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Original Article

Computational Fluid Dynamics (Cfd) Simulation of Phase Change Material (Pcm) As Thermal Comfort Regulator for Residential Buildings in Hot Climates

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Abstract

Phase Change Materials (PCMs) have garnered significant attention in the field of sustainable architecture due to their potential to enhance energy efficiency in buildings. PCMs in building materials help stabilize temperatures by storing heat during the day and releasing it at night, reducing the need for traditional heating and cooling. This paper examines the integration of PCMs into building envelopes, evaluating their impact on energy consumption and indoor comfort. Calcium Chloride Hexahydrate was chosen as the PCM bearing in mind its excellent thermal properties. Hourly climatic data for an arid climate were imported into Fluent. Solar radiation was applied as a boundary condition, while diurnal temperature variations and wind profiles were imposed. Also, Thermophysical properties of the PCMs were modeled with temperature-dependent properties to capture latent heat effects. The result shows that the PCM-integrated wall demonstrated a delayed heat transfer response. During daytime, the PCM layer absorbed a substantial portion of the incoming thermal energy, thereby reducing the rate at which heat was transmitted into the interior space. The results showed that the peak indoor temperature was reduced by 3-5 °C compared to the conventional wall. This reduction is significant in Sahara climates, where daily temperature swings are extreme.

Keywords: *Thermal comfort, phase change material, thermal regulation, Simulation, Climate.*

Introduction

Climate change and global warming have significantly increased the need for sustainable and energy efficient building solutions, particularly in hot-arid regions where buildings experience excessive heat gain and thermal discomfort. The building sector accounts for a substantial proportion of global energy consumption and greenhouse gas emissions due to heavy reliance on mechanical cooling systems (Mwizerwa, 2019). Climate-responsive building design has gained considerable attention as a strategy for improving indoor thermal comfort while reducing energy demand. One promising passive cooling approach involves the integration of Phase Change Materials (PCMs) into building envelopes. PCMs can absorb, store, and release large amounts of latent heat during phase transitions, thereby stabilizing indoor temperature fluctuations and reducing cooling loads (Hossain *et al.*, 2023). Previous studies have demonstrated that PCM integration within walls, roofs, floors, and ceilings can significantly improve thermal performance and energy efficiency in buildings located in hot climates (Louanate *et al.*, 2021; Jangeldinov *et al.*, 2020). This study employed a Computational Fluid Dynamics (CFD) approach using ANSYS Fluent to investigate the thermal performance of a climate-responsive building integrated with phase change materials (PCMs) under Sahara environmental conditions.

Methodology

The methodology combined numerical modeling, climatic data integration, and thermophysical material characterization to evaluate heat transfer and energy storage behavior within the building envelope.

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The phase change material selected for this study was Calcium Chloride Hexahydrate ($CaCl_2 \cdot 6H_2O$), chosen for its suitable thermal storage characteristics Its thermophysical properties including density, specific heat capacity, thermal conductivity, latent heat of fusion, and phase transition temperatures were defined within the simulation to accurately capture melting and solidification behavior. The building materials (brick and EPS) were also characterized based on their thermal conductivity, density, and specific heat capacity.

Table 1: Properties of Calcium Chloride Hexahydrate CaCl26H20

Property	Values
Liquidous temperature [K]	302
Solidus Temperature[K]	301
Density of solid phase [kg/m³]	2100
Laten Heat of Phase Change [J/kg]	160,000
Thermal Conductivity [W/m·K]	0.54
Specific Heat Capacity [J/kg·K]	1470

Table 2: Material properties for building

Name of the material	Thermal Conductivity	Density	Specific Heat
Brick	0.84	1900	1880
Expanded-polystyrene (EPS)	0.035	25	1300

The simulation workflow involved: geometry development, mesh generation with refined PCM and boundary-layer regions, material property assignment, and integration of climatic data. Transient simulations were then executed to analyze dynamic heat transfer, PCM phase transition behavior, and overall thermal performance of the building envelope. Post-processing was conducted using ANSYS visualization tools and Microsoft Excel to generate temperature profiles, contour plots, and comparative performance charts.

Step 1: Geometric Modeling
Architectural models of building wall components were created using Revid and Ansys Design Modeller. PCM and EPS layers were incorporated.

