# "A Comprehensive Review of Heat Transfer Enhancement in Solar Thermal Collectors Using Dimpled Tubes, Artificial Roughness, and Nanofluids"

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## Abstract

Solar thermal collectors have become one of the most promising renewable energy technologies for domestic, industrial, and agricultural heating applications due to their simplicity, environmental friendliness, and ability to harness abundant solar radiation. However, the relatively low heat transfer coefficient between the absorber surface and the working fluid limits their thermal efficiency. Over the past two decades, researchers have investigated numerous passive heat transfer enhancement techniques, including artificial roughness, dimpled absorber plates, dimpled receiver tubes, twisted tape inserts, and nanofluids, to overcome these limitations. Recent advances have also focused on combining multiple enhancement techniques to maximize thermal and exergy performance while maintaining acceptable pressure losses.

This review critically analyzes recent developments in heat transfer enhancement techniques employed in solar air heaters, flat-plate solar collectors, and parabolic trough solar collectors. Particular emphasis is given to dimpled geometries, absorber plate modifications, receiver tube enhancements, twisted tape inserts, and nanoparticle-based working fluids. Experimental investigations, computational fluid dynamics (CFD) simulations, numerical modeling, and exergy analyses are comparatively discussed to identify the strengths and limitations of different enhancement methods. Furthermore, the influence of artificial roughness geometries, including V-shaped ribs, W-shaped ribs, arc-shaped ribs, reverse L-shaped ribs, and dimpled configurations, on turbulence generation and thermal performance is reviewed.

The literature demonstrates that dimpled receiver tubes significantly improve turbulence intensity and convective heat transfer, whereas nanofluids such as $Al_2O_3$, $TiO_2$, ZnO, and hybrid nanofluids further enhance thermal conductivity and collector efficiency. Hybrid enhancement techniques combining dimpled tubes, twisted tapes, and nanofluids consistently outperform conventional solar collectors. Despite these advances, challenges related to pressure drop, pumping power, long-term stability of nanofluids, manufacturing complexity, and economic feasibility remain. The review concludes by identifying research gaps and suggesting future directions for optimizing solar thermal collector performance through integrated passive enhancement techniques.

**Keywords:** Solar thermal collector, Parabolic trough collector, Solar air heater, Dimpled tube, Artificial roughness, Nanofluids, CFD, Heat transfer enhancement, Exergy analysis.

## 1. Introduction

The increasing demand for clean and sustainable energy has accelerated the development of renewable energy technologies worldwide. Among these technologies, solar thermal energy has emerged as one of the most practical and environmentally friendly solutions for meeting domestic and industrial heating requirements. Solar water heaters, solar air heaters, and parabolic trough collectors have gained widespread attention because they directly convert solar radiation into useful thermal energy without producing greenhouse gas emissions or consuming fossil fuels (Salvi et al., 2018).

Classification of solar thermal collectors is represented by fig.1


**Fig. 1: Classification of solar thermal collectors (Flat Plate Collector, Evacuated Tube Collector, Solar Air Heater, Parabolic Trough Collector).**

Despite their advantages, conventional solar collectors exhibit relatively low thermal efficiency because of limited convective heat transfer between the absorber surface and the working fluid. Heat transfer enhancement has therefore become a major research focus over the last two decades. Researchers have proposed numerous passive techniques such as artificial roughness, ribbed absorber plates, dimpled surfaces, twisted tape inserts, porous media, and surface coatings to increase turbulence and improve thermal performance while minimizing additional pumping power (Hobbi & Siddiqui, 2009).

Artificial roughness is among the earliest passive enhancement methods investigated for solar air heaters. Various rib geometries including arc-shaped ribs, V-shaped ribs, W-shaped ribs, reverse L-shaped ribs, and transverse inverted T-shaped ribs have demonstrated significant improvements in Nusselt number and thermal efficiency compared with smooth ducts (Saini & Saini, 2008; Lanjewar et al., 2011; Gawande et al., 2016; Mahanand & Senapati, 2020). Computational fluid dynamics (CFD) has further enabled detailed visualization of flow structures and optimization of rib parameters to maximize heat transfer while controlling friction losses (Karmare & Tikekar, 2010; Kumar & Kim, 2016).

