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# Enhancement Techniques for Vacuum Tube Solar Collectors: A Review of Recent Advances in Design, Materials, and Thermal Efficiency

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**ABSTRACT**

**The need to establish sustainable energy sources has led to the increased interest on using vacuum tube solar collectors (VTSCs) for water and air heating. This review looks into the recent development in the design, materials, and techniques for the improvement of VTSCs' performance which includes nanofluids, various configurations of heat pipes, and phase change materials (PCMs). Several studies indicate that nanofluids, especially carbon based nanofluids composed of carbon nanotubes and graphene, enhance the thermal conductivity which improves the heat absorption and storage of the collector. Furthermore, the use of high-emissivity coatings and configurations such as U-pipes enhances heat transfer efficiency. These solar collectors are suitable to be used in hybrid systems such as parabolic trough-integrated vacuum tube solar collectors for enhanced performance and these advances are discussed. The review ends with the identification of several significant gaps and the proposal of how these gaps may be addressed, specifically the integration of VTSCs in diverse environmental circumstances and functional conditions.**

## INTRODUCTION

Vacuum tube solar collectors (VTSCs) are increasingly used for water and air heating in residential, industrial, and agricultural applications due to their high thermal efficiency and adaptability to different environmental conditions. VTSCs utilize evacuated tubes to minimize thermal losses, making them more effective than flat plate collectors, especially in cooler climates. Recent innovations focus on enhancing VTSCs' heat transfer efficiency, including the use of advanced materials like nanofluids and phase change materials (PCMs), improved heat pipe designs, and innovative coatings. This paper reviews these developments, highlighting their contributions to energy efficiency

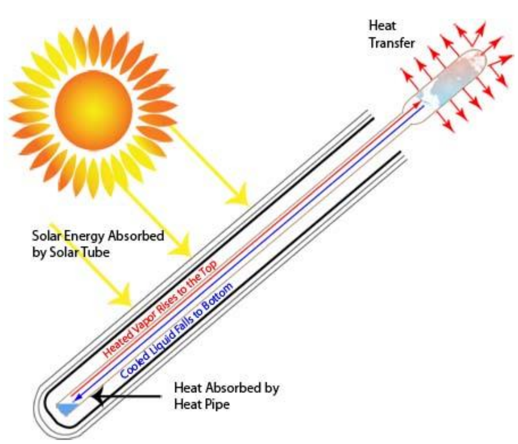


**Fig1.1: Heat pipe based vacuum tube receiver**

**Fig1.2: U-shape copper heat pipes with Aluminum fin**

## LITERATURE RIVEW

### Introduction

Various researchers worked upon water heating by using different type of solar receivers. Also some investigate has been reported for water heating application by using vacuum tube solar receivers. Some of the research works which has been recently reported is discussed below.

Thermal efficiency has been shown [1-3] to increase significantly with the usage of nanofluids Likewise, it has been discovered that carbon nanotubes (CNTs) improve the effectiveness of evacuated and flat plate collectors When compared to systems without them, hybrid nanofluids have also demonstrated notable gains in energy and exergy effectiveness.

The study looks at how geometrical characteristics and heat transfer enhancers affect solar thermal collectors' energy and exergy efficiency. It emphasizes the employment of phase change materials on collection plates, twisted tapes, carbon and black chrome coatings, hybrid nanofluids, and booster reflectors. The best solar thermal collectors for maximum energy and exergy efficiency with low thermal losses can be selected with the aid of these discoveries.An experimental study to improve the performance of a novel evacuated tube solar collector through the use of nanofluids was conducted. Their research focused on assessing the impact of different types of nanofluids on thermal efficiency and heat transfer characteristics. The findings revealed that the integration of nanofluids significantly enhanced the thermal performance of the collector, resulting in improved energy absorption and overall efficiency. This study highlights the advantages of employing advanced materials, such as nanofluids, in optimizing solar thermal systems, indicating a promising pathway for enhancing renewable energy technologies in practical applications.

