

Thermal Performance Optimisation, Energy Efficiency Analysis, and Parametric CFD Modelling of Phase Change Material-Integrated Hollow Clay Brick Wall Systems for Hot-Arid Climatic Conditions in Rajasthan, India

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Abstract

The built environment accounts for approximately 33% of India's total final energy consumption, with space cooling in hot-arid climatic zones — principally Rajasthan, Gujarat, and parts of Maharashtra and Andhra Pradesh — representing the fastest-growing energy demand component as urbanisation, rising incomes, and worsening urban heat island intensity converge to drive near-universal air conditioning adoption. Passive building envelope strategies that attenuate peak indoor temperature and time-shift thermal load from peak grid hours can substantially reduce both cooling energy demand and peak electrical demand on distribution infrastructure whose upgrade cost in Rajasthan's secondary cities is estimated at ₹4,200 crore by 2030. Phase Change Materials (PCMs), which exploit the high latent heat of solid-liquid phase transitions to store and release thermal energy at near-isothermal temperatures, represent an emerging envelope technology whose integration into conventional hollow clay brick masonry — the dominant wall construction typology in Rajasthan — has been investigated at component level but not at the whole-wall or building energy performance level under representative Rajasthani climate boundary conditions.

This study presents: (i) laboratory thermal characterisation of three commercial PCMs (RT28HC, RT42, and HS29) encapsulated in the hollow cores of standard IS 2180:1988 hollow clay bricks at three fill ratios (25%, 50%, 75% core volume); (ii) experimental measurement of dynamic thermal transmittance (U -value), decrement factor (f), and time lag (ϕ) for nine PCM-brick wall assemblies relative to a conventional hollow clay brick control wall in a calibrated outdoor test cell in Jaipur (26.9°N, 75.8°E) during peak summer (May-June 2023); and (iii) parametric CFD simulation in ANSYS Fluent using the enthalpy-porosity method for PCM melting-solidification, validated against experimental data, to explore the sensitivity of thermal performance to PCM selection, fill ratio, brick orientation, and wall thickness. Peak indoor temperature reduction of 4.8°C and time lag extension of 3.2 hours were achieved with RT28HC at 75% fill ratio in a 230 mm double-skin wall configuration relative to the unmodified hollow clay brick control. Building energy simulation in EnergyPlus, using the validated wall thermal model as input, predicts annual cooling energy savings of 18.4–31.6 kWh/m² depending on building typology and occupancy schedule, representing 22–38% reduction in space cooling energy consumption for representative Rajasthani residential and commercial building archetypes.

Keywords: phase change material, hollow clay brick, thermal energy storage, building envelope, hot-arid climate, CFD, enthalpy-porosity method, decrement factor, time lag, EnergyPlus, Rajasthan, passive cooling

1. Introduction

Rajasthan's climate is characterised by extreme diurnal temperature swings — daily ranges of 15–22°C are common in May and June — and peak outdoor temperatures regularly exceeding 45°C in Jaipur, Jodhpur, and Bikaner. These conditions impose severe thermal stress on building envelopes, driving rapid heat gain during daylight hours that overwhelms passive ventilation strategies and necessitates mechanical cooling during the peak demand window of 14:00–19:00 IST. The thermal mass of conventional solid or hollow clay brick construction attenuates diurnal temperature swings

through sensible heat storage, but the limited heat capacity of standard brick assemblies (typical decrement factor $f = 0.45$ – 0.60 , time lag $\phi = 5$ – 7 hours for a 230 mm wall) is insufficient to fully time-shift peak indoor thermal load to the cooler overnight hours when natural ventilation or free-cooling is available.

Phase Change Materials address this limitation by providing latent heat storage capacity — typically 150–250 kJ/kg for organic PCMs in the 25–45°C transition temperature range relevant to building envelope applications — that is 10–20 times the sensible heat storage capacity of an equivalent mass of brick per degree of temperature change. By selecting PCMs whose phase transition temperature lies within the comfort band (24–32°C for Indian climatic conditions per NBC 2016), the wall assembly can absorb solar heat gain during daytime without raising the inner surface temperature above the PCM melting point, effectively decoupling the indoor thermal environment from the diurnal outdoor temperature cycle until the PCM is fully melted. Overnight solidification, driven by natural ventilation or radiation cooling, resets the storage capacity for the following day's cycle.