In recent years, dimpled absorber plates and receiver tubes have attracted considerable attention because they generate localized vortices and secondary flow structures without introducing excessive pressure penalties. Numerical investigations have demonstrated that dimpled geometries provide superior thermal performance compared with conventional smooth tubes and several ribbed configurations (Huang et al., 2015). Experimental studies have confirmed that aluminum-coated dimpled tubes significantly improve collector efficiency when compared with plain tubes (Dimple, 2023). The various passive heat transfer techniques is shown by fig. 2

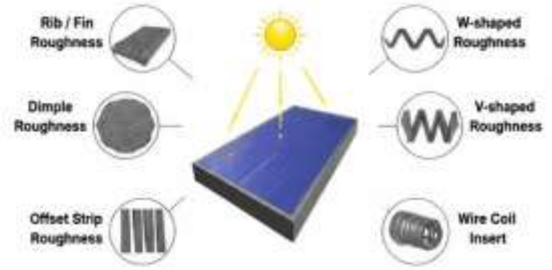


**Fig. 2: Various passive heat transfer enhancement techniques used in solar collectors.**

The integration of twisted tape inserts with dimpled tubes has further enhanced collector performance by increasing fluid mixing and prolonging residence time. Munusamy et al. (2024) reported considerable improvement in heat transfer using helically twisted tape inside aluminum-coated copper dimple tubes. Similar studies by Arun et al. (2024) also demonstrated enhanced thermal performance through the combined use of twisted tape and ZnO nanofluids.

Nanofluids have emerged as another promising heat transfer enhancement technique because suspended nanoparticles substantially increase the effective thermal conductivity of conventional working fluids. Experimental investigations involving $Al_2O_3$, $TiO_2$, ZnO, and other nanoparticles consistently report higher heat transfer coefficients and improved collector efficiency compared with water-based systems (Arun et al., 2022; Arun et al., 2024; Debabrata et al., 2024). The synergistic combination of nanofluids with dimpled tubes and twisted tape inserts represents one of the most significant recent developments in solar thermal technology.

Recent studies have also emphasized exergy analysis as a more comprehensive performance evaluation tool than conventional energy efficiency. Exergy analysis accounts for irreversibilities within the collector system and provides better insight into thermodynamic optimization. Kumar et al. (2025) investigated the exergy performance of dimple-roughened solar thermal collectors using MATLAB simulations and reported substantial improvements compared with conventional collectors.

Alongside experimental investigations, CFD simulations have become indispensable for optimizing collector geometry, absorber configuration, and flow behavior. Advanced numerical models enable prediction of turbulence intensity, temperature distribution, pressure drop, and entropy generation under varying operating conditions, thereby reducing experimental costs and accelerating design optimization (Manjunath et al., 2012).

Although numerous review articles discuss artificial roughness and solar collector enhancement techniques (Salvi et al., 2018; Panda & Kumar, 2022), relatively few reviews comprehensively integrate recent developments in dimpled receiver tubes, aluminum coatings, nanofluids, twisted tape inserts, CFD analysis, and exergy optimization. Considering the rapid growth of research in this area between 2022 and 2025, an updated synthesis is necessary.

Therefore, the objective of this review is to critically examine recent advances in heat transfer enhancement techniques for solar thermal collectors with particular emphasis on dimpled geometries, artificial roughness, nanofluids, hybrid enhancement methods, CFD investigations, and thermodynamic performance analysis. The review also identifies current research gaps and provides recommendations for future investigations aimed at developing high-efficiency solar thermal systems.

