Reviewing the Optimization of Thermal Enhancement Techniques in Evacuated Tube Solar Collectors through Computational Fluid Dynamics Analysis

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Abstract

In recent times, a sharp surge in energy demand has imposed a significant burden on conventional energy sources, leading to their depletion. Consequently, there has been a heightened emphasis on leveraging non-conventional sources of energy for various applications. Solar energy, being abundant and eco-friendly, is particularly noteworthy, and India is fortunate to be endowed with ample solar resources.

Evacuated Tube Solar Collectors (ETSCs) serve as equipment designed to harness solar energy. The energy captured by ETSCs finds applications in both domestic and industrial settings. Numerous techniques have been employed to augment the efficiency of ETSCs. This article offers an overview of diverse techniques utilized for enhancing the efficiency of these solar collectors. Some of these techniques involve using collectors as a foundation for optimization processes. Parameters optimized in the literature encompass tube length, tube radius, the number of tubes, heat pipe geometry, and the shape of the evacuated tube.

This review delves into Computational Fluid Dynamics (CFD)-based studies, illustrating the impact of nano-fluids as heat-transferring fluids and the influence of different phase-changing materials on ETSCs efficiency. Additionally, the work summarizes the effects of reflectors and various techniques employed to mitigate heat losses on the performance of ETSCs. The findings of this study hold significance for applications requiring optimal performance at cost-effective measures.

Keywords: Solar thermal collector, Heat transfer enhancement, Phase change materials, Tilt angle, Nano fluids.

1. Introduction

With the escalating demand for energy, the utilization of alternative energy sources has become imperative. Solar energy, being one of the most extensively exploited renewable resources today, holds significant promise. Given the substantial energy consumption associated with water heating, it is crucial to harness solar energy for this purpose. Over the years, various solar-based water heaters have been developed, and current efforts are directed towards enhancing their performance. Extensive research has been conducted in this domain.

Solar collectors (SC) are categorized based on their operating temperatures. Low-temperature SC includes unglazed panels and flat plate collectors, while high-temperature SC comprises evacuated tube collectors, line focusing, and point focusing collectors. To expedite research and development, tools such as Computational Fluid Dynamics (CFD) can be employed to simulate solar water heating systems. CFD simulations use dummy conditions to provide results close to reality, thus reducing costs and time associated with experimentation. This approach bypasses the major hindrance of installation and maintenance costs in actual experiments.

Simulation analysis not only offers cost and time savings but also enables in-depth analysis, such as temperature distribution within the apparatus. Through CFD simulations, one can calculate the optimum design of the system and analyze complex energy systems. Additionally, simulations facilitate the study of the apparatus under various weather conditions, a task that would be time-consuming through traditional experimentation.

This review focuses on the application of various techniques in Evacuated Tube Solar Collectors (ETSCs) to enhance their performance using CFD. Some articles explore the optimization of parameters like the geometry and shape of the heat pipe in ETC collectors to improve efficiency. Others investigate the use of various nanofluids to enhance heat transfer—an approach that contributes to the ongoing efforts in improving solar water heating systems. The text discusses various methods to improve the performance of solar water heating systems, particularly focusing on Evacuated Tube Solar Collectors (ETSCs). Key points include:

1.1 Improving Performance by Reducing Losses

The text mentions the enhancement of solar water heating system performance by minimizing losses. This can involve the use of techniques such as reflective surfaces and the incorporation of phase change materials to enhance the system's heat-retaining capacity.

2. Computational Fluid Dynamics (CFD)

CFD is described as a computer-based simulation method for analyzing systems involving fluid flow, heat transfer, and chemical reactions. The text highlights the use of the ANSYS 16.0 (Fluent) version for solving equations governing these processes. The selection of turbulence models is a crucial step in the CFD analysis, involving a preliminary and final selection based on comparisons with experimental outcomes. The text introduces turbulence modeling, emphasizing the influence of walls on turbulent flows and the importance of the near-wall region (NWR). Various turbulence models, such as Renormalization k-model, Standard k-e model, Realizable k-model, and Shear Stress Transport k-model, are mentioned. Model selection and validation involve comparing Nusselt numbers calculated by different models and using statistical methods like the coefficient of determination (R^2).

