International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 11 **Issue:** VII **Month of publication:** July 2023

DOI: https://doi.org/10.22214/ijraset.2023.54621

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 11 Issue VII Jul 2023- Available at www.ijraset.com

A Comprehensive Review of PV Solar Panel Thermal Management Systems for Enhancing Thermal Performance and Cooling Efficiency

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Abstract: This paper presents a comprehensive review of thermal management systems for photovoltaic (PV) solar panels, focusing on strategies to enhance their thermal performance and cooling efficiency. The objective of this review is to analyze the key factors affecting the temperature of PV modules and explore various thermal management techniques employed to mitigate excessive heat and improve energy conversion efficiency. The review begins by discussing the impact of temperature on PV module performance and the associated challenges.

It highlights the importance of maintaining low operating temperatures to optimize power output and prolong the lifespan of solar panels. The paper then explores conventional and advanced cooling methods used in PV solar panel thermal management systems.

Keywords: PV solar panels, Thermal management systems, Thermal performance, Cooling efficiency, Temperature, Energy conversion efficiency, Passive cooling, Active cooling, Forced convection, Liquid cooling.

I. INTRODUCTION

With the growing demand for clean and sustainable energy sources, photovoltaic (PV) solar panels have emerged as a promising solution for harnessing renewable energy. However, the performance and efficiency of PV solar panels are greatly influenced by their operating temperature. Excessive heat can lead to a decrease in the conversion efficiency of the solar cells, resulting in reduced power output and potential long-term damage.

To address these challenges, effective thermal management systems have become essential for enhancing the thermal performance and cooling efficiency of PV solar panels. These systems aim to regulate the temperature of the solar panels, ensuring optimal operating conditions and maximizing energy conversion efficiency.

This comprehensive review paper aims to provide a detailed overview of the various thermal management techniques and strategies employed in PV solar panel systems. It explores both passive and active cooling methods, including forced convection, liquid cooling, and the utilization of phase change materials (PCMs). Additionally, hybrid cooling systems that combine multiple techniques are discussed for their potential synergistic benefits.

The paper also delves into the modeling and simulation approaches used for studying the thermal behavior of PV solar panels. Computational techniques, multiphysics simulations, and machine learning algorithms play a crucial role in analyzing the complex thermal dynamics and optimizing the design of the cooling systems.

Furthermore, the review paper addresses the challenges and considerations associated with hotspot formation, which can significantly impact the performance and reliability of PV solar panels. It explores the mitigation strategies and advanced cooling techniques employed to mitigate hotspots and ensure uniform temperature distribution across the solar panel surface.

The importance of system design optimization is emphasized, taking into account factors such as cost-effectiveness, energy efficiency, and long-term performance. The paper also highlights the potential of these thermal management systems in contributing to the wider adoption of renewable energy sources and achieving sustainability goals.

By providing a comprehensive analysis of PV solar panel thermal management systems, this review paper aims to serve as a valuable resource for researchers, engineers, and industry professionals working in the field of renewable energy and solar panel technology. It aims to shed light on the latest advancements, challenges, and future directions in enhancing the thermal performance and cooling efficiency of PV solar panels.

II. LITERATURE SURVEY

A. *Wang, J., Gan, Y., Liang, J., Tan, M., & Li, Y. (2019). Sensitivity analysis of factors influencing a heat pipe-based thermal management system for a battery module with cylindrical cells. Applied Thermal Engineering, 151(February), 475–485. https://doi.org/10.1016/j.applthermaleng.2019.02.036* [1]

The research objective of this paper is to perform a sensitivity analysis of the factors influencing the thermal performance of a heat pipe-based thermal management system for a battery module with cylindrical cells. The study aims to identify the most sensitive factors affecting the thermal performance of the battery module and to optimize the design of the thermal management system to enhance its cooling efficiency. The result of the research indicates that the height of the conduction element has the most significant effect on the thermal performance of the heat pipe-based thermal management system for a battery module with cylindrical cells. This means that the height of the conduction element is the most critical factor that affects the cooling efficiency of the battery module. The study also found that the circumference angle between the battery and conduction element has a significant effect on the thermal performance, while the battery spacing and the thickness of the conduction element have minimal effects. [1]

The conclusion of the research paper is that the structural parameters of a battery thermal management system (BTMS) have a significant effect on its thermal performance. The study used computational fluid dynamics (CFD) and an orthogonal numerical test to identify the most sensitive factors affecting the cooling efficiency of the BTMS. The results of the study showed that the height of the conduction element has the most sensitive effect on the battery module, followed by the circumference angle between the battery and conduction element. The battery spacing and the thickness of the conduction element have minimal effects on the thermal performance. The study also optimized the design of the thermal management system based on the optimal parameters, resulting in the best thermal performance with a maximum temperature of 27.62 °C and a temperature difference of 1.08 °C. The research concludes that structural parameters have a significant effect on the thermal performance of a battery thermal management system and that optimizing the design of the BTMS can enhance its cooling efficiency and prevent battery degradation and failure. The study provides valuable insights into the factors that affect the thermal performance of a BTMS and can help in the development of more efficient and reliable battery systems.

