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ARTICLE

# Modeling Thermophysical Properties of Hybrid Nanofluids: Foundational Research for Future Photovoltaic Thermal Applications

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## ABSTRACT

The primary objective of this study is to develop an innovative theoretical model to accurately predict the thermophysical properties of hybrid nanofluids designed to enhance cooling in solar panel applications. This research lays the groundwork for our future studies, which will focus on photovoltaic thermal applications. These nanofluids consist of water and nanoparticles of alumina ($Al_2O_3$), titanium dioxide ($TiO_2$), and copper (Cu), exploring volumetric concentrations ranging from 0% to 4% for each type of nanoparticle, and up to 10% for total mixtures. The developed model accounts for complex interactions between the nanoparticles and the base fluid, as well as synergistic effects resulting from the coexistence of different nanoparticles. Detailed simulations have shown exceptional agreement with experimental results, reinforcing the credibility of our approach in accurately capturing the thermophysical behavior of these hybrid nanofluids. Based on these results, our study proposes significant advancements in the design and optimization of nanofluids for cooling applications in solar panels. These developments are crucial for improving the efficiency of solar installations by mitigating overheating effects, providing a solid foundation for practical applications in this rapidly evolving field.

## KEYWORDS

Nanoparticle; thermophysical properties; solar panel; thermal conductivity; specific heat

## Nomenclature

| | |
|---|---|
| $\varphi$ | Volume fraction |
| $\beta$ | The clustering effect |
| K | Thermal conductivity |
| Cp | Specific heat |
| $\rho$ | Density |
| *hnf* | Hybrid nanofluid |
| *np* | Nanoparticle |
| *bf* | Base fluid |

## 1 Introduction

As the global transition to sustainable energy gains momentum, solar panels have emerged as linchpins in the pursuit of clean and renewable power sources [1]. However, the efficiency of solar panels is intricately tied to a formidable challenge–the impact of elevated operating temperatures on overall performance [2]. The quest for optimal thermal management strategies has thus become an imperative facet of advancing solar energy technologies [3].

In addressing this challenge, conventional cooling methods such as air cooling and passive techniques have shown limitations, particularly as solar technologies evolve with increased power densities [4]. To meet the demands of contemporary solar systems, innovative and efficient cooling strategies are essential [5]. In this context, nanofluids, which are colloidal suspensions of nanoparticles such as alumina ($Al_2O_3$), titanium dioxide ($TiO_2$), copper (Cu), silicon dioxide ($SiO_2$), Graphene and so on, in a base fluid, have emerged as promising candidates for revolutionizing heat transfer fluid technologies. With their enhanced thermophysical properties, such as increased thermal conductivity and superior heat transfer capacity, nanofluids offer an innovative and efficient solution to overcome challenges associated with heat management in various industrial and energy applications. Their use could not only improve the efficiency of heat transfer systems but also contribute to a significant reduction in energy consumption and operational costs [6,7].

This study positions itself at the dynamic crossroads of nanotechnology and solar energy, aiming to explore and harness the potential of nanofluids as advanced heat transfer fluids tailored explicitly for the cooling of solar panels [8]. The interplay between temperature and efficiency in photovoltaic systems underscores the pivotal role that effective cooling mechanisms play in enhancing overall energy conversion efficiency [9].

The nanofluids under scrutiny in this study are hybrid in nature, incorporating nanoparticles of alumina ($Al_2O_3$), titanium dioxide ($TiO_2$), and copper (Cu) into a water base fluid. Our primary focus is to unravel the thermophysical properties of these hybrid nanofluids, with a specific emphasis on thermal conductivity and specific heat. This work serves as a pre-study for our subsequent research, which will concentrate on photovoltaic thermal applications. Recent research has demonstrated that hybrid nanofluids, combining different types of nanoparticles, exhibit superior thermal properties compared to their single-nanoparticle counterparts [10]. This observation reinforces their relevance in addressing the thermal challenges inherent in solar panel applications.

Understanding how these properties evolve across varying volumetric concentrations for each nanoparticle type is pivotal to our research objectives. This study specifically investigates concentrations ranging from 0% to 4% for each type of nanoparticle, as well as mixtures reaching up to 10% total volumetric concentration. Importantly, our model maintains a constant temperature and nanoparticle diameter throughout these concentrations, ensuring a focused exploration of their impact on thermal properties.