The integration of PCMs into hollow clay bricks — as opposed to wallboards, gypsum panels, or concrete masonry units investigated in the majority of existing PCM building research — is motivated by three features of the Indian construction market: hollow clay bricks are the most widely produced and lowest-cost masonry unit in Rajasthan's construction supply chain; their hollow core geometry provides a natural containment cavity for encapsulated PCM without structural modification; and their fired clay shell provides the thermal and chemical stability required to contain organic PCM over a building service life of 50+ years without degradation. This study quantifies the thermal performance benefit of PCM-hollow clay brick integration under actual Rajasthani summer climate conditions and provides a validated simulation framework for its extrapolation to building-level energy performance prediction.

2. Materials Characterisation and Experimental Setup

2.1 Phase Change Material Selection and Characterisation

Three commercial organic PCMs were selected based on phase transition temperature compatibility with Rajasthani summer indoor comfort targets: RT28HC (Rubitherm GmbH, Germany; $T_m = 28^\circ\text{C}$), HS29 (Microtek Laboratories, USA; $T_m = 29^\circ\text{C}$), and RT42 (Rubitherm GmbH; $T_m = 42^\circ\text{C}$). RT28HC and HS29 target the comfort band ceiling, absorbing heat gain before indoor temperature exceeds 28–29°C; RT42 targets peak envelope surface temperature attenuation, absorbing conducted heat before it reaches the indoor air. Differential Scanning Calorimetry (DSC) at 0.5°C/min heating rate confirmed latent heats of 250 kJ/kg (RT28HC), 226 kJ/kg (HS29), and 165 kJ/kg (RT42); all PCMs exhibited sharp, well-defined phase transition peaks with less than 1.8°C hysteresis between melting and solidification onset.

PCM encapsulation employed macro-encapsulation in high-density polyethylene (HDPE) pouches (0.3 mm wall thickness) heat-sealed under vacuum to prevent air inclusion that would reduce effective thermal contact. Encapsulated PCM parcels were sized to fill 25%, 50%, and 75% of the hollow core volume of standard IS 2180:1988 hollow clay bricks (nominal 190×90×90 mm, three horizontal cores of 50×55 mm each). Remaining core volume in partial-fill configurations was left as still air to preserve thermal resistance contribution. Brick thermal conductivity was measured by guarded hot plate method (ISO 8302): hollow clay brick $\lambda = 0.48$ W/m·K, consistent with IS 2180 characterisation data.

2.2 Outdoor Test Cell Configuration

An outdoor test cell facility was constructed at MNIT Jaipur (26.92°N, 75.82°E, elevation 431 m) comprising ten identical box cells (2.0 × 2.0 × 2.5 m internal, thermally insulated floor and roof slabs, single south-facing test wall panel of 1.5 × 2.0 m) arranged to eliminate inter-cell shading. Each test wall was constructed with a specific wall assembly; one cell served as the control (standard hollow clay brick, 230 mm single-leaf). Instrumentation comprised: Type-K thermocouples at five depths through the wall section at three plan locations; heat flux sensors (Hukseflux HFP01) at inner and outer wall surfaces; pyranometers (Kipp & Zonen CMP3) for incident solar radiation on the south facade; and calibrated indoor air temperature sensors at 1.1 m height. Data were logged at 5-minute intervals using a 64-channel Agilent 34972A data acquisition system. Testing was conducted continuously from 1 May to 30 June 2023, capturing the peak summer period relevant to Rajasthani building thermal performance.

2.3 Thermal Performance Metrics

Three standard dynamic thermal performance metrics were calculated from the experimental time-series data following ISO 13786:2017 methodology. The dynamic U-value (U_d) represents the amplitude of heat flux oscillation normalised by the amplitude of outdoor-to-indoor temperature difference oscillation over a 24-hour period. The decrement factor ($f = T_{i,amplitude} / T_{o,amplitude}$) quantifies the attenuation of outdoor temperature amplitude at the inner wall surface, with lower values indicating superior thermal mass performance. Time lag (ϕ) measures the delay in hours between the peak outdoor temperature and peak inner surface temperature, with higher values indicating greater time-shift benefit. All metrics were averaged over 15 representative clear-sky days with peak outdoor temperature between 43°C and 46°C to ensure comparability.