Heat transfer enhancement was explored by [4-8] in U-pipe evacuated tube solar absorbers through the application of high-emissivity coatings on metal fins. Their study demonstrated that these coatings significantly improved the thermal performance of the absorber by increasing the emissivity, which facilitates better heat transfer from the fins to the heat transfer fluid. Experimental results showed that the enhanced emissivity led to higher energy absorption rates and improved overall efficiency of the solar collector. This research highlights the importance of surface treatment and material selection in optimizing the thermal performance of evacuated tube solar collectors, paving the way for more effective solar energy solutions in building applications. The thermal performance of an evacuated tube solar collector equipped with inserted baffles was investigated for air heating applications. Their experimental study demonstrated that the inclusion of baffles significantly enhanced the heat transfer characteristics within the collector. The baffles promoted turbulence in the airflow, leading to improved heat absorption and overall thermal efficiency. The results indicated that this modification could optimize the collector’s performance, making it more suitable for air heating purposes. This research underscores the potential of design innovations, such as baffles, in enhancing the effectiveness of solar thermal systems, contributing to more efficient energy utilization in renewable applications. An experimental investigation into an evacuated tube solar collector was conducted that incorporates nano-enhanced phase change materials (PCMs) as thermal boosters. Their study demonstrated that the addition of nanomaterials to PCMs significantly improved the thermal energy storage and release characteristics, leading to enhanced overall collector performance. The results indicated that this innovative approach not only increases heat retention during solar collection but also stabilizes the output temperature under varying solar conditions. This research highlights the potential of integrating nano-enhanced PCMs in solar thermal systems, offering a promising solution for improving energy efficiency and storage capabilities in renewable energy applications.

An experimental investigation to analyze the effects of phase change materials (PCMs) on the performance of evacuated tube solar collectors was conducted. Their study focused on how the integration of PCMs influences the thermal efficiency and energy management of the solar collector system. The results demonstrated that PCMs significantly enhance energy storage capabilities, allowing for improved heat retention and more stable output temperatures during fluctuating solar conditions. This research highlights the potential benefits of incorporating PCMs in solar thermal systems, suggesting that such integration can lead to more efficient and reliable solar energy solutions, particularly in enhancing energy conversion and management strategies. Researchersimproved the heating potential of vacuum tubes that compare to heat pipes. They examined the three cases (1) an vacuum tube with fins (2) an vacuum tube with circular finned surface but filled with thermal oil (3) an vacuum tube filled with oil and foamed copper instead of finned circular surface. They examined that the heating time and cooling time of heat pipe has been improved about 12 minutes to 50 minutes in case of thermal oil and 70 minutes for thermal oil and foamed cu and cooling time has increased 69 minutes to 340 minutes i.e. 4.9 times more in third case. In this research they resulted that the efficiency of the vacuum tube has increased about 42.7% in case of thermal oil and 55.6% increase for thermal oil and foamed cu compared to the simple case i.e. vacuum tube with circular fins. Multiple other studies showed similer observations [9-26].

Researchers [27-32] presented an overview of comparative examine flat plate and vacuum tube solar receiver. Studies of Nano-fluids reveals that thermal conductivities and heat transfer coefficient is giving higher thermal performance compared to that of conventional solar receiver. If flat plate receiver is integrated with heat pipe technology it gives better thermal performance than the plain flat plate solar receiver. Vacuum tube solar receivers have more snow shed problem as compared to flat plate solar receivers as flat plate receiver can shed snow very easily in little sunshine. Through literatures it can be resulted out that the use of nano fluids gives higher thermal performance.

They used abio-superconductor heat pipe as a heat transfer medium in the vacuum tube. They presented experimentally the overall heat loss coefficient, efficiency and heat removal factor of superconductor heat pipe. They compared the experimental instantaneous efficiency and theory instantaneous efficiency. They observed that theory efficiency is more as compare to experimental efficiency. They also shows that the heat capacity is more in case of heat pipe than normal vacuum tube. The experimental setup was fabricated for vacuum tube receiver in which U-shape pipe is inserted and study is analyzed using the Response surface methodology. The outlet temperature of each vacuum tube, ambient temperature and solar radiation are recorded for different model. They determine the behavior of vacuum tube receiver at various Centre distance and optimized the values using RSM. Optimization of efficiency and outlet temperature for the system is done with the help of genetic algorithm in RSM to improve the heating performance of the vacuum tube solar receiver.

Researcher [33-38] studied the operational parameter and operational characteristics of the vacuum tube receiver system and to study this work a CFD software is used. The ANSYS-CFX commercial software is used for the simulation of the temperature distribution of water in glass vacuum tube receiver which uses the Finite volume method. They observed that there is no significant variation in temperature due to inclination angles. They also concluded that the CFD numerical simulations are useful in identifying the method to improve the solar receivers.

The experimental result of the flat plate receiver to the vacuum tube receiver was compared. From the results it is concluded that during sunny day flat plate receiver produces 21-37% more energy as compared to the vacuum tube receiver and during cloudy days vacuum tube receiver produces 21-64% more thermal energy. They concluded that use of solar tracker increases the productivity 48% more and 41% more in case of flat plate receiver and vacuum tube receiver respectively.

