of PCM states

IV. CONCLUSIONS

This study has effectively demonstrated the significant potential of Phase Change Material (PCM)-integrated Trombe walls in enhancing building thermal performance and energy efficiency. Through the development and application of a numerical model using TRNSYS simulation software, the research provided a comprehensive comparative analysis between conventional and PCM-integrated Trombe wall systems.

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The integration of PCM into the Trombe wall design yielded notable improvements in thermal regulation. The PCM-enhanced system demonstrated superior heat retention capabilities, resulting in an approximate 1.13°C increase in daytime temperatures compared to the conventional Trombe wall. This improvement in thermal performance translated into substantial energy savings, with the PCM Trombe wall achieving an average overall reduction in heating loads of 60% compared to its conventional counterpart.

Furthermore, the study provided valuable insights into the phase transition behaviour of the PCM during heating periods, highlighting the importance of optimizing PCM volume and surface area for maximum efficiency. These findings contribute to the growing body of knowledge on passive solar technologies and offer practical implications for improving building energy efficiency.

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