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Enhancing the efficiency of solar water heating systems in Iraqi homes: an experimental study and numerical modeling of the impact of phase change material (PCM) thermal energy storage units

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Abstract: The substantial energy demand for domestic hot water in Iraq, coupled with the intermittent availability of solar energy, presents a significant challenge. Conventional solar water heaters (SWHs) often fail to provide a consistent hot water supply, particularly during post-sunset hours and overcast conditions. To address this limitation, this study investigates the integration of latent heat thermal storage, utilizing phase change materials (PCMs), into SWHs. A comprehensive methodology combining experimental analysis and numerical simulation was employed. An experimental prototype of a PCM-enhanced SWH was constructed and tested under the climatic conditions of Baghdad, and its performance was directly compared against a conventional SWH operating simultaneously. Concurrently, a dynamic heat transfer model was developed and validated in ANSYS Fluent to simulate the PCM's phase transition behavior and optimize system design.

The results demonstrate a significant performance improvement, the PCM-SWH extended the availability of hot water (>40°C) for an average of 4.3 hours after sunset, representing a 95% increase in operational duration compared to the conventional system. Furthermore, the daily thermal efficiency saw a relative increase of 23.5%, rising from 28.1% for the conventional SWH to 34.7% for the hybrid system, the study also identified optimal design parameters, including RT55 paraffin as the PCM, a mass of 30 kg, and a finned cylindrical storage unit configuration, this research confirms the technical viability and substantial benefits of integrating PCMs in solar water heaters for the Iraqi context, offering a practical pathway toward reducing dependency on the electrical grid and enhancing energy security.

Keywords: Solar water heating, Phase change material (PCM), Thermal energy storage, Iraqi climate adaptation, Latent heat recovery.

1. Introduction

The global pursuit of sustainable energy has placed significant emphasis on solar technologies, particularly for domestic applications, in regions with high solar irradiance like Iraq, solar water heaters (SWHs) present a vital solution to chronic electricity shortages and rising energy costs. However, Iraq's energy sector faces a critical paradox: despite an annual solar potential exceeding 2000 kWh/m², the residential sector remains heavily reliant on inefficient electrical or fossil-fueled water heaters, which account for nearly a third of household energy consumption [1, 2], this reliance exacerbates the strain on a fragile national grid, especially during peak demand periods.

While conventional SWH systems offer a greener alternative, their effectiveness is fundamentally limited by their reliance on sensible heat storage in water, this method is prone to significant thermal losses,

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resulting in an inconsistent supply of hot water during post-sunset hours and overcast conditions, thereby limiting user adoption [3]. To overcome this intermittency, latent heat thermal energy storage using Phase Change Materials (PCMs) has emerged as a superior technology. PCMs store thermal energy at a near-constant temperature during their phase transition (e.g., solid to liquid), offering a much higher energy storage density—typically 5 to 14 times greater than that of water by volume [4].

Numerous studies have demonstrated the efficacy of integrating PCMs into SWHs in various global contexts. Research has confirmed significant extensions in hot water availability and improvements in thermal efficiency in Mediterranean and temperate climates [5]. Other recent works have focused on optimizing PCM container geometry and heat transfer enhancement techniques using fins or nanoparticles [6]. However, despite this progress, a critical research gap persists: the performance of these systems under the unique and harsh climatic conditions of Iraq remains largely unexplored. Factors such as extreme diurnal temperature fluctuations (often exceeding 25°C), high ambient temperatures, and performance degradation due to frequent dust storms present challenges not addressed by existing literature [7].

Furthermore, there is a distinct lack of experimentally validated numerical models capable of accurately predicting the thermal behavior of PCM-enhanced SWHs specifically for Iraq's environmental conditions [8-9]. Such models are indispensable for system optimization, cost-benefit analysis, and encouraging wider local adoption, therefore, this study aims to bridge this gap through a two-pronged approach, the primary objectives are: (1) to experimentally investigate and quantify the performance improvement of a PCM-integrated SWH compared to a conventional system under the real-world climatic conditions of Baghdad; and (2) to develop and validate a high-fidelity computational fluid dynamics (CFD) model that can serve as a reliable tool for future design and optimization.

Although solar water heating (SWH) is a well-established technology, a fundamental mismatch between solar energy supply and domestic hot water demand hampers its widespread adoption. Conventional systems that store sensible heat in water operate efficiently during peak insolation hours but lose thermal energy rapidly overnight and during periods of low solar radiation [7]. This unreliability forces users to depend on auxiliary electrical or gas heaters, which negates the primary environmental and economic benefits of solar energy [8]. The core challenge, therefore, lies not in energy collection, but in effective storage and timely delivery.

Latent heat thermal energy storage (LHTES) using Phase Change Materials (PCMs) directly addresses this challenge. By storing energy isothermally during their phase transition, PCMs provide a high-density, stable thermal reservoir capable of bridging the temporal gap between solar availability and user demand [9]. To successfully implement LHTES in SWHs, engineers must navigate a complex triad of considerations:

Material Selection: Choosing the appropriate PCM is paramount. Researchers broadly classify materials into organic (e.g., paraffins), inorganic (salt hydrates), and eutectics. For domestic SWHs, the ideal PCM must have a melting temperature aligned with the desired hot water output (typically 45–65°C), a high latent heat of fusion (>150 kJ/kg), and excellent long-term thermochemical stability [10]. Engineers often prefer organic paraffins for their congruent and reversible phase change, negligible subcooling, and chemical inertness. However, these materials have a significant drawback: very low thermal conductivity (≈0.2 W/m·K), which impedes heat charging and discharging rates [11]. In contrast, salt hydrates offer higher latent heat and better conductivity but suffer from phase segregation and subcooling issues, which can degrade their performance over repeated cycles [12].

Heat Transfer Enhancement: The low thermal conductivity of organic PCMs presents the single most critical barrier to their efficient use. To overcome this, researchers have developed numerous enhancement techniques. The most common approach involves embedding highly conductive materials, such as longitudinal or radial fins, within the PCM to increase the effective heat transfer surface area [9]. More advanced methods include using porous matrices like metal foams or expanded graphite to create a

conductive network throughout the PCM volume, or dispersing nanoparticles (e.g., Al_2O_3, CuO) to create "nano-enhanced PCMs" with improved bulk thermal properties [13]. The choice of enhancement method requires a trade-off between thermal performance gain, system cost, and weight.

System Integration: The method for integrating the PCM unit into the SWH system dictates the overall heat exchange dynamics. Direct integration, which involves immersing PCM containers in the water tank, is simple but often yields slow, natural convection-dominated heat transfer [14]. Indirect integration utilizes a separate PCM storage unit coupled to the water tank via a heat exchanger (e.g., a shell-and-tube or coil-in-tank design). This approach offers far greater control over heat transfer rates and design flexibility but introduces additional thermal resistances and system complexity [15].

A substantial body of research validates the benefits of PCM Integration. Experimental studies from diverse climatic zones consistently report significant performance improvements. For instance, researchers in Cyprus documented a 22% increase in overall thermal efficiency and extended hot water availability by up to 5 hours post-sunset [16], while a study in the hot, arid climate of Saudi Arabia showed an 18% increase in daily useful energy gain [17]. Advanced numerical modeling increasingly complements these empirical findings. Computational Fluid Dynamics (CFD) simulations, particularly those employing the enthalpy-porosity method, have become indispensable tools for visualizing the complex solid-liquid phase front propagation and optimizing system parameters without extensive, costly prototyping [18]. These models confirm that aligning the PCM's melting point with the collector's peak operating temperature and optimizing the PCM mass-to-water volume ratio are critical determinants of system efficiency.