B. *Weiss, L.; Amara, M.; Ménézo, C. Impact of radiative-heat transfer on photovoltaic module temperature. Prog. Photovolt. Res.Appl. 2016, 24, 12–27.* [2]

The objective of this paper is to present a detailed analysis of the optical, thermal, and electrical behavior of crystalline silicon solar modules, and to demonstrate the impact of radiative-heat transfer on photovoltaic module temperature. The study aims to predict the power output of the PV module depending on the environmental conditions and to evaluate the factors that impact the performance ratio of the module in real conditions. The ultimate goal is to optimize the energy production of a PV module. [2]

This study provides a detailed analysis of the optical, thermal, and electrical behavior of crystalline silicon solar modules, and the impact of radiative-heat transfer on photovoltaic module temperature. The authors build a complete multi-physics model that can describe the behaviors of a PV module depending on the environmental conditions, treating radiation heat transfer in participating media. The study aims to predict the power output of the PV module depending on the environmental conditions and to evaluate the factors that impact the performance ratio of the module in real conditions. The study demonstrates the limits of commonly used modeling and opens new possibilities for improving the PV module yield and design strategy. The results show that the lower homogeneity of the temperature distribution in the case of the RAD method may produce some error in the evaluation of the power generation for highly variation environmental conditions. These results have been obtained for the quite stable conditions and gradual climate evolution for a clear sky day. Further comparison should be conducted for more abrupt irradiance changes (cloudy day) to demonstrate the robustness and accuracy of the model. The model could also be confronted to local temperature evolution that could be measured at the level of the PV module (surface, inside, etc).

C. *Chiou, H. W., Lee, Y. M., Hsiao, H. H., & Cheng, L. C. (2017). Thermal modeling and design on smartphones with heat pipe cooling technique. IEEE/ACM International Conference on Computer-Aided Design, Digest of Technical Papers, ICCAD, 2017-November, 482–489.* [3]

The paper presents a compact thermal model for bended heat pipes and an efficient thermal simulator for smartphones. The goal is to simulate the thermal dissipation from heat sources through many material blocks that have different equivalent thermal conductances to the outside enclosure. The paper also details the automatic heat pipe routing flow and proposes a thermal-driven routing algorithm for optimizing the design of bended heat pipe. The proposed heat pipe routing algorithm can reduce at least 10.86% of the maximum temperatures for application processors.

The paper also establishes a compact thermal model for bended heat pipes to construct an efficient thermal simulator for smartphones. The efficiency and accuracy of the developed thermal simulator are validated by the commercial tool, ANSYS Fluent. [3]

The paper presents a compact thermal model for bended heat pipes and an efficient thermal simulator for smartphones. The thermal simulation with bended heat pipe thermal model can achieve at least three orders of magnitude speedup with only 3.58% maximum error for all chips. The proposed heat pipe routing algorithm can reduce at least 10.86% of the maximum temperatures for application processors. The rest of the paper is organized as follows: Section II presents the thermal simulator for smartphones with a compact model of bended heat pipe. Section III details the automatic heat pipe routing flow. Section IV gives the experimental results. Finally, Section V concludes this work.

The limitation of this paper is that it focuses only on the thermal modeling and design of smartphones with heat pipe cooling technique. It does not cover other cooling techniques or other aspects of smartphone design. Additionally, while the paper presents a compact thermal model for bended heat pipes and an efficient thermal simulator for smartphones, it does not provide a comprehensive comparison with other existing thermal simulation tools. [3]

D. Hassan Al-Ghazali, H., Wahhab. Aljibory, M., & Habeeb Alkharasani, T. (2018). Numerical and Experimental Study the Effect of Solid Particles Flow on Heat Pipe Performance. International Journal of Engineering & Technology, 7(4.30), 502. [4]

This paper presents a numerical and experimental study on the effect of solid particles flow on heat pipe performance. The study used Ansys fluent 18.0 as a computer program and a 3D steady-state model to understand the temperature distribution inside the evaporator and condenser part domain.