In terms of our unique contribution, this study not only extends the theoretical understanding of hybrid nanofluid behavior but also offers practical insights for the design and optimization of nanofluids in real-world solar panel applications. Our developed model has undergone verification against experimental data available in the literature, demonstrating a commendable agreement with established results. This verification process enhances the reliability and applicability of our model to real-world scenarios.

## 2 Materials and Methods

Hybrid nanofluids, an innovative subclass within the nanofluid spectrum, were employed in this study. Comprising a combination of two or more distinct nanoparticles, the choice of nanoparticle types and their relative proportions was of paramount importance for influencing thermophysical properties [11]. Despite the

promising potential, observations from collective research indicated instances where thermal properties of hybrid nanofluids experienced a decline compared to conventional counterparts [12]. The incorporation of nanoparticles into the base fluid induces alterations in thermophysical properties (Fig. 1) such as thermal conductivity, viscosity, and specific heat, impacting heat transfer through convection [13]. Various nanomaterials modify their parameters to varying extents, and factors such as nanoparticle concentration, purity level, shape, and size significantly alter thermophysical properties [14].

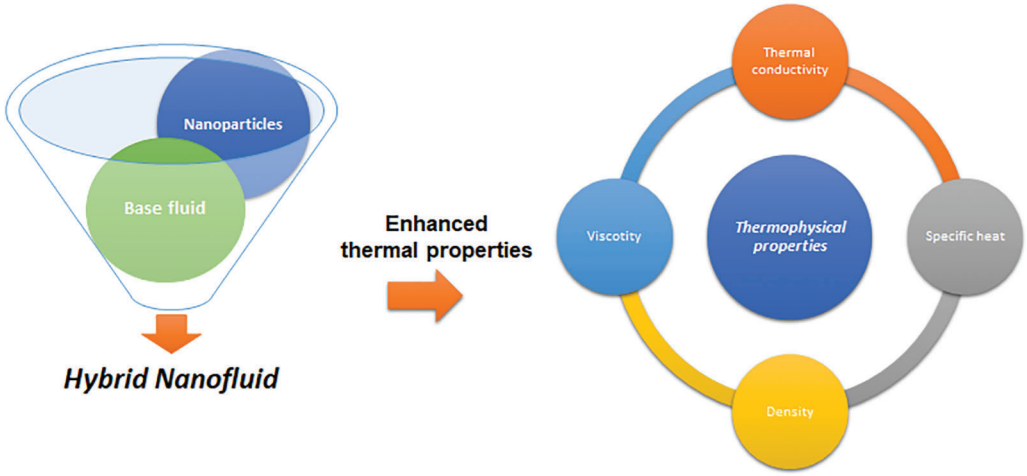


**Figure 1:** The visual representation depicting the enhanced thermal properties of hybrid nanofluids

The paramount thermophysical characteristic governing the performance of any working fluid within a thermal system is its thermal conductivity. This critical property in hybrid nanofluids is intricately influenced by a multitude of variables, encompassing the type and composition of the base fluid, the specificities of the nanoparticles in terms of type, combination, and composition, as well as temperature, volume concentration, particle size, and shape [15].

In earlier investigations, efforts were made to estimate the thermal conductivity of hybrid nanofluids by adapting modified versions of models initially designed for individual nanofluids as presented in Table 1. This intricate formulation takes into account diverse elements, including particle volume fraction, temperature, particle shape (cylindrical, spherical…), pH value, nanoparticle diameter, and the influence of Brownian motion resulting from the erratic movement of particles [16]. A comprehensive understanding of these interconnected factors is indispensable for the accurate modeling and prediction of thermal conductivity in hybrid nanofluids, ultimately enhancing the efficiency of thermal systems [17].