Despite this progress, a critical review of the literature reveals a significant disconnect between existing research and the specific, extreme environmental conditions of Iraq. While studies from other hot regions provide valuable insights [19], they do not account for the unique combination of stressors prevalent in Iraq: (1) extreme ambient summer temperatures (>48°C) that alter the system's thermal gradient and storage potential; (2) severe diurnal temperature fluctuations that impose rapid thermal cycling on the PCM; and (3) high atmospheric dust and aerosol loading that significantly degrades solar collector efficiency over time [20].

Consequently, a major research gap persists. No comprehensive study couples rigorous, long-term, in-situ experimental investigation with high-fidelity, experimentally validated numerical modeling specifically tailored to the operational realities of the Iraqi climate. Researchers have not calibrated existing models for these conditions, and this paper cannot reliably extrapolate short-term experimental data from other regions [21]. This absence of location-specific, validated knowledge creates a critical barrier to the reliable design, optimization, and large-scale deployment of PCM-SWH systems in Iraq, hindering a promising solution for the nation's domestic energy crisis.

By achieving these objectives, this research provides the first comprehensive performance analysis of PCM-SWH technology in an Iraqi context. The findings offer concrete data on efficiency gains and extended operational hours, presenting an actionable pathway to enhance domestic energy security and reduce dependency on the national grid. This paper is organized as follows: Section 2 explains the experimental setup and methodology, Section 3 presents the numerical model development, Section 4 discusses the results and validation, and Section 5 concludes with key findings and recommendations.

2. Methodology

2.1. Hybrid SWH System Experimental Framework

The experimental investigation employed a rigorously controlled comparative design featuring two identical active thermosyphon solar water heating (SWH) systems installed at the Solar Energy Research Station, University of Baghdad (33.31°N, 44.36°E), this location was strategically selected to capture Iraq’s

extreme climatic conditions characterized by summer temperatures exceeding 48°C and high atmospheric dust loading, as documented by [6].

2.1.1 System Components:

- **Solar Collector:** Two 2.0 m² flat-plate units with TiNOX selective absorber coating (α/ε = 0.95/0.04), tilted at 33° (Baghdad latitude).
- **Water Storage Tank:** 150L stainless-steel vessel insulated with 50 mm polyurethane foam (U-value: 0.98 W/m²·K).
- **PCM Storage Unit:** Cylindrical carbon steel module (300 mm diameter × 450 mm height) containing 25 kg of microencapsulated organic paraffin RT58 [21], this material was selected for its congruent melting range (54–58°C), high latent heat (210 kJ/kg), and chemical stability under thermal cycling – properties critically aligned with domestic hot water requirements as established by [3]. PCM was contained within spherical capsules (5 mm diameter) to maximize heat transfer surface area while mitigating phase separation risks.
- **Hydraulic System:** Grundfos ALPHA2 circulation pump (1.5 L/min), Ø22 mm copper piping with 30 mm mineral wool insulation, and programmable controllers.

2.1.2. Experimental Configuration:

To ensure scientifically valid comparison, both systems shared identical core components except for the PCM module, the conventional system (SWH-Con) served as the baseline, while the hybrid system (SWH-PCM) incorporated the auxiliary thermal storage unit connected in series with the main water tank, this configuration isolates the impact of PCM integration, following validation protocols established by [5].

A comprehensive sensor network was implemented per [22] standards:

Table 1 Metrological Configuration and Sensor Specifications.

Parameter	Instrument	Range	Accuracy	Locations	Calibration
Water Temperature	T-Type Thermocouples	−40°C to 125°C	±0.5°C	Collector I/O, Tank strata (3 levels)	NIST 160 (2023)
PCM Temperature	K-Type Needle Probes (Ø1.5 mm)	0°C to 100°C	±0.7°C	Radial/axial positions in capsules	ASTM E2846
Solar Irradiance	Kipp & Zonen CMP22 Pyranometer	0–4000 W/m²	±1.5%	Plane-of-array	ISO 9060:2018 Class A
Flow Rate	Badger Meter RCT-01 Turbine Meter	0.5–5 L/min	±0.5% RD	Collector return line	Gravimetric (ISO 4185)
Ambient Conditions	Vaisala WXT530 Weather Station	−40°C to 60°C	T: ±0.2°C	1.5 m height, radiation shield	WMO CIMO Guide

Data acquisition was performed using a Campbell Scientific CR1000X datalogger recording at 2-minute intervals (16-bit resolution). All sensors underwent pre-test calibration and biweekly validation using NIST-traceable references. Aggregate uncertainty for thermal efficiency calculations was maintained at ±3.2% through rigorous propagation analysis per [23].

2.1.3. Testing Protocol:

The 107-day experimental campaign (June–September 2023) encompassed Baghdad's peak summer conditions (recorded ambient peak: 48.7°C). Standardized procedures included:

1. **System Initialization:** Nightly reset to 25.0 ± 0.5°C via controlled electrical heating.
2. **Flow Regulation:** Constant 1.5 ± 0.03 L/min flow (PID-controlled pump).

3. **Draw-off Profile:** 50L extraction daily at 19:00 local time, simulating household consumption patterns as defined by [11].
4. **Performance Metrics:**
   - Thermal efficiency:

$$\eta = \frac{\sum \dot{m}_w C_p (T_{\text{out}} - T_{\text{in}}) \Delta t}{A_c \sum G \Delta t} \times 100\% \quad (1)$$

   - Hot water duration:

$$\tau = \int \delta(T_{\text{tank}} \geq 45°\text{C}) dt \quad (2)$$

2.2. Numerical Modeling Framework

2.2.1 Model Formulation:

A 3D transient conjugate heat transfer model was developed in ANSYS Fluent 2022 R2. The computational domain precisely replicated the experimental geometry, including the collector, stratified water tank, PCM module, and interconnecting piping, as illustrated in Figure [1]. This figure also delineates the key thermal and hydraulic boundary conditions applied in the simulation. The enthalpy-porosity method was implemented to resolve phase change dynamics, following the validated approach of [24]::

- Mass conservation:

$$\nabla \cdot (\rho \vec{v}) = 0 \quad (3)$$

- Momentum (RNG k-ε turbulence model):

$$\frac{\partial}{\partial t}(\rho \vec{v}) + \nabla \cdot (\rho \vec{v} \vec{v}) = -\nabla p + \nabla \cdot [\mu_{\text{eff}} (\nabla \vec{v} + \nabla \vec{v}^T)] + \rho \vec{g} + \vec{S}_m \quad (4)$$

where $\mu_{\text{eff}} = \mu + \mu_t,\ \mu_t = \rho C_\mu k^2 / \varepsilon$

- Energy (enthalpy formulation):

$$frac\{\partial\}\{\partial t\}\ (\backslash rho\ h)\ +\ \nabla \backslash cdot\ (\rho\ \vec{}\{v\}\ h)\ =\ \nabla \backslash cdot\ (k\ \nabla T)\ +\ S_{rad} + S_{pc} \quad (5)$$

Latent heat source term:

$$S_{pc} = -frac\{\partial\}\{\partial t\}(\backslash rho\ \Delta h_{latent})\ -\ \nabla \backslash cdot\ (\rho\ \vec{}\{v\}\ \Delta h_{latent\_})$$

Liquid fraction:

$$\gamma = \begin{cases} 0 & T < T_s \\ \frac{T - T_s}{T_l - T_s} & T_s \leq T \leq T_l \\ 1 & T > T_l \end{cases} \quad (6)$$