## 2. Literature Review

### 2.1 Solar Thermal Collectors and Heat Transfer Enhancement

Solar thermal collectors are widely employed for converting incident solar radiation into usable thermal energy for domestic water heating, industrial process heating, drying, desalination, and power generation. Depending on the concentration ratio and operating temperature, these collectors are generally classified as flat-plate collectors (FPCs), evacuated tube collectors (ETCs), solar air heaters (SAHs), and concentrating solar collectors such as parabolic trough collectors (PTCs). While each collector type offers unique advantages, all suffer from the common limitation of relatively low convective heat transfer between the absorber surface and the working fluid, which restricts overall thermal efficiency (Salvi et al., 2018).

Conventional solar collectors typically operate under laminar or transitional flow conditions, resulting in the formation of a thermal boundary layer over the absorber surface. This boundary layer acts as thermal resistance, reducing the heat transfer rate from the absorber to the circulating fluid. Consequently, significant research efforts have focused on passive heat transfer enhancement techniques that improve fluid mixing without requiring additional external energy input (Hobbi & Siddiqui, 2009).

Heat transfer enhancement methods are generally categorized into active and passive techniques. Active techniques require external power sources, such as mechanical vibration or fluid injection, whereas passive techniques modify the geometry or flow path to promote turbulence naturally. Passive techniques are preferred in solar collectors because they are simpler, more reliable, and require minimal maintenance (Martín et al., 2011).

Among passive enhancement techniques, artificial roughness has received the greatest attention due to its ability to disrupt the viscous sublayer adjacent to the absorber surface. Properly designed roughness elements generate localized turbulence, enhance fluid mixing, and significantly increase the convective heat transfer coefficient. However, excessive roughness may increase friction losses and pumping power. Therefore, the optimization of roughness geometry remains an important research objective (Panda & Kumar, 2022).

Recent technological developments have expanded beyond conventional rib roughness to include dimpled surfaces, twisted tape inserts, porous media, surface coatings, and nanofluids. Hybrid combinations of these methods have demonstrated even greater thermal enhancement than individual techniques alone (Arun et al., 2024).

### 2.2 Artificial Roughness in Solar Air Heaters

Artificial roughness is one of the most extensively investigated passive enhancement techniques for solar air heaters. The basic principle involves introducing repeated surface protrusions on the absorber plate to disturb the laminar sublayer and induce secondary flow structures. Increased turbulence improves the convective heat transfer coefficient while maintaining acceptable pressure losses when the roughness geometry is properly optimized.

Early investigations by **Saini and Saini (2008)** developed empirical correlations for the Nusselt number and friction factor in solar air heaters equipped with arc-shaped wire roughness. Their study demonstrated that arc-shaped roughness substantially increased heat transfer compared with smooth ducts while providing valuable design equations for engineering applications.

Similarly, **Lanjewar et al. (2011)** experimentally investigated W-shaped rib roughness and reported significant improvements in thermal performance due to enhanced turbulence generation. The W-shaped configuration was found to produce stronger recirculation zones than conventional straight ribs, thereby improving heat transfer effectiveness.

The influence of reverse L-shaped ribs was examined experimentally and numerically by **Gawande et al. (2016)**. Their CFD analysis accurately predicted flow separation, vortex formation, and temperature distribution within the roughened duct. The results indicated that reverse L-shaped ribs generated superior thermal enhancement while maintaining moderate friction penalties.

Further improvements were reported by **Mahanand and Senapati (2020)** using transverse inverted T-shaped ribs. Their investigation showed that optimized rib dimensions increased the Nusselt number substantially compared with smooth absorber plates, confirming the effectiveness of modified rib geometries.

Computational investigations by **Karmare and Tikekar (2010)** and **Kumar and Kim (2016)** provided additional insights into turbulent flow structures generated by rib roughness. CFD simulations enabled detailed visualization of velocity contours, temperature fields, and pressure distributions that are difficult to measure experimentally. These numerical approaches have become essential tools for optimizing roughness geometry before prototype fabrication.

