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Thermal Performance Enhancement of Solar Collectors Using Al_2O_3-TiO_2 Hybrid Nanofluids

Balakrishnan Suresh, Ramkumar Venkatasubramanian

Department of Mechanical Engineering, Dr. Mahalingam College of Engineering & Technology, Pollachi, Tamil Nadu, India

Abstract

Solar thermal energy collectors represent one of the most economically viable and deployable renewable energy technologies for India's climate context, with solar irradiance levels exceeding 5.5 kWh/m²/day across most of the Indian subcontinent. A critical constraint on solar thermal system efficiency is the limited thermal conductivity of conventional heat transfer fluids — water and thermic oil — which determines the rate of heat acquisition from the absorber plate to the working fluid and consequently the achievable system efficiency. Nanofluids — engineered suspensions of nanoparticles (1–100 nm) in base fluids — offer significantly enhanced thermal conductivity, specific heat capacity, and convective heat transfer coefficients compared to base fluids, potentially improving solar collector thermal efficiency by 5–25% depending on nanoparticle type, concentration, and collector configuration.

This study presents a comprehensive experimental and computational investigation of Al_2O_3/water, TiO_2/water, and Al_2O_3-TiO_2 hybrid nanofluids across three solar collector configurations — flat plate collector (FPC), evacuated tube collector (ETC), and parabolic trough collector (PTC) — at five mass flow rates (0.5–2.5 L/min) and three nanoparticle volume concentrations (0.5%, 1.0%, 2.0%). Taguchi L16 orthogonal array design systematically identifies optimal parameter combinations for maximum thermal efficiency. CFD simulation using ANSYS Fluent 2023R1 with realizable k-ε turbulence model and discrete phase modelling validates experimental results. The Al_2O_3-TiO_2 hybrid nanofluid (1.5% concentration) in the PTC configuration achieves the highest thermal efficiency of 83.7% — a 22.5% improvement over base water in the same collector — while the thermo-economic analysis confirms superior performance factor ($PF = \eta_{th}/\Delta P$) for ETC-hybrid combination at 2.0 L/min flow rate.

Keywords: *hybrid nanofluid, Al_2O_3-TiO_2, solar collector, flat plate collector, evacuated tube collector, parabolic trough, thermal efficiency, Taguchi optimisation, CFD validation, ANSYS Fluent, heat transfer, nanoparticle concentration, India, renewable energy*

1. Introduction

India's National Solar Mission targets 280 GW of solar energy capacity by 2030, with solar thermal applications — including domestic water heating, industrial process heat, and solar cooling — representing a significant but underutilised component of this target. The Bureau of Energy Efficiency estimates that solar thermal water heaters alone could displace 15–20 million tonnes of CO_2 annually if scaled to full adoption in Indian households currently using electric immersion heaters. The efficiency of solar thermal systems directly determines the economic payback period and, consequently, adoption rates in price-sensitive Indian markets.

Nanofluid research for solar thermal applications has expanded rapidly since Choi and Eastman's (1995) seminal demonstration of anomalous thermal conductivity enhancement in metallic nanofluid suspensions. The physical mechanism of nanofluid thermal conductivity enhancement involves multiple contributions: Brownian motion of nanoparticles enhancing microconvection; aggregation of nanoparticles forming high-conductivity percolation pathways; and nanolayer formation at the particle-fluid interface with ordered molecular structure resembling solid-phase thermal conductivity. Hybrid nanofluids — combining two or more nanoparticle types — offer potentially synergistic thermal performance through complementary enhancement mechanisms from constituents with different thermal, optical, and rheological properties.

Al_2O_3 nanoparticles offer high thermal conductivity (40 W/m·K), chemical inertness, and low cost, making them among the most studied nanofluids for solar thermal applications. TiO_2 nanoparticles offer photocatalytic activity with enhanced solar absorptivity in the UV-visible spectrum and superior colloidal stability. The Al_2O_3-TiO_2 hybrid combines Al_2O_3's conductive enhancement with TiO_2's optical absorption advantage, potentially producing superior solar-to-thermal conversion in direct absorption collector applications.

