

Performance Analysis and Enhancement of Solar Water Heaters Using Passive Augmentation Techniques

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Abstract — With conventional fossil fuels depleting rapidly and process heating consuming over 42% of refined crude oil, solar water heating systems (SWHS) have emerged as a paramount renewable technology. Solar thermal systems achieve conversion efficiencies exceeding 70%, greatly surpassing photovoltaic systems (~20%). However, flat-plate and evacuated-tube solar collectors (ETSC) suffer from severe internal thermohydraulic bottlenecks, including laminar flow regimes, boundary-layer conductive resistance, and bi-filamental counter-current flow with stagnant bottom dead-zones. This review synthesizes key experimental, numerical, and thermodynamic findings across three foundational review documents, covering continuous twisted tapes, pitch variation, strip orientation, cutouts, circular perforations, wavy tapes, and phase change materials (PCMs). Passive inserts induce secondary swirl flow, generate Dean vortices, disrupt thermal boundary layers, and reduce hydraulic diameter, enhancing convective heat transfer coefficients by 18% to 70%. In evacuated tubes, drilled twisted tapes elevate water temperature to 82.4°C (+28.8°C over plain) and daily thermal efficiency to 87.9% (+28.4%). Perforated wavy tapes eliminate bottom dead-zones, achieving 49.36% energy efficiency and 5.20% exergy efficiency (+70.2%). Combining wavy tapes with eutectic PCM (stearic-palmitic acid) yields peak temperatures of 74.4°C and a 75.5% surge in daily exergy efficiency while mitigating up to 42.81 tons of CO₂ annually. Authentically reproduced diagrams from all three uploaded papers are integrated to visually elucidate the underlying hydrodynamics, test facilities, and thermal performance characteristics.

Keywords: Evacuated Tube Solar Collector; Twisted Tape; Wavy Tape; Phase Change Material; Convective Heat Transfer Augmentation; Exergy Efficiency

I. INTRODUCTION

Escalating energy consumption and rising fossil fuel costs necessitate sustainable thermal technologies. Process and domestic heating consume over 42% of global refined oil, and residential water heating accounts for nearly 20% of domestic energy expenditure. Solar water heating systems (SWHS) represent the most commercially viable application, holding >80% market share with thermal conversion efficiencies exceeding 70%, versus ~20% for solar PV.

Solar collectors include flat-plate solar collectors (FPSC) and evacuated-tube solar collectors (ETSC). FPSCs suffer from high convective and radiative losses to ambient air. In contrast, ETSCs maintain a high-vacuum annulus ($P < 10^{-3}$ Pa) between concentric borosilicate glass tubes with selective cermet coatings (absorptance $\alpha \geq 0.93$, emittance $\varepsilon \leq 0.06$), virtually eliminating external conduction and convection losses. However, ETSCs are constrained by internal thermohydraulic bottlenecks:

Laminar Flow and Viscous Boundary Layer: Under low mass flow rates (0.001–0.040 kg/s) and small conduit diameters (18–47 mm), flow operates in the laminar regime ($Re < 2300$). A thick viscous boundary layer creates high conductive thermal resistance, resulting in severe radial temperature stratification.[1]

Bi-Filamental Flow and Stagnant Dead-Zones: In single-ended evacuated tubes, solar-heated water ascends along the top while cold water descends along the bottom. This counter-current flow creates an inactive, stagnant dead-zone at the sealed bottom tip, severely degrading circulation.[2]

Passive Augmentation Mechanisms: Passive turbulators (twisted and wavy tapes) solve these bottlenecks by generating secondary helical swirl (Dean vortices), scrubbing the conduit walls to thin the thermal boundary layer, and reducing hydraulic diameter (D_h) without external pumping power. Latent heat PCMs buffer nocturnal heat losses, bridging the diurnal demand gap.[3]

II. EXPERIMENTAL SETUP

The reviewed literature evaluates outdoor experimental rigs spanning evacuated-tube, once-through flat-plate, thermosyphon, and concentrating V-trough configurations:

A. Evacuated Tube Pitch, Direction, and V-Trough Rigs [1]:

Chaudhary & Namjoshi (2021) and Chaudhary (2023) [Paper 1] tested three evacuated glass tubes (1000 mm length, 40 mm OD, 20 mm ID) manifolded to a mild-steel tank at low, medium, and high flow rates (0.00136, 0.00144, 0.00162 L/s) comparing short vs. long pitch and left-hand vs. right-hand tape directions. Jaisankar et al. (2008) and Prasanna et al. (2017) [Paper 1] examined left-right alternating twisted tapes in a 1 m² flat-plate thermosyphon collector and a 5-unit V-trough concentrating collector (Figure 1).