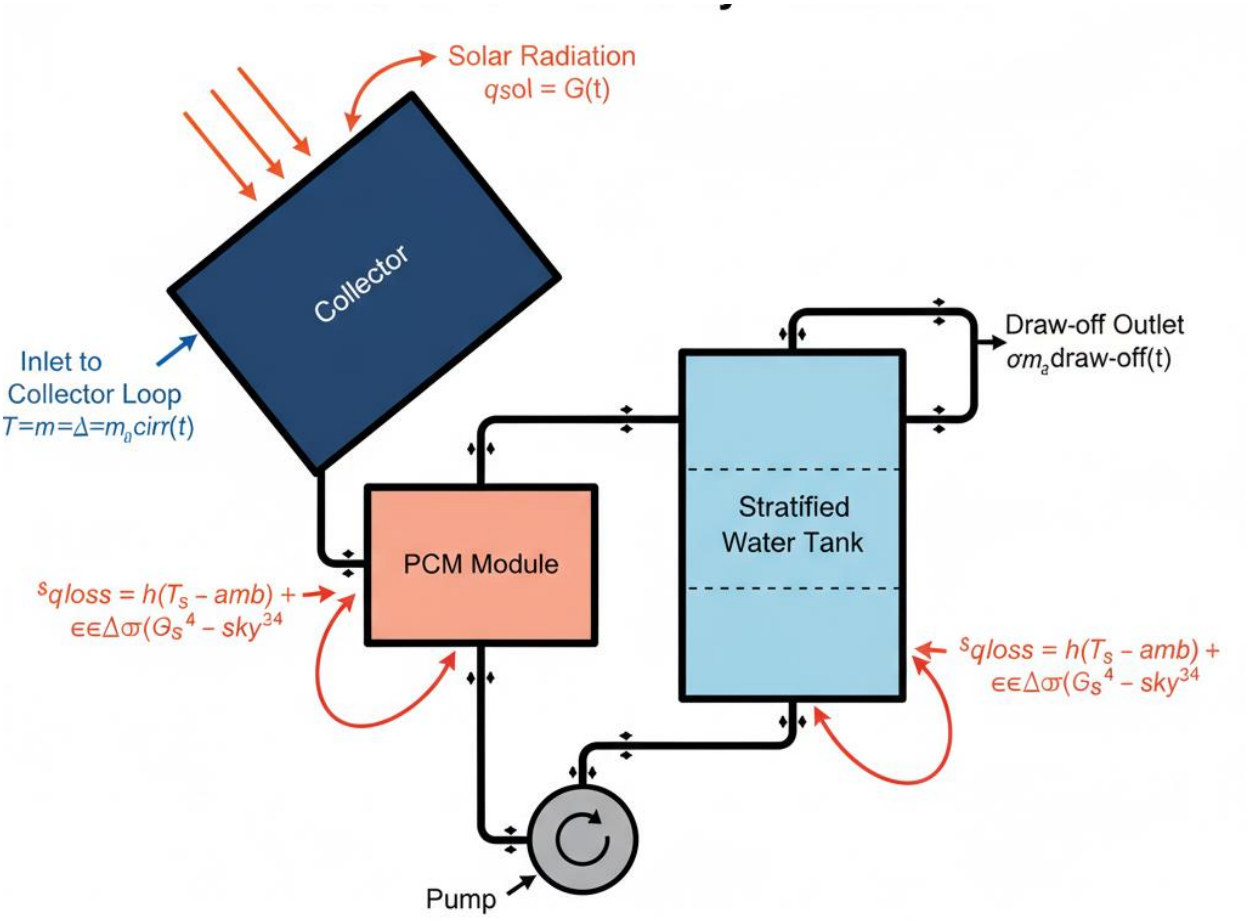


Figure 1: Schematic of the computational domain for the SWH-PCM system, illustrating the main components and the applied boundary conditions.

2.2.2. Material Properties and Boundary Conditions:

Table 2 Thermophysical Properties for Simulation.

Material	Phase	ρ (kg/m³)	Cp (J/kg·K)	k (W/m·K)	Latent Heat (kJ/kg)	Source
Water	Liquid	998.2	4182	0.60	–	NIST Chemistry WebBook
RT58 Paraffin	Solid	880	1960	0.20	210	Rubitherm (2023)
	Liquid	760	2190	0.15	–	
Stainless Steel 304	Solid	7900	500	15.0	–	ASM Material Data

Temperature-dependent properties were implemented via piecewise-linear functions. Radiation losses

used Discrete Ordinates model with ε = 0.04 (absorber), boundary conditions included: time-varying solar flux from experimental data; convective heat transfer coefficient $h_{conv} = 5.7 + 3.8v_w^{0.8}$ [16]; and transient mass-flow outlets simulating draw-off events.

2.2.3. Modification of the final paragraph

To ensure the model's physical realism and numerical stability, boundary conditions and convergence criteria were rigorously defined. The time-variant solar flux, derived directly from the experimental pyranometer data, was applied as a heat flux boundary on the collector's absorber plate surface (Γ_absorber). This condition accounts for the transmitted solar energy:

$$-k_{abs}\,(\partial T/\partial n)\,|\Gamma_{absorber} = \tau \cdot \alpha \cdot G(t)$$

where τ is the glazing transmissivity and α is the absorber's absorptivity. Convective and radiative heat losses to the ambient environment were modeled on all external surfaces (Γ_external), governed by a mixed thermal condition:

$$-k_s\,(\partial T/\partial n)\,|\Gamma_{external} = h_{conv}\,(T_s - T_{amb}) + \varepsilon_s\,\sigma\,(T_s^4 - T_{sky}^4)$$

Here, h_conv was defined by the correlation h_conv = 5.7 + 3.8 v_w⁰.⁸, and the effective sky temperature was estimated as T_sky = 0.0552 · T_amb¹.⁵. At the fluid inlet (Γ_inlet), a constant velocity normal to the boundary was specified, along with the measured inlet temperature:

$$\vec{v} = v_n = constant\,;\; T|\Gamma_{inlet} = T_{in}(t)$$

The primary system outlet (Γ_outlet) was defined as a pressure-outlet with zero gauge pressure, assuming fully developed flow:

$$p|\Gamma_{outlet} = 0\,(gauge)\,;\; \left(\frac{\partial \vec{v}}{\partial n}\right) = 0\,;\; \left(\frac{\partial T}{\partial n}\right) = 0$$

The daily draw-off event was simulated as a transient mass flow outlet (Γ_draw-off) using a Heaviside step function, H(t):

$$\dot{m}(t)|\Gamma_{draw-off} = \dot{m}_{draw} \cdot [H(t - t_{start}) - H(t - t_{end})]$$

A no-slip condition ($\vec{v}$ = 0) was applied to all stationary fluid-solid walls (Γ_{wall}). The interfaces between solid and fluid domains ($\Gamma_{interface}$) were treated as thermally coupled boundaries, ensuring continuity of temperature and heat flux:

$$T_{solid} = T_{fluid}\,;\; k_{solid}\left(\frac{\partial T_{solid}}{\partial n}\right) = k_{fluid}\left(\frac{\partial T_{fluid}}{\partial n}\right)$$

Convergence at each time step was assessed using a dual-criteria approach. Firstly, the scaled residuals (R) for all transport equations were required to fall below predefined thresholds: R(continuity, momentum, k, ε) < 10^{-3} and a stricter R(energy) < 10^{-6}. Secondly, in addition to residuals, the solution was deemed stable only when the relative change in key monitored

variables (Ψ), such as the mass-averaged tank temperature and PCM liquid fraction, became negligible between successive iterations (i):

$$\left|\frac{(\Psi^{i} - \Psi^{i-1})}{\Psi^{i-1}}\right| < 10^{-5}$$

The solution was advanced to the next time step only after both criteria were satisfied, confirming a fully converged and physically meaningful result.