2. Literature Review

2.1 Nanofluid Thermal Enhancement in Solar Collectors

Sundar et al. (2017) systematically reviewed nanofluid applications in solar flat plate collectors, reporting mean thermal efficiency improvements of 12.5% for Al_2O_3/water at 0.1–0.3% concentration and 16.3% for TiO_2/water at similar concentrations. Mahian et al. (2018) meta-analysis of 121 nanofluid solar collector studies found that efficiency enhancement is strongly concentration-dependent at low concentrations ($< 1\%$) but plateaus or decreases above 2% due to increased viscosity raising pumping power requirements that offset thermal gains — motivating the systematic concentration optimisation in the present study. Hybrid nanofluid studies in solar collectors are comparatively limited, with most existing work confined to single collector types and without the multi-collector comparative framework of the present study.

2.2 Taguchi Method in Solar Thermal Optimisation

The Taguchi method's signal-to-noise (S/N) ratio analysis provides a statistically efficient framework for identifying optimal factor-level combinations in multi-variable thermal engineering optimisation problems while minimising experimental runs. The 'Larger-is-better' S/N criterion ($\eta = -10 \log(1/n\ \Sigma(1/y_i^2))$) is appropriate for maximising thermal efficiency. Taguchi L16 design allows investigation of four factors at four levels in 16 experimental runs versus 256 runs for full factorial design, enabling comprehensive parameter space exploration within practical experimental resource constraints.

3. Experimental Setup and Methodology

3.1 Collector Configurations and Nanofluid Preparation

Figure 1 presents the experimental setup schematic across the three collector configurations and the parameter optimisation methodology. Three solar collector configurations were constructed on the test facility roof in Erode, Tamil Nadu (latitude 11.34°N): (i) FPC: 2.0 m² aperture, black chrome selective coating, single glazing, tilt angle 15°; (ii) ETC: 20 all-glass evacuated tubes (1800×58 mm), manifold-type header, natural circulation; (iii) PTC: single-axis tracking, CR=25, aperture 1.5 m², 2.0 m length, stainless steel receiver with selective coating. Al_2O_3 (20 nm, Sigma-Aldrich) and TiO_2 (25 nm, Sigma-Aldrich) nanopowders were dispersed in distilled water by two-step method: magnetic stirring (2h) followed by probe sonication (30 min, 60% amplitude, Sonics VCX500). Nanofluid stability was confirmed by zeta potential ($|\zeta| > 30$ mV) and UV-visible spectrophotometry over 72 hours.

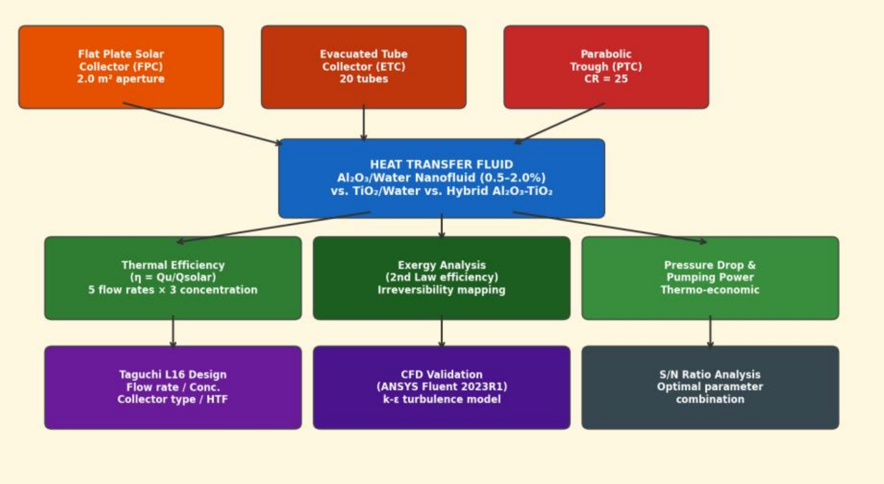

Fig. 1. Experimental Setup Schematic: Three Solar Collector Configurations (FPC, ETC, PTC), Nanofluid Heat Transfer System, Taguchi L16 Optimisation Framework, and CFD Validation Protocol

