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Experimental Investigation Of Phase Change Material–Integrated Solar Water Heaters With Varying Structural And Thermal Storage Designs

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Abstract

Phase change material-integrated solar water heaters (PCM-ISWHs) incorporate latent heat storage to extend usable hot water supply beyond daylight hours, mitigating solar intermittency. This article details experimental investigations into structural variations such as encapsulation types (cylindrical, slab), fin enhancements, and cascaded PCM layers and thermal storage designs, including HTF flow rates and tank geometries. Paraffin waxes (RT42, RT50, RT58) dominate due to melting points (42-58°C) aligning with domestic needs (45-60°C). Key experiments show single PCM boosting temperatures by 9-23°C over sensible storage, cascaded setups achieving 3-7% higher collection efficiency via uniform phase transitions, and finned designs accelerating charging by 20-30%. Productivity rises 35-92% in hybrid configurations, with exergy efficiencies up to 71%. Challenges like low conductivity (addressed by nano-additives) and leakage are explored, alongside CFD validations. Findings advocate cascaded, fin-augmented cylindrical encapsulations for 52-85°C delivery, reducing payback to 2-3 years in tropical climates. Future hybrid nano-PCMs promise further gains.

Fundamentals of PCM in Solar Water Heaters

Solar water heaters traditionally rely on sensible storage (water tanks), where capacity scales with volume and temperature swing: $Q_s = mc_p\Delta T$. PCMs offer 5-14 times higher density via latent heat: $Q_l = m\Delta h_f$, where Δh_f (150-250 kJ/kg) sustains near-isothermal storage at phase transition. Organic PCMs like paraffin excel in chemical stability, no supercooling, and compatibility with water HTF, though conductivity (0.2 W/mK) limits rates. Encapsulation prevents leakage: HDPE cylinders, aluminum tubes, or slabs immerse in tanks, with HTF tubes coiled around or through. Integration sites include collector backs, tank sides, or standalone units post-collector. Varying designs test melting/solidification dynamics, quantified by Stefan number Ste = $c_p\Delta T/\Delta h_f$ (<0.5 for conduction dominance).

Experimental Methodologies

Setups typically feature flat-plate/evacuated tube collectors (1-2 m², tilt 20-30°), linked to insulated tanks (100-200 L) with PCM modules (5-20 kg). Sensors (thermocouples ±0.1°C, pyranometers) log at 5-min intervals under

ASHRAE-like conditions (G=800-1200 W/m², Ta=25-35°C). Variables span structures: encapsulation (copper tubes 15-50 mm dia., slabs 50-100 mm thick); enhancements (fins 1-3 mm thick, spaced 20-50 mm); cascades (2-3 layers, ΔT_melt=10-15°C). Thermal parameters: HTF rates (1-15 L/min), PCM mass (5-10 kg). Metrics include charging time (to full melt), temperature profiles, efficiency $\eta = \dot{m}c_p(T_{out} - T_{in})/(AG)$, and storage capacity $Q_{stored} = \int (T_{PCM} - T_{ref})c_{eff}dm + m\Delta h_f$.ijrpr+1

Structural Design Variations

Cylindrical encapsulations (Al/PVC tubes, 50-100 mm long) in tanks yield 20-25% faster charging than slabs, as higher surface area (A/V ratio 4-8 m⁻¹) boosts convective transfer. Paraffin-filled copper rods (15 mm dia., 12 per basin) in modified heaters maintained 42°C overnight, extending supply 5-7 h. Fins (Al, longitudinal/perforated) bridge PCM-HTF gaps; 100 mm long, 20 mm spaced fins in U-tube collectors cut charging by 2 h at 15 L/min, raising peak T by 10-15°C via k_eff=1-2 W/mK. Vertical heat exchangers with sand-core paraffin hybrids gained 7 kJ/min heat rate, 48% over plain PCM, due to porous conduction paths. Tank geometries rectangular with slab PCM or coiled HTF optimize flow; horizontal packing parallels water, minimizing ΔP.

Thermal Storage Design Effects

Single PCM (RT50, 54°C melt) sustains 52°C for 16 h, storing 1000+ kJ extra at high flows (15 L/min vs 3 L/min halves melt time). Mass scaling (10 kg >5 kg) proportionally lifts capacity but slows full charge by 30-50 min due to conduction limits. Cascaded PCMs (RT42|RT58|RT75°C slabs) achieve 0.97 melt fraction vs 0.90 single, storing 3.47% more latent heat by matching solar ramp-up: lower layers charge first, reducing sensible needs. Dual water-PCM (50 mm paraffin +100 mm water) hit 85°C peaks, 26-35% efficiency gain. Flow rate governs: 5 L/min optimal for RT42, balancing h_conv (200-500 W/m²K) and residence time.

Performance Outcomes

PCM-ISWHs yield 52-71% η (vs 40-60% conventional), with 9.3°C higher peaks and 23% T uplift. Evacuated tubes + combi-storage delivered 85°C at 1200 W/m², exergy 71.7% with nano-PCM. Cascades excel dynamically: 7-8 min longer discharge under 3 W/cm² equiv., 92% productivity in hybrids. Finned cascades at 1162 W/m² stored 48 kJ/min. Nocturnal yields: 5-7 h at >42°C, ideal for India (Ranchi insolation).

Challenges and Mitigations

Low k_PCM causes incomplete melt (Ste>1); nano-additives (Ag, SiO_2 1-1.5 wt%) boost 10-20%, but aggregate post-50 cycles. Leakage solved by robust HDPE/Al shells; supercooling rare in paraffins. Overcharge risks boiling (add relief valves); volume changes (5-10%) need expansion space.

Modeling and Validation

Enthalpy-porosity CFD (ANSYS Fluent) predicts melt fronts (error<5%), coupling buoyancy (Boussinesq) and radiation. RT models forecast daily Q with weather inputs.

Future Prospects

Nano-encapsulated cascades with pin-fins target 80% η; BIPV integration for institutions. AI-optimization of fin spacing/flow aligns with sustainable education goals.pmc.ncbi.nlm.nih+1

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