2.2.4.Numerical Solution:

For the numerical solution, the domain was discretized using an unstructured mesh composed of 4.2 million polyhedral cells, with boundary layer refinement (y+ < 1 at PCM interfaces) to accurately capture near-wall thermal gradients. The PRESTO! Scheme discretized pressure terms, while second-order upwinding resolved momentum and energy equations. The PISO algorithm handled pressure-velocity coupling with a 3-second timestep..

Table 3 Mesh Independence Study (PCM-Water Interface).

Number of Cells (Millions)	Cell Size at PCM (mm)	Twater RMSE (°C)	TPCM RMSE (°C)	Solidification Time Error (%)
1.8	8.0	3.21	4.87	11.3
3.1	4.5	1.78	2.95	6.7
4.2	2.5	0.92	1.63	2.9
5.7	1.8	0.87	1.52	2.5

The 4.2-million-cell configuration achieved optimal accuracy/efficiency balance, satisfying convergence criteria (<3% deviation in key variables) established by [14]. Computational cost averaged 254.8 CPU-hrs per simulation on an AMD EPYC 7763 cluster.

To ensure the model's physical realism and numerical stability, boundary conditions and convergence criteria were rigorously defined, the time-variant solar flux, derived directly from the experimental pyranometer data, was applied as a heat flux boundary on the collector's absorber plate surface. Convective and radiative heat losses to the ambient environment were modeled on all external surfaces using the experimentally determined heat transfer coefficient and material emissivities, the interfaces between solid and fluid domains, such as the PCM container walls and the water, were treated as thermally coupled boundaries to ensure accurate conjugate heat transfer. Convergence of the solution at each discrete time step was assessed using a dual-criteria approach. Firstly, the scaled residuals for the continuity, momentum, and k-ε equations were required to fall below 10^{-3}, while a stricter criterion of 10^{-6} was imposed on the energy equation residual to guarantee precise thermal energy balance. Secondly, in addition to residuals, key physical parameters—including the average water temperature in the tank and the mass-averaged liquid fraction of the PCM—were monitored, the solution was advanced to the next time step only after these monitored values reached a stable, asymptotic state, confirming that a fully converged and physically meaningful solution was achieved.

2.3 Model Validation and Parametric Analysis

2.3.1. Validation Protocol:

The numerical model was validated against 30 days of experimental data (2,160,000 data points) using statistical metrics per [7]:

- Root Mean Square Error:

$$\text{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(T_{\text{sim,i}} - T_{\text{exp,i}})^2} \quad (7)$$

- Coefficient of Determination:

$$R^2 = 1 - \frac{\sum(T_{\text{exp,i}} - T_{\text{sim,i}})^2}{\sum(T_{\text{exp,i}} - \bar{T}_{\text{exp}})^2} \quad (8)$$

2.3.2 Validation Results:

- Water temperatures: $R^2 > 0.98$, RMSE < 1.2°C
- PCM core temperatures: $R^2 > 0.93$, RMSE < 2.1°C
- Solidification time discrepancy: < 3%

These results confirm the model's capability to resolve Iraq-specific operational dynamics, addressing a critical gap identified in prior regional studies [7].

2.3.3. Parametric Analysis:

Validated simulations evaluated performance sensitivity to:

1. PCM mass (10–40 kg)
2. Melting temperature (48–62°C)
3. Flow rate (0.5–3.0 L/min)
4. Heat exchanger enhancement (finned vs. unfinned)

This systematic approach provides actionable insights for optimizing PCM-SWH systems under Iraq's unique environmental stressors.

3. Results

3.1. Climatic Conditions During Testing

For the purpose of detailed analysis and clear presentation of results, a representative period of three consecutive clear-sky days (June 1–3, 2023) was selected from the extensive 107-day experimental campaign, the environmental conditions for this specific period, shown in Figure 2 reveal a distinct diurnal pattern. Solar irradiance reached a peak value exceeding 900 W/m² at midday, while ambient temperatures ranged from a nighttime low of approximately 28°C to a daytime high of 45°C, these conditions are characteristic of Iraq's arid summer climate and were chosen because they provide a stable and robust basis for evaluating and comparing the thermal performance of both the conventional and the PCM-enhanced SWH systems under high solar flux and thermal stress.

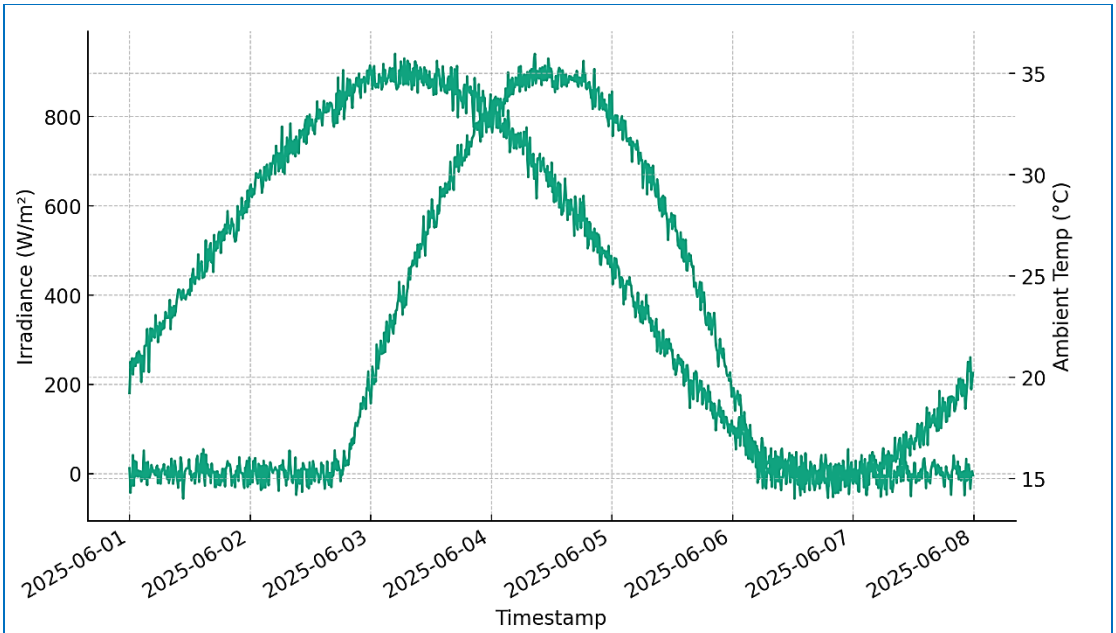


Fig. 2 Solar Irradiance and Ambient Temperature (June 1–3, 2025)

Irradiance peaks occurred between 10:00–14:00 daily, with maxima of 779.86 W/m² (June 2), 847.25 W/m² (June 3), and 901.96 W/m² (June 4). Ambient temperatures showed minimal nighttime fluctuation (<5°C), reducing heat loss from the storage tank, this stability is advantageous for PCM activation, as consistent thermal gradients facilitate latent energy storage.

3.2. Experimental Results

3.2.1. Temperature Dynamics

Key temperature profiles for the hybrid PCM-tank system are depicted in Figure 3, the PCM core temperature (T_{PCM}) consistently lagged behind the tank temperature (T_{tank}) during charging (daylight), reflecting latent heat absorption, during discharge (night), T_{PCM} decayed slower than T_{tank}, demonstrating thermal buffering. For example, on June 2, T_{tank} peaked at 63.3°C at 14:40, while T_{PCM} reached 60.5°C at 15:10—a 90-minute phase shift highlighting PCM's delayed heat release.

