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PERFORMANCE ENHANCEMENT OF FLAT-PLATE SOLAR COLLECTORS USING NOVEL ABSORBER CHANNEL GEOMETRIES AND FLOW ARRANGEMENTS: A CRITICAL REVIEW

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ABSTRACT

This critical review evaluates the thermal and hydraulic consequences of replacing conventional parallel-riser flat-plate solar collector absorbers with serpentine, spiral, dual-inlet, full-flow, and internally enhanced flow-channel arrangements. Published experimental and numerical investigations are synthesized in terms of useful heat gain, collector efficiency, temperature uniformity, pressure drop, pumping demand, exergy, and manufacturability. Reported improvements are meaningful only when collector area, irradiation, inlet temperature, flow rate and measurement method are comparable. The evidence indicates that extended flow contact and induced mixing can improve thermal performance, although added flow resistance may offset part of the gain. An integrated CFD–experimental methodology and reporting matrix are proposed to support reproducible comparative studies. This article is a literature review and reports no new measurements or computational results.

KEYWORDS: Flat-Plate Solar Collector; Absorber Geometry; Serpentine Channel; Spiral Flow; Heat-Transfer Enhancement; Cfd; Thermohydraulic Performance.

1. INTRODUCTION

Flat-plate solar collectors (FPSC) convert incident solar radiation into sensible heat transferred to a circulating liquid. Their enduring relevance comes from mechanical simplicity, moderate operating temperatures and compatibility with process preheating, domestic hot water and solar-assisted heat pumps. Classical collector theory establishes the

useful-gain relation $Q_u = A_c F_R[(\tau\alpha)G_T - U_L(T_{in} - T_a)]$, where heat-removal factor F_R depends partly on the absorber-to-fluid thermal pathway. The geometric arrangement of riser tubes or channels is consequently a design variable rather than merely a fabrication detail [1–4].

In conventional header-riser layouts, comparatively short parallel flow paths limit hydraulic resistance, but maldistribution among branches and incomplete absorber coverage can promote nonuniform plate temperature. Serpentine circuits increase residence time and wetted area; spiral paths redistribute heat extraction spatially; full-flow absorbers enhance absorber-fluid contact; and passive inserts intensify convection. No configuration is uniformly superior because improvement in thermal pickup may be accompanied by higher pressure loss, additional fabrication complexity or higher cost [8–15].

This review has two objectives. First, it critically compares the dominant absorber channel and flow arrangements without conflating results from dissimilar solar or hydraulic boundary conditions. Second, it outlines a defensible numerical–experimental framework for the paper title, while identifying the unresolved optimization issue: simultaneous maximization of useful heat output and exergy with minimization of pumping power and manufacturing burden.

2. Historical Development and Importance

Early flat-plate collector development emphasized optical absorption, conductive coupling of a bonded metal plate to headers and risers, and reduction of top, bottom and edge losses. Standardized efficiency curves and heat-removal factors enabled evaluation across many designs [1–3]. With CFD and affordable numerical solvers, researchers began examining local temperature fields, recirculation and fluid distribution rather than judging designs solely by outlet temperature.

The more recent shift is from a single flow passage toward spatially optimized channel networks: serpentine and spiral paths, full-width channels, multi-inlet routing, fins, porous media, grooved tubing and flow inserts [8–18]. This transition is important because future solar applications may demand compact panels with acceptable pumping power and reliable manufacturing rather than only the maximum laboratory thermal efficiency. Rigorous characterization must therefore include hydraulic, exergy and economic metrics.

3. Review Methodology

This paper uses a structured narrative approach. Directly relevant journal studies and collector-testing sources were selected around the terms flat-plate solar collector, absorber channel, parallel/serpentine/spiral, hydraulic losses, CFD and experimental validation. Preference was given to investigations defining their geometry, working fluid, operating conditions, thermal metric and baseline. PV/T collector geometry papers were considered only as indirect supporting evidence because electrical cooling changes the objective function.

The included works were qualitatively coded by absorber layout, evidence type, comparative baseline, reported performance direction and limiting uncertainty. Extracted results were not pooled as a meta-analysis because solar irradiance, collector area, mass-flow regime, glazing, inlet temperature, working fluid and metric definitions are not standardized across all reports. Literature claims are referenced in numerical order; proposed comparison protocols are author synthesis, not findings of a new experiment.

4. Literature Survey

Vengadesan and Senthil [8] evaluated straight and twisted inserts under specified flow and reported that double-slit twisted tape provided a much larger convective coefficient than the plain absorber; the same study explicitly noted an increase in pressure drop. Their work therefore supports the mechanism of mixing-induced heat transfer while cautioning that a fair design ranking must include pumping work. A related field study [9] reported higher energy and exergy efficiency for serpentine channels than a conventional FPSC under comparable water-flow conditions, but this does not imply identical benefits for all temperatures and collector sizes.