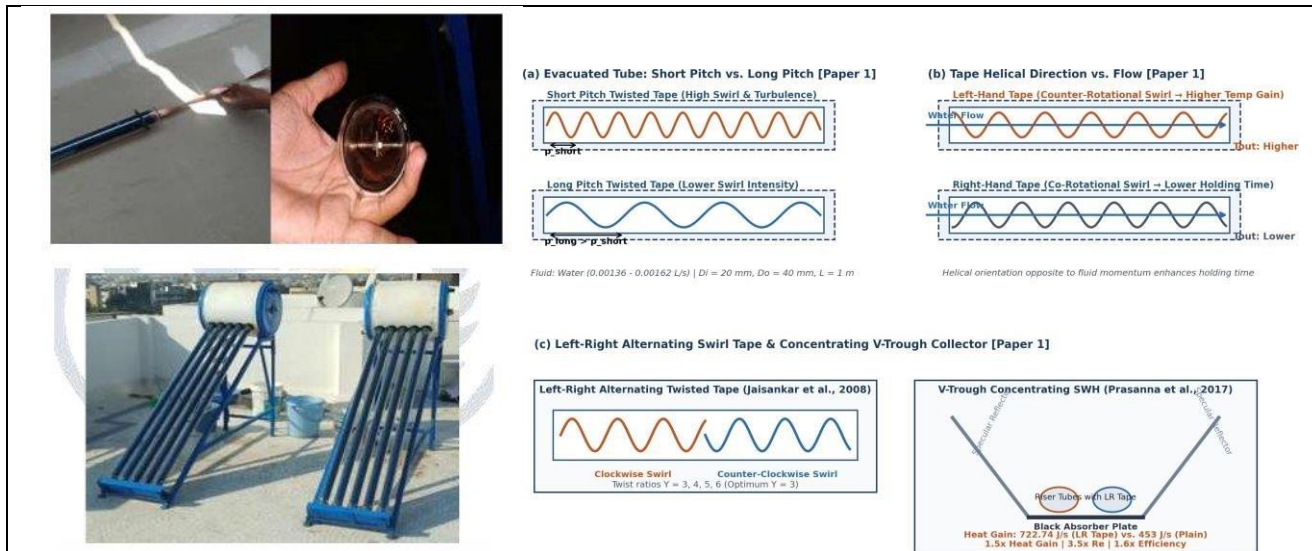


Fig. 1: Authentic experimental concepts from 1: (a) Evacuated tube comparing short vs. long pitch; (b) Tape helical direction vs. water flow; and (c) Left-right alternating swirl tape and concentrating V-trough collector [Chaudhary & Namjoshi, 2021; Chaudhary, 2023; Jaisankar et al., 2008; Prasanna et al., 2017].

Flat-Plate and Multi-Pipe Experimental Systems [2 & 3]: Sharma & Karwa (2014) [2 & 3] developed a once-through flat-plate collector with two parallel copper riser tubes (1500 mm length, 19.5 mm ID) comparing full- width against 75% reduced- width tapes (13.8 mm) with centering projection tabs under laminar flow ($Re = 125-500$). Abdullah & Hasan (2023) [2] constructed a 4-pipe collector (1000 mm length, 18 mm ID) testing 0, 1, 3, and 5 twists. Keen & Prajapati (2018) [Paper 2] tested an evacuated-tube rig (1800 mm length, 47 mm ID, 50 L tank) with 1200 mm long copper twisted tape (180 mm pitch). Advanced Geometries, Perforated Wavy Tapes, and PCM [3]: Abd et al. (2025) [3]

tested a 16-tube evacuated collector (2000 mm length, 40 mm ID, 200 L tank) with six aluminum tape geometries (Figure 2): Type 1 (normal, $p=180$ mm), Type 2 (regularly spaced, $spacer=50$ mm), Type 3 (triangular-cut, 10×50 mm), Type 4 (rectangular-cut, 10×50 mm), Type 5 (semicircular-cut, $r=25$ mm), and Type 6 (drilled circular holes, $r=2.5$ mm). Agade et al. (2025) [Paper 3] deployed an 8-tube evacuated collector (150 L tank) testing wavy tape (WT, 20 mm pitch, 60° fold), 6 mm / 9 mm perforated wavy tapes (6 PWT / 9 PWT), and cylindrical encapsulated eutectic PCM (36% stearic acid + 64% palmitic acid, $T_m = 52.9^\circ C$).