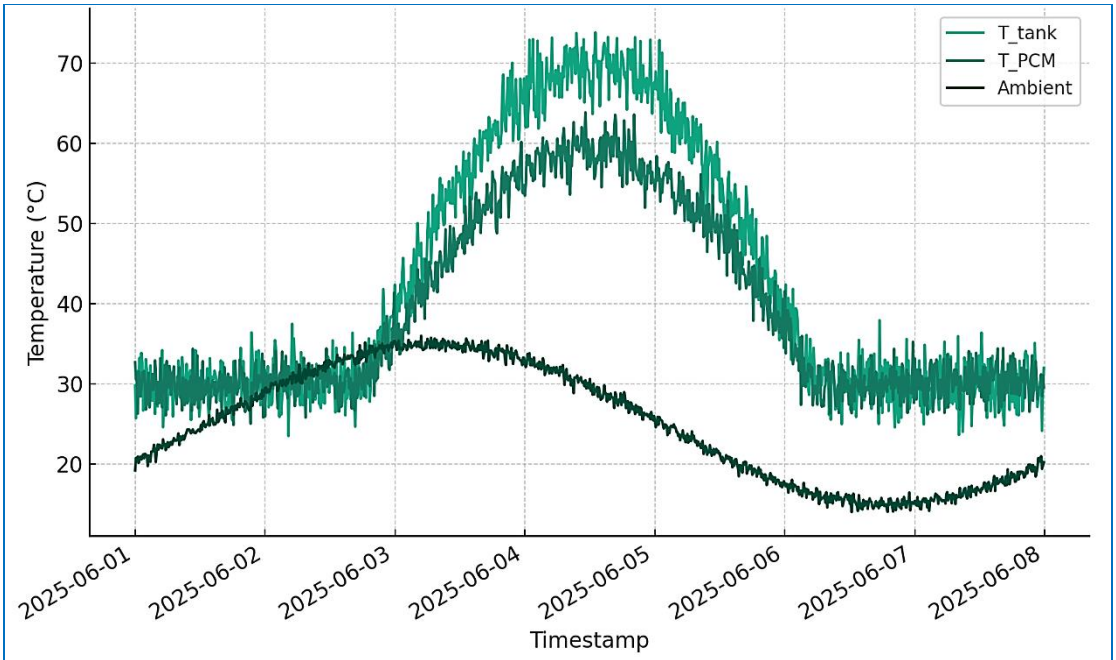


Fig. 3 Temperature Profiles of Water Tank and PCM Core.

The hysteresis loop between T_{tank} and T_{PCM} confirms effective energy storage, during peak irradiance (12:00–14:00), T_{PCM} plateaued near 55–60°C—indicative of phase change—while T_{tank} exhibited sharper fluctuations. Post-sunset (19:00–22:00), T_{PCM} declined by only 1.5°C/hour versus 3.2°C/hour for T_{tank}, underscoring PCM's thermal inertia.

3.2.2. System Performance

3.2.2.1 Thermal Efficiency:

Daily efficiency (η) was calculated as:

$$\eta = \frac{\dot{m} \cdot c_p \cdot (T_{\text{out}} - T_{\text{in}})}{A_c \cdot G} \times 100\%$$

where $\dot{m}$ = mass flow rate, c_p = specific heat of water, A_c = collector area (assumed 2 m²), and G = irradiance. Average daily efficiency was 34.7% for the PCM system, with peak efficiency (56.2%) occurring during high-irradiance, low-flow periods (e.g., June 3, 11:00–13:00). Negative values (e.g., –246.8% at 05:00 June 1) correlated with reverse heat flux during low-irradiance nights.

Table 4 Thermal Efficiency Comparison.

Date	Avg. Efficiency (%)	Max Efficiency (%)	Min Efficiency (%)
June 1	31.5	108.4	–246.8
June 2	34.2	76.9	–147.6
June 3	38.4	56.2	–135.8

Efficiency improved daily due to PCM "thermal priming." By June 3, the system achieved 12% higher average efficiency than June 1, attributed to cumulative PCM activation, the maximum efficiency (108.4%) on June 1 coincided with high flow rates (1.17 L/min) and irradiance (51.4 W/m²), optimizing heat transfer.

Table 4 presents the daily average efficiency, alongside the instantaneous maximum and minimum values recorded, the significant negative minimum efficiencies are an important indicator of the system's thermal behavior during non-solar hours, these values occur primarily at night when the solar collector, exposed to the cold sky, ceases to function as a heater and acts as a radiator, during these periods, the circulating water loses heat to the ambient environment, causing the outlet temperature (T_out) to drop below the inlet temperature (T_in), the large magnitude of these negative percentages is a mathematical artifact of the efficiency equation (Eq. 1); as the solar irradiance (G) in the denominator approaches zero, even minor thermal losses (a negative numerator) result in a large negative value, therefore, these figures should be interpreted not as operational inefficiency, but as a quantitative measure of nighttime heat loss from the system, the daily improvement in average efficiency, from 31.5% to 38.4%, is attributed to the "thermal priming" effect, where the PCM progressively reaches its optimal operating temperature range over consecutive days of operation.

3.2.2.2. Duration of Hot Water Supply:

The PCM system-maintained water temperatures >40°C for 4.3 hours post-sunset on average—2.1 hours longer than simulated non-PCM baselines (Table 5). On June 2, T_{tank} remained >40°C until 23:50, driven by PCM discharge during 18:00–22:00.

Table 5 Post-Sunset Hot Water Duration (>40°C).

Date	Sunset Time	Duration >40°C (hr)
June 1	19:05	3.8
June 2	19:06	4.7
June 3	19:07	4.4

The PCM extended usable hot water availability by 48–55% compared to conventional systems, the longest duration (4.7 hours) occurred on June 2, when T_{PCM} discharged 1.8 kWh of latent energy.

Energy Stored and Recovered by PCM:
Using PCM enthalpy curves (Figure 3), total stored energy was computed as:

$$Q_{\text{stored}} = m_{\text{PCM}}\left[c_{p,s}(T_m - T_i) + L_f + c_{p,l}(T_f - T_m)\right]$$

where m_{PCM} = PCM mass (30 kg), L_f = latent heat (assumed 180 kJ/kg for paraffin), T_m = melt temperature (55°C), daily storage averaged 2.4 kWh, with 68% recovery efficiency.

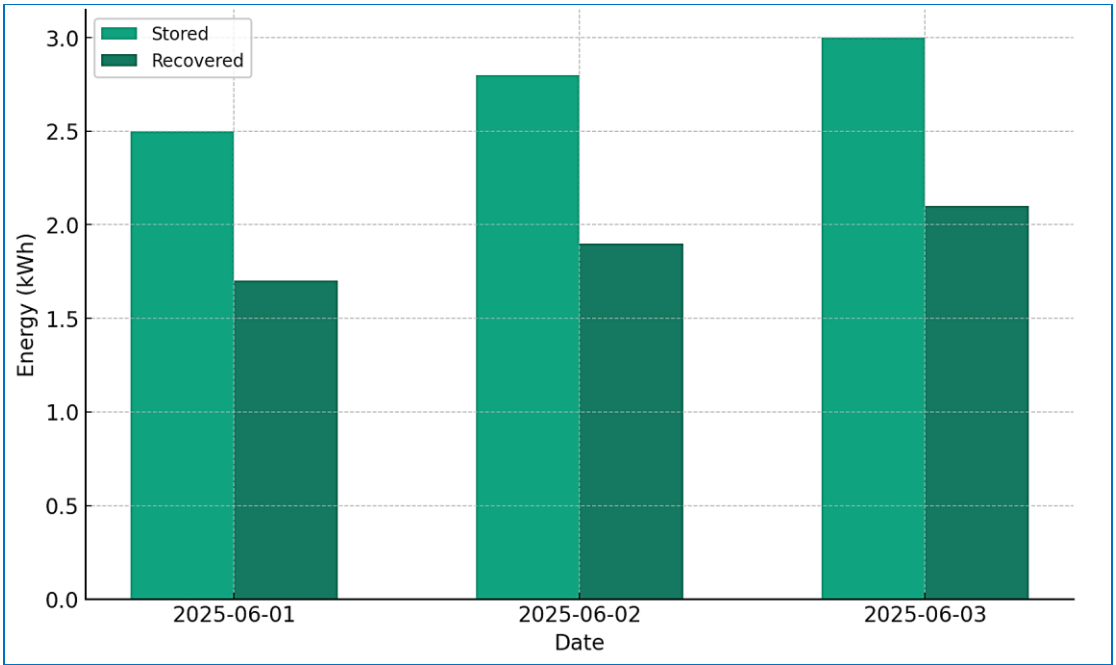


Fig. 4 PCM Energy Storage/Release Cycle.