The different artificial roughness geometries is shown in fig. 3

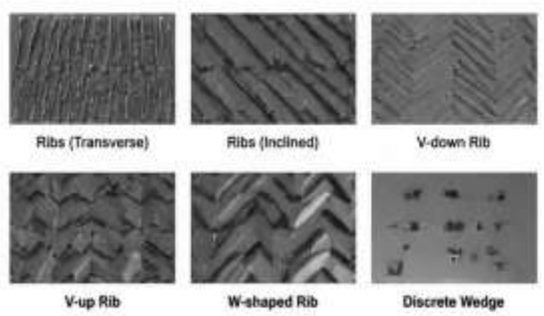


**Fig. 3: Artificial roughness geometries used in solar air heaters.**

Overall, artificial roughness significantly enhances collector performance by increasing heat transfer through turbulence generation. Nevertheless, excessive rib height or improper spacing may produce excessive pressure losses, highlighting the need for balanced optimization between thermal enhancement and hydraulic performance.

### 2.3 Dimpled Absorber Plates and Receiver Tubes

Dimpled surfaces have emerged as an effective alternative to conventional rib roughness because they generate localized vortices with comparatively lower pressure penalties. Unlike ribs that project into the flow field, dimples create recirculation zones inside shallow cavities, producing efficient mixing while reducing form drag.

Different type of dimple geometries is shown in fig. 4

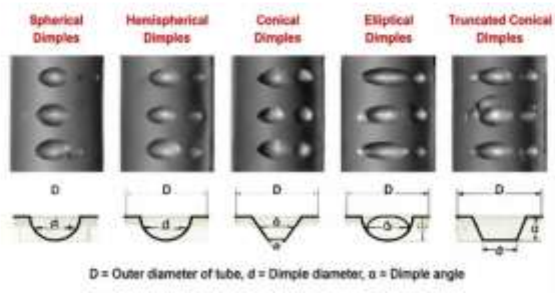


**Fig. 4: Different dimple geometries used in receiver tubes.**

One of the earliest numerical investigations was conducted by **Huang et al. (2015)**, who compared dimples, protrusions, and helical fins in parabolic trough receiver tubes. Their simulations demonstrated that dimpled geometries produced significant improvements in heat transfer due to enhanced secondary flow development while maintaining lower pressure drops than protruded surfaces.

Experimental studies have confirmed these numerical findings. **Perwez and Kumar (2019)** investigated flat and spherical dimple absorber plates in solar air heaters. Their results showed that spherical dimples generated stronger turbulence and higher thermal efficiency than flat dimple configurations, indicating the importance of dimple geometry in determining collector performance.

In flat-plate collectors, **Manjunath et al. (2012)** employed CFD analysis to compare dimpled absorber plates with conventional flat absorbers. The dimpled plate exhibited more uniform temperature distribution and improved convective heat transfer, resulting in higher collector efficiency.

Similarly, **Sable (2017)** evaluated dimpled concrete solar collectors for domestic water heating applications. The study demonstrated that dimpled absorber surfaces enhanced heat transfer while offering low manufacturing costs, making them attractive for rural and low-cost solar heating systems.

Recent experimental work by **Dimple (2023)** investigated aluminum-coated dimple tubes in solar water heaters. Compared with conventional plain tubes, aluminum-coated dimpled tubes achieved higher thermal efficiency due to improved surface conductivity and enhanced turbulence generation. The aluminum coating also improved corrosion resistance and long-term durability.

A significant advancement was reported by **Munusamy et al. (2024)**, who combined copper dimple tubes with aluminum coating and helically twisted tape inserts in a parabolic solar water heater. The hybrid configuration produced superior heat transfer enhancement because the dimpled geometry generated localized vortices while the twisted tape promoted continuous fluid rotation. This combination substantially increased the collector's thermal efficiency.

The latest investigation by **Ismail and Kaood (2025)** evaluated conical dimpled receiver tubes in parabolic trough collectors using hydrothermal performance analysis. Their results indicated that conical dimples produced stronger turbulence and higher heat transfer coefficients than conventional hemispherical dimples, suggesting promising opportunities for future receiver tube optimization.

Collectively, these studies demonstrate that dimpled geometries effectively improve thermal performance across different solar collector configurations. Their ability to enhance turbulence with relatively moderate pressure penalties makes them particularly attractive for next-generation solar thermal systems.