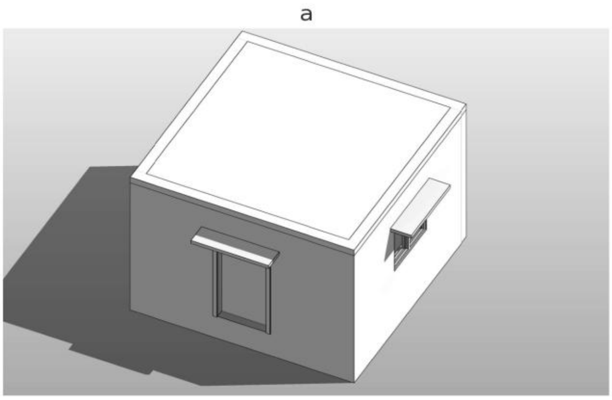

fig 1a: 3D building Modelling

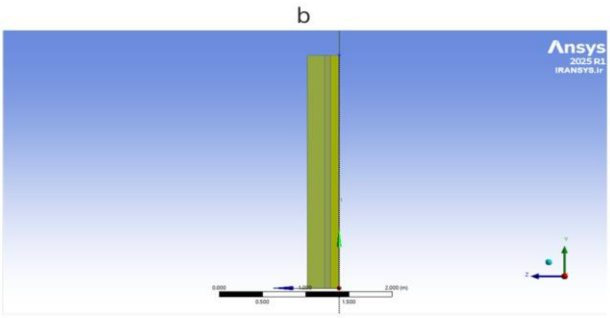

fig 1b: building integrated with CaCl26H20 as PCM

Step 2: Mesh Generation
The computational mesh was generated for all building components. Local mesh refinement was applied around PCM regions and airflow zones. Inflation layers were included to capture boundary layer effects.