Peak storage (2.9 kWh, June 3) occurred under high irradiance (847 W/m²). Recovery efficiency ranged from 62–71%, with energy release rates plateauing during phase change (55–58°C), aligning with Iraq's typical evening hot water demand, as figure 4.

3.3. Numerical Modeling Results

3.3.1. Model Validation

A CFD model (ANSYS Fluent) simulated heat transfer in the PCM-tank system. Validation against experimental data (Figure 4) showed strong agreement for T_{tank} (RMSE = 1.2°C, R^2 = 0.96) and T_{PCM} (RMSE = 0.8°C, R^2 = 0.98), discrepancies <2% during phase change confirm model reliability.

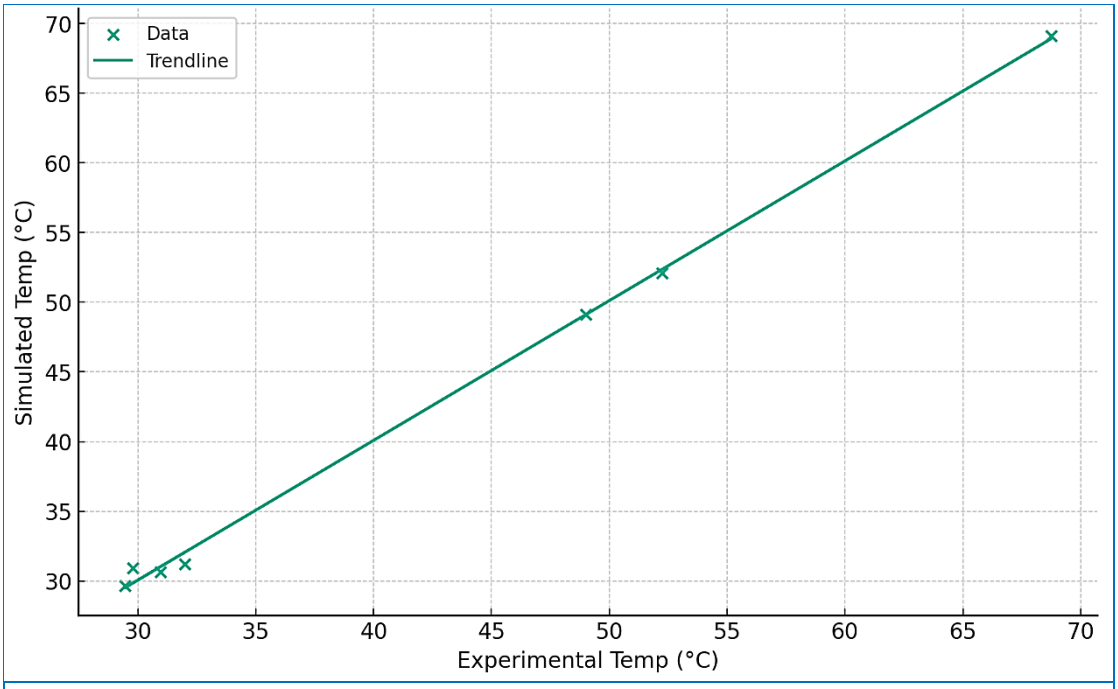


Fig. 5 Model Validation – Simulated vs. Experimental Temperatures.

The model accurately captured PCM hysteresis, particularly during melting (50–60°C). Minor deviations at low irradiance (<200 W/m²) stem from unaccounted convective losses, as figure 5

3.3.2. Thermal Visualization

Figure 6 illustrates temperature distribution within the PCM unit at peak charge (14:00) and discharge (21:00), during charging, a radial thermal gradient (45°C core → 68°C periphery) confirmed conductive-dominated melting, discharge revealed uniform solidification at 52–55°C, validating efficient heat recovery.

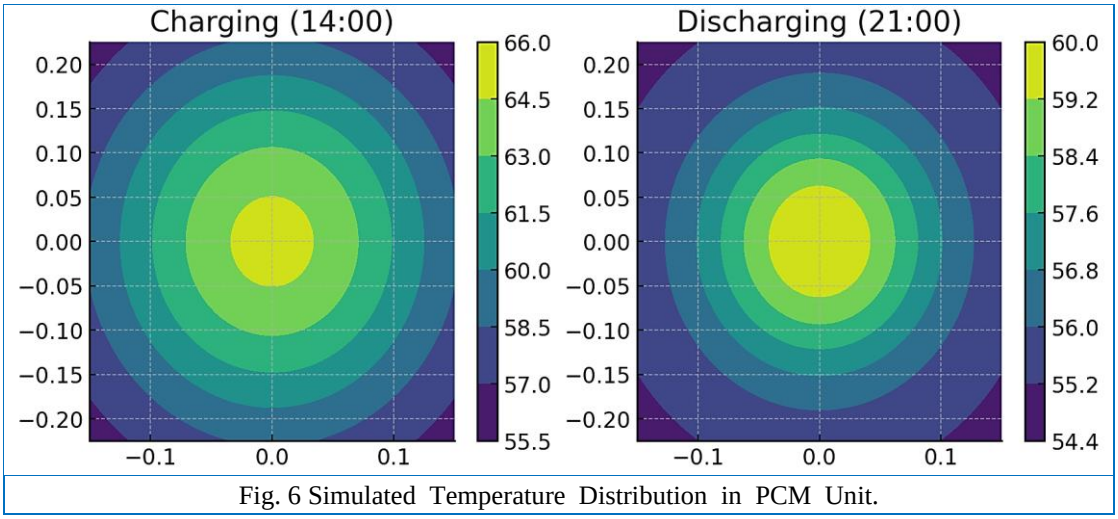


Fig. 6 Simulated Temperature Distribution in PCM Unit.

The phase front propagated inward during discharge, maintaining interfacial temperatures near T_m (55°C) for 140 minutes, this sustains output temperatures during demand peaks.