**Table 1:** Theoretical models of hybrid nanofluid

| | | |
|---|---|---|
| Thermal conductivity of hybrid Nanofluid | Maxwell model (1881) [18] | $\frac{K_{hnf}}{K_f} = \frac{(1+2\varphi)(\varphi_{np1}K_{np1} + \varphi_{np2}K_{np2}) + 2\varphi_f(1-\varphi)}{(1-\varphi)(\varphi_{np1}K_{np1} + \varphi_{np2}K_{np2}) + K_f\varphi(2+\varphi)}$ |
| | Yu-Choi model (2003) [19] | $\frac{K_{hnf}}{K_{bf}} = \frac{K_{np2} + 2K_{bf} - 2\varphi(K_{bf} - K_{np1})(1+\beta)^3}{K_{np2} + 2K_{bf} - \varphi(K_{bf} - K_{np1})(1+\beta)^3}$ |

(Continued)

**Table 1 (continued)**

| | | |
|---|---|---|
| | Hamilton-Crosser model (1962) [20] | $\frac{K_{hnf}}{K_{nf}} = \frac{K_{np2} + (n-1)K_{nf} - \varphi_{np2}(n-1)(K_{nf} - K_{np2})}{K_{np2} + (n-1)K_{nf} + \varphi_{np2}(K_{nf} - K_{np2})}$<br>Spherical particles (n = 3)<br>Cylindrical particles (n = 6) |
| Specific heat of hybrid Nanofluid | Pak et al. (1998) [21] | $Cp_{hnf} = (1 - \varphi_{np1} - \varphi_{np2})Cp_f + \varphi_{np1}Cp_{np1} + \varphi_{np2}Cp_{np2}$ |
| | Xuan et al. (2000) [22] | $(\rho Cp)_{hnf} = (1 - \varphi_{np1} - \varphi_{np2})(\rho Cp)_f + \varphi_{np1}(\rho Cp)_{np1} + \varphi_{np2}(\rho Cp)_{np2}$ |

## 3 Results and Discussion

In the context of this study, anchored in the results and discussion section, the values of thermal conductivity and specific heat are listed in Table 2. This table highlights the properties of both the base fluid and nanoparticles used in this research. The investigation focuses on the influence of nanoparticle volume fraction at various concentrations, relying on a specialized computer modeling program. This program incorporates heat transfer equations, particularly emphasizing thermal conductivity and specific heat, for nanofluids, including hybrid nanofluids such as $TiO_2/Al_2O_3$-Water, $TiO_2$/Cu-Water, and Cu/$Al_2O_3$-Water. The graphical representation of results takes into account multiple factors. In this section, we discuss the outcomes derived from comparing the ratios of thermal conductivity and specific heat among hybrid nanofluids ($TiO_2/Al_2O_3$-Water, $TiO_2$/Cu-Water, and Cu/$Al_2O_3$-Water). This comparison relied on well-established models, including Maxwell and the Xuan and Roetzel model, considering the volume fraction range from 0% to 4% ($0 \leq \varphi \leq 4\%$)and 0% to 10% ($0 \leq \varphi \leq 10\%$).

**Table 2:** Thermal conductivity and specific heat values of base fluid and nanoparticles used in this investigation

| Nanoparticle | $TiO_2$ | $Al_2O_3$ | Cu | Water |
|---|---|---|---|---|
| Thermal conductivity (W/m·K) | 8.9 | 40 | 401 | 0.613 |
| Specific heat (J/kg.°K) | 686.2 | 765 | 385 | 4179 |

According to Fig. 2, the obtained results reveal significant variations in the increase of thermal conductivity for the different studied hybrid nanofluids. For the $TiO_2/Al_2O_3$-Water hybrid nanofluid, an increase of 1.59% was observed as the volume fraction increased. This slight increment may indicate a moderate reactivity of this specific nanoparticle mixture, suggesting a less pronounced influence on thermal conductivity. In contrast, the $TiO_2$/Cu-Water hybrid nanofluid exhibited a more pronounced increase of 2.065%, signaling a more substantial response to the increase in volume fraction. This substantial improvement could be attributed to synergistic interactions between $TiO_2$ and Cu nanoparticles, contributing to an enhanced thermal conductivity. On the other hand, the Cu/$Al_2O_3$-Water hybrid nanofluid showed a more modest increase of 0.46%, indicating a relatively weaker reactivity of this particular combination. These findings underscore the dependence of the thermal performance of hybrid nanofluids not only on the volume fraction but also on the specific interactions between the employed nanoparticles.