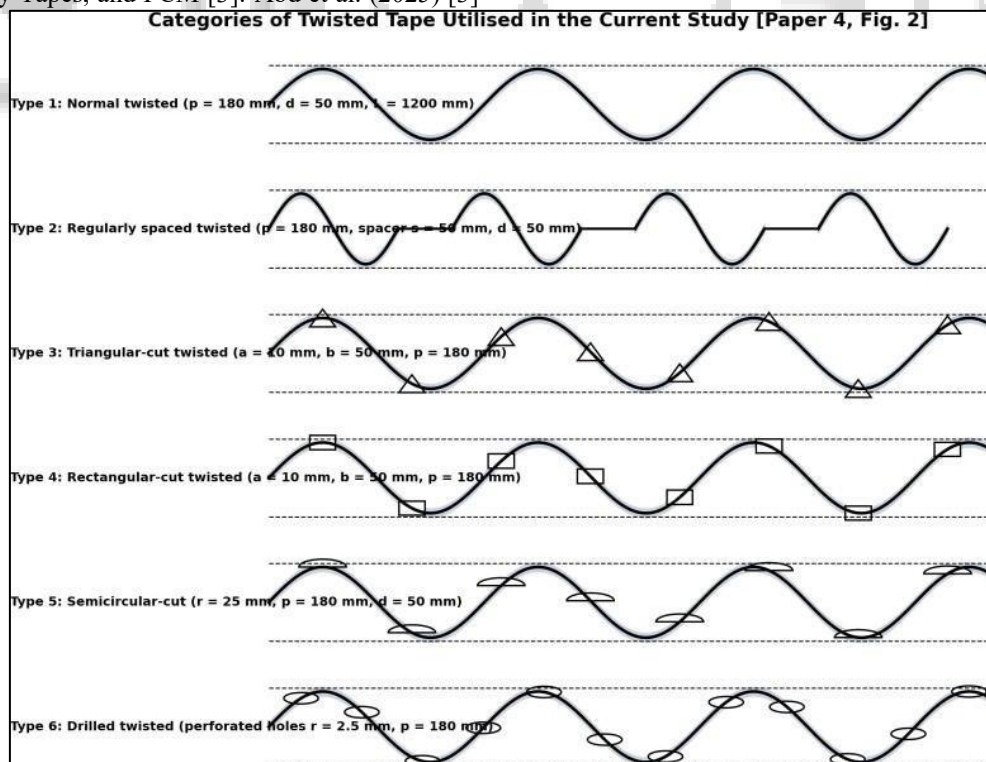


Fig. 2: Categories of twisted tape inserts utilised in experimental testing (Types 1 to 6) [reproduced from Abd et al. (2025), Fig. 2, as reviewed in 3]: Type 1: Normal; Type 2: Regularly spaced; Type 3: Triangular-cut; Type 4: Rectangular-cut; Type 5: Semicircular-cut; and Type 6: Drilled twisted tape.