## 2.4 Nanofluids for Solar Thermal Collectors

The application of nanofluids has become one of the fastest-growing research areas in solar thermal engineering. Nanofluids are prepared by dispersing nanoparticles with high thermal conductivity into conventional base fluids such as water, ethylene glycol, or oil. The resulting suspension exhibits enhanced thermal conductivity, improved convective heat transfer, and increased solar energy absorption.

Among the various nanoparticles investigated, aluminum oxide ($Al_2O_3$), titanium dioxide ($TiO_2$), zinc oxide (ZnO), copper oxide (CuO), and hybrid nanofluids have shown promising performance in solar collector applications.

**Arun et al. (2022)** experimentally investigated $Al_2O_3$ nanofluids flowing through plain and dimple tubes in solar water heaters. Their findings demonstrated that combining $Al_2O_3$ nanofluids with dimpled tubes significantly increased collector efficiency compared with water flowing through plain tubes.

Similarly, **Arun et al. (2024)** evaluated $TiO_2$ nanofluids in parabolic trough collectors equipped with dimpled receiver tubes. The study reported notable improvements in heat transfer due to the combined effects of increased thermal conductivity and turbulence generated by the dimples.

A comprehensive experimental and CFD investigation by **Debabrata et al. (2024)** analyzed various nanofluids in dimple tube parabolic trough collectors. The numerical predictions closely matched experimental observations, validating CFD as a reliable design tool for nanofluid-based solar collectors.

More recently, **Arun et al. (2024)** examined the influence of ZnO nanofluids together with twisted helical tape inserts. The combined enhancement technique significantly improved heat transfer while maintaining acceptable pressure losses, highlighting the benefits of hybrid enhancement strategies.

Nanofluids offer several advantages, including higher thermal conductivity, improved convective heat transfer coefficients, reduced collector size, and increased thermal efficiency. However, practical implementation still faces challenges such as nanoparticle agglomeration, long-term suspension stability, erosion of system components, increased pumping power, and higher operating costs. Future research should focus on improving nanofluid stability and evaluating long-term system performance under real operating conditions.

### 2.5 Computational Fluid Dynamics (CFD) and Numerical Investigations

Computational Fluid Dynamics (CFD) has become one of the most valuable tools for analyzing and optimizing the thermal and hydraulic performance of solar thermal collectors. Compared with experimental studies, CFD enables detailed visualization of fluid flow, temperature distribution, turbulence characteristics, pressure drop, and entropy generation under a wide range of operating conditions. It also reduces prototype development costs and shortens design cycles by allowing researchers to evaluate multiple geometries before fabrication.

One of the pioneering CFD investigations on artificial roughness was conducted by **Karmare and Tikekar (2010)**, who analyzed fluid flow and heat transfer in rib-roughened solar air heaters. Their numerical simulations accurately predicted the formation of recirculation zones downstream of the ribs, which enhanced mixing between the heated wall and the core flow. The study demonstrated that CFD predictions closely agreed with experimental data, validating numerical modeling as a reliable approach for solar collector design.

Similarly, **Kumar and Kim (2016)** investigated the thermal-hydraulic performance of a solar air heater duct with multi V-shaped roughened ribs. The numerical analysis showed that V-shaped ribs significantly improved the Nusselt number because they generated strong secondary vortices that disrupted the thermal boundary layer. However, the study also highlighted the associated increase in friction factor, emphasizing the need for optimizing rib dimensions and spacing.

For dimpled configurations, **Manjunath et al. (2012)** compared conventional flat-plate collectors with dimpled absorber plates using CFD simulations. Their results indicated that dimpled surfaces enhanced heat transfer by promoting localized turbulence and reducing thermal resistance. The temperature distribution over the absorber plate became more uniform, leading to higher overall collector efficiency.

Numerical studies on parabolic trough collectors have also demonstrated the effectiveness of dimpled receiver tubes. **Huang et al. (2015)** compared dimples, protrusions, and helical fins inside receiver tubes. Their simulations revealed that dimpled geometries produced significant heat transfer enhancement while maintaining lower pressure losses than protrusions. The balance between improved heat transfer and acceptable hydraulic performance makes dimpled receivers attractive for practical solar thermal applications.

