



PASSIVE HEAT TRANSFER ENHANCEMENT TECHNIQUES IN FLAT-PLATE SOLAR COLLECTORS: A COMPREHENSIVE

Ahmed Qahtan Bahlol¹

Ansam Adil Mohammed^{2*}

Shylesha Channapattana³

ahmedbayatly6@gmail.com

ansam.a.mohammed@nahrainuniv.edu.iq

shylesha@gmail.com

^{1,2*} Department of Mechanical Engineering, College of Engineering, Al- Nahrain University, Jadriya, Baghdad, Iraq

³Department of Mechanical Engineering, Karnatak Law Society's Vishwanathrao Deshpande Institute of Technology, Haliyal, Visvesvaraya Technological University, Karnataka, India

ABSTRACT

This comprehensive review consistently investigates the techniques of passive enhancement for refining convective heat transfer in flat plate solar collectors (FPSCs) and concentrate on the techniques that persuade swirling flow to deactivate the thermal boundary layer in the flow of the fluids. The main aim is to introduce a structured evaluation of four strategic classifications: geometric modifications on the absorber surfaces, insertion of vortex generators devices, exploitation of Nanofluids and amalgamation of phase change materials (PCMs). This analysis summarizes the results that were obtained from numerical and experimental studies to estimate thermal performance against associated hydraulic compensations. The main results mentioned that V-corrugated absorber surfaces can improved the thermal efficiency by (25%–30%), while the twisted tape inserts upgrade the heat transfer coefficient by up to 70% compared to the smooth tubes nevertheless Nanofluids particularly the Copper oxide/water mixture contributed to an increase in the thermal efficiency approximately (20%). However, these thermal enhancements are consistently escorted by increased pressure drop confirmation of a critical balance in performance. This explanation emphasizes that hybrid systems, such as combining geometric modifications of absorbent surfaces with the use of Nanofluids, offer the most viable solution for improving overall thermos hydrodynamic performance.

Future research should prioritize the development of such integrated systems, alongside comprehensive economic and lifecycle assessments to ensure practical viability.

Keywords: Corrugated Absorber Plate, Flat-Plate Solar Collectors, Thermal Efficiency, Fins, Heat Transfer Enhancement.

NOMENCLATURE

ΔP

Pressure drops

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ΔT	Temperature difference
Re	Reynolds number
Pr	Prandtl number
Nu	Nusselt number
HTC	Heat transfer coefficient
CHTC	Convective heat transfer coefficient
PEC	Performance evaluation criterion
ℓ	Length or spacing
ID	Inner diameter
OD	Outer diameter
L	Length
SAH	Solar air heater
FPSC	Flat-plate solar collector
PCM	Phase change materials
MF	Metal foam
TiN	Titanium nitride
Al ₂ O ₃	Aluminum oxide
CuO	Copper oxide
TiO ₂	Titanium dioxide
SWCNT	Single-wall carbon nanotube
CQDs	Carbon quantum dots
TR	Twist ratio
Gr	Grashof number
Ra	Rayleigh number
Ri	Richardson number
P _{mpp}	Maximum power point power
FEM	Finite element method
CFD	Computational fluid dynamics
SST-K ω	Shear stress transport turbulence model
TRNSYS	Transient system simulation software
OD	Outer diameter
ID	Inside diameter

INTRODUCTION

Flat-plate solar collectors represent one of the most widely deployed technologies in the renewable energy sector, primarily employed for meeting domestic and commercial hot water demands, as well as to secure hot air needs for heating homes and buildings, as shown in Figure 1 (Natarajan et al., 2024). The most prominent problem facing these systems is that the conversion and transfer of energy from the absorbing surfaces to the water or air is limited, where this flow creates a thermal boundary layer that acts as a type of insulator to a decrease in the thermal performance of the solar collector (Vengadesan et al., 2025); (Jaber

et al., 2022); (Shbailat et al., 2023). To address this limitation, research has explored passive heat transfer intensification techniques, which does not require an external energy source (Abbas et al.,2024) ; (Al-Qalamchi and A.,2007), as shown in Figure 2 (Vijayakumar et al., 2017) .The most prominent of these important methods is the creation of a spiral or swirling flow in the flow path, as this work leads to a continuous reduction of the boundary layer by creating turbulent or swirling movements in the fluid, which works to mix more between the fluid adjacent to the hot surface and the fluid in the middle of the flow, which in turn works to enhance heat transfer by convection (Mustafa et al.,2025) ; (Mohammed et al., 2024) .A spiral flow can be created using many methods, such as: Use twisted strips, corrugated pipes, spiral grooves, or other engineering design for the channels. (Mohammed et al.,2022) ; (Mohammed et al.,2023); (Mohammed et al.,2023) ; (Mohammed et al., 2025); (Mohammed et al.,2024); (Shakir et al.,2025).

This literature review aims to explore and summarize the various methodologies used across the components of a flat-plate solar thermal collector , and analyze their impact on hydrodynamic properties encompassing both hydraulic characteristics (such as pressure drop) and key thermal performance metrics (including the heat transfer coefficient and thermal efficiency), presenting a systematic assessment of the feasibility and effectiveness of this technology in improving the performance of solar collectors. Some studies have used experimental methodologies, others have used numerical methodologies, and others have used comparisons between practical and theoretical solar collectors.

This review presents a study on solar collectors that use water, air, or nanofluids to generate electricity or hot water in engineering applications. With the presentation of studies using different configurations of solar collectors using corrugated absorber surfaces, inserting wire coils, metal strips or spiral tubes across the components of a flat-plate solar thermal collector, flat plate solar collector with cover, sheath or coating, use of different geometric tubes, panels and outlets in the solar collector, use of fins, protrusions or holes, use of phase change materials, use of triangular solar collector, use of different air gaps within the interstitial space separating the absorber plate and the transparent cover across the components of a flat-plate solar thermal collector, and solar collector with twisted evaporator.

This reference study aims to provide a systematic and critical analysis of passive heat transfer optimization techniques in flat-plate solar collectors, with a particular focus on vortex-generating methods that break the thermal boundary layer. Although several previous reviews have addressed individual optimization strategies separately, a clear gap remains in the scientific literature regarding the comparative evaluation of these techniques against standardized thermal and hydraulic performance criteria. Furthermore, the potential synergies of hybrid systems combining multiple optimization methods have not been systematically compiled and analyzed. Therefore, this research seeks to systematically classify passive optimization techniques based on their underlying fluid dynamics and to

quantitatively compare thermal gains versus hydraulic losses using standardized performance indicators such as the performance evaluation criterion.