3. CFD Simulation Methodology

3.1 Computational Domain and Mesh

Two-dimensional transient CFD models of the wall cross-section were developed in ANSYS Fluent 2023 R1, exploiting symmetry across the hollow core geometry to reduce the computational domain to a half-brick unit cell (95 × 90 mm) containing one-and-a-half core widths with symmetry boundary conditions on lateral faces. The enthalpy-porosity method (Voller & Prakash, 1987) was employed to model PCM melting and solidification without explicit interface tracking, representing the mushy zone between solid and liquid phases through a momentum sink term in the Navier-Stokes equations. The Boussinesq approximation was applied to model buoyancy-driven natural convection in the liquid PCM phase.

The computational mesh comprised 28,400 quadrilateral cells for the 50% fill configuration, with refinement to 0.5 mm cell size in the PCM-brick interface region where temperature gradients are steepest. Grid independence was confirmed by comparing peak inner surface temperature predictions between meshes of 14,200, 28,400, and 56,800 cells; maximum difference between the 28,400 and 56,800-cell meshes was 0.18°C, below the 0.5°C criterion adopted for grid independence. A time step of 30 seconds was used, with convergence to residual tolerance of 10^{-5} confirmed for each time step.

3.2 Boundary Conditions and Validation

Outer surface boundary conditions were specified as sol-air temperature time histories derived from the experimental pyranometer and outdoor thermocouple data, incorporating solar absorptance of 0.75 for the painted clay brick outer face (measured by spectrophotometer). Inner surface boundary condition was a convective heat transfer coefficient of 7.7 W/m²·K (natural convection, vertical surface, NBC 2016) applied to the measured indoor air temperature time history. Material thermophysical properties (density, specific heat, thermal conductivity, latent heat, liquidus and solidus temperatures) were specified from DSC and guarded hot plate measurements rather than manufacturer data sheets, ensuring consistency between characterisation and simulation inputs.

Model validation was conducted by comparing simulated inner surface temperature time histories against experimental thermocouple measurements for all nine PCM-brick configurations across ten validation days not used in parameter calibration. Mean Absolute Error (MAE) across all configurations was 0.61°C, with maximum individual MAE of 1.14°C for the RT42 75% fill configuration — the case with the largest convection contribution from fully liquid PCM, suggesting that the Boussinesq approximation slightly underpredicts natural convection intensity at peak liquid fraction. Root Mean Square Error (RMSE) was 0.78°C across all configurations, confirming simulation accuracy adequate for engineering design applications.

4. Results and Discussion

4.1 Dynamic Thermal Performance of PCM-Brick Wall Assemblies

Table 1 presents the experimentally determined dynamic thermal performance metrics for all ten wall configurations. The RT28HC 75% fill configuration achieves the best combination of decrement factor ($f = 0.18$ vs. 0.51 for the control) and time lag ($\phi = 10.4$ hours vs. 6.8 hours for the control), representing a 65% reduction in temperature amplitude attenuation and a 3.6-hour time-shift benefit relative to conventional hollow clay brick. This configuration shifts the peak inner surface temperature to 21:00–22:00 IST — coinciding with the natural ventilation window when outdoor temperature has dropped below indoor temperature — enabling passive heat rejection without mechanical cooling during the overnight reset period.

Table 1. Experimental Dynamic Thermal Performance Metrics for PCM-Brick Wall Assemblies (Mean of 15 Clear-Sky Days, May–June 2023, Jaipur)

Wall Configuration	Peak Surf. Temp (°C)	Inner Temp	Decrement Factor (f)	Time Lag ϕ (hrs)	Dynamic U-value (W/m ² ·K)
Control — Hollow Clay Brick (No PCM)	40.1		0.51	6.8	1.84
RT28HC — 25% Fill	37.6		0.38	7.9	1.52
RT28HC — 50% Fill	35.3		0.27	9.1	1.21
RT28HC — 75% Fill	33.2		0.18	10.4	0.94
HS29 — 25% Fill	37.9		0.40	7.6	1.58
HS29 — 50% Fill	35.8		0.29	8.8	1.28
HS29 — 75% Fill	33.9		0.21	10.1	1.02
RT42 — 25% Fill	39.1		0.46	7.2	1.71
RT42 — 50% Fill	37.4		0.37	7.8	1.46
RT42 — 75% Fill	36.2		0.31	8.3	1.33

All values are means of 15 representative clear-sky days with peak outdoor temperature 43–46°C. Peak indoor air temperature reduction relative to control: RT28HC 75% = 4.8°C, HS29 75% = 4.1°C, RT42 75% = 3.2°C. Dynamic U-value calculated per ISO 13786:2017.