Recent studies have integrated CFD with experimental validation. **Debabrata et al. (2024)** conducted combined experimental and CFD analyses of dimple tube parabolic trough collectors using various nanofluids. The numerical predictions closely matched measured temperatures and pressure drops, confirming the reliability of CFD models for evaluating nanofluid-based solar collectors. Likewise, **Arun et al. (2024)** employed CFD to investigate $TiO_2$ nanofluids in dimpled receiver tubes, demonstrating enhanced turbulence intensity and improved thermal performance.

Overall, CFD has evolved into an indispensable tool for optimizing collector geometry, minimizing pressure losses, and predicting thermal performance under different operating conditions. Future research is expected to employ advanced turbulence models, machine learning-assisted optimization, and multi-objective numerical techniques for further improvements.

### 2.6 Exergy Analysis and Thermodynamic Performance

While thermal efficiency remains the most common performance indicator for solar collectors, it does not account for the quality of energy or thermodynamic irreversibilities occurring within the system. Exergy analysis provides a more comprehensive assessment by evaluating the maximum useful work obtainable from the collected thermal energy. Consequently, exergy analysis has become increasingly important in the design and optimization of advanced solar thermal systems.

**Kumar et al. (2025)** investigated the exergy performance of dimple-roughened solar thermal collectors using MATLAB simulations. Their study demonstrated that dimpled roughness significantly increased both thermal and exergy efficiencies by enhancing convective heat transfer while reducing entropy generation. The authors emphasized that exergy analysis provides deeper insight into collector performance than conventional energy efficiency calculations.

Similarly, **Tonekaboni et al. (2021)** analyzed an enhanced solar combined cooling, heating, and power (CCHP) system incorporating porous media and nanofluids. Their results showed that combining porous structures with nanofluids substantially reduced exergy destruction and improved the overall thermodynamic efficiency of the system.

Exergy analysis has also been extended to hybrid enhancement techniques involving dimpled tubes, twisted tape inserts, and nanofluids. These combined approaches increase heat transfer rates and improve temperature uniformity, leading to lower irreversibility within the collector. However, the associated increase in pumping power due to higher friction losses must be considered when evaluating overall exergy performance.

In general, studies indicate that the highest exergy efficiencies are achieved when heat transfer enhancement techniques are carefully optimized to maximize thermal gains while minimizing hydraulic losses. Therefore, exergy analysis should complement conventional thermal efficiency evaluations in future solar collector research.

## 3. Comparative Analysis of Previous Studies

The reviewed literature demonstrates significant progress in the development of passive heat transfer enhancement techniques for solar thermal collectors. Artificial roughness, dimpled geometries, twisted tape inserts, and nanofluids have all contributed to improving thermal efficiency, although each technique exhibits distinct advantages and limitations.

Artificial roughness remains one of the most mature enhancement methods for solar air heaters. Studies by **Saini and Saini (2008)**, **Lanjewar et al. (2011)**, **Gawande et al. (2016)**, and **Mahanand and Senapati (2020)** consistently reported increased Nusselt numbers due to turbulence generation. However, these improvements are accompanied by increased friction factors and pumping power. Therefore, optimization of rib geometry is essential to achieve the best thermal-hydraulic performance.

Dimpled absorber plates and receiver tubes represent a relatively newer approach. Compared with rib roughness, dimples generate localized vortices with comparatively lower pressure losses. Experimental investigations by **Perwez and Kumar (2019)** and **Dimple (2023)** demonstrated higher thermal efficiency than conventional smooth surfaces, while numerical studies by **Huang et al. (2015)** confirmed superior thermal performance for dimpled receiver tubes. Recent developments involving conical dimples (**Ismail & Kaood, 2025**) suggest additional opportunities for geometry optimization.