METHODOLOGY

The present review is planned by a construct methodology prepared to make certain a comprehensive and unbiased valuation of the passive heat transfer enhancement in flat plate solar collectors.

The premier stage requires the systematic correspondence and categorization of relevant literature into distinct groups according to the primary enhancement strategy employed: geometric modifications, swirl flow devices, Nanofluids, and phase change materials. The next step involved comparing and stabilize the development in heat transfer and the raised of flow resistant using a certain methodology to review each type according to its performance such as thermal efficiency, pressure drop and heat transfer coefficient. Finally, by combining the information from large scales experimental and numerical research this review delivers a well-documented summary of each method and its effectiveness and appropriate approach, thus given a solid base of conclusion and suggestions for more advanced research also this review is navigable by a structured methodology intended to secure a comprehensive and unbiased estimation of passive heat transfer enhancement in solar collector.

The chosen studies maintain predefined process and exclusion standard. Studies were included that: examined passive convection heat transfer optimization mechanism in flat plate solar collectors focusing on spiral or vortex flow generation, provided quantitative evidence on thermal performance (e.g., efficiency and Nusselt number) and hydraulic performance (e.g., pressure drop) that converge essentially on photovoltaic systems, concentrated solar system collectors or active optimization methods needed an external power source were eliminated.

HEAT TRANSFER ENHANCEMENT METHODS FOR CORRUGATED ABSORBERS

Most of the research in the field of flat plate solar collectors that uses improvements in the thermal energy transfer and conversion processes works on modifying or adding to the absorbing surfaces, where the use of absorbing surfaces with undulations such as undulations in the shape of the letter (V) or sinusoidal undulations is the most prominent factor to maximize heat transfer, as it works to increase the surface area for conduction and by reducing the insulating blocking layer and creating turbulence that leads to increased thermal energy and convection transfer between the absorbing surface and the fluid. The methodology for studying these additions and improvements is divided into a numerical methodology, including computational fluid dynamics (CFD), finite element methods (FEM), and difference-seeking models to simulate complex thermos-hydrodynamic behavior, and practical experiments, which are often used together to verify the validity of the results. As well as improving the geometric shapes such as the ripple shapes, angles,

wavelength, and predicting the efficiency measures and Nusselt number and the friction coefficient. Also, practical studies show experimental evidence in real conditions where critical results including exit temperature, thermal efficiency, and pressure drop are measured and compared to determine the internal balance between thermal improvement and related increases in pumping power. The tables 1, 2, and 3 classify the reviewed articles based on their approach to investigation, identifying the design parameters and the main results.

In Table 1: Simulation models showed that V-shaped corrugated panels (at a 45° angle) achieve the highest Nusselt number improvement (up to ~27%) compared to smooth surfaces, due to effective boundary layer disruption. Fins conjunction also upgrades the thermal performance but remarkable increases the pressure loss that requires a multi-target for optimization.

In Table 2: the experimental research has consistently established the advantage of (V) shaped corrugated absorbers reaching to (8%- 14.5%) higher thermal efficiency than smooth flat plate, Dimples or metallized foam (MF) surfaces at a 45° angle also reveals an exceptional performance that made the efficiencies raised up to (98.8%) and highlighting of the importance of surface geometry in generating turbulence.

In Table 3: The conjunction of numerical and experimental conclusively assert that corrugation progress the heat transfer with a (12%–35%) increase in efficiency but it also highlights the critical trade-off with increased of pressure loss. This proposal is needed for a balanced optimization that gives through to overall thermal-hydraulic performance.

NANOFLUIDS AND STRUCTURAL MODIFICATIONS

Solar energy is a renewable energy source, flat-plate solar collectors are widely utilized for conversion the thermal energy due to their structural robustness and easy for operation. However, a major limitation is the ingrained thermophysical properties of available heat transfer fluids. To tying this suppression, research has increasingly turned to designed colloidal suspensions of nanoparticles in a base fluid. These new-generation fluids have improved thermal conductivity and convective heat transfer performance. Current research has systematically investigated a wide range of nanofluid formulations, such as single-phase nanoparticles and composite hybrid configurations, to evaluate their potential to enhance collector performance, and structural modifications such as corrugated absorbers or turbulence inducers to improve collector performance. This brief presents all the numerical and experimental results from selected studies, focusing on the main changes in heat transfer and how to improve thermal efficiency.

The second part presents an analysis of the innovations and how they can improve solar thermal technology. Studies have shown that the most important part of improving the thermal efficiency of solar collectors is structural modifications and the application of nanofluids. These fluids progress heat transfer and thermal storage while structural variations focus on changes in the absorber surfaces such as corrugated surfaces or

turbulence spoiler and the results confirm that the use of hybrid nanofluids and hybrid engineering process can supply significant advantage on improving the heat transfer as shown in Table 4.

In Table 4: a copper oxide/water (CuO/water) mixing show an excellent thermal efficiency up to (87.8%) due to its high thermal conductivity.

WIRE COILS AND SPIRAL INSERTS

The researchers (MARTÍN et al., 2011); (García et al., 2013); (Ibrahim, and Ahmed, 2025) discussed the wire-coiled solar collectors and their benefits for improving heat transfer. A comparison was made between a wire-coiled collector and a conventional one under the same conditions and performance. The results were in favor of the wire-coiled collector, especially in low flow conditions. This indicates that this method as one of the effective methods for improving heat transfer.

(Vijayakumar et al., 2014) studied the improvement in thermal performance achieved through the addition of a composite passive insert in the riser tubes of a flat-plate solar collector. The insert arrangement is a coiled-wire turbulator situated adjacent to the tube wall, supplemented by a twisted-tape insert positioned within the coaxial core of the coil. This geometry results in the formation of uninterrupted vortices in both peripheral and central flow regions, which creates a good mixing mechanism that disrupts the thermal boundary layer throughout the flow system.

(García et al., 2018) demonstrate a comprehensive comparison of experimental studies on a flat-plate solar collector used for water heating, which was provided with various geometric shapes, including three wire coil geometries and three twisted strip geometries. It was found that there is a pressure drop, which led to obtaining a fully developed friction coefficient within the Reynolds number range of 80-9000.

(Verma et al., 2020) showed a new flat-panel collector design, using a continuous-flow, spiral-shaped tube instead of the traditional multi-tube design. This new collector type, under the same operating conditions as conventional collectors, showed a clear and tangible improvement in performance, with a 21.94% improvement in thermal efficiency compared to the old conventional design. The reason for this improvement is that the flow distribution in the spiral shape prevents fluid flow distribution problems while maintaining structural simplicity.