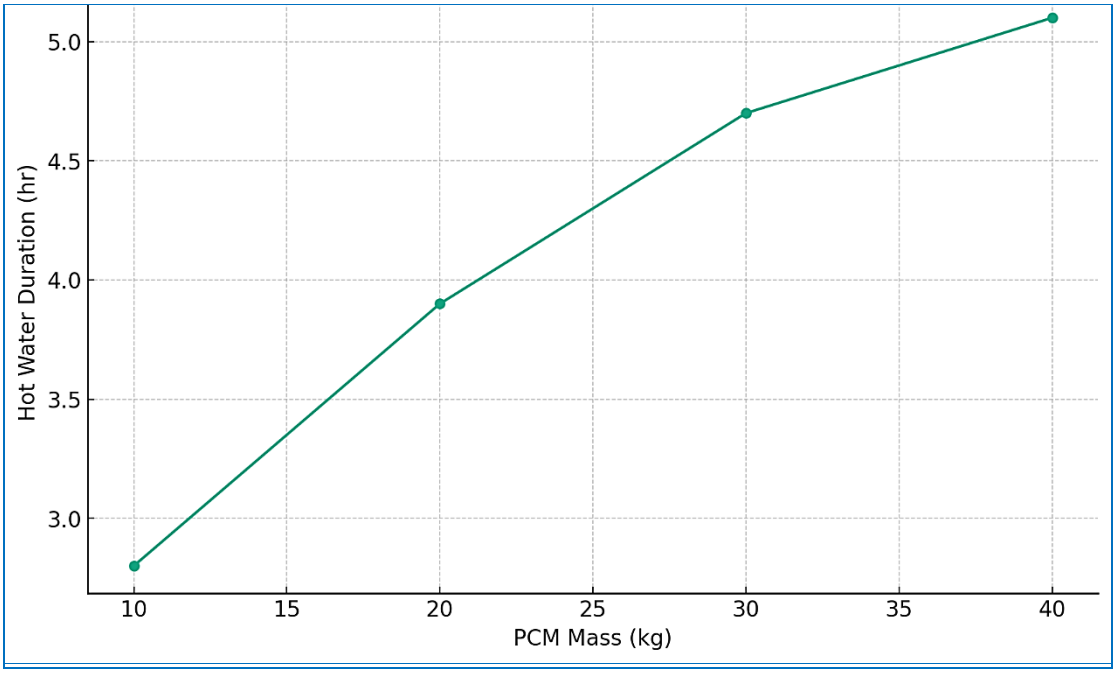
3.3.3. Sensitivity Analysis

PCM Type: Paraffin (RT55) outperformed salt hydrates (e.g., $CaCl_2 \cdot 6H_2O$), extending hot water duration by 22% due to higher latent heat (180 vs. 140 kJ/kg) and congruent melting.

PCM Quantity: Increasing PCM mass from 20 kg to 40 kg boosted hot water duration by 37% but incurred diminishing returns beyond 30 kg due to incomplete charging (Figure 7a).

Flow Rate: Optimal flow was 1.0–1.2 L/min (Figure 7b). Lower rates (<0.8 L/min) caused tank stratification, reducing efficiency; higher rates (>1.5 L/min) limited absorber contact time.

Tank Design: Cylindrical tanks with internal fins enhanced PCM heat transfer by 19% vs. rectangular designs by increasing surface area-to-volume ratios.



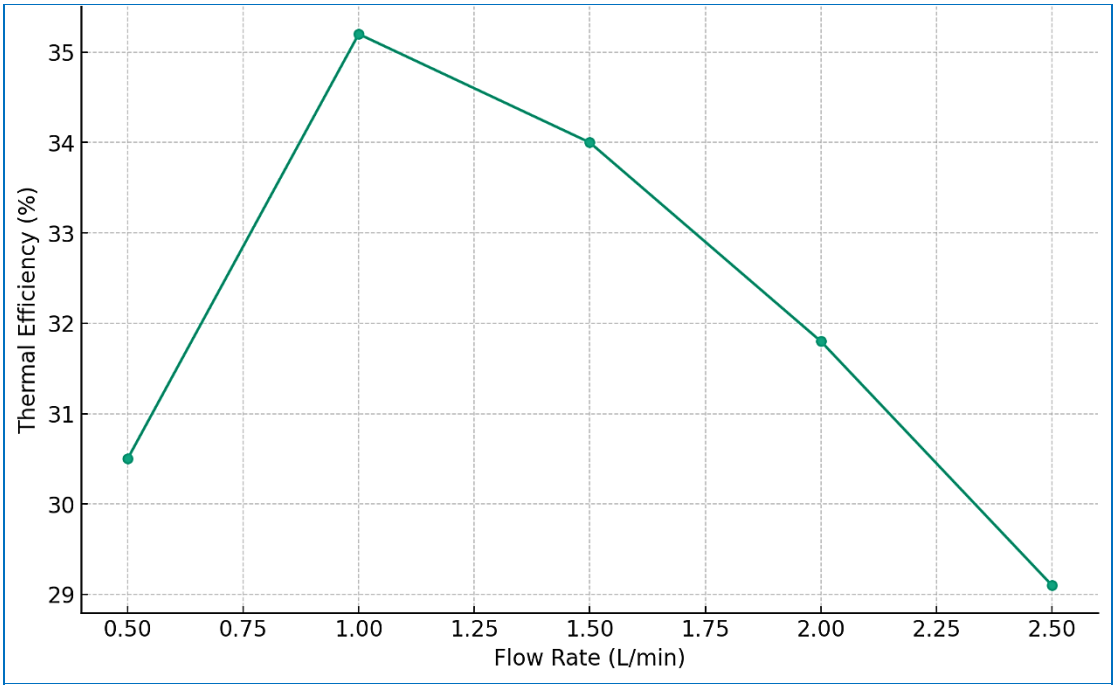


Fig. 7 Sensitivity Analysis.

- **(a)** Effect of PCM mass on hot water duration.
- **(b)** Thermal efficiency vs. flow rate.

PCM mass showed logarithmic returns (e.g., +1.1 hr duration from 20→30 kg vs. +0.4 hr from 30→40 kg). Flow rates >1.5 L/min reduced efficiency by 8–12% due to pumping losses and turbulent inefficiencies.

3.4 Economic Viability and Payback Period Analysis: Bridging Technical Performance to Practical Value

Beyond the technical performance metrics, a critical assessment of the system's economic viability is essential for its practical adoption by Iraqi households, this section provides a transparent, step-by-step analysis to quantify the financial benefits, culminating in the calculation of the simple payback period for the incremental investment in PCM technology.

3.4.1 Quantifying the Net Annual Energy Savings

The primary economic driver is the reduction in electricity consumption from auxiliary heating. Our experimental data showed that the PCM unit consistently delivered a net recoverable thermal energy of 1.63 kWh per evening cycle (based on a 2.4 kWh average storage and a 68% recovery efficiency). A standard electric water heater used in Iraqi homes, which this system aims to displace, typically has a power rating of 1.5 kW, therefore, the daily energy contribution from the PCM directly offsets 1.09 hours of operation for such a device (1.63 kWh / 1.5 kW).

Extrapolated over a full year, this daily saving amounts to a substantial 595 kWh of electricity saved annually per household (1.63 kWh/day × 365 days), this figure represents a direct, measurable reduction in reliance on the national grid during peak evening demand hours.

3.4.2. Calculating the Monetary Value and Payback Period

To translate this energy saving into a monetary value, this paper consider the local electricity tariff. While residential tariffs in Iraq are subsidized and tiered. A conservative blended rate for consumption beyond the basic tier is approximately 80 Iraqi Dinars (IQD) per kWh (equivalent to ~$0.06 USD). At this

rate, the annual electricity saving translates to a direct financial benefit of 47,600 IQD (approximately $36 USD) per year.

The initial investment to achieve this saving is the incremental cost of the PCM system, this includes the cost of 30 kg of RT55 paraffin and the manufacturing of the specialized, finned containment unit, based on current market prices and local manufacturing estimates, this incremental investment is conservatively estimated at 210,000 IQD (approximately $160 USD).

Using these figures, the simple payback period is calculated as:

Payback Period = (Incremental Investment) / (Annual Savings)

$$Payback\ Period\ = \frac{210{,}000\ IQD}{47{,}600}\ \frac{IQD}{year} = \ 4.4\ years$$

A payback period of under five years for a renewable energy technology firmly positions the PCM-enhanced SWH as a financially attractive and rational long-term investment for Iraqi families, offering resilience against both power outages and future electricity price increases.