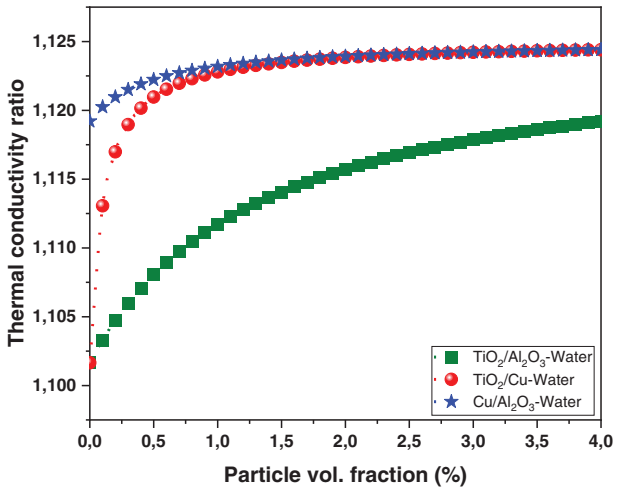


**Figure 2:** The impact of changing the volume fraction on the ratio of thermal conductivity in operational nanofluids within the range of ($0 \leq \phi \leq 4\%$)

Based on the obtained results Fig. 3, the analysis reveals further insights into the thermal conductivity variations of the studied hybrid nanofluids. For the $TiO_2/Al_2O_3$-Water hybrid nanofluid, there was a notable increase of 3.87% as the volume fraction ranged. This significant enhancement suggests a heightened reactivity of this nanoparticle combination, potentially leading to improved thermal conductivity. Similarly, the $TiO_2$/Cu-Water hybrid nanofluid exhibited a substantial increase of 5.04%, indicating a robust response to the changing volume fraction. This noteworthy improvement could be attributed to synergistic interactions between $TiO_2$ and Cu nanoparticles, contributing to an amplified enhancement in thermal conductivity. On the other hand, the $Cu/Al_2O_3$-Water hybrid nanofluid showed a moderate increase of 1.12%, indicating a comparatively lower reactivity for this specific combination. These findings further underscore the impact of volume fraction changes on the thermal performance of hybrid nanofluids, emphasizing the role of nanoparticle interactions in influencing thermal conductivity.

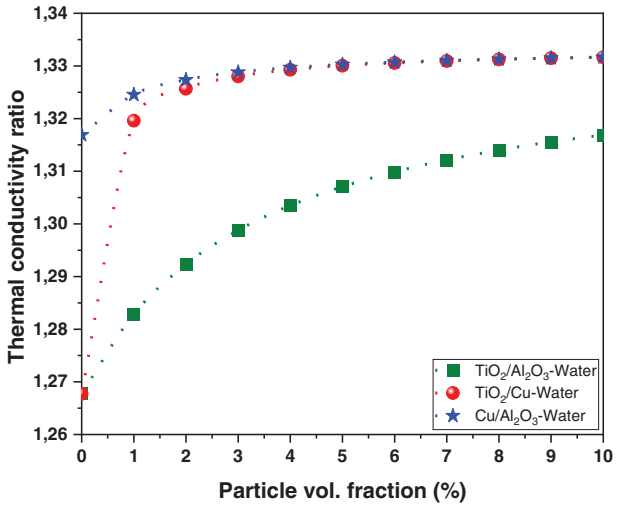


**Figure 3:** The impact of changing the volume fraction on the ratio of thermal conductivity in operational nanofluids within the range of ($0 \leq \phi \leq 10\%$)

In summary, the analysis of thermal conductivity variations across different volume fraction ranges highlights nuanced behaviors within the studied hybrid nanofluids. For the initial range of 0% to 4%, subtle yet discernible changes were observed, with the $TiO_2$/Cu-Water hybrid nanofluid standing out with a noteworthy increase of 2.065%. As the volume fraction expanded to 10%, more pronounced enhancements were evident, particularly in the $TiO_2/Al_2O_3$-Water and $TiO_2$/Cu-Water hybrids, showcasing increases of 3.87% and 5.04%, respectively. These results underscore the dynamic interplay between nanoparticle combinations and volume fraction, elucidating the potential for tailored adjustments to optimize thermal conductivity in specific applications. The findings contribute valuable insights for the strategic design of hybrid nanofluids, paving the way for enhanced thermal performance in various heat transfer systems.