(Abbas et al., 2023) establish the thermo-hydraulic performance of microbubble injection in the hydronic circuit of a solar water heater apparatus. Experimental flow circuit consisted of an 11-turn copper pipe 15 meters in overall length and 0.012 meters inner diameter. For increased solar energy absorption, the inner absorber surface was treated with a nanocomposite coating made up of a matte black matrix with 5% titanium nitride (TiN) thermochromics pigment to absorb irradiance. As shown in Table 5.

In Table 5: incorporating spiral wire coils or tubes significantly improves thermal efficiency (1–22%), especially in low-flow systems. Continuous spiral designs outperform

conventional multi-tube designs by up to 21.94%, due to better flow distribution and reduced pressure issues.

TWISTED INSERTS FOR SWIRL FLOW

The studies confirm that the primary mechanism for improving heat transfer using these (twisted) inserts is the creation of turbulent flow and vorticity, which breaks the thermally stratified fluid region adjacent to a surface and enhances fluid mixing. Shape and geometry are the concern to determine the optimal shape or geometry for the enhancer. More complex shapes (double, truncated) were found to be better in (Ameen et al., 2015); (Merzha et al., 2019) while a lower twist ratio was found to be better in (Hassan et al., 2015); (Abbas, and Mohammed, 2023). When comparing materials copper always exhibited better thermal performance than aluminum due to the larger thermal conductivity of copper. The research concurred that system efficiency is greatly influenced by fluid flow rate, with the optimum values or better performance achieved with increasing flow .

In Table 6: twisted double bands (DT) and winged pairs (RWP) are superior in generating longitudinal vortices and disrupting the boundary layer. Copper, as a material, outperforms aluminum due to its higher thermal conductivity. The flow rate (Reynolds number) has a significant impact; increasing it improves heat transfer but also increases of the drop pressure.

PASSIVE TECHNIQUES AND TRADE-OFFS

Some studies have used passive techniques to improve heat transfer, meaning they do not require external energy to operate and rely on changes in engineering design. All methods have shown significant improvements in system performance, whether through increased thermal energy or improved electrical efficiency. A common underlying mechanism is the disruption and replacement of the boundary layer (thermal or hydrodynamic) by increasing turbulence or surface area. Research acknowledges that the improved of heat transfer is substitute by increased pressure drop that requiring a greater pumping power or further cost and weight. The studies depend on advanced analytical equipment such as computational fluid dynamics (CFD) software or mathematical modeling to reach at and validate their results.

In Table 7: all passive technique operates by a main mechanism that disrupting the thermal boundary layer by increasing turbulence or surface area. The visible global is a compromise between thermal improvement (16–20%) and increased the flow resistance (1.3) times higher pressure loss that focus on the need for multi-parameter optimization.

SURFACE TREATMENTS AND COATINGS

Conducted an advanced surface treatment study to increase heat transfer, using black coating on the absorber tubes and plates. It focuses on achieving high thermal efficiency while reducing pumping energy consumption, and combines improved thermal performance

with cost-effectiveness, making it a successful example of combining performance and cost in Solar-thermal energy conversion systems (Hobbi, and Siddiqui, 2009).

Inspected on the thermo hydraulic performance enhancement of a flat plate solar collector (FPSC) through surface modification of its copper elements. The absorber plate canal affords an abrasive surface treatment process utilizing compressed steel grains conducting in controlled micro-scale roughness that improves fatigue resistance, mechanical strength and surface area. The primary research objective focuses on augmenting the convective heat transfer coefficient (CHTC) while minimizing parasitic pumping power requirements. This is achieved by promoting the thermal communication between the irradiated absorber surface and heat transfer fluid through extended surface structure (Poongavanam et al., 2020).

In Table 8: the results indicate that shot peening of the surface to increase micro-roughness, combined with a high-quality black coating, offers a balanced solution for enhancing convection heat transfer (CHTC) while maintaining relatively acceptable pumping efficiency. While eddy current generators improve performance, their relative effectiveness is highly dependent on the prevailing convection system.

MATERIAL AND DESIGN INNOVATIONS

Demonstrated that the creation of a system with increased thermal efficiency and improved economic viability was the main goal driving the design and testing of the solar air collector system by using energy and exergy analysis to determine the best operating parameters and component selection. To assess collector performance under standardized settings, experiments were carried out in compliance with European Standard EN 12975 2006 and ASHRAE Standard 93-86 (Ion, and Martins, 2006). Provided a comprehensive overview of techniques used to improve heat transfer in a flat-plate solar collector. It presents the possible improvements of nanofluids and conductive properties such as the material used for the absorber plate. It also demonstrates the effects that occur when combining more than one strategy, providing results that include information about system components, performance, and environmental impacts to guide future research in improving the shapes and materials of solar collectors (Sharma et al., 2022).

In Table 9: that a systematic design approach based on energy and exergy analysis is fundamental to achieving efficient and cost-effective collector systems. It highlights that optimizing the entire collector system requires a holistic consideration of all components (absorbent plate, tubing, transport fluid) and their materials, rather than focusing on an isolated component.

TRIANGULAR COLLECTOR EVALUATION

Used a flat solar collector as a triangular shape in the Figure 3 and an experimental comparison between the plain and winding tube designs according to the guidelines of the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). This experimental study was managed in a hot and dry region in the Islamic Republic of

Iran to measurement the system response to changes such as fluid flow rate, ambient temperature and solar radiation intensity. The results reveal that a maximum thermal efficiency of (58.9%) was carried out and the pressure drop was maintained at less than (0.1) bar which supports the suitability of this type of solar collector for water heating (Moravej M,2021).

GEOMETRY OPTIMIZATION

With a focus on the geometric configuration several researches had been used advanced numerical modeling and experimental methodologies to raise the thermal performance of flat-plate solar collectors (FPSCs). A verified numerical model was created to determine an ideal collector design for particular weather patterns (Al-Ajlan et al.,2003). While that the geometry of a circular tube compared to that of a flat plate has a significant effect on the convective heat transfer and provides a fundamental engagement for laminar flow (Amirgaliyev et al., 2019). A CFD simulations have demonstrated that scaling up collector units can improve the efficiency by (1%-4%)because of their superior heat retention characteristics and Later studies have reinforced the importance of geometric optimization in achieving further gains (Wang et al.,2019). Heat transmission to the working fluid is intensified by extending fluid flow channels and implementing bio-inspired cross-sectional geometries, including a circular flower design (Quitiaquez et al.,2021). In support of this, found that, in laminar conditions, absorber plate corrugation more especially, rib height and pitch offers the most noticeable gains in thermal and flow performance, surpassing even other variables like tube diameter or inclination angle (Quitiaquez et al.,2023); (Lopes, and Salviano, 2024).