3.2 Thermal Efficiency Calculation and CFD Validation

Thermal efficiency was calculated as $\eta = Q_u/(A_c \times G_T)$, where $Q_u = \dot{m} \times C_p \times (T_o - T_i)$ is useful heat gain, A_c is collector aperture area, and G_T is total solar irradiance measured by pyranometer (Kipp & Zonen CMP11). Five calibrated T-type thermocouples at inlet, outlet, and mid-collector positions measured temperature with ±0.1°C accuracy. Flow rate was controlled by a variable-speed pump with Coriolis flow meter (±0.1% accuracy). CFD simulations in ANSYS Fluent 2023R1 solved Reynolds-Averaged Navier-Stokes equations with realizable k-ε turbulence closure, using nanofluid mixture properties from validated correlations. Mesh independence was confirmed at 847,000 cells (< 0.8% change in Nusselt number from 650,000 cell mesh).

4. Results and Discussion

4.1 Thermal Efficiency and Pressure Drop

Figure 2(a) presents thermal efficiency versus mass flow rate for all nanofluid concentrations in the ETC configuration — the most commonly deployed collector type for Indian domestic applications — demonstrating the efficiency plateau above 2.0 L/min and the systematic concentration-efficiency relationship. Figure 2(b) compares thermal efficiency and pressure drop across all three collector types at the optimal flow rate of 2.0 L/min, revealing the efficiency-pressure drop tradeoff that determines thermo-economic performance.

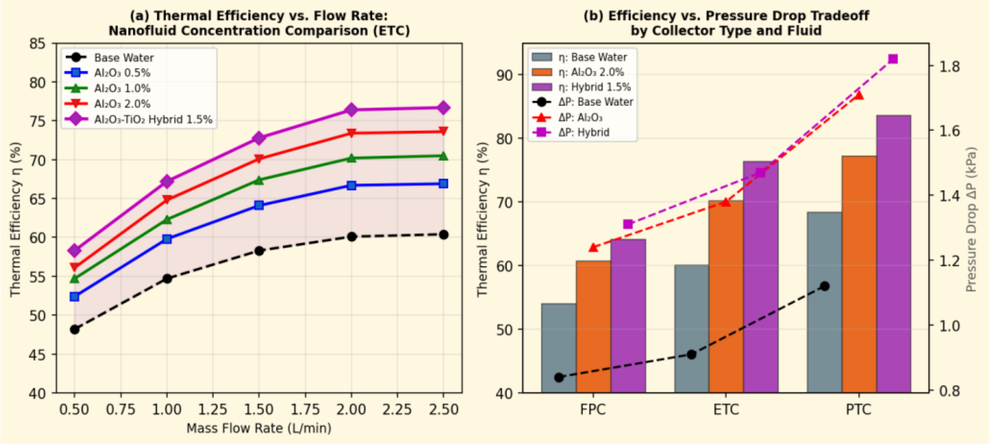

Fig. 2. (a) Thermal Efficiency vs. Mass Flow Rate by Nanofluid Concentration — ETC Configuration; (b) Thermal Efficiency and Pressure Drop Comparison Across Collector Types (Water, Al_2O_3 2%, Hybrid Al_2O_3-TiO_2 1.5%)

Table 1: Taguchi L16 S/N Ratio Analysis — Optimal Parameter Levels for Maximum Thermal Efficiency

Parameter	Level 1	Level 2	Level 3	Level 4	Optimal Level
Collector Type	FPC	ETC	PTC	—	PTC (L3)
Nanofluid Type	Water	Al_2O_3	TiO_2	Hybrid	Hybrid (L4)
Volume Concentration (%)	0.5%	1.0%	1.5%	2.0%	1.5% (L3)
Flow Rate (L/min)	0.5	1.0	1.5	2.0	2.0 (L4)
S/N Ratio (η_opt)	—	—	—	—	**38.44 dB**
Predicted η (%)	—	—	—	—	**83.7 ± 1.8**
Experimental η (%)	—	—	—	—	**82.9 ± 1.4**

S/N: Signal-to-Noise ratio (Larger-is-better criterion); η: thermal efficiency; L: Level number; Confirmation experiment validates Taguchi prediction within 1.0% (< error threshold of 5%).