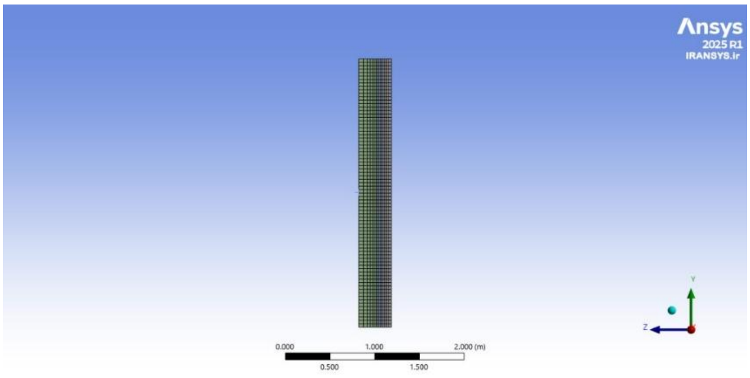

Fig 2: Building Wall Mesh

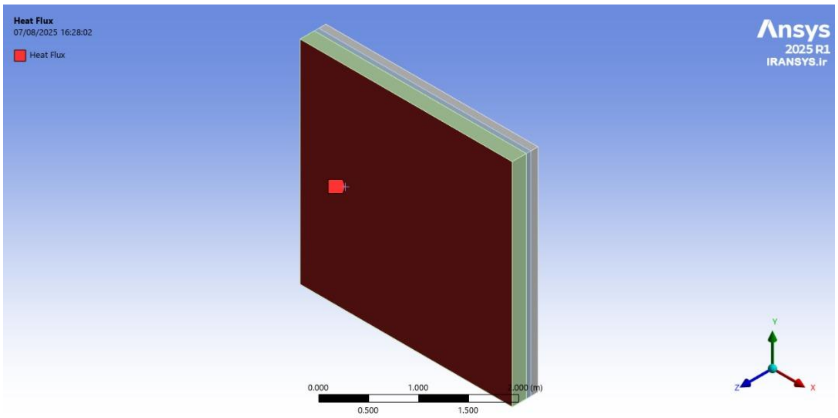

Fig 3: Building wall showing heat flux zone

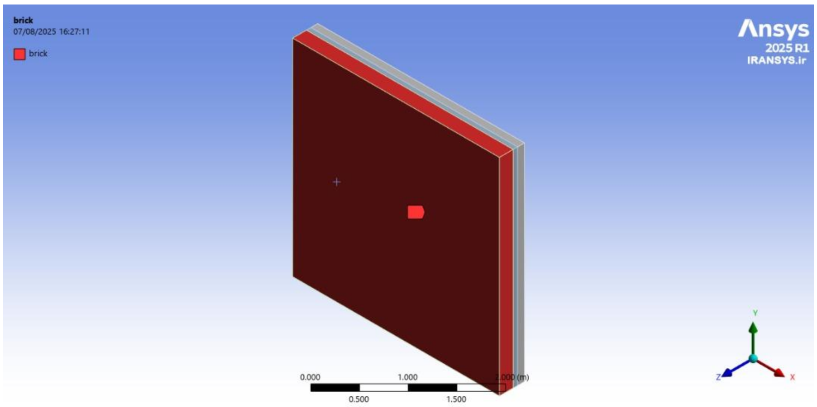

Fig 4: Building wall showing Brick layer zone

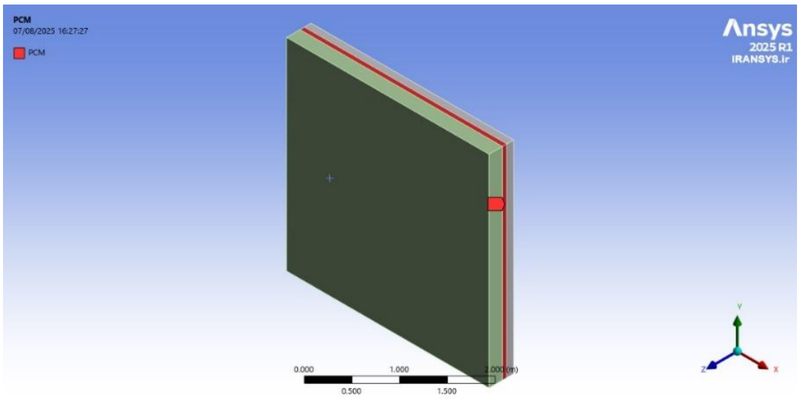

Fig 5: Building wall showing PCM layer zone

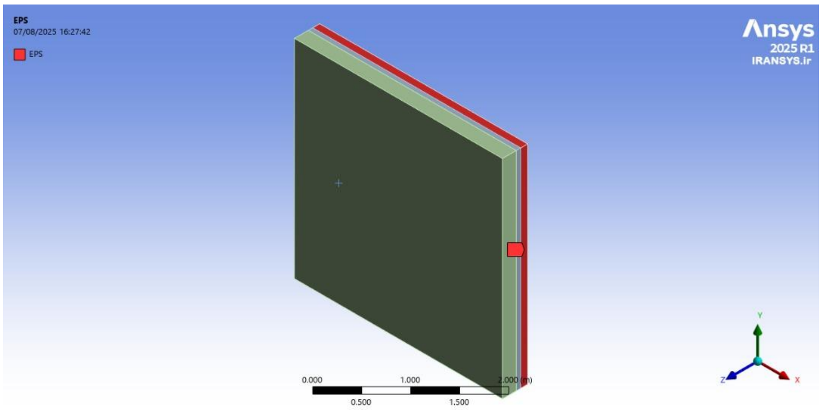

Fig 6: Building wall showing Expanded Polystyrene (EPS) layer zone

1. **Results And Discussions**

A. Temperature distributions

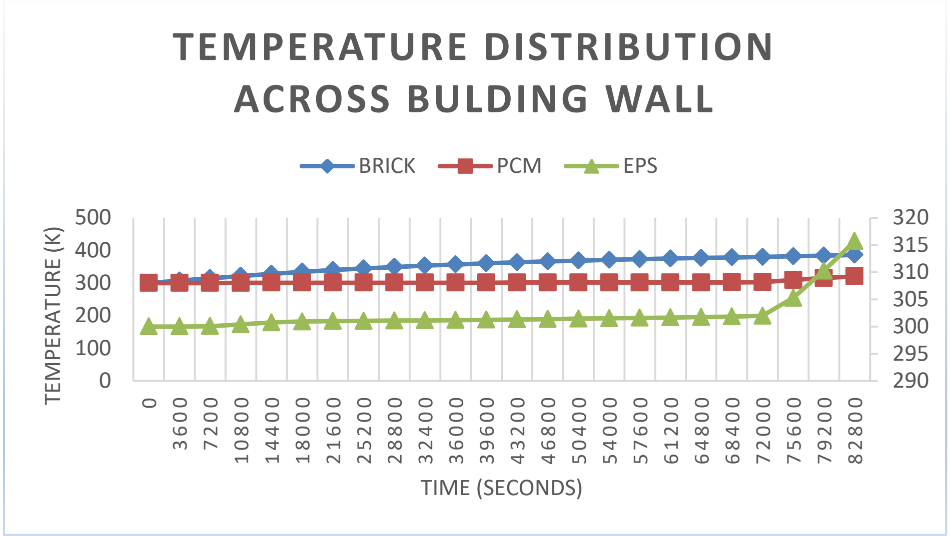

Fig 7 Temperature distribution across building wall with PCM

The temperature distribution across the multilayer wall shows a progressive reduction in thermal wave amplitude from the brick layer to the EPS layer. In particular, the PCM layer appeared as a thermal stabilization zone, as its isotherms were flatter compared to the brick. The contour plots reinforced this behavior, visually demonstrating the buffering capacity of the PCM. This evidence confirms that the integration of PCM in the wall structure enhances thermal inertia and reduces direct conduction, leading to improved indoor thermal comfort.