In Table 10: optimizing the absorber surface geometry (corrugation, height, pitch) has the greatest impact on thermal performance (14-25% improvement) under laminar flow, outperforming other changes such as pipe diameter or angle of inclination. Nature-inspired geometries (such as rosettes) and large-scale collectors achieve higher efficiency by improving heat distribution and retention.

CRITICAL COMPARISON

Flat-plate solar collectors often suffer from limited thermal efficiency due to the insulating effect of the laminar thermal boundary layer. Passive enhancement techniques that encourage swirling flow present a promising settling by disrupting the boundary layer and elevate turbulent mixing. This review was inspected of four primary classifications: geometric modifications to absorber surface plates such as the (V) corrugations, insertion of swirl or vortex generating devices (e.g., twisted tapes), utilization of nanofluids and the integration of phase change materials (PCMs). Each method can boost convective heat transfer, with (V)corrugated surfaces raising the thermal efficiency by (25%–30%) and twisted tapes increased the heat transfer coefficient by up to (70%). However, these thermal gains are joined by a considering hydraulic loses that increased the pressure drop that required a careful thermo hydraulic performance trade-off. Hybrid systems also combining

multiple techniques such as corrugated surfaces with nanofluids, emerge as the most effective approach for optimizing of overall collector performance balancing enhanced heat transfer with manageable flow resistance. Future work should be concentrated on standardized performance evaluation and lifecycle analysis of these integrated systems.

CONCLUSION

This review dissolve that the passive techniques notably enhanced the thermal performance of the flat-plate solar collectors, Geometric modifications further improved by this effect specially with V-shaped corrugate surfaces that the efficiency increased by (25%–30%) by unsettle the thermal boundary layer, Vortex generator devices such as the twisted strip provided the top increase in heat transfer coefficient by reaching (70%) in spite of a notable pressure loses of (30%–80%) , The conjunction of copper oxide/water nanofluids and phase-change materials lend to an increased in the thermal energy settlement and improved the efficiency by (20%). To equilibrium the thermal gains and pressure losses future research should prioritize optimizing the multiple parameters using performance valuation. Furthermore, assessments of total economic cost and environmental impact, as well as the development of hybrid systems, are essential to ensure the viability of these technologies on a large scale under diverse climatic conditions.

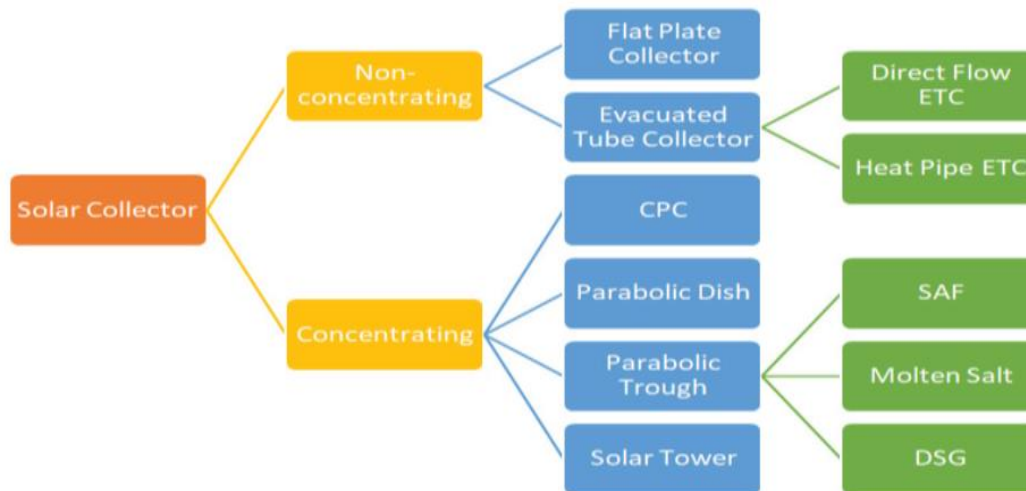


Fig. 1. Kinds of solar collectors.

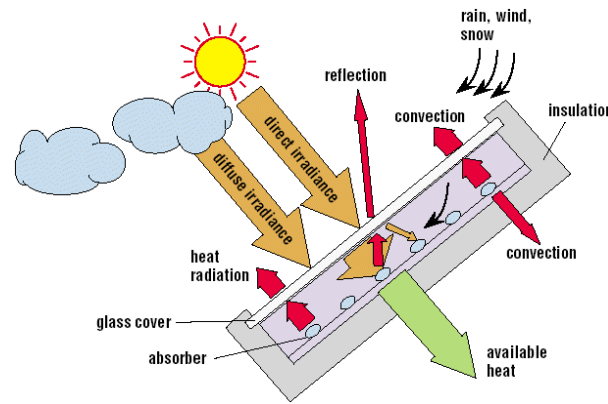
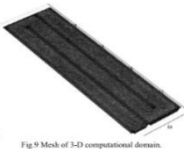
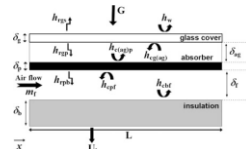


Fig. 2. Schematic of a standard flat-plate solar collector (FPSC).



Fig. 3. Photo of the triangular flat plate collector.

Table 1. Numerical studies on corrugated absorber solar collectors.

(Author, Year)	Configuration	Design Specifications	Key Findings
(Álvarez et al.,2010)	 Fig.9 Mesh of 3-D computational domain.	Serpentine tube collector.	Simulated thermal/hydrodynamic behavior; achieved 84.5% thermal efficiency.
(Ferouali et al.,2015)		Transient model for flat and V-corrugated air collectors.	Model showed >95% accuracy against experimental data for outlet temperature.