Comparative Difference of the Reviewed Studies

Study & Source	Collector Type	Fluid	Insert / Storage Technique	Flow Regime / Geometry	Primary Result / Quantitative
Arjun Singh (2017) [P1, P2]	Tube-in-Fin FPC	Water	Twisted tape in last 1/3 (w=25 mm)	Re = 5568, p/d = 5, p = 127 mm	Heat transfer enhancement of 22.77%–25.92%; p/d = 5 optimum.
Chaudhary (2021) [P1]	Evacuated Tube (3T)	Water	Short-pitch vs. long-pitch tapes	0.00136–0.00162 L/s	Short pitch gave higher turbulence; temp gain lower at high flow rate.
Chaudhary (2023) [P1]	Evacuated Tube (3T)	Water	Right-hand vs. left-hand tapes	Fixed pitch, L-to-R flow	Left-hand tape generated higher temp rise due to counter-rotational swirl.
Jaisankar (2008) [P1]	Thermosyphon 1 m ²	Water	Left-right twisted tape (dia 11 mm)	Y = 3, 4, 5, 6; thermosyphon	Twist ratio Y = 3 gave highest efficiency; Nu and f increased with lower Y.
Prasanna (2017) [P1]	V-Trough SWH (5U)	Water	Left-right twisted tape in risers	Natural thermosyphon flow	Heat gain: 722.74 J/s vs 453 J/s plain (1.5x gain, 3.5x Re, 1.6x efficiency).
Abdullah (2023) [P2]	Multi-Pipe SWH (4T)	Water	Copper tapes: 0, 1, 3, 5 twists (y/w=3)	mfr = 0.875 L/min, tilt 33°	Outlet temp increased 5.33%, 14.09%, 20.27% for 1, 3, 5 twists.
Kumar (2023) [P2]	Flat Plate Collector	Air/Water	Small-height twisted tape (3D CFD)	Re ≈ 9000, TH/Dh = 0.022	Maximum thermo-hydraulic performance = 2.41 at optimum parameters.
Keen (2018) [P2]	Evacuated Tube (50 L)	Water	Copper tape (1 mm thk, 180 mm pitch)	Natural circulation; outdoor	Average efficiency 68.35% with tape vs 59% plain; avg temp 54°C.

III. DATA CALCULATION (MATHEMATICAL MODELING)

Thermal and hydraulic evaluation is governed by First Law energy conservation, Second Law exergy destruction, and dimensionless flow parameters:

- 1) Useful Thermal Heat Gain: $Q_u = m \cdot w \cdot C_{p,w} \cdot (T_{out} - T_{in})$
- 2) $Q_{stored} = m_{tank} \cdot C_{p,w} \cdot (T_{final} - T_{initial})$
- 3) Hybrid PCM Heat Storage: $Q_{sys} = Q_w + Q_{PCM} = Q_w + m_{PCM} \cdot [C_{p,PCM} \cdot \Delta T_{PCM} + A_m \cdot \Delta h_{PCM}]$
- 4) First Law Thermal Efficiency: $\eta_{th} = Q_u / (A_c \cdot I_t)$; $\eta_{daily} = Q_{stored} / [A_c \cdot \sum (I_t \cdot \Delta t)]$

- 5) Fluid Exergy Gain & Stored Exergy: $Ex_{out} = m \cdot w \cdot C_{p,w} \cdot [(T_{out} - T_{in}) - T_a \cdot \ln(T_{out} / T_{in})]$
- 6) Second Law Exergy Efficiency: $\psi = Ex_{out} / Ex_{in}$ (or Ex_{stored} / Ex_{in})
- 7) Reynolds Number & Nusselt Number: $Re = (4 \cdot m \cdot w) / (\pi \cdot D_i \cdot \mu)$; $Nu = (h_i \cdot D_i) / k_f$

CFD Numerical Framework [2]: Numerical CFD modeling in ANSYS Fluent solves the Reynolds- Averaged Navier-Stokes (RANS) continuity, momentum, and energy equations using finite-volume tetrahedral meshes with wall boundary refinement and the standard k-epsilon model (Figure 3). While flat tapes maintain purely axial streamlines, helical twists generate intense circumferential swirl vectors.