Nanofluids have further improved collector performance by increasing the effective thermal conductivity of the working fluid. Experimental investigations involving $\mathbf{Al_2O_3}$, $\mathbf{TiO_2}$, and **ZnO** nanoparticles consistently reported higher collector efficiencies than conventional water-based systems (Arun et al., 2022; Arun et al., 2024; Debabrata et al., 2024). Nevertheless, practical challenges such as nanoparticle stability, sedimentation, erosion, and increased operating costs remain unresolved.

The most promising trend identified in recent literature is the integration of multiple passive enhancement techniques. For example, **Munusamy et al. (2024)** combined aluminum-coated copper dimple tubes with helically twisted tape inserts, achieving substantially higher thermal efficiency than conventional collectors. Likewise, **Arun et al. (2024)** demonstrated that ZnO nanofluids combined with twisted tape inserts significantly enhanced heat transfer while maintaining acceptable hydraulic performance.

Another notable development is the increasing use of CFD simulations. Numerical investigations now accompany most experimental studies, enabling detailed analysis of velocity fields, turbulence structures, temperature distributions, and pressure losses. These simulations reduce experimental costs and facilitate optimization of complex collector geometries.

Overall, the literature indicates that hybrid enhancement techniques, which combine dimpled geometries, nanofluids, and twisted tape inserts, offer the greatest potential for improving the thermal performance of future solar thermal collectors. However, further studies are required to evaluate their long-term reliability, economic feasibility, and large-scale implementation.

## 4. Research Gaps

Despite considerable progress in heat transfer enhancement technologies, several research gaps remain.

- Most experimental investigations are conducted under controlled laboratory conditions. Long-term outdoor performance under varying climatic conditions is still insufficiently studied.
- There is limited research on the combined effects of optimized dimple geometry, nanofluids, and artificial intelligence-based control systems for maximizing collector efficiency.
- Most CFD studies assume steady-state conditions and homogeneous nanofluid properties. More realistic transient and multiphase models are needed.

- The long-term stability, corrosion behavior, and environmental impact of nanofluids require comprehensive investigation before commercial adoption.
- Few studies have evaluated the economic feasibility and life-cycle cost of hybrid enhancement techniques.
- Experimental validation of advanced dimple geometries, such as conical, elliptical, and biomimetic dimples, remains limited.
- Most studies focus primarily on thermal efficiency, while fewer investigations consider entropy generation, exergy destruction, and sustainability indices simultaneously.
- The integration of enhanced solar collectors with thermal energy storage systems has received relatively little attention.

## 5. Future Research Directions

The literature reviewed indicates that substantial improvements have been achieved in the thermal performance of solar thermal collectors through artificial roughness, dimpled geometries, nanofluids, and hybrid enhancement techniques. Nevertheless, several promising research opportunities remain to further improve collector efficiency, reliability, and commercial feasibility.

One of the most important future directions is the optimization of dimple geometry. Although hemispherical, spherical, and conical dimples have demonstrated considerable thermal enhancement, limited studies have investigated elliptical, teardrop-shaped, biomimetic, or hybrid dimple configurations. Advanced optimization techniques, including genetic algorithms and topology optimization, could identify optimal dimple dimensions, spacing, and arrangements that maximize heat transfer while minimizing pressure losses.

Another promising area is the development of hybrid heat transfer enhancement techniques. Recent studies have shown that combining dimpled receiver tubes with helically twisted tape inserts and nanofluids produces significantly higher thermal efficiencies than using individual enhancement methods. Future investigations should focus on optimizing the interaction between these techniques to achieve maximum thermal performance with minimum pumping power.

Nanofluids continue to be one of the most attractive research topics in solar thermal engineering. Although nanoparticles such as $\mathbf{Al_2O_3}$, $\mathbf{TiO_2}$, and **ZnO** have shown encouraging results, challenges related to long-term stability, sedimentation, corrosion, erosion, and preparation cost still limit their practical application. Future research should emphasize environmentally friendly nanoparticles, hybrid nanofluids, and advanced surfactants capable of maintaining stable suspensions over extended operating periods.