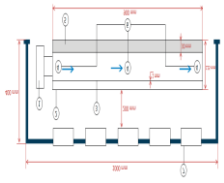
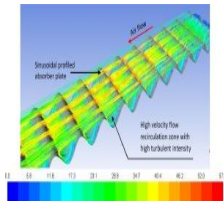
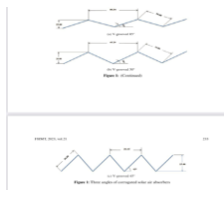
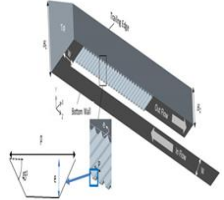
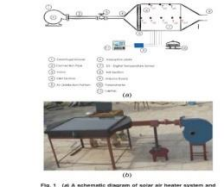
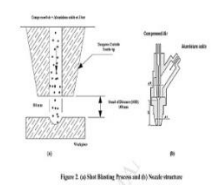
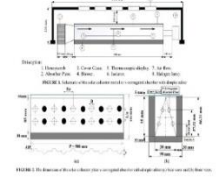
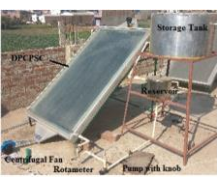

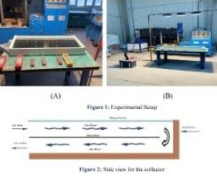
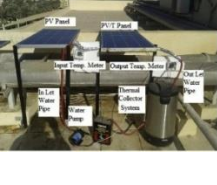
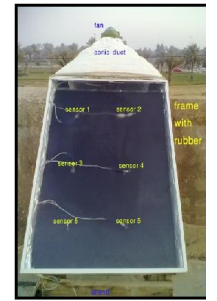
<p>(Mohamad et al., 2016)</p>		<p>V-corrugated absorber plate with prismatic fins; fin thickness: 3–5 mm; spacing: $0.25l$–$0.75l$; simulated via FLUENT (SST-$k\omega$ model).</p>	<p>Optimal performance: 3 mm fin thickness + $0.50l$ spacing ($\Delta P/\Delta T = 37.07$). Fins enhanced heat transfer via turbulence but increased pressure drop.</p>
<p>(Manjunath et al., 2018)</p>		<p>Sinusoidal corrugated absorber.</p>	<p>Heat transfer enhanced by 18-25% at low flow rates, despite a 30% rise in pumping power.</p>
<p>(Ayad et al., 2023)</p>		<p>V-grooved absorber (15° angle).</p>	<p>Demonstrated 8-14% efficiency gain over flat plates due to intensified convective transfer.</p>
<p>(Aneeq et al., 2024)</p>		<p>Double-pass duct with trapezoidal corrugations.</p>	<p>Inline corrugation arrangement enhanced heat transfer by 33% and increased friction by 27%.</p>
<p>(Nabil Jet et al., 2024)</p>	<p>-</p>	<p>Four absorber types (flat, sinusoidal, $45^\circ V$, $30^\circ V$); dimensions: 0.9×0.9 m; air gap: 0.2 m; irradiance: 250–1000 W/m².</p>	<p>45° V-grooved plate performed best, increasing Nusselt number by 27% compared to flat plate.</p>

Table 2. Experimental studies on corrugated absorber solar collectors.

(Author, Year)	Configuration	Design Specifications	Key Findings
<p>(Kabeel et al., 2016)</p>		<p>V-corrugated vs. flat/finned absorbers.</p>	<p>V-corrugated design outperformed flat plate by 8–14.5% in efficiency.</p>

<p>(Ganesh et al.,2018)</p>		<p>V-corrugated absorber with sandblasted duct.</p>	<p>Achieved higher Nusselt number but with increased friction factor.</p>
<p>(Marsianus et al.,2019)</p>		<p>V-corrugated absorber with dimples.</p>	<p>A 9mm dimple produced the highest heat output (51.59 W) and an efficiency of 48%.</p>
<p>(Piyush et al.,2019)</p>		<p>Dual-purpose corrugated collector (water/air).</p>	<p>Provided a comparative performance evaluation between single and dual-purpose designs.</p>
<p>(Janusz et al.,2019)</p>		<p>New type (corrugated surface) vs. Reference (flat surface)</p>	<p>cooling capacity \uparrow 55% $\downarrow \Delta T$</p>
<p>(Jalal et al.,2021)</p>		<p>Double-pass heater with wavy-fin absorber.</p>	<p>Thermal efficiency increased by 80% and 84% for 3-fin and 7-fin configurations.</p>
<p>(Mokhlif et al.,2023)</p>		<p>Integrated system with V-corrugated absorber.</p>	<p>Improved overall system efficiency through enhanced turbulence and surface area.</p>
<p>(Saleh ,2016)</p>		<p>Corrugated plates increase turbulence and convective heat transfer coefficient</p>	<p>Shows efficiency higher than flat plates due to increased turbulence.</p>

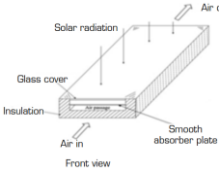


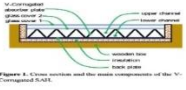
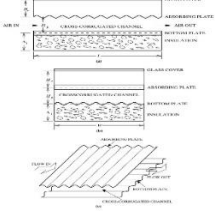
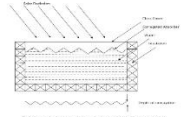
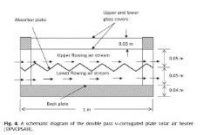
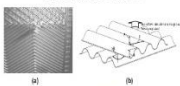
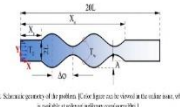
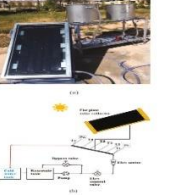

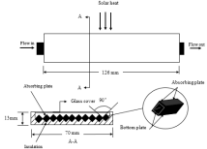
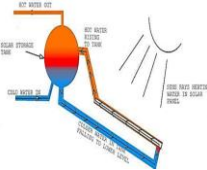
(AF Abed ,2023)		V-corrugated absorber plates	Improve thermal efficiency up to 46.7% compared to smooth plates (33%).
(Wisam et al.,2023)		Three absorber plates: flat plate, metal foam (MF) at 0°, MF at 45°; tested in Iraq climate.	The thermal efficiency of the metal foam was 98.8% higher at a 45° angle compared to 62.6% at a 0° angle and 33.8% for the flat panel due to greater turbulence and increased heat transfer.

Table 3. Combined numerical and experimental studies.

(Author, Year)	Configuration	Design Specifications	Key Findings
(Ashwini et al.,2017)		Corrugated absorber plates.	Confirmed thermal efficiency increases of 12–35% but noted need to manage pressure drop.
(Murat et al.,2022)		V-grooved absorber with selective coatings.	Demonstrated a 15–20% efficiency improvement over flat designs via combined strategies.
(Wenfeng et al.,2007)		Two distinct configurations of cross-corrugated Solar-powered air heating collectors with wavy absorbing and bottom plates.	Type 2 slightly outperformed Type 1; both significantly better than flat-plate designs. Coatings on absorber plates improved performance.
(Rakesh et al.,2010)		Corrugated absorber surface in solar water heater	Corrugation improves heat transfer but may slightly reduce efficiency due to increased heat losses.