He et al. [10] developed a stainless-steel full-flow configuration and used numerical design analysis followed by experimental validation. This study suggests a route toward improved plate-fluid thermal coupling and manufacturing integration, yet transferability depends on channel hydraulic dimensions and flow resistance. Zheng et al. [11] addressed a different axis of collector enhancement—reduced thermal losses using advanced insulation—showing why an absorber geometry comparison must hold optical and loss-side design features constant rather than credit every change to the channels.

Kansara et al. [12] combined CFD and experiment to assess internal fins and porous media, reporting improved behavior over an empty channel. The result illustrates the value of local flow-field interrogation but also raises questions regarding fouling, cleaning and

repeatability. A later numerical twisted-tape investigation [13] reported a thermohydraulic performance factor up to 2.41 for a specific insert geometry and Reynolds-number window; this represents a study-specific criterion, not a universal collector-efficiency multiplier.

Experimental comparison of parallel and spiral tube collectors [14] found improved efficiency and exergy with spiral routing, while the measured pressure-drop direction depended on its particular geometry and test circuit. The dual-spiral study [15] likewise demonstrated gains at selected mass-flow rates. These works imply that increased total flow-path length does not determine hydraulic loss on its own: diameter, parallelization, bends and manifold design must all be considered. A modified dual-inlet serpentine absorber [16] directly addresses fluid distribution, providing an alternative to simply extending channel length.

Collector heat-removal-factor experiments [17] compared serpentine, parallel-wall-to-wall and spiral configurations and established that changes in F_R are sensitive to mass-flow and thermal conditions. Modern studies of grooved tubes and helically structured absorbers [18,19] add newer microgeometry and optimization variables. Samad et al. [18] distinguished maximum Nusselt enhancement from the geometry achieving maximum overall performance criterion, demonstrating that a single heat-transfer metric can select a hydraulically unattractive configuration.

PV/T-related investigations [21–26] enrich the geometry discussion by comparing serpentine, multipath, spiral, and fractal-inspired distributions. However, PV/T electrical efficiency and cell temperature are not direct substitutes for a stand-alone water-heating collector efficiency. Their findings should inform hypotheses on temperature uniformity and routing while the final FPSC ranking remains anchored to a separately validated thermal and hydraulic dataset.

5. Proposed Numerical and Experimental Methodology

A recommended investigation would manufacture equal-aperture-area collectors (for example, 1 m² each) with identical glazing, insulation, absorber alloy, coating and inclination. The baseline would be parallel risers, compared with single serpentine, dual-inlet serpentine, spiral, dual-spiral and full-flow layouts. Important controlled quantities are hydraulic diameter, total fluid volume, channel-wall thickness, inlet water temperature, measured global irradiance and ambient wind. A design-of-experiments matrix should vary water flow rate and inlet reduced temperature while capturing at least three irradiance regimes.

A steady or transient CFD model should solve continuity, momentum and energy equations in the fluid, with conjugate conduction in the metal absorber and externally defined solar

loading and heat loss. Mesh independence should be established using outlet-temperature, useful-heat and pressure-drop convergence; turbulence-model selection must be based on actual Reynolds numbers. Boundary conditions must match laboratory measurements. Model validation should report mean absolute percentage error or normalized RMSE across multiple independent time points, with sensor calibration and energy balance closure.

Useful heat is $Q_u = m_{dot}\, c_p(T_{out} - T_{in})$, collector thermal efficiency is $\eta_{th} = Q_u/(A_c\, G_T)$, pumping power is $W_p = \Delta p\, V_{dot}/\eta_p$, and net thermal gain may be expressed as $Q_{net} = Q_u - W_p$ where electrical and thermal energy accounting conventions are explicitly stated. A physically meaningful ranking should consider η_{th} and heat-removal factor together with Δp, entropy generation, exergy efficiency, material mass, fabrication cost and long-term fouling. A multi-objective Pareto front is preferable to an unweighted list of highest temperatures.

6. Discussion and Comparative Analysis

Table 1 contrasts the designs on mechanisms and plausible penalties; qualitative descriptors are not numerical measurements. Table 2 collects reportable evidence from selected published papers and deliberately preserves the original study context. An observed increase in efficiency in one paper cannot be compared numerically with a percentage change in heat-transfer coefficient in another without reconciling the reference definition and operating point.

The central trade-off is between thermal contact and pumping demand. A long serpentine channel can suppress flow maldistribution but raise resistance; parallel circuits may reduce pump loading but require carefully balanced headers; a spiral can target hotter regions but may have challenging bend fabrication. Full-flow channels can reduce plate conduction paths yet require reliable watertight joints. Inserts and surface textures increase local convection while also raising cleaning and pressure-loss concerns. Performance should be normalized to absorber area, pump consumption and useful delivery temperature.

The literature also indicates a gap between computationally optimized geometry and outdoor reliability. CFD outcomes are sensitive to simplified thermal radiation and wind conditions; experimental datasets may cover limited seasons. Future studies should evaluate not only maximum instantaneous gain, but annual useful yield, flow control, scaling, freezing, manufacturing variation and life-cycle cost under climate-specific load profiles.

Table 1. Qualitative comparison of absorber flow-path families (author synthesis).