The increasing availability of computational resources offers new opportunities **for high-fidelity numerical simulations**. Future CFD studies should employ Large Eddy Simulation (LES), Direct Numerical Simulation (DNS), and transient multiphase models to capture complex flow behavior more accurately. Coupling CFD with optimization algorithms and machine learning techniques may significantly reduce computational effort while improving design accuracy.

Another important research direction involves the integration of artificial intelligence (AI) and machine learning into solar thermal systems. AI-based predictive models can optimize collector operation under varying weather conditions, forecast thermal performance, detect faults, and improve system reliability. Data-driven optimization can complement traditional CFD and experimental methods by enabling real-time performance prediction.

The integration of phase change materials (PCMs) with enhanced solar collectors also presents considerable potential. Combining dimpled absorber surfaces with thermal energy storage systems can improve heat availability during periods of low solar radiation and increase the overall utilization of collected energy.

Long-term durability studies are equally important. Most current investigations focus on short-term laboratory experiments, whereas commercial applications require comprehensive evaluation of corrosion resistance, coating degradation, nanoparticle stability, and maintenance requirements over several years of operation.

Finally, future studies should incorporate techno-economic analysis, life-cycle assessment, and environmental impact evaluation alongside thermal performance analysis. Such comprehensive assessments will help determine the commercial viability of advanced heat transfer enhancement techniques and facilitate their large-scale implementation in renewable energy systems.

## 6. Conclusion

Solar thermal collectors continue to play an essential role in the global transition toward renewable energy by providing sustainable solutions for water heating, space heating, industrial process heating, and power generation. However, improving their thermal efficiency remains a major research challenge due to the relatively low convective heat transfer between absorber surfaces and working fluids.

This review has examined recent advances in passive heat transfer enhancement techniques for solar thermal collectors, with particular emphasis on artificial roughness, dimpled absorber plates, dimpled receiver tubes, twisted tape inserts, nanofluids, CFD simulations, and exergy analysis. The reviewed studies consistently demonstrate that these enhancement techniques substantially improve thermal performance by increasing turbulence intensity, disrupting thermal boundary layers, and promoting better fluid mixing.

Among the various techniques, dimpled receiver tubes have emerged as one of the most promising passive enhancement methods because they generate localized vortices while maintaining relatively low pressure losses. Experimental and numerical investigations have confirmed that dimpled geometries outperform conventional smooth tubes and, in many cases, provide better thermal-hydraulic performance than traditional rib roughness.

Artificial roughness remains a mature and effective technology for solar air heaters. Various rib geometries—including arc-shaped, W-shaped, reverse L-shaped, and transverse inverted T-shaped ribs—have demonstrated significant increases in heat transfer. Nevertheless, optimization is necessary to balance thermal enhancement against frictional losses.

Nanofluids have further improved collector performance by increasing the effective thermal conductivity of the working fluid. Studies involving $Al_2O_3$, $TiO_2$, and ZnO nanoparticles consistently reported higher collector efficiencies compared with conventional water-based systems. However, practical issues such as sedimentation, long-term stability, and increased operating costs remain barriers to widespread commercialization.

Recent investigations clearly indicate that hybrid enhancement techniques, combining dimpled tubes, twisted tape inserts, surface coatings, and nanofluids, produce the highest thermal efficiencies among all passive enhancement methods. These integrated approaches represent the future direction of high-performance solar thermal collector design.

Computational Fluid Dynamics has become an indispensable design tool by enabling detailed visualization of flow structures, temperature fields, and pressure distributions. The excellent agreement between CFD predictions and experimental observations confirms its effectiveness in optimizing collector geometries before fabrication.

Despite remarkable progress, further research is required to investigate long-term durability, outdoor performance, economic feasibility, and environmental sustainability. Future studies integrating artificial intelligence, advanced numerical optimization, thermal energy storage, and hybrid nanofluids are expected to significantly improve the performance and commercial viability of next-generation solar thermal collectors.

Overall, the reviewed literature demonstrates that passive heat transfer enhancement technologies offer considerable potential for increasing the efficiency of solar thermal collectors and supporting the broader adoption of renewable energy systems.

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