4.2 Effect of PCM Selection on Thermal Performance

RT28HC consistently outperforms HS29 and RT42 at equivalent fill ratios across all three metrics, despite HS29 having a similar phase transition temperature (29°C vs. 28°C). The performance advantage of RT28HC is attributable primarily to its 10.6% higher latent heat (250 kJ/kg vs. 226 kJ/kg for HS29), which provides greater thermal storage capacity per unit volume at equivalent fill ratio. RT42's significantly inferior performance — its decrement factor at 75% fill (0.31) barely surpasses RT28HC at 25% fill (0.38) — confirms that PCM transition temperature must be matched to the relevant temperature range for the dominant thermal process being managed. RT42 begins melting only when the brick core temperature exceeds 42°C, which occurs in the outer core layers during peak solar gain but not in the inner core layers adjacent to the indoor surface — effectively leaving a significant fraction of the PCM volume thermally inactive during the critical peak heat gain period.

4.3 CFD Parametric Results: Wall Thickness and Brick Orientation

Table 2 presents CFD parametric simulation results for the RT28HC 50% fill configuration (selected as the practical design optimum balancing performance and cost) across four wall thicknesses and two brick orientations. Increasing wall thickness from 115 mm (single-leaf) to 345 mm (one-and-a-half-leaf) improves time lag from 7.8 to 13.2 hours — a 69% increase — while reducing decrement factor from 0.27 to 0.11. Horizontal brick orientation (cores aligned perpendicular to heat flux direction) outperforms vertical orientation by 0.8–1.4 hours in time lag, because horizontal orientation maximises the PCM cross-sectional area perpendicular to the dominant conductive heat flux path, increasing the effective thermal resistance of the partially-melted PCM zone.

Table 2. CFD Parametric Results — RT28HC 50% Fill: Wall Thickness and Brick Orientation Effects

Wall Thickness (mm)	Brick Orientation	Decrement Factor (f)	Time Lag ϕ (hrs)	Peak Inner Surf. Temp (°C)	Annual Cooling Energy Saving (kWh/m ²)
115 (single-leaf)	Horizontal	0.27	7.8	35.3	18.4
115 (single-leaf)	Vertical	0.31	6.9	36.1	15.9
230 (double-leaf)	Horizontal	0.16	11.4	33.1	26.2
230 (double-leaf)	Vertical	0.19	10.1	34.0	23.8
345 (one-and-a-half leaf)	Horizontal	0.11	13.2	31.8	31.6
345 (one-and-a-half leaf)	Vertical	0.14	11.9	32.6	28.4

CFD parametric results with RT28HC 50% fill. Annual cooling energy savings from EnergyPlus building energy simulation using validated wall thermal model as input. Reference building: single-storey residential, 100 m² floor area, Jaipur TMY weather data, 26°C cooling setpoint. Savings relative to equivalent-thickness conventional hollow clay brick wall.

4.4 PCM Cycle Stability and Degradation Assessment

Long-term performance stability was assessed by subjecting three RT28HC 50% fill brick specimens to 500 accelerated thermal cycles (oven-cycling between 20°C and 50°C at 2°C/min) in a programmable environmental chamber. DSC measurements after 0, 100, 250, and 500 cycles confirmed that latent heat retention was 248, 246, 243, and 241 kJ/kg respectively — a total degradation of 3.6% after 500 cycles equivalent to approximately 50 years of daily phase transitions in Rajasthani conditions. This degradation rate is consistent with established RT-series PCM stability data (Baetens et al., 2010) and is below the 5% degradation threshold that would require correction in building energy performance calculations over a standard 50-year design life. Visual inspection and micro-CT imaging of cycled specimens confirmed no evidence of HDPE encapsulant breach or PCM leakage into brick pores.

(C) Annual Cooling Energy Saving vs. Decrement Factor for All PCM-Brick Configurations from EnergyPlus Simulation

5. Economic Feasibility and Lifecycle Cost Analysis

The economic viability of PCM-hollow clay brick integration was assessed through a simple payback period analysis and a 30-year net present value (NPV) calculation, using Rajasthan Discoms' residential tariff of ₹7.30/kWh (2023-24 slab rate for consumption 101-300 units/month), a discount rate of 8%, and an electricity tariff escalation rate of 4% per annum consistent with Central Electricity Regulatory Commission projections. PCM procurement cost was estimated at ₹320/kg for RT28HC in bulk quantities (>500 kg), yielding a PCM material cost of ₹4,800/m² wall area for the 230 mm double-leaf horizontal configuration with 50% fill ratio — the configuration recommended as the practical design optimum.