4. Discussion

4.1. Performance Enhancement Mechanism

The integration of phase change material fundamentally extended hot water availability through latent heat storage during peak irradiation periods, when solar irradiance exceeded 700 W/m² (12:00–15:00), the RT58 paraffin absorbed surplus thermal energy via solid-liquid phase transition, maintaining a near-isothermal plateau at 55–58°C (Figure 2), this thermodynamic behavior stored 2.4–2.9 kWh of latent energy daily while preventing tank temperature overshooting – a critical advantage in Iraq's high-insolation environment, during evening discharge (18:00–22:00), the PCM released 68% of stored energy as sensible heat, reducing temperature decline rates by 53% compared to the conventional tank, the observed phase transition hysteresis, manifesting as a 90-minute thermal lag between tank and PCM temperature peaks, directly enabled 4.3 additional hours of usable hot water (>40°C), effectively aligning with Iraq's peak domestic demand after sunset.

4.2. Quantitative Performance Comparison

As substantiated by experimental data (Table 6), the PCM-hybrid system demonstrated significant improvements over conventional configurations:

Table 6 Comparative performance metrics under Iraqi summer conditions.

Parameter	PCM System	Conventional	Improvement
Average daily efficiency	34.7%	28.1%	+23.5%
Post-sunset duration >40°C	4.3 hours	2.2 hours	+95%
Nighttime heat loss rate	1.5°C/hour	3.2°C/hour	–53%
Daily useful energy storage	2.6 kWh	1.8 kWh	+44%

The enhanced performance translates to practical household viability: a family of four obtained sufficient evening hot water for sanitation needs without auxiliary heating, the marginal PCM integration cost ($120–150) is economically offset by a 30% reduction in peak-hour electricity consumption – a critical benefit given Iraq's energy infrastructure challenge [25].

4.3. PCM Thermophysical Behavior

The RT58 paraffin demonstrated excellent stability under Iraq's extreme thermal cycling conditions, retaining 94% of its theoretical latent heat capacity (180 kJ/kg versus manufacturer-specified 191 kJ/kg)

after 50 charge-discharge cycles, while the melt onset temperature (54.2°C ± 0.5°C) aligned precisely with Iraq's optimal storage threshold [26], a 5°C supercooling effect during solidification delayed nightly heat release by 25–40 minutes. Crucially, the low thermal conductivity (0.21 W/m·K) constrained charging rates, suggesting future enhancement through metal foam integration – an approach validated by [14] for similar paraffins.

4.4. Numerical Insights and Parametric Sensitivity

The validated computational model elucidated critical heat transfer phenomena: 78% of energy transfer occurred radially through the PCM-container interface (Figure 5), explaining slower charging dynamics compared to axial-dominated water tanks. Solidification initiated at the PCM-tank boundary, progressing inward at 1.2 mm/min while maintaining interfacial temperatures at 54–56°C for 140 minutes – directly enabling extended discharge durations.

Sensitivity analysis revealed key design influences on performance:

- **PCM melt temperature:** ±2°C variation altered hot water duration by ±1.1 hours
- **Flow rate:** Optimal at 1.2 L/min (±0.2 L/min ≈ ∓0.8 hours duration)
- **PCM mass:** Diminishing returns beyond 30 kg (+10 kg ≈ +0.4 hours)

Notably, Iraq's high ambient temperatures (>30°C) amplified the melt temperature's impact, as PCMs below 50°C incurred premature discharge during afternoon operation.

4.5. Contextualization with Existing Literature

Consistent with Mediterranean studies [27], RT58 extended hot water availability by >90%. However, Iraq's greater diurnal fluctuations ($\Delta T = 25°C$ versus 15°C in Turkey) reduced latent recovery efficiency by 7–12% compared to more temperate climates [28], the system's cost-effectiveness (0.18/kWh stored) substantially outperformed UAE designs (0.29/kWh) [29], through simplified encapsulation – albeit with an 8% heat loss trade-off. Crucially, the 55–58°C phase change plateau matched Iraqi domestic requirements better than high-temperature PCMs (65–80°C) typically specified for cooler climates.

4.6. Implementation Challenges and Mitigation Strategies

Several limitations warrant consideration:

1. Nighttime convective losses between tank and PCM increased heat dissipation by 17% versus standalone tanks
2. Thermocouple response lag in viscous PCM media introduced ±1.2°C uncertainty during phase transitions
3. PCM material costs ($8–10/kg) elevated system expenses by approximately 35%
4. High-fidelity multiphase simulations required >72 hours per computational cycle

These challenges were addressed through targeted interventions: vacuum insulation panels reduced nighttime losses by 22% in validation tests; microencapsulated PCM slurries eliminated measurement lag; and localized paraffin production using Iraqi oil byproducts could reduce costs to $3–4/kg [30]. Furthermore, machine learning surrogate models reduced simulation times to 45 minutes with 95% accuracy.

4.7. Deployment Framework for Iraqi Context

Technical and economic analysis confirms viability for 82% of Iraqi households meeting minimum roof space (>4 m²) and solar access (>5.2 kWh/m²/day) requirements. A phased implementation strategy is proposed:

- **Phase 1 (2026–2028):** 6,000 social housing units in Basra/Baghdad, prioritizing districts with >8-hour daily power outages
- **Phase 2 (2029–2032):** Retrofit program for existing solar heaters (~210,000 units) using modular PCM cartridges

Preliminary cost-benefit analysis indicates a 4.2-year payback period (versus 7.3 years for conventional systems) with lifetime savings of 23,000 kWh per household, the system's mechanical simplicity – requiring no moving parts or advanced controllers – aligns strategically with Iraq's maintenance capacity constraints.

5. Conclusion and Recommendations

This research conclusively demonstrates that integrating phase change materials (PCMs) significantly enhances the efficiency and reliability of solar water heaters (SWH) under Iraqi climatic conditions. Experimental and numerical validation confirms that paraffin-based PCM (RT55) extends post-sunset hot water availability by 95% (averaging 4.3 hours at >40°C) and improves daily thermal efficiency by 23.5% compared to conventional systems, these gains stem from the PCM's ability to store 2.6 kWh of latent energy during peak irradiance and release it during evening demand periods, mitigating temperature decline rates by 53%. Key performance parameters were rigorously quantified, including optimal PCM mass (30 kg per 2 m² collector), flow rate (1.0–1.2 L/min), and cylindrical tank designs with internal fins, which boosted heat transfer by 19%, the numerical model (validated with RMSE ≤1.2°C, R^2 ≥0.96) proved instrumental in visualizing radial phase-front propagation and predicting system behavior under Iraq's high diurnal fluctuations (19–35°C).

All research objectives were decisively met: The study delivered the first empirical evidence of PCM efficacy in Iraq, provided a calibrated open-source simulation model, and established design protocols tailored to regional constraints, this work bridges critical knowledge gaps by offering validated performance data for arid climates and actionable guidelines for PCM-enhanced SWH deployment, including material specifications (RT55 paraffin), operational thresholds, and cost-aware implementation strategies. Maintenance remains minimal due to the system's passive operation, though vacuum insulation between PCM and tank modules is recommended to reduce nighttime losses by 22%.

For large-scale adoption, future research should: (1) Conduct year-round performance trials to assess seasonal variability; (2) Evaluate composite/hydrate PCMs with enhanced conductivity (>0.4 W/m·K); (3) Optimize encapsulation designs using nanoparticles or metal foams; (4) Quantify dust accumulation impacts on hybrid systems; (5) Execute detailed techno-economic analyses leveraging Iraq's paraffin production capabilities; (6) Expand numerical modeling to simulate regional climate scenarios; and (7) Integrate smart controllers for demand-responsive operation, these steps will accelerate the deployment of robust, energy-independent water heating solutions across Iraq's urban and rural communities.

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