Arrangement	Heat-transfer mechanism	Main limitation
Parallel risers	Short paths; multiple channels	Branch maldistribution; less plate coverage
Single serpentine	Extended contact, sequential heating	Potential high Δp and outlet hot spot
Spiral / dual spiral	Spatially distributed pickup	Bend losses; fabrication complexity
Dual-inlet serpentine	Reduced local flow-path burden	Manifold/control balance
Full-flow absorber	Large plate–fluid contact	Sealing, fabrication, fouling
Internal inserts / grooves	Boundary-layer disruption	Pressure penalty and cleaning

Table 2. Representative published evidence (different conditions; not a pooled ranking).

Study	Configuration	Reported observation
[8] Vengadesan & Senthil	Double-slit twisted insert	Higher heat-transfer coefficient; higher Δp
[9] Vengadesan & Senthil	Serpentine vs. conventional	Higher energy/exergy at selected flow
[10] He et al.	Stainless-steel full-flow	Experimental corroboration of model
[12] Kansara et al.	Fins and porous media	Improved performance over empty channel
[14] Spiral/parallel study	Spiral tube collector	Improved thermal/exergy in tested case
[18] Samad et al.	Helical grooves and turbulator	Best Nu differs from best PEC

7. Research Outcomes and Future Scope

The synthesized evidence supports four conclusions: (i) channel geometry affects both heat transfer and flow distribution; (ii) enhanced mixing can improve collector performance but frequently changes pressure demand; (iii) reported percentages are strongly contingent on testing and metric definitions; and (iv) hybrid numerical–experimental validation is required before recommending a design for practice. A research gap remains in same-area, same-material, same-boundary-condition comparisons among six or more channel families with a unified economic metric.

A suitable next study would use verified 3D conjugate CFD to construct response surfaces for channel topology, manifold count and flow rate, validate selected prototypes outdoors, then identify Pareto-optimal combinations of net useful energy, exergy, pressure drop and life-cycle cost. The novelty would come from the specific geometry and reproducible comparison—not merely from the use of CFD or an existing serpentine path.

7.1. Critical Design Issues for Future Numerical Studies

For strict comparisons, hydraulic diameter is a particularly important confounder. Holding channel cross-sectional area fixed is not equivalent to holding wetted perimeter, Reynolds number, fluid residence time or pump power fixed. Investigators should therefore present at least two normalizations: equal mass flow and equal pumping power. A geometry that appears favorable under equal-flow conditions may lose its advantage when pump demand is constrained. This distinction matters in low-cost solar thermal installations, where parasitic electricity may be a non-negligible part of delivered heat cost.

The choice of thermal boundary condition is similarly decisive. Prescribed uniform heat flux on the absorber is convenient for CFD but understates the feedback between absorber temperature and radiation/convection losses. A more realistic simulation resolves the metal plate, tube contact conductance, solar absorptance, glazing loss and wind-dependent external convection. If vacuum insulation, selective coating or glazing are altered between design cases, their contribution must be separated from the effect of channel geometry. Use measured irradiance, ambient temperature and wind speed, and report whether the flow is laminar, transitional or turbulent in every geometry.

An experiment should quantify uncertainty in inlet and outlet temperature, thermocouple placement, flow-meter calibration, irradiance measurement and pressure transducer readings. The uncertainty in water-side useful heat is amplified when the inlet–outlet temperature rise is small. Pressure measurements should ideally include the collector core alone and the complete test rig separately, because manifolds, valves and connecting tubes can obscure changes due to absorber topology. Test repetitions under steady solar simulator operation and outdoor conditions would help determine whether the apparent optimal channel is robust.

Temperature uniformity deserves a distinct outcome variable. Two collectors could deliver equal useful heat yet produce different absorber hot spots, which affects thermal stresses, material fatigue and, in a PV/T variant, cell power loss. Surface temperature maps from calibrated infrared images or distributed thermocouples should therefore complement mean outlet-temperature measurements. Long-term service assessment should also address scaling, stagnation temperatures, freeze protection, tube corrosion and ease of cleaning, particularly for small-hydraulic-diameter or insert-enhanced channels.

A practical reporting checklist would disclose a dimensioned channel drawing, absorber thickness, wetted area, number of passes, manifold strategy, total fluid volume, flow distribution, local Reynolds-number definition, solver and mesh convergence, sensor uncertainties, test duration, ambient conditions and pump efficiency. The recommended

design is the one that maintains useful thermal advantage across realistic flow and inlet-temperature ranges while satisfying pressure, cost and durability constraints—not simply the configuration with the highest instantaneous efficiency in a single test.

8. CONCLUSION

Novel flat-plate absorber flow paths provide credible opportunities to improve thermal performance and temperature uniformity. The most informative published works combine a defined baseline with detailed hydraulic reporting and experimental support. Serpentine, spiral, multi-inlet and full-flow collectors all offer distinct benefits; none can be declared globally superior from heterogeneous literature. Future contributions should use common boundary conditions, report pump penalties alongside thermal gains, and connect model-derived optimum designs to experimental and economic validation.

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