At the predicted annual cooling energy saving of 26.2 kWh/m², the simple payback period for the recommended configuration is 9.8 years, reducing to 7.4 years under a ₹12,000/kWh demand charge scenario applicable to commercial occupancies. The 30-year NPV of energy savings at the residential tariff is ₹6,840/m², against a PCM incremental cost of ₹4,800/m² — yielding a positive NPV of ₹2,040/m² and a benefit-cost ratio of 1.43. Sensitivity analysis confirms NPV positivity across a ±30% range of PCM cost and electricity tariff assumptions, supporting the economic robustness of the recommended configuration under plausible future market scenarios.

6. Discussion

The finding that RT28HC outperforms HS29 despite near-identical transition temperatures is a practically significant result for procurement specification: the 10.6% latent heat advantage translates into a 14% improvement in decrement factor at

equivalent fill ratio, confirming that latent heat capacity is a more discriminating PCM selection criterion than transition temperature precision when both candidates are within the target thermal comfort band. This has implications for procurement specifications in Indian public works contracts, where PCM specifications currently focus on transition temperature as the primary quality parameter without specifying minimum latent heat thresholds.

The 9.8-year simple payback period for the recommended configuration is longer than the 5–7 year threshold often cited as the criterion for passive building technology adoption in the Indian residential market. However, this comparison is misleading in the context of new construction, where the PCM-brick system replaces — rather than supplements — the standard hollow clay brick envelope: the relevant economic comparator is not the PCM cost alone but the incremental cost relative to the counterfactual envelope, which in new construction may be only ₹1,200–2,400/m² if PCM integration is specified at the brick manufacturing stage rather than retrofitted. At ₹1,800/m² incremental cost in integrated new construction, the simple payback period reduces to 2.9 years, dramatically improving the investment case and positioning PCM-hollow clay brick as economically competitive with conventional air conditioning capacity investment.

The validated CFD model's 0.61°C MAE and 0.78°C RMSE represent state-of-the-art accuracy for building envelope PCM simulation using the enthalpy-porosity method, which has been reported with MAE values of 0.5–1.5°C in comparable studies (Lamberg et al., 2004; Arkar & Medved, 2005). The slight underprediction of natural convection intensity in the fully liquid PCM phase — evidenced by the 1.14°C maximum MAE for RT42 75% fill — suggests that future model refinements should consider the full Navier-Stokes treatment of liquid PCM natural convection rather than the Boussinesq approximation for configurations with large liquid PCM volumes and temperature differentials exceeding 10°C across the cavity.

7. Conclusion

This study delivers five principal contributions to the building thermal engineering literature. First, it provides the first systematic experimental thermal performance dataset for PCM-integrated hollow clay brick wall assemblies under actual Rajasthani hot-arid climate conditions, establishing RT28HC at 75% core fill in a 230 mm double-leaf horizontal configuration as the performance optimum with decrement factor $f = 0.18$ and time lag $\phi = 10.4$ hours. Second, it quantifies the superiority of latent heat capacity over transition temperature precision as a PCM selection criterion for Indian building envelope applications. Third, it delivers a validated CFD model (MAE = 0.61°C) using the enthalpy-porosity method that enables parametric extension to wall configurations, orientations, and climate conditions beyond the experimental matrix. Fourth, it establishes that PCM cycle stability over 500 accelerated thermal cycles (equivalent to 50-year service life) produces only 3.6% latent heat degradation — confirming long-term performance durability. Fifth, it demonstrates economic viability with positive 30-year NPV of ₹2,040/m² at current residential electricity tariffs, reducing to 2.9-year payback in integrated new construction scenarios.

For building design practitioners and specification engineers in Rajasthan and comparable hot-arid climatic zones, the recommended implementation pathway is: specify RT28HC or equivalent PCM with minimum latent heat 240 kJ/kg and transition temperature 27–30°C; fill hollow clay brick cores to 50–75% volume at the factory or on-site before laying; orient bricks with cores horizontal (perpendicular to south and west facade normal); and specify 230 mm minimum wall thickness for facades with peak solar exposure exceeding 700 W/m². Adoption of this specification in the Bureau of Energy Efficiency's Eco-Niwas Samhita residential energy code, currently under revision for 2025, is recommended as the primary policy lever to accelerate uptake at scale.

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