The results obtained for specific heat at the volume fraction ranging from 0% to 4% (Fig. 4) reveal subtle variations in the performance of hybrid nanofluids. The $TiO_2/Al_2O_3$-Water hybrid nanofluid exhibited a slight increase in specific heat, reaching 0.078%. Similarly, $TiO_2$/Cu-Water showed an increment of 0.29%, while Cu/$Al_2O_3$-Water recorded an increase of 0.37%. These findings suggest moderate responses of specific heat to the increase in volume fraction for all studied hybrid nanofluids. It is noteworthy that these modest variations, although subtle, can have significant implications in applications where slight changes in specific heat are critical, emphasizing the influence of nanoparticle interactions on the thermal properties of hybrid nanofluids.

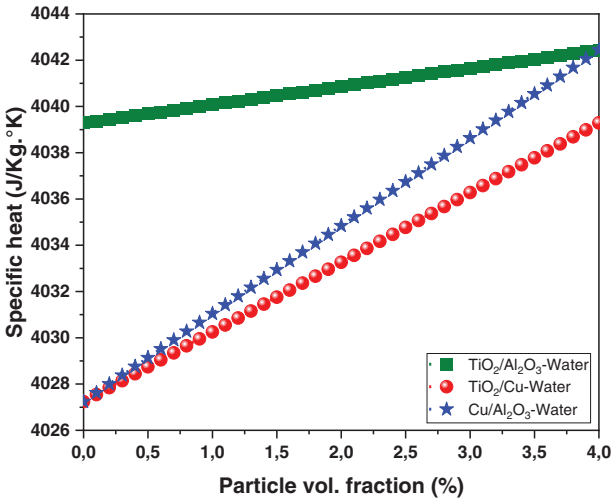


**Figure 4:** The influence of altering the volume fraction on the specific heat of operational nanofluids within the range of ($0 \leq \phi \leq 4\%$)

In Fig. 5, the trends underscore the continuation of the observed phenomenon, portraying a clear positive correlation between specific heat and the increasing volume fraction of nanoparticles in the hybrid nanofluids. The specific heat values for the $TiO_2/Al_2O_3$-Water, $TiO_2$/Cu-Water, and Cu/$Al_2O_3$-Water hybrid nanofluids at the extended volume fraction range of 0% to 10% further solidify this trend. Specifically, the $TiO_2/Al_2O_3$-Water hybrid nanofluid exhibited a specific heat increase of 0.20%, indicating a sustained alignment with the escalating volume fraction. In comparison, the $TiO_2$/Cu-Water hybrid nanofluid demonstrated a more pronounced increment of 0.79%, emphasizing a heightened positive correlation. Notably, the Cu/$Al_2O_3$-Water hybrid nanofluid displayed a significant increase of 1%,

substantiating the consistent trend of rising specific heat with the continuous augmentation of nanoparticle volume fraction. These insights, as depicted in Figs. 4 and 5, further emphasize the intricate relationship between specific heat and volume fraction, offering valuable guidance for optimizing thermal properties in diverse applications.

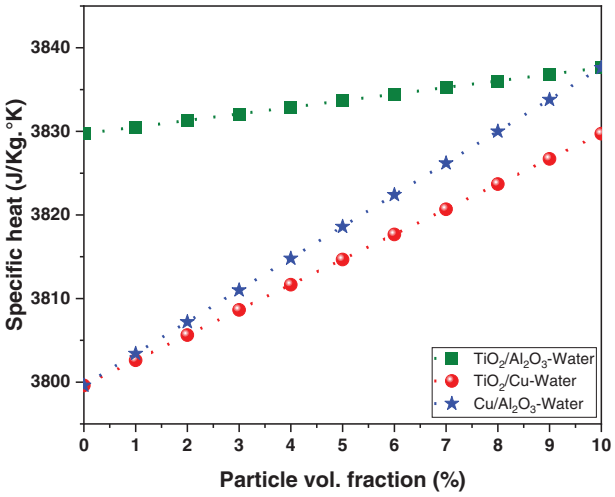


**Figure 5:** The influence of altering the volume fraction on the specific heat of operational nanofluids within the range of ($0 \leq \phi \leq 10\%$)

Our numerical model has been previously validated through experimental studies conducted by Chakar et al. [10] for thermal conductivity and for specific heat by Çolak et al. [23], as presented in Figs. 6 and 7, respectively, maintaining the same parameters as the latter. Our analysis deduces that the experimental results exhibited good agreement with the values obtained from our numerical model.