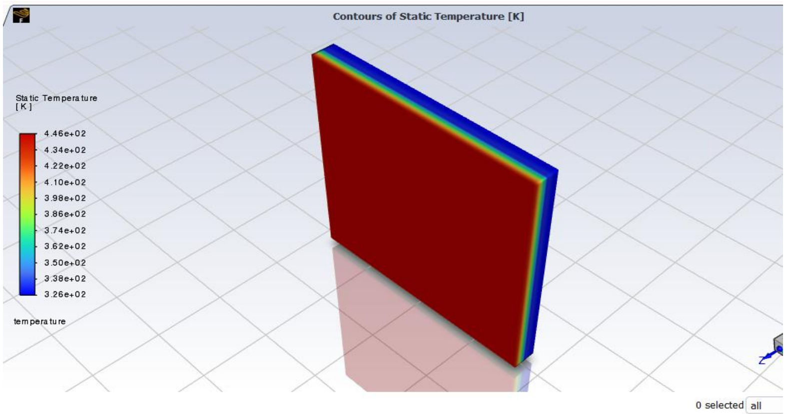

Fig 9 Temperature Distribution Contour

B Heat Flux Across the Wall

The heat flux across the building wall was analyzed to evaluate the effectiveness of PCM in reducing conductive heat transfer.

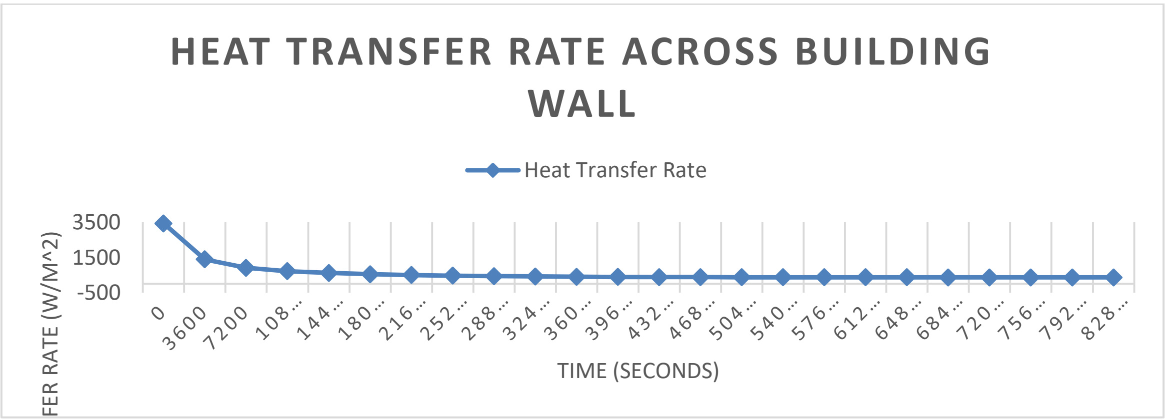

Fig 10 Heat Transfer rate across build

The heat transfer rate analysis revealed that the PCM layer significantly reduced and delayed peak heat flux into the building interior. During midday, when the outdoor temperature and solar radiation peaked, the PCM absorbed heat, lowering the magnitude of heat flux transmitted through the wall. In the evening, the stored heat was gradually released, reducing nighttime heat losses and maintaining stable indoor conditions. This shifting of heat loads demonstrates PCM's role as a thermal storage medium, effectively flattening peak demands and contributing to energy savings in cooling.

C PCM Phase Transition and Liquid Fraction Evolution

The **liquid fraction curve** indicated the degree of melting and solidification over the diurnal cycle (14000s-72000s).