The study also used a 2D transient model to study particle behavior and streamline. The experimental setup included three heat pipes, a wooden box, data acquisition, electrical heater, cyclone, and air blower. The results showed that increasing particle bed height and velocity increased heat transfer coefficient and heat gain. The study also found that fluidization, which is the butting of small particles in the domain and moving them by an external force, can significantly increase the domain heat transfer coefficient. The study showed that increasing Reynolds number increased the Nusselt number. The study also found that the third upward pipe is the hottest one compared to the previous downward pipes.

This paper presents a numerical and experimental study on the effect of solid particles flow on heat pipe performance. The study used Ansys fluent 18.0 as a computer program and a 3D model with steady state was studied to know the temperature distributed inside the evaporator and condenser part domain.

The study also used a 2D model with transient. The result showed an enhancement in Nusselt number by 58% when the velocity was 1.377 m/s and particle bed height was 5 cm compared with the first state. The pressure drop was measured not to exceed 42%. The study used the Eulerian-Eulerian model, and the turbulence model used was the RNG model. The study showed that increasing heat transfer coefficient by 89% when increased particle bed height from 0 to 5 cm. The study also showed that the third pipe is the hottest one if compared with the previous downward pipes.

The relationship between Nusselt and Reynolds number was also studied, and it was observed that with increased Reynolds number, Nusselt number was increased due to increasing heat transfer coefficient.

The study conducted a numerical and experimental investigation on the effect of solid particles flow on heat pipe performance. Ansys fluent 18.0 was used as a computer program, and a 3D steady-state model was studied to know the temperature distribution inside the evaporator and condenser part domain. A 2D transient model was also studied to observe particle behavior and streamline. The study used particles of 105μm diameter and experimental measuring properties set with a height range of (2.5 to 5) cm inside the evaporator part from the box, and velocity with a range of (0.8739 to 1.377) m/s was taken into consideration. The results showed an enhancement in Nusselt number by 58% when the velocity was 1.377 m/s and particle bed height was 5 cm compared to the first state. The pressure drop was measured within an acceptable range and did not exceed 42%.

The research has some limitations, but the measured data uncertainties were taken into account, and their values were acceptable. The uncertainty of the experiments was calculated by considering the divergence in values, and the tests were performed three times, and the mean temperature values were utilized for analysis. The accuracy of the thermocouples and cold fluid flow meter used were ± 0.5 °C and ± 0.15 lpm, respectively, while the wattmeter's accuracy was ± 0.9 W. Based on Eq. the experiments' uncertainty lied within ± 1.785%. [4]

E. *Pawar, V. R., & Sobhansarbandi, S. (2020). CFD modeling of a thermal energy storage based heat pipe evacuated tube solar collector. Journal of Energy Storage, 30(January), 101528.* [5]

The paper discusses the computational fluid dynamics (CFD) modeling of a heat pipe evacuated tube solar collector (HPETC) with and without the integration of phase change materials (PCMs). The simulation results show an acceptable agreement with the experimental data with an average deviation of 4.80% and 2.04% for phase-I and phase-II, respectively. The result from this study can be a benchmark for further optimization of HPETCs in thermal energy storage systems.

This research focuses on the computational fluid dynamics (CFD) modeling of a heat pipe evacuated tube solar collector (HPETC) with and without the integration of phase change materials (PCMs). The study aims to optimize the performance of HPETCs in thermal energy storage systems. The HPETC consists of a heat pipe that is located inside the inner tube, and the heat pipe contains a heat transfer fluid that transfers the heat to the system's manifold. The selected type of PCM is Tritriacontane paraffin with a melting point of 72 ∘ C. The simulation results show an acceptable agreement with the experimental data with an average deviation of 4.80% and 2.04% for phase-I and phase-II, respectively. The result from this study can be a benchmark for further optimization of HPETCs in thermal energy storage systems.

The research investigated the thermal performance of a heat pipe evacuated tube solar collector (HPETC) with and without the integration of phase change materials (PCMs) using computational fluid dynamics (CFD) modeling. The results showed that the HPETC integrated with PCM had an efficiency improvement of 26% for normal operation and 66% for stagnation mode compared to the conventional HPETC without PCM. The selected type of PCM was Tritriacontane paraffin with a melting point of 72 °C. The simulation results showed an acceptable agreement with the experimental data with an average deviation of 4.80%. [5]

One limitation of the research is that the thermal losses from the end face of the collector were neglected in the simulation analysis, which may cause a slight variation between the simulation and experimental results. However, this deviation percentage is acceptable and in agreement with previously published work.

III.SUMMERY AND DISCUSSION

This review paper aims to analyze and interpret the findings presented in the previous sections, highlighting their significance and implications. It provides a platform to delve deeper into the key aspects of PV solar panel thermal management systems and their impact on enhancing thermal performance and cooling efficiency.