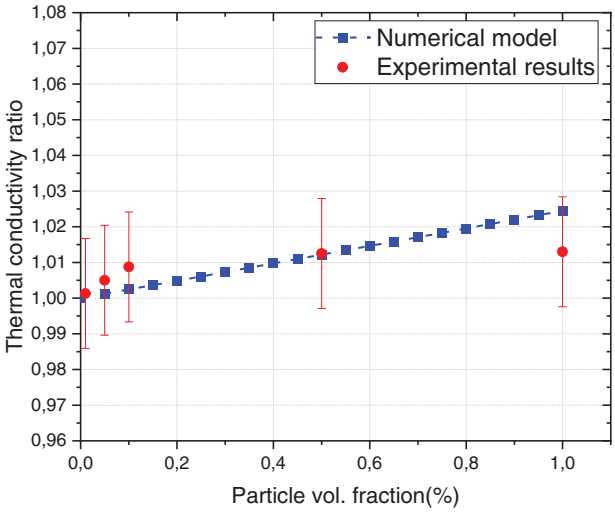


**Figure 6:** Comparing the thermal conductivity ratio results between the experimental data and those obtained from the current model for $TiO_2$/water [10]

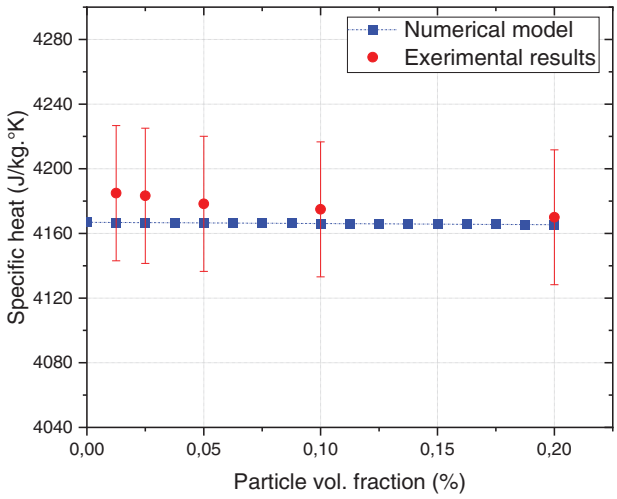


**Figure 7:** Comparing the specific heat results between the experimental data and those obtained from the current model for $Al_2O_3$/water

## 4 Conclusions

In conclusion, our comprehensive examination of the thermal properties of hybrid nanofluids has provided valuable insights into their performance across various volume fractions. The observed substantial variations in thermal conductivity and specific heat as the volume fraction increases underscore the dynamic nature of these nanofluids. Notably, the $TiO_2$/Cu-Water hybrid nanofluid emerged as a standout performer, exhibiting an impressive 5.04% increase in thermal conductivity at a volume fraction of 10%. Similarly, the Cu/$Al_2O_3$-Water hybrid nanofluid demonstrated a notable 1% increase in specific heat within the same volume fraction range. These key quantitative results highlight the significant improvements in thermal properties achieved through the use of hybrid nanofluids. Considering the application-specific context of solar panel cooling, the choice of the optimal hybrid nanofluid hinges on a multitude of factors, encompassing operational constraints and specific thermal requisites. Our results strongly advocate for the $TiO_2$/Cu-Water hybrid nanofluid as a preferable option, primarily due to its superior thermal conductivity performance. Nevertheless, it is imperative to acknowledge that decisions should factor in additional considerations, such as long-term stability and cost implications, which could influence the ultimate selection of the optimal hybrid nanofluid for enhancing the cooling efficiency of solar panels.

These findings not only contribute to the fundamental understanding of nanofluid behavior but also present promising prospects for targeted applications that demand heightened thermal performance. Beyond solar panel cooling, the improvements in thermal conductivity and specific heat of hybrid nanofluids have potential impacts on other applications such as electronics cooling and automotive systems. As the field continues to evolve, the optimization of nanofluid formulations based on specific volume fractions holds considerable potential for advancing thermal management solutions in diverse technological applications, thereby contributing to the broader field of thermal management and renewable energy.