<p>(EL-SEBAII et al.,2011)</p>		<p>A solar thermal air heater featuring a dual-flow passage and a V-trough absorber plate geometry.</p>	<p>A comparative performance analysis revealed a measurable efficiency enhancement of 11-14% in the modified configuration relative to the conventional double-pass flat-plate design.</p>
<p>(DOVIĆ et al.,2012)</p>		<p>Chevron-type corrugated absorber plates (no tubes)</p>	<p>Improved thermal efficiency beyond commercial glazed and unglazed solar water heaters.</p>
<p>(Mohammad et al.,2016)</p>		<p>Channel with wavy walls (amplitude 0–0.35, wavelength 2–8)</p>	<p>Best heat transfer at 90° phase difference; flow becomes unsteady at lower Re.</p>
<p>(Seyed et al.,2021)</p>		<p>Helically corrugated tubes with PCM in FPC</p>	<p>Heat losses reduced by 39.8%; efficiency increased from 41.5% to 48.9%. Hot water available in evening via PCM discharge.</p>
<p>(Ahmed et al.,2022)</p>		<p>Serpentine copper tube (ID: 9.5 mm, OD: 12 mm, L: 1000 mm)</p>	<p>TRNSYS model validated; input temp stable at 37.7°C.</p>
<p>(Dutta et al.,2022)</p>	<p>-</p>	<p>Corrugated vs. flat plate SAH (black-coated aluminum)</p>	<p>Max efficiency of corrugated SAH: 68% (higher than flat plate); max outlet temp: 60°C.</p>
<p>(Jalil et al.,2020)</p>		<p>Novel corrugated absorber shape; tested under varying solar radiation and inlet air velocity.</p>	<p>Achieved exit air temperature of 69.1°C (725 W/m², 1.0 m/s); outperformed other corrugated designs; numerical/experimental results aligned closely.</p>
<p>(Yehualashet,2022)</p>		<p>Chevron (sinusoidal) corrugated absorber plate in a solar water collector.</p>	<p>Enhanced heat transfer and collector outlet temperatures measured experimentally for different corrugated geometries.</p>
<p>(Kasi et al.,2024)</p>	<p>-</p>	<p>Six-tube evacuated collector with</p>	<p>Distillate output increased by 146.3%; cost reduced to 0.43₹/L; CO₂ reduction 2.44× conventional.</p>

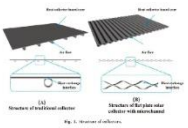
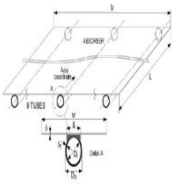

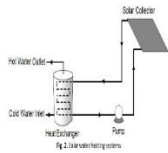
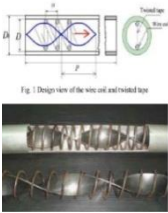
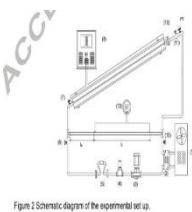
		corrugated fins and blue metal stone	
(Fatima et al., 2024)	-	Corrugated channel SAH with perforated barriers	Model error <2.4%; good airflow distribution and thermal performance.
(Yihe et al., 2024)		Stainless steel FPSC with microchannels	Momentary efficiency up to 86.10%; homogeneous temperature distribution.

Table 4. Studies that used a nanofluids in flat plate solar collector.

(Author, Year)	Nanofluid Type	Concentration	Enhancement Method	Key Finding
(Rajput et al., 2019)	Al ₂ O ₃ /water	0.1–0.3% by volume	Nanofluid only	A thermal efficiency enhancement of 21.32% was achieved under optimized parameters, corresponding to a nanoparticle concentration of 0.3% by volume and a volumetric flow rate of 3 liters per minute.
(Ziyadanogullari et al., 2018)	Al ₂ O ₃ , CuO, TiO ₂ /water	Experimental 0.2–0.8% vol.	Nanofluid only	Max efficiency increase: Al ₂ O ₃ (71%), CuO (87.8%), TiO ₂ (52.5%)
(Qin et al., 2024)	CQDs/ethylene glycol	Experimental	Corrugated substrate	Efficiency increased by 12.9% compared to flat plate
(Nabi et al., 2022)	SWCNT-CuO/water	Experimental 1–5% vol.	Turbulence-inducing elements	HTC increased by 31.31% (geometry) and 8.79% (nanofluid at 5%)
(Sundar et al., 2018)	Al ₂ O ₃ /Water	Numerical and Experimental 0.3%	Longitudinal Strip	Collector efficiency increased by 84% with the insert.
(Sundar et al., 2020)	Cu/Water	Numerical and Experimental 0.1%	Twisted Tape	Heat transfer coefficient increased by 46.9%; efficiency improved by 6%.
(Munuswamy et al., 2020)	Al ₂ O ₃ - CuO/Water (Hybrid)	Numerical and Experimental 0.2%	Fin	Thermal efficiency reached 72% with combined enhancements.

(Khan. et al.,2023)	TiO ₂ - Ag/Water Hybrid Nanofluid	Numerical and Experimental 0.1% and 0.2% by volume	Using a hybrid nanofluid as The thermal transport medium in a standard Flat Plate Solar Collector (FPSC) without any structural modifications	The maximum heat transfer coefficient (HTC) enhancement was about 16.1% for 0.2 vol.% at 0.01 kg/s. Energy efficiency enhanced by ~1.03% and exergy efficiency by ~3.52% for 0.2 vol.% compared to water.
(Baby. et al.,2016)	ZnO/Water Nanofluid	0.5% to 2% (Numerical analysis)	Using nanofluid in a solar collector with helically grooved tubes (e/D = 0.023, 0.0175) to induce swirl flow.	The heat transfer is enhanced considerably by the simultaneous application of grooved tubes and nanofluids, a combination that promotes secondary flow as well as swirl. Such a phenomenon results in an increased heat transfer coefficient and improved absorption efficiency.
(Khudhayer et al.,2018)	CuO/Water Nanofluid	0.1% by volume	Using nanofluid in a a flat-plate solar thermal collector featuring a unitary spiral flow channel	CuO/water nanofluid had an elevated performance with highest accessibly performance of 55% for TiO ₂ /water compared to 54% for water and 50% for water. The temperature gradient of CuO/water was 7.9°C as opposed to 6.6°C for water at 1.5 L/min.
(Saffarian et al.,2019)	TiO ₂ /Water Nanofluid	0.1% by volume	Using nanofluid in a A flat-plate solar thermal collector featuring a unitary spiral flow channel.	TiO ₂ /water nanofluid Demonstrated superior efficacy than water, with an efficiency of 54% and a temperature difference of 7.1°C, but lower than CuO/water nanofluid.