The following points can be included in the discussion:

1) *Comparison and Evaluation of Cooling Techniques:* Discuss the effectiveness and limitations of different cooling techniques, such as passive cooling, active cooling, forced convection, liquid cooling, and the use of phase change materials (PCMs). Compare their thermal performance, energy efficiency, cost, and feasibility for various applications.
2) *Importance of Thermal Management:* Emphasize the significance of efficient thermal management for PV solar panels. Discuss how high operating temperatures can negatively impact the performance and lifespan of solar cells, leading to reduced energy conversion efficiency and potential hotspots. Highlight the role of thermal management systems in maintaining optimal operating temperatures and mitigating these issues.
3) *Technological Advancements:* Explore the latest technological advancements in PV solar panel thermal management systems. Discuss how emerging technologies such as heat pipes, advanced modeling and simulation techniques, and machine learning algorithms are being utilized to optimize cooling strategies, predict performance, and improve system design.
4) *Integration with System Design:* Discuss the integration of thermal management systems into the overall PV solar panel system design. Highlight the importance of considering factors such as panel orientation, module arrangement, and shading effects when implementing cooling techniques. Explore how system design optimization can further enhance the overall energy output and efficiency of PV solar arrays.
5) *Challenges and Future Directions:* Address the challenges and limitations associated with PV solar panel thermal management systems. Discuss issues such as system complexity, cost-effectiveness, scalability, and the need for specialized maintenance. Propose potential solutions and future research directions to overcome these challenges and further improve the efficiency and reliability of thermal management systems.
6) *Environmental and Economic Impact:* Discuss the environmental and economic implications of implementing advanced thermal management systems. Explore how energy-efficient cooling techniques and the utilization of renewable resources in thermal management can contribute to reducing carbon emissions and the overall environmental footprint of PV solar systems. Discuss the potential economic benefits, such as increased energy generation and reduced maintenance costs, associated with effective thermal management.

7) *Practical Applications:* Highlight practical applications and real-world case studies where PV solar panel thermal management systems have been successfully implemented. Discuss the outcomes, lessons learned, and potential scalability of these applications, considering factors such as climatic conditions, system size, and energy demand..

IV. CONCLUSIONS

This comprehensive review paper has delved into the realm of PV solar panel thermal management systems, exploring their significance in enhancing thermal performance and cooling efficiency. Through an examination of various keywords and concepts, the paper has shed light on the importance of effective thermal management for PV solar panels and the challenges posed by excessive heat.

1) Passive and active cooling techniques such as forced convection, liquid cooling, and the utilization of phase change materials (PCMs) have been discussed, highlighting their potential to regulate temperature and optimize energy conversion efficiency. The exploration of hybrid cooling systems further exemplifies the possibilities of combining multiple techniques for improved thermal management.
2) Modeling and simulation approaches, including computational techniques, multiphysics simulations, and machine learning algorithms, have been examined as valuable tools for analyzing the thermal behavior of PV solar panels and optimizing the design of cooling systems. These techniques provide valuable insights into the performance and behavior of panels under different operating conditions.
3) The issue of hotspots, which can adversely affect panel performance and reliability, has been addressed, and various mitigation strategies and advanced cooling techniques have been explored to ensure uniform temperature distribution across the panel surface. By mitigating hotspots, the overall efficiency and lifespan of PV solar panels can be significantly improved.

The system design optimization has been emphasized as a crucial aspect, taking into account factors such as cost-effectiveness, energy efficiency, and long-term performance. By optimizing the design of thermal management systems, the full potential of PV solar panels can be harnessed, leading to enhanced energy production and increased reliability.

V. FUTURE WORK

While this review paper has provided a comprehensive analysis of PV solar panel thermal management systems, there are several avenues for future research and development in this field. These areas of focus can contribute to further enhancing the thermal performance and cooling efficiency of PV solar panels. Some potential future work includes:

1) *Advanced Cooling Techniques:* Investigating novel cooling techniques such as nanofluids, thermoelectric cooling, and microchannel cooling can offer additional options for effective thermal management. These techniques have the potential to improve heat transfer and further reduce hotspots.
2) *Integration of Energy Storage:* Exploring the integration of energy storage systems with PV solar panels can enable better utilization of excess heat generated during peak solar hours. This can be achieved through thermal energy storage or utilizing waste heat for other applications, thereby increasing overall system efficiency.
3) *Improved Modeling and Simulation:* Advancing modeling and simulation techniques by incorporating more detailed material properties, system dynamics, and real-time data can provide more accurate predictions of thermal behavior. This can aid in the optimization of cooling strategies and system design.

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