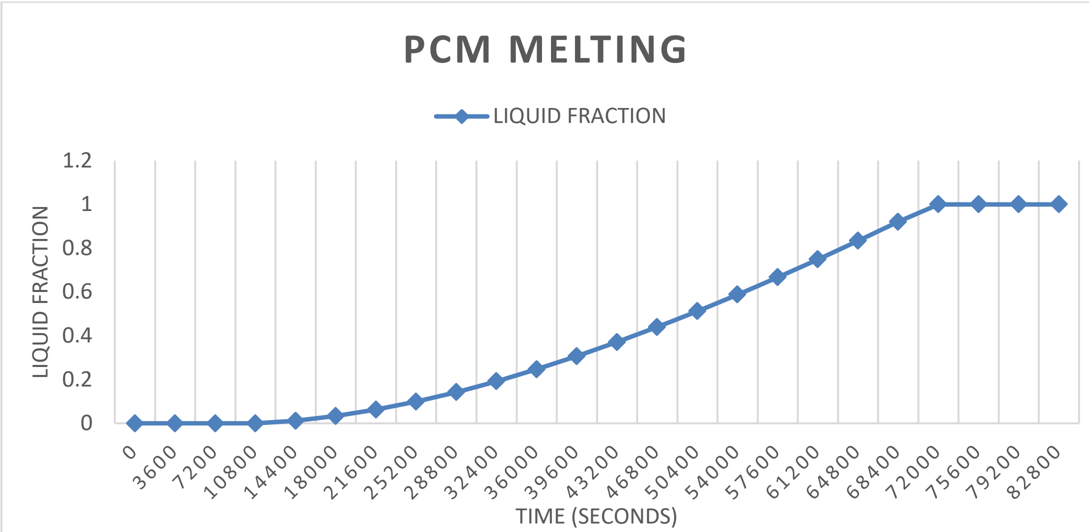

Fig 11 PCM liquid fraction

The liquid fraction curve clearly illustrates the PCM's phase-change behavior. Melting began in the early hours of the day as wall temperatures rose, with the PCM reaching peak liquid fraction during midday when heat gain was at its highest. By evening and nighttime, the PCM gradually solidified, with liquid fraction values returning toward zero. This cyclical melting and solidification validated PCM's function as a "thermal battery," capable of storing excess heat during hot periods and releasing it when temperatures fall. The results underscore the effectiveness of calcium chloride hexahydrate as a PCM for climate-responsive design in hot–arid regions.

The PCM began melting around **14000seconds** as external temperatures and solar radiation increased.

By midday, a significant proportion of the PCM had transitioned into the liquid state, storing latent heat energy.

During the evening and night, as ambient temperatures dropped, the PCM gradually solidified, releasing stored heat back into the building envelope.