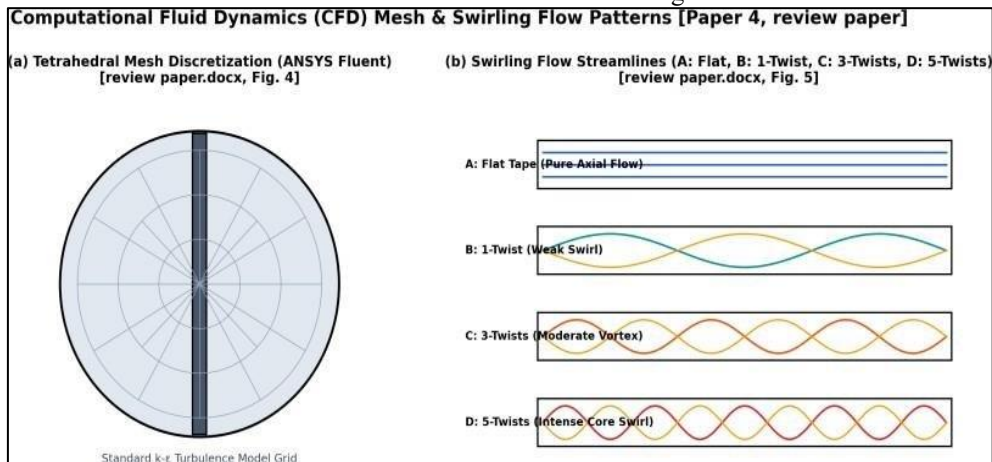


Fig. 3: Computational Fluid Dynamics (CFD) modeling from Paper 2 (Review Paper / Abdullah & Hasan, 2023): (a) Finite-volume tetrahedral mesh domain in ANSYS Fluent; and (b) Numerical velocity streamlines across (A) flat tape, (B) 1 twist, (C) 3 twists, and (D) 5 twists.

IV. RESULTS AND DISCUSSION

The synthesized experimental data provide compelling evidence of heat transfer augmentation across all tested configurations:

Twisted Tape Geometrical Configurations [Paper 3]: Abd et al. (2025) [Paper 3] demonstrated that end-of-day tank water temperatures reached 53.6°C (plain), 56.7°C (Type 1: normal), 60.4°C (Type 2: spaced), 66.4°C (Type 3:

triangular-cut), 71.6°C (Type 4: rectangular-cut), 77.8°C (Type 5: semicircular-cut), and 82.4°C for Type 6 (drilled tape, +28.8°C over plain). Corresponding daily thermal efficiencies were 59.5% (plain), 69.8% (Type 1), 72.6% (Type 2), 77.9% (Type 3), 80.6% (Type 4), 82.4% (Type 5), and 87.9% (Type 6, Figure 4). Circular perforations ($r=2.5$ mm) permit fluid jetting across the tape partition, shearing the thermal core without forming large stagnant recirculating wakes.

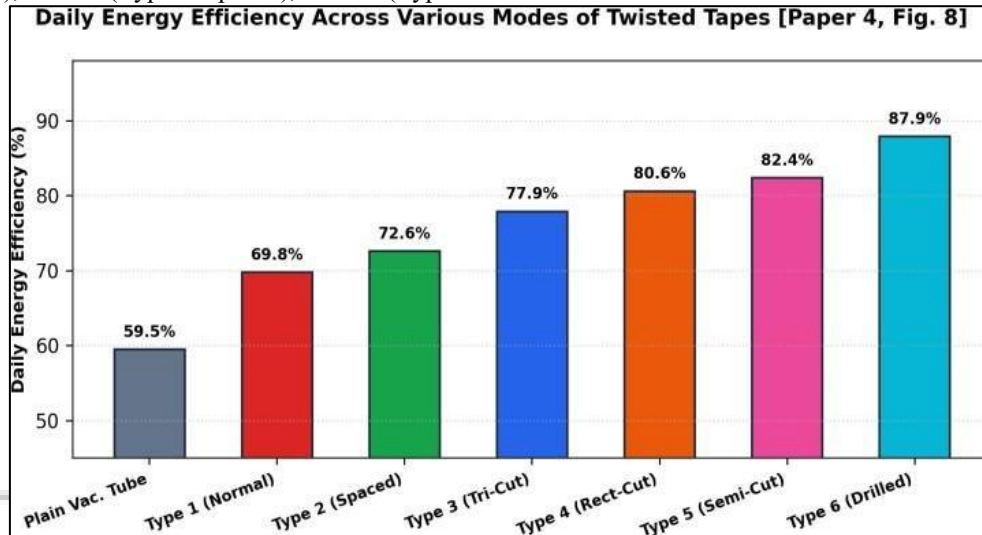


Fig. 4: Daily thermal energy efficiency across various modes of twisted tapes in evacuated tube solar water heaters [reproduced from Abd et al. (2025), Fig. 8, as reviewed in Paper 3], progressing from 59.5% (plain) to 87.9% (drilled twisted tape).