Table 5. Experimental performance of inserting wire or tapes in flat-plate solar collectors.

(Author, Year)	Configuration	Design Specifications	Operating Conditions	Key Findings
(MARTÍN et al.,2011)		<ul style="list-style-type: none"> • Wire coil inserts in riser tubes • Side-by-side test rig 	<ul style="list-style-type: none"> • EN12975-2 standards • Identical mass flow rates • Same inlet temperatures and climate 	<ul style="list-style-type: none"> • Significant thermal efficiency improvement • Higher useful power ratio vs. standard collector • Effective in low-flow/low-turbulence regimes
(García Iberto et al.,2013)		<ul style="list-style-type: none"> • Wire-coil inserts • Optical efficiency: 77% • Heat loss coefficient: 5.76 W/m²·K 	<ul style="list-style-type: none"> • Specified mass flow rate: 0.04 kg/s • EN 12975-2 standard testing • Identical operating/weather conditions 	<ul style="list-style-type: none"> • Direct performance comparison enabled • Enhanced collector vs. standard collector
(Ahmed,2025)		<ul style="list-style-type: none"> • Helical coils integrated in solar heating tanks 	<ul style="list-style-type: none"> • Elevated temperatures • Peak solar hours 	<ul style="list-style-type: none"> • Thermal performance improvement: 1-8% • Power output increase: ~10% (390W → 440W) • Enhanced heat absorption and retention
(Kashefi et al.,2014)		<ul style="list-style-type: none"> • Coiled wire + twisted tape inserts in riser tubes • Dual turbulator configuration 	<ul style="list-style-type: none"> • Experimental setup for flat plate collectors 	<ul style="list-style-type: none"> • Heat transfer rate increase: 18-70% vs. plain tubes • 30% thermal efficiency improvement • Reduced heat losses in solar water heaters
(García et al.,2018)		<ul style="list-style-type: none"> • Various insert geometries • Pressure drop measurement system 	<ul style="list-style-type: none"> • Re range: 80-9000 (pressure tests) • Re ≈ 400-2500 (thermal tests) • Five mass flow rates 	<ul style="list-style-type: none"> • Friction factor ratio (fi/fs): 1.3-79.8 • Increased internal heat transfer coefficient • Significant absorber temperature reduction


(Verma et al.,2020)		<ul style="list-style-type: none"> • Single spiral-shaped collector tube • Replaces conventional multi-riser design 	<ul style="list-style-type: none"> • Forced flow conditions • Identical parameters to standard collector 	<ul style="list-style-type: none"> • Thermal efficiency: +21.94% vs. conventional • Exergy efficiency: +6.73% • Better energy conversion quality
(Abbas et al.,2023)	-	<ul style="list-style-type: none"> • Two spiral copper tubes (15m × 0.012m) • 11 coils each • Matte black paint + 5% TiN nanomaterial 	<ul style="list-style-type: none"> • Air bubble injection in water flow • Babylon, Iraq (32.4°N, 44.4°E) • Optimal climatic conditions 	<ul style="list-style-type: none"> • Enhanced solar absorption • Impact assessment of air bubbles on thermal performance

Table 6. Comparative examination of the twisted tape inserts on thermal-hydraulic performance.

(Author, Year)	(Ameen et al.,2015)	(Merzha et al.,2019)	(Hassan et al.,2015)	(Abbas, A.et al., 2023)
Optimal Enhancer Type/Shape	Double Twisted Tape (DT)	Twisted Evaporator Section	Twisted Strip with low twist ratio (TR = 3)	Rectangular Winglet Pair (RWP)
Outlet Temp. Increase	Increased by $\approx 10^{\circ}\text{C}$ compared to plain tube.	(Not directly specified, but overall heat transfer is enhanced).	(Efficiency was measured instead of direct outlet temp.).	Increased due to stronger mixing and boundary layer disruption
Collector Efficiency	(Showed significant improvement over ST and SDT).	Performance greater than conventional by 13.5%.	Daily efficiency reached 63% at highest flow rate (150 L/h).	Highest with RWP (PEC ≈ 1.125 at Re = 1400)
Best Performing Material	Copper (outperformed aluminum by $\sim 6^{\circ}\text{C}$).	(Heat pipes used, material not compared).	Aluminum (the material used for the strips).	Same metal fin (no material change studied)
Flow Rate Impact	Higher Reynolds number (Re=10,000) improved heat transfer.	An optimal volumetric flow rate (20 L/h) for max efficiency.	Efficiency increased with flow rate (60, 100, 150 L/h).	Higher Reynolds number \rightarrow higher heat transfer (+22.2%) but more pressure drop

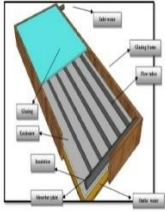

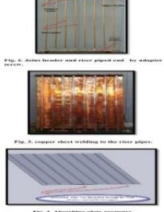
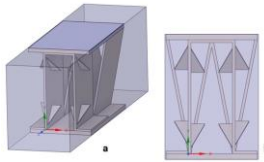
Heat Transfer Mechanism	Vortex generation & reduction of boundary layer thickness.	Reduced thermal resistance, increased heat transfer from evaporator to condenser.	Increased swirl generation and fin effect.	Longitudinal vortices enhance mixing and thin boundary layer, boosting convection
Methodology	Experimental & Numerical (CFD)	Experimental	Experimental	Numerical (CFD)
				

Table 7. Performance evaluation of passive heat transfer techniques: efficacy and flow resistance trade-offs.