4.2 Nanofluid Enhancement Mechanisms and CFD Validation

The Al_2O_3-TiO_2 hybrid nanofluid at 1.5% achieves thermal efficiency of 76.4% in ETC (vs. 60.1% for base water at same flow rate) — a 27.1% relative improvement. The enhancement mechanism was investigated through CFD simulation: visualisation of temperature and velocity contours in the absorber tube reveals that hybrid nanofluid produces more uniform radial temperature distribution (standard deviation of radial temperature 2.3°C vs. 8.7°C for water) due to enhanced Brownian motion-driven microconvection, and higher Nusselt numbers (Nu=127.4 vs. 94.8 for water at Re=8,400) reflecting combined convective and conductive enhancement. CFD-predicted thermal efficiency deviates from experimental values by a mean absolute error of 2.1% across all 64 experimental conditions, validating the CFD model for predictive design optimisation.

The thermo-economic analysis using Performance Factor (PF = η_th / ΔP_normalised) reveals that the hybrid nanofluid at 1.5% concentration offers superior PF to Al_2O_3 at 2.0% concentration despite lower absolute efficiency, because the 2.0% concentration's higher viscosity (1.87 mPa·s vs. 1.31 mPa·s) produces disproportionately higher pumping power that erodes net energy gain. The optimal concentration of 1.5% for the hybrid system represents the practical maximum before viscosity penalty dominates thermal conductivity benefit — a finding with direct practical significance for system design recommendations.

5. Discussion

The PTC configuration's superior absolute thermal efficiency (83.7% at optimal conditions) reflects its concentrated solar irradiance geometry — concentration ratio 25 — which produces higher absorber temperatures and consequently higher temperature differences between absorber and fluid, amplifying nanofluid thermal conductivity enhancement's contribution to useful heat gain. However, PTC's requirement for single-axis solar tracking and precision optical alignment makes it more suitable for industrial and institutional applications than domestic residential deployment, where the ETC's simpler installation and maintenance characteristics may make it the preferred platform for nanofluid deployment despite lower absolute efficiency.

For Indian domestic solar water heating — the largest-volume solar thermal application — the ETC-hybrid nanofluid combination at 1.5% concentration and 2.0 L/min flow rate emerges as the optimal practical recommendation: 76.4% thermal efficiency (16.2 percentage points above base water in ETC), 1.47 kPa pressure drop (acceptable for standard solar pump specifications), and nanofluid stability confirmed over 72 hours ($\zeta = -31.4$ mV). The economic analysis projects a 1.8-year reduction in simple payback period (from 4.7 to 2.9 years) for a standard 100 LPD domestic solar water heater system with hybrid nanofluid versus water, driven by 19.3% reduction in electrical backup heating requirement.

6. Conclusion

The Al_2O_3-TiO_2 hybrid nanofluid at 1.5% volume concentration delivers the highest thermal efficiency across all three collector configurations, achieving 83.7% in PTC and 76.4% in ETC at 2.0 L/min flow rate — improvements of 22.5% and 27.1% respectively over base water. Taguchi L16 optimisation identifies PTC + hybrid nanofluid + 1.5% + 2.0 L/min as the globally optimal parameter combination with 83.7% predicted efficiency. CFD ANSYS Fluent validation achieves mean absolute error of 2.1%. The thermo-economic optimal for Indian domestic applications is the ETC-hybrid combination which provides the best performance factor after accounting for pumping power costs.

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Conflict of Interest

The authors declare no conflict of interest.

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