Pitch, Twist Ratio, and Flow Rate [Papers 1 & 2]: Chaudhary & Namjoshi (2021) [Paper 1] found that shortpitch tapes generate greater turbulence and higher outlet temperatures than long-pitch tapes. However, higher flow rates (0.00136 to 0.00162 L/s) reduced temperature gain due to decreased retention time. Jaisankar et al. (2008) [Paper 1] established that twist ratio $Y = 3$ yielded the highest Nusselt number and thermal efficiency among $Y = 3-6$. Arjun Singh et al. (2017) [Papers 1 & 2] showed $p/d = 5$ provided optimum heat collection enhancement (22.77%–25.92%) at $Re = 5568$.

Strip Helical Direction [1]: Chaudhary (2023) [Paper 1] demonstrated that under left-to-right flow, left-hand twisted tapes generated higher water temperatures than right-hand tapes because counter-rotational shear increases fluid holding time and solar absorption.

Annular Clearance (75% Width) [2 & 3]: Sharma & Karwa (2014) [Papers 2 & 3] showed that a 75% reduced-width tape achieved higher thermal efficiency gains (6.5%–8.0%) than full-width tape (4.5%–5.5%). The 25% annular wall clearance provides a path of least resistance for swirl-displaced fluid to scrub the heated conduit wall at high velocity with reduced skin friction drag.

Perforated Wavy Tapes and Eutectic PCM [3]: Agade et al. (2025) [Paper 3] showed that 6 mm perforated wavy tape (6 PWT) eliminated the bottom stagnant dead-zone in evacuated tubes, achieving 49.36% daily energy efficiency (+27.5%) and 5.20% exergy efficiency (+70.2%), outperforming 9 mm PWT (47.82%). Coupling wavy tape with binary eutectic PCM (SA-PA) reached 74.4°C peak temperature, 45.92% daily efficiency, and 6.11% exergy

efficiency (+75.5% over conventional), mitigating 42.81 tons of CO₂ annually.

V-Trough Concentrators and Multi-Twists [1 & 2]: In concentrating V-trough collectors, Prasanna et al. (2017) [Paper 1] reported that left-right twisted tapes increased average useful heat gain to 722.74 J/s (vs. 453 J/s plain, 1.5x gain, 1.6x efficiency). Abdullah & Hasan (2023) [Paper 2] confirmed that temperature rise increased from 5.33% (1 twist) to 20.27% (5 twists) due to sustained secondary Dean vortices.

V. CONCLUSION

This unified review synthesizes passive convective augmentation techniques and thermal storage across solar water heaters based on three foundational review documents:

- 1) Core Hydrodynamic Mechanisms: Twisted and wavy tapes enhance convective heat transfer coefficients by 18% to 70% in laminar regimes by generating secondary helical swirl, Dean vortices, boundary layer suppression, and hydraulic diameter reduction.
- 2) Superiority of Perforated Tapes: Drilled twisted tapes (Type 6, $r=2.5$ mm) achieve 82.4°C water temperature (+28.8°C over plain) and 87.9% daily efficiency (+28.4% absolute gain) by enabling cross-partition fluid jetting without large recirculating wake penalties.
- 3) Annular Wall Clearance Advantage: A 75% reduced-width tape with centering tabs creates an unobstructed annular boundary passage, delivering superior efficiency gains (6.5%–8.0%) over full-width tapes (4.5%–5.5%) by lowering viscous friction.

- 4) Dead-Zone Elimination: Perforated wavy tapes (6 PWT) eliminate the bottom inactive dead-zone in evacuated tubes, yielding 49.36% daily energy efficiency (+27.5%) and 5.20% exergy efficiency (+70.2%).
- 5) Latent Heat Storage Integration: Integrating binary eutectic PCM (36% stearic acid + 64% palmitic acid, $T_m = 52.9^\circ\text{C}$) in storage tanks buffers nocturnal heat loss, achieving 74.4°C peak temperature, 45.92% daily efficiency, 6.11% exergy efficiency (+75.5%), and 42.81 tons annual CO₂ mitigation.
- 6) Pitch and Direction Dynamics: Twist ratio $Y = 3$ is optimal among $Y = 3-6$. Short pitch increases turbulence, while left-hand tape orientation opposite to flow momentum extends residence time, maximizing solar thermal collection.

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