(Author, Year)	(Hassan et al., 2017)	(Arifin et al., 2020)	(Ramasamy et al., 2020)
Optimal Enhancer Used	Helical spring surrounding a solid shaft	Perforated fin aluminum heat sink	Rectangular heat transfer enhancer inside the tube
Improvement in Thermal Performance	Increase of 16.2% in useful energy	Reduction in panel temperature by 12.5°C	Increase in thermal efficiency by 18-20%
Improvement in Electrical Performance	(Not the focus of the study)	Increase of 18.67% in maximum power point (P _{mpp})	(Not the focus of the study)
Primary Heat Transfer Enhancement Mechanism	Creation of vortices and increased flow turbulence	Increased surface area and disruption of the thermal boundary layer	Increased surface area and enhancement of natural convection
Impact on Pressure Drop	Leads to an increase in pressure drop (implicitly mentioned)	No additional pressure drop (passive cooling system)	Increase in pressure drop by 1.3 times compared to plain tube
Primary Enhancer Material	Copper (for the plate and tubes)	Aluminum (for the heat sink)	Copper (for the heat transfer enhancer)

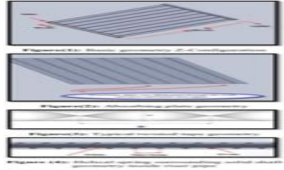
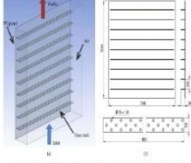
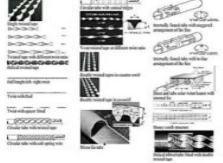
Methodology Used	Numerical modeling (CFD) using ANSYS Fluent	Numerical modeling (CFD) and experimental	Theoretical and mathematical analysis
Type of Enhancement Technique	Passive technique	Passive technique	Passive technique
			

Table 8. Effective of surfaces treatments and turbulators on solar collector efficiency.

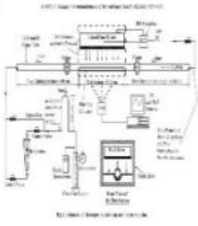
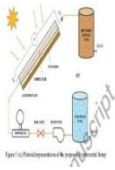
(Author, Year)	Configuration	Design Specifications	Operating Conditions	Key Findings
(Alireza et al., 2009)		<p>Passive heat devices:</p> <ul style="list-style-type: none"> Twisted tape inserts Coil-spring wire turbulators Conically ridged surfaces 	Comparative analysis in solar collectors	<ul style="list-style-type: none"> Mixed convection regime (free convection dominant) <ul style="list-style-type: none"> High Grashof/Richardson/Rayleigh numbers No significant difference in heat flux contribution between devices Turbulence promotion with free convection dominance
(Ganesh et al., 2020)		<ul style="list-style-type: none"> Shot peened FPSC Enhanced copper absorber tube/plate Black-painted surfaces 	Flow rate: 0.02 kg/s	<ul style="list-style-type: none"> Max thermal efficiency: 54.24% Cost per liter hot water: ~\$0.3 Increased convective heat transfer coefficient (CHTC)

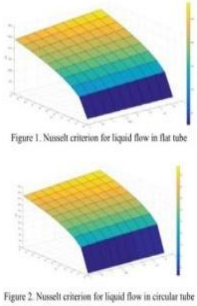
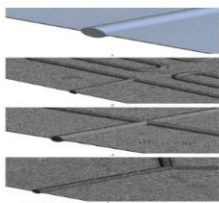
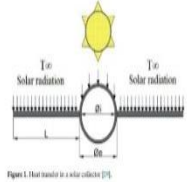
Table 9. Solar collector performance through material and design development.

(Author, Year)	Configuration	Design Specifications	Operating Conditions	Key Findings
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<p>(ION et al., 2006)</p>		<p>Solar air collector designed using energy/exergy analyses</p>	<ul style="list-style-type: none"> • ASHRAE Standard 93-86 • European Standard EN 12975-2006 • Standardized testing conditions 	<ul style="list-style-type: none"> • Optimized component selection and operating parameters • Development of efficient/cost-effective energy system • Performance evaluation under controlled conditions
<p>(Sharma, et al., 2022)</p>		<p>Comprehensive review of FPSC components:</p> <ul style="list-style-type: none"> • Absorber plate • Absorber tube • Heat transfer fluid 	<p>Comparative analysis of enhancement methods</p>	<ul style="list-style-type: none"> • Identification of effective conductive/convective heat transfer methods • Performance improvement strategies for key components • No experimental data (review study)

Table 10. Optimizing the effect of geometry on solar collector thermal performance.

Author (Year)	Design Appearance	Design Specifications	Operating Conditions	Key Findings
<p>(AL-AJLAN et al., 2003)</p>	<p>Fig. 1. Block diagram of the flat plate collector component.</p>	<p>A computational framework was established that integrates local climate data with flexible parameters to fine-tune collector designs.</p>	<p>Site-specific conditions in Riyadh's environment, with the model validated against experimental data.</p>	<p>Highlights the critical importance of using local weather data to maximize thermal efficiency and energy yield. The excellent correspondence between simulation and experiment shows how well the model handles the intricate real-world variables influencing solar collector performance.</p>

<p>(Yedilkhan et al.,2019)</p>	 <p>Figure 1. Nusselt criterion for liquid flow in flat tube</p> <p>Figure 2. Nusselt criterion for liquid flow in circular tube</p>	<p>Developed comprehensive Nusselt number relationships (correlations) for convective heat transfer.</p>	<p>Laminar flow regimes in flat plate solar collector tubes, accounting for flow orientation, convection mode (e.g., free, forced), and fluid properties (Prandtl number).</p>	<p>this research produced new connection that exactly described the convective heat transfer coefficients and creating a crucial foundation for improving the thermal performance optimization</p>
<p>(Dengjia et al.,2019)</p>	<p>-</p>	<p>3-D CFD modeling of large-scale vs. small-scale flat-plate collectors.</p>	<p>Various operating conditions (simulated).</p>	<p>Larger collectors achieved 1–4% higher thermal efficiency due to reduced relative heat loss and improved heat retention dynamics.</p>
<p>(William et al.,2021)</p>		<p>Superficial section geometry optimization via elongated fluid paths and reduced thermal resistance.</p>	<p>Standard solar irradiance conditions.</p>	<p>Thermal performance improved by 12–18% without increasing external surface area, demonstrating minimized thermal resistance.</p>
<p>(William et al.,2023)</p>	 <p>Figure 1. Flat-plate solar collector [25]</p>	<p>Circular floral evaporator/collector cross-section design.</p>	<p>Specified solar radiation conditions.</p>	<p>Enhanced heat absorption and fluid heat transfer by 15–22% compared to conventional designs, optimizing thermal distribution.</p>
<p>(Ewerton et al.,2024)</p>	<p>-</p>	<p>Corrugation profile optimization (rib height/pitch) with</p>	<p>Laminar flow regimes (Re: 1,500–5,000).</p>	<p>Rib geometry adjustments boosted thermal efficiency 14–</p>

		variable tube diameters and inclination angles.		25%, while tube diameter/inclination had <5% impact under laminar flow.
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