Researcher presented a detailed non-linear model is presented in this work. The change of the temperature along circumferential and longitudinal direction is considered. He observed that the maximum energy generation is at 25 degree tilt angle and for receiver facing south (azimuth angle=0 degree). He also obtained that the maximum efficiency of the receiver obtained is 0.53 at optimum mass flow rate equal to 30kg/h.m$^2$.

The various hybrid model and factors affecting the thermal performance of the vacuum tube receivers was discussed. They also presented the receiver performance of different type of vacuum tubes under different operating conditions. They mainly focused on high temperature working model through experimental and analytic study of various literatures and suggested some future scope for research. The experimental results for the 2 types of heaters single stage and two stage heater was explained. The working fluid used for heat transfer is sunflower oil. The performance of the vacuum tube solar receiver with and without heat exchanger is studied. They observed that the efficiency of the two stage system is higher than the single stage system and efficiency is 10%-12% higher. They also concluded that the heat collected by the system decrease as the inlet temperature increases so to perform better there should be lower inlet temperature. Experimental research by combining PCM and porous metal within a heat pipe evacuated tube solar collector was conducted. Their findings highlight that this hybrid setup enhances thermal conductivity and energy absorption while stabilizing the collector’s performance during fluctuations in solar radiation. These advancements contribute to improving the reliability and efficiency of solar thermal systems, making them more suitable for real-world applications.

Studies in 2018 [39] demonstrated that utilizing carbon nanotube (CNT) nanofluids within evacuated tube solar collectors significantly enhances heat transfer and thermal efficiency due to the superior thermal conductivity of nanofluids. This approach not only improves energy absorption rates but also ensures better system performance under varying solar conditions, underscoring the potential of nanofluids to boost the effectiveness and reliability of solar thermal systems.

A 2016 review [40] highlighted the potential of nanofluids to enhance the thermal performance of flat-plate and evacuated tube solar collectors. The study noted that the high thermal conductivity of nanofluids improves heat transfer efficiency, with critical factors being nanoparticle type, concentration, and stability. The review emphasizes the growing importance of nanofluids in solar thermal applications, suggesting they offer promising solutions for improved energy efficiency and sustainability.

Research from 2017 [41] investigated the thermal performance of evacuated tube solar collectors using graphene nanoplatelets (GNP) nanofluid. The findings showed that GNP nanofluids significantly enhance heat transfer and energy absorption within the system. These results highlight the potential of graphene-based nanofluids to advance solar thermal technology, offering cleaner and more efficient solutions for energy applications.

In 2023, a study [42] explored the enhancement of evacuated tube solar collectors using multi-walled carbon nanotube (MWCNT), aluminum oxide ($Al_2O_3$), and hybrid MWCNT/$Al_2O_3$ nanofluids. The results indicated that all three nanofluid types improved heat transfer efficiency, with the hybrid nanofluid exhibiting the highest thermal performance due to the combined thermal conductivity of MWCNT and $Al_2O_3$. This research emphasizes the effectiveness of nanofluid formulations in optimizing solar thermal systems, paving the way for more advanced energy solutions.

An experimental and computational fluid dynamics (CFD) investigation in 2023 [43] examined the heat transfer enhancement in evacuated tube solar collectors using coiled wire inserts. The results demonstrated that coiled wire inserts significantly improved thermal performance by promoting turbulence and enhancing heat transfer rates within the collector. The experimental findings, validated through CFD simulations, underscore the potential of innovative insert designs to optimize heat transfer in solar thermal systems.

A comprehensive review in 2023 [44] analyzed various techniques to increase the efficiency of evacuated tube solar collectors. Key advancements included design modifications, improved heat transfer fluids, and enhanced insulation. The study emphasized optimizing operational parameters and highlighted the importance of advanced materials in boosting energy absorption, supporting ongoing research in enhancing the efficiency of solar thermal systems for sustainable energy applications.

In 2021, a review [45] focused on the use of CFD for optimizing thermal enhancement techniques in evacuated tube solar collectors. The study explored methodologies including nanofluid applications, design modifications, and innovative heat transfer techniques. Through CFD analysis, critical parameters influencing thermal performance were identified, offering insights into the effectiveness of these enhancement strategies. This highlights CFD's role as a key tool in solar thermal system design and optimization.