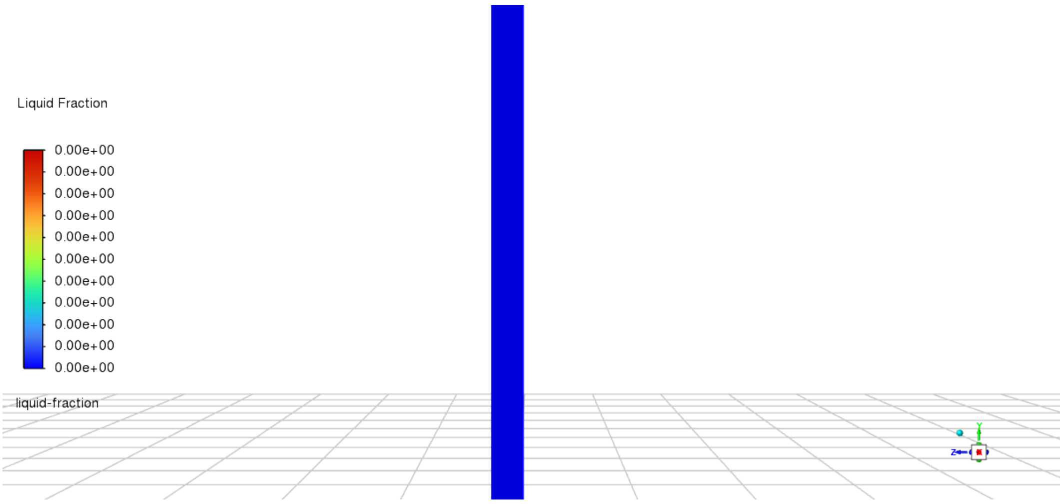

Fig 12: Liquid fraction at starting point

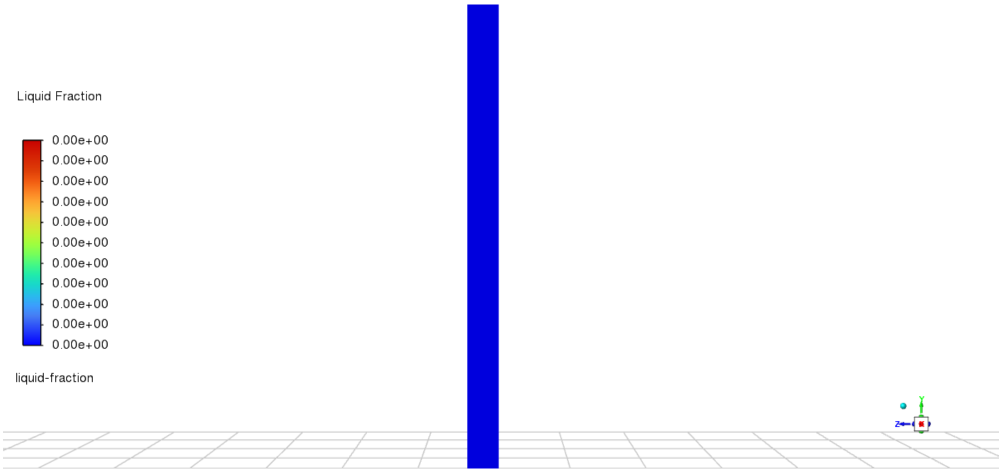

Fig 13: Liquid fraction at 3600 seconds

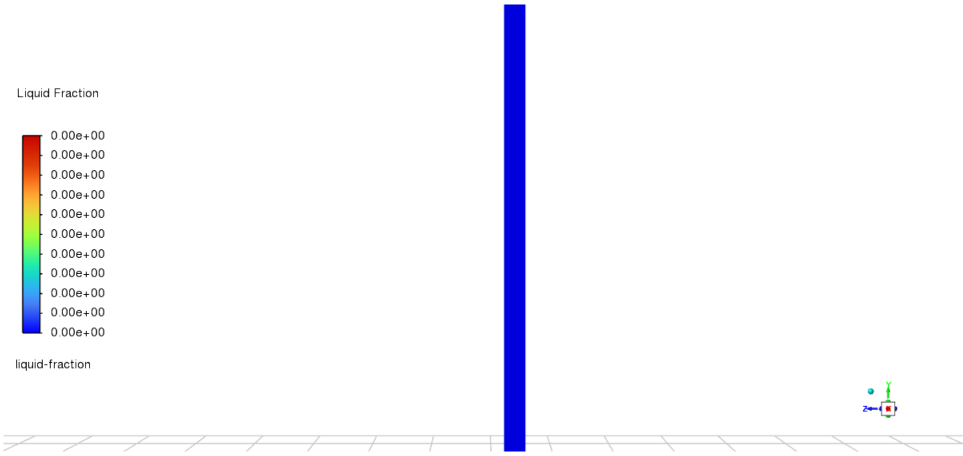

Fig 14: Liquid fraction at 7200 seconds

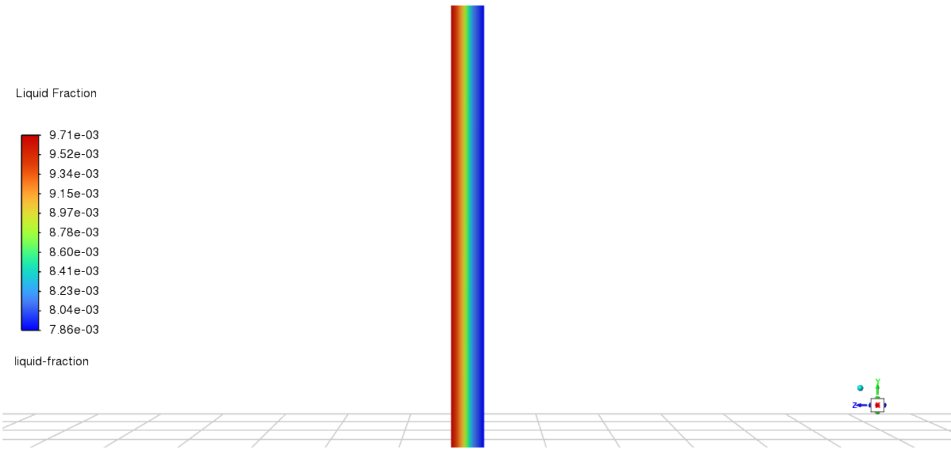

Fig 15: Liquid fraction at nearly 14400 seconds

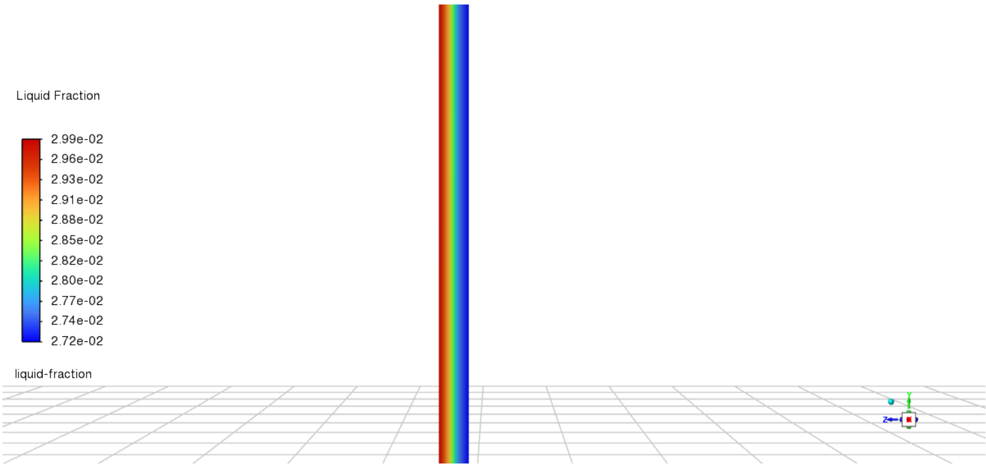

Fig 16: Liquid fraction at18000 seconds

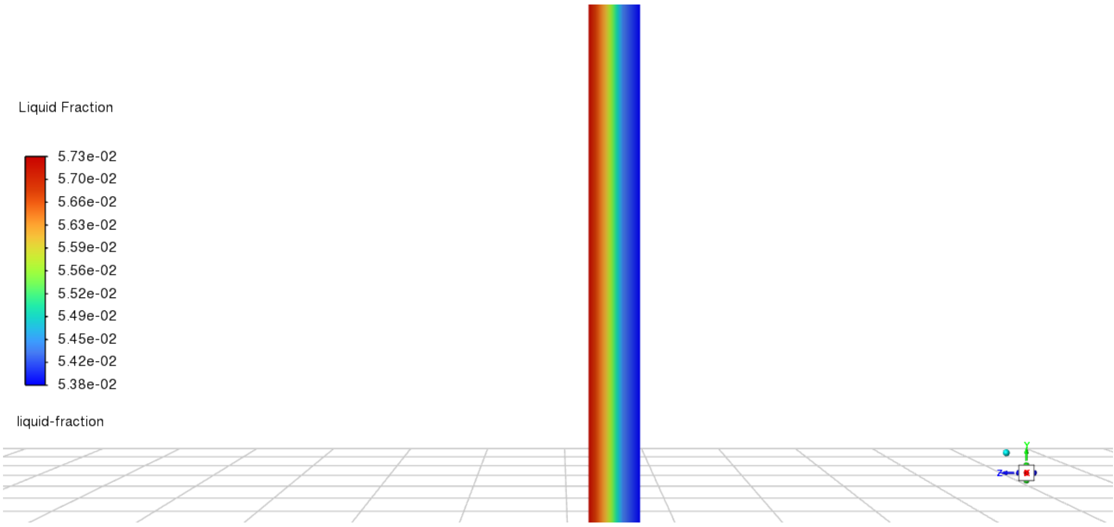

Fig 17: Liquid fraction at 21600 seconds

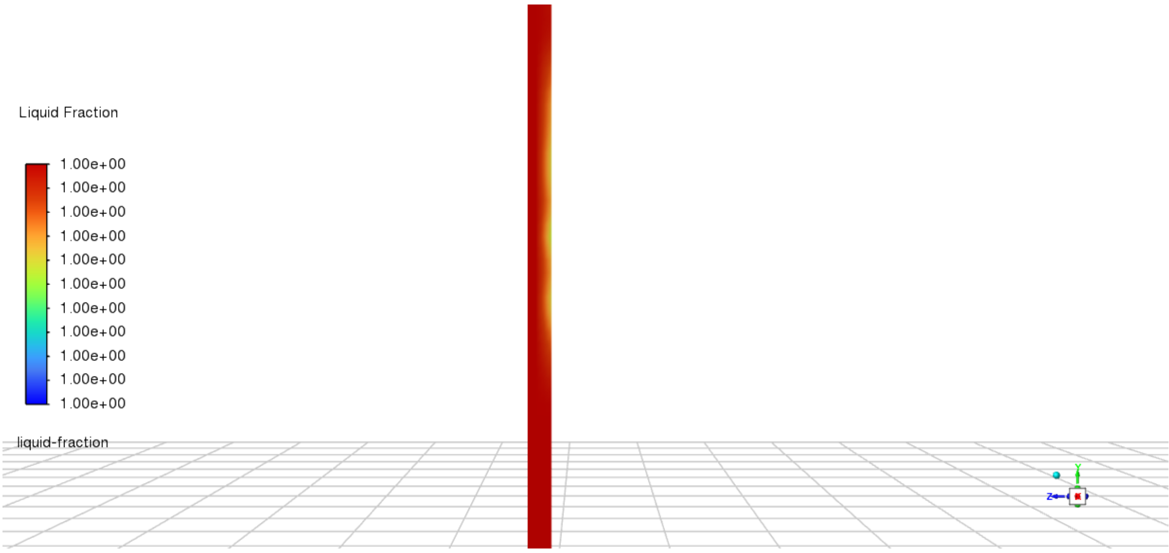

Fig 18: Liquid fraction at 72000seconds

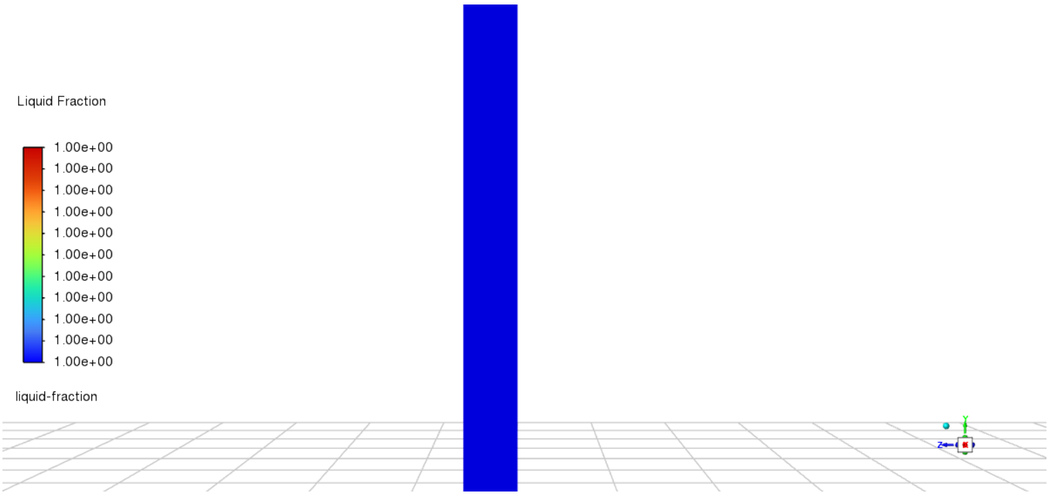

Fig 19: Liquid fraction at 75600 seconds

1. The PCM began melting around **14000seconds** as external temperatures and solar radiation increased.
2. By midday, a significant proportion of the PCM had transitioned into the liquid state, storing latent heat energy.
3. During the evening and night, as ambient temperatures dropped, the PCM gradually solidified, releasing stored heat back into the building envelope.

Validation of Results

The simulation outputs were validated against published experimental and numerical studies in similar climatic contexts. Louanate *et al.* (2021) reported that PCM-enhanced envelopes in Moroccan climates achieved indoor temperature reductions of up to 3–5 °C and energy savings of 10–15%. Similarly, Babaharra *et al.* (2023) observed temperature amplitude reductions of 18% when nanoparticle-enhanced PCMs were integrated into building floors.

Conclusion

Building wall with PCM and EPS layers has been modelled; thermal energy storage have been accomodated into the model with the CFD simulation. The following conclusion has been drawn from the simulation:
1. PCM integration reduced peak indoor temperatures compared to conventional walls.
2. Heat flux across the building envelope was reduced thereby demonstrating improved thermal resistance.
3. The PCM exhibited effective phase-change behavior, thereby stabilizing indoor conditions.
4. Energy demand for cooling was reduced, confirming PCM's role in energy efficiency.

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Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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