2.1 Types of Evacuated Tube Collectors

The text explains that solar energy can be utilized through direct and indirect methods. Different types of ETSCs are introduced, including Thermosyphon, U-pipe Evacuated Tubular Solar Collectors (UPETSCs), and Heat Pipe ETSC. Thermosyphon ETSC, also known as water in glass ETC, utilizes evacuated tubes filled with water. The thermosyphon effect is achieved as heated water travels into the tank due to reduced density. UPETSC employs a copper U-pipe with aluminum fins between the copper pipes inside the evacuated tube, facilitating energy transfer. Heat Pipe ETSC, also known as two-phase ETSC, involves a copper tube divided into evaporator and condenser sections. The working fluid in the evaporator section is transformed into a gaseous state, transferring heat energy to the water tank.

2.2 Performance Enhancement Methods and Technical Developments:

The text explores methods to enhance the thermal performance of solar thermal systems, emphasizing the significance of efficient heat transfer to the working fluid. Geometrical modifications, such as optimizing the position of fins, exploring different shapes of heat pipes, and studying absorber area under various conditions, are discussed. Overall, the text provides insights into the efforts to improve the efficiency of solar water heating systems through various techniques, simulations, and research developments.

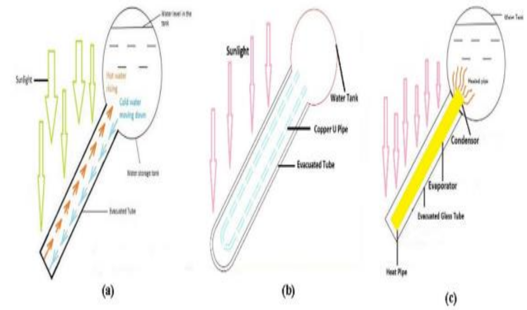

Fig. 1. (a) Thermosyphon ETSC (b) U-Pipe ETSC (c) Heat Pipe ETSC.

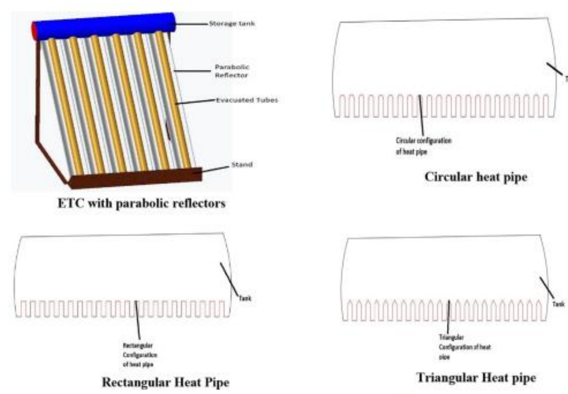

Fig. 2. Various geometrical modification for heat transfer augmentation.

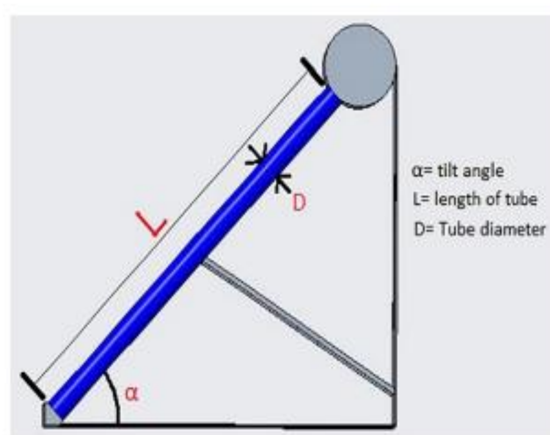

Fig. 3. ETSC shown with variation in tilt angle (α).

The passage details several research endeavors focused on enhancing the efficiency of Evacuated Tube Solar Collectors (ETSCs) through the application of innovative techniques. Researchers have explored the use of nanofluids, such as Cu-water nanofluid, to significantly improve heat transfer, resulting in

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noteworthy increases in both energy and exergy efficiency. Studies also investigate the impact of various nanoparticles, like MWCNT, TiO2, and Cu, on thermal performance, emphasizing the potential for heightened efficiency in ETSCs. Additionally, investigations into the integration of Phase Change Materials (PCMs), such as Tritriacontane paraffin, reveal promising outcomes in improving the thermal performance of ETSC systems. These studies collectively underscore the importance of advanced materials and methodologies in optimizing the functionality and overall effectiveness of solar collectors, offering potential advancements for sustainable energy solutions.