Research from 2023 [46] investigated the thermal efficiency enhancement of evacuated tube collectors using a combination of experimental, numerical, and analytical approaches. The findings revealed significant improvements in energy absorption and overall efficiency, demonstrating the effectiveness of integrated methodologies in optimizing solar thermal system performance and providing valuable insights for more efficient design.

A 2021 study [47] conducted a detailed investigation into the thermal performance of evacuated tube solar collectors with an inner reflective coating for concentration. The results indicated substantial improvements in thermal performance due to the reflective coating's ability to enhance solar radiation absorption, showcasing the potential of reflective materials to advance solar thermal technology.

In 2022, CFD modeling was performed on an evacuated U-tube solar collector with a novel heat transfer fluid [48]. The simulations provided insights into temperature distribution and fluid dynamics, revealing enhancements in thermal performance compared to conventional fluids. This research underscores the potential of innovative heat transfer fluids in optimizing solar thermal systems.
An investigation in 2014 [49] examined efficiency enhancement in direct flow evacuated tube solar collectors using water-based titanium oxide nanofluids. The incorporation of titanium oxide nanoparticles significantly improved heat transfer rates, demonstrating the potential of nanofluids to optimize solar thermal systems.

Research in 2013 [50] focused on convective heat transfer and natural circulation within evacuated tube solar collectors. Experimental methods measured temperature gradients and fluid dynamics, highlighting the impact of natural convection on thermal performance and underscoring the importance of optimized design parameters.

A study in 2019 [51] performed an energy and environmental analysis of evacuated tube solar collectors using copper nanofluids. The results indicated increased heat transfer rates and improved energy absorption. Additionally, the environmental analysis emphasized the potential of nanofluids to reduce greenhouse gas emissions in solar thermal systems.

In 2020, research [52] investigated the energy performance enhancement of solar thermal power plants through the integration of solar parabolic trough collectors and evacuated tube collectors. The study revealed that preheating units in thermal power generation systems significantly improved energy capture and reduced fuel consumption, highlighting advanced solar technologies' role in enhancing energy performance.

An experimental analysis from 2015 [53] examined the thermal efficiency of evacuated tube solar collectors using nanofluids. Findings indicated that nanofluids improve heat transfer and overall efficiency due to their unique thermal properties, supporting their use as a promising solution for solar energy applications.

A comprehensive review in 2017 [54] analyzed thermal performance in evacuated tube solar collectors using various nanofluids. This review highlighted improvements in heat transfer rates and overall efficiency due to nanofluids' superior thermal properties, suggesting that continued research could further optimize solar thermal systems.

An experimental study in 2017 [55] explored the effect of aluminum oxide ($Al_2O_3$) nanofluids on energy efficiency in evacuated tube solar collectors. The results showed that $Al_2O_3$ nanoparticles enhance thermal conductivity and energy absorption, highlighting the role of nanofluids in optimizing solar collector performance through advanced fluid technology.

## ANALYSIS AND DISCUSSION

### Key Trends and Insights

1. **Nanofluid Integration**: Nanofluids, especially CNT- and $Al_2O_3$-based, improve heat transfer efficiency, with optimal nanoparticle concentrations achieving the best results.
2. **PCM Stability and Energy Storage**: PCM-enhanced VTSCs offer better temperature stability and are particularly effective in low-irradiance settings.
3. **Design Innovations**: High-emissivity coatings and U-pipe configurations improve heat absorption and reduce energy loss, while parabolic trough integration enables higher efficiency under varied solar conditions.

### Limitations and Future Research Directions

While nanofluids and PCMs have shown great potential, challenges remain in their cost, stability, and scalability for large applications. Future research should explore:

- The long-term stability of nanofluids and their compatibility with different heat transfer fluids.
- Advanced coatings and materials to further reduce heat losses in extreme weather conditions.
- Developing hybrid designs that integrate VTSCs with other renewable systems, such as photovoltaic panels, to maximize efficiency across seasons.

## CONCLUSION

This review underscores the substantial progress made in enhancing the thermal efficiency of VTSCs through advanced materials, innovative configurations, and hybrid systems. Nanofluids and PCMs offer promising pathways for improved energy storage and thermal performance. High-emissivity coatings and U-pipe designs further enhance the VTSCs' heat transfer capabilities, making them more adaptable to diverse climates and applications. As renewable energy demand grows, VTSCs' role in sustainable energy solutions is increasingly vital. Future research should focus on refining these technologies for cost-effectiveness, stability, and scalability, paving the way for broader adoption of solar thermal systems.

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