The research encompasses a variety of approaches to enhance the efficiency of solar collectors, particularly Evacuated Tube Solar Collectors (ETSCs). Integrating Phase Change Materials (PCMs), such as Tritriacontane paraffin, with ETSCs results in an increase in input thermal energy, particularly at air flow rates of 0.025 and 0.05 kg/s. Pawar and Sarvenaz Sobhansarbandi demonstrate through experimental and CFD simulations that Tritriacontane paraffin integration leads to a significant improvement in the benchmark efficiency of ETSCs. The use of PCM is explored further by Essa and Mostafa, showing that changes in the direction and intensity of solar radiation influence the flow profiles within the tubes of ETSCs. Other modifications, such as incorporating nano fluids like Cu-water nanofluid, geometrical adjustments, and simulations using various mathematical models, contribute to the comprehensive exploration of strategies aimed at optimizing the thermal performance of ETSCs. The studies collectively highlight the potential of advanced materials and design considerations in advancing the effectiveness of solar collectors for sustainable energy solutions.

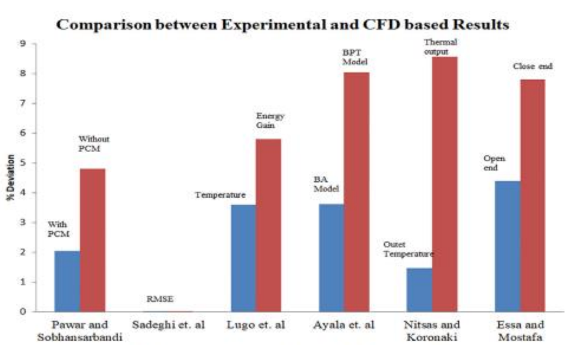

Fig. 4. Deviation of CFD based results from experimental results.

3. Comparative Study

In this comprehensive review of Computational Fluid Dynamics (CFD) studies on heat transfer augmentation in Evacuated Tube Solar Collectors (ETSCs), various factors influencing thermal performance are explored. The findings highlight key conclusions, including the effectiveness of rectangular heat pipe geometry with a specific water inlet-outlet configuration for optimal thermal stratification. The research emphasizes the reduction in collector area for optimal geometry, leading to a cost reduction of 38.9% and a simultaneous increase in thermal efficiency by 26.3%. Additionally, the significance of collector angle, number of tubes, and flow rate for achieving optimal results is underlined. The use of Cu-Water nano-fluid is identified for obtaining the best thermal performance, with a 5% volume fraction causing a notable 6.8% increase in heat transfer. The review also discusses the impact of tank temperature on natural circulation rate and thermal stratification. Furthermore, insights into the influence of tilt angle adjustments, water's superior heat absorption capacity, and the optimal diameter of absorber tubes are provided. The integration of parabolic reflectors and nanofluids is recognized for enhancing energy and exergy efficiencies in ETSCs. Overall, the synthesis of these CFD studies contributes valuable insights for advancing the thermal performance of ETSCs in solar energy applications.

4. Conclusion

In conclusion, this comprehensive review of Computational Fluid Dynamics (CFD) studies on Evacuated Tube Solar Collectors (ETSCs) underscores the critical factors influencing their thermal performance. The identified key parameters, including heat pipe geometry, collector configuration, and the integration of nanofluids, parabolic reflectors, and phase-change materials, significantly impact the efficiency of ETSCs. The optimal design considerations involve rectangular heat pipe geometry with a specific inlet-outlet arrangement, reducing collector area and costs while enhancing thermal efficiency. Cu-Water nano-fluid emerges as a superior choice, demonstrating a substantial 6.8% increase in heat transfer efficiency with a 5% volume fraction. Moreover, the influence of tank temperature on natural circulation rate and thermal stratification is recognized, providing insights into the operational dynamics of ETSCs. The importance of collector angle, number of tubes, and flow rate is emphasized, with specific configurations, such as a 30-degree angle, 24 tubes, and a 0.025 kg/s flow rate, identified as optimal. Tilt angle adjustments are deemed significant, with a 10-degree tilt providing higher temperature and thermal stratification compared to a 45-degree tilt. Water's superior heat absorption capacity, as highlighted in comparison to air and LiCl-H2O solution, underscores its efficacy as a working fluid. Additionally, the optimal diameter of absorber tubes is identified as 5 cm, further contributing to enhanced thermal performance. In essence, this review consolidates valuable insights from CFD studies, providing a comprehensive understanding of the intricate interplay of factors influencing ETSC thermal performance. These findings offer a roadmap for optimizing ETSC design, ensuring sustainable and efficient utilization of solar energy in various applications

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