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**Author Contributions:** The authors confirm contributions to the paper as follows: Study conception and design, data collection, analysis and interpretation of results, and draft manuscript preparation: Chakar Khadija; reviewing the results and approving the final version of the manuscript: El Mouden Mahmoud and Hajjaji Abdelowahed. All authors reviewed the results and approved the final version of the manuscript.

**Availability of Data and Materials:** The data used in this study are available upon request from the authors, but some sensitive data cannot be shared due to privacy and ethical restrictions.

**Ethics Approval:** Not applicable.

**Conflicts of Interest:** The authors declare no conflicts of interest to report regarding the present study.

## References

1. Vijayan D, Koda E, Sivasuriyan A, Winkler J, Devarajan P, Kumar R, et al. Advancements in solar panel technology in civil engineering for revolutionizing renewable energy solutions–a review. Energies. 2023;16:6579. doi:10.3390/en16186579.
2. Parthiban R, Pathipooranam P. An enhancement of the solar panel efficiency: a comprehensive review. Front Energy Res. 2022;10:937155. doi:10.3389/fenrg.2022.937155.
3. Tripathi BM, Shukla SK, Rathore PKS. A comprehensive review on solar to thermal energy conversion and storage using phase change materials. J Energy Storage. 2023;72:108280. doi:10.1016/j.est.2023.108280.
4. Rashid FL, Eleiwi MA, Mohammed HI, Ameen A, Ahmad S. A review of using solar energy for cooling systems: applications, challenges, and effects. Energies. 2023;16(24):8075. doi:10.3390/en16248075.
5. Akrouch MA, Chahine K, Faraj J, Hachem F, Castelain C, Khaled M. Advancements in cooling techniques for enhanced efficiency of solar photovoltaic panels: a detailed comprehensive review and innovative classification. Energy Built Enviro. 2023. doi:10.1016/j.enbenv.2023.11.002.
6. Chichghare K, Barai D, Bhanvase B. Applications of nanofluids in solar thermal systems. In: Nanofluids and their engineering applications. Taylor & Francis Group; 2019. p. 275–314. doi:10.1201/9780429468223.
7. Abdullatif Alshuhail L, Shaik F, Syam Sundar L. Thermal efficiency enhancement of mono and hybrid nanofluids in solar thermal applications–a review. Alex Eng J. 2023;68(6):365–404. doi:10.1016/j.aej.2023.01.043.
8. Kandeal AW, Algazzar AM, Elkadeem MR, Thakur AK, Abdelaziz GB, El-Said EMS, et al. Nano-enhanced cooling techniques for photovoltaic panels: a systematic review and prospect recommendations. Sol Energy. 2021;227(1):259–72. doi:10.1016/j.solener.2021.09.013.
9. Chakar K, Ennawaoui C, El Mouden M, Hajjaji A. Nanofluids for the cooling system. Mater Today: Proc. 2022;66:346–8. doi:10.1016/j.matpr.2022.05.448.
10. Chakar K, Ennawaoui C, El Mouden M, Hajjaji A. Hybrid nanofluids multi performance optimizations for the cooling system coupling with hybrid photovoltaic thermal collectors. Eur Phys J Appl Phys. 2022;97:70. doi:10.1051/epjap/2022220117.
11. Mahamude ASF, Kamarulzaman MK, Harun WSW, Kadirgama K, Ramasamy D, Farhana K, et al. A comprehensive review on efficiency enhancement of solar collectors using hybrid nanofluids. Energies. 2022;15(4):1391. doi:10.3390/en15041391.
12. Hemmat Esfe M, Kiannejad Amiri M, Bahiraei M. Optimizing thermophysical properties of nanofluids using response surface methodology and particle swarm optimization in a non-dominated sorting genetic algorithm. J Taiwan Inst Chem Eng. 2019;103:7–19. doi:10.1016/j.jtice.2019.07.009.
13. Said Z, Sohail MA. 10-Challenges and difficulties in developing hybrid nanofluids and way forward. In: Hybrid nanofluids. Elsevier; 2022. p. 233–59. doi:10.1016/B978-0-323-85836-6.00010-7.
14. Borode A, Tshephe T, Olubambi P, Sharifpur M, Meyer J. Experimental study and ANFIS modelling of the thermophysical properties and efficacy of GNP-$Al_2O_3$ hybrid nanofluids of different concentrations and temperatures. SN Appl Sci. 2023;5:337. doi:10.1007/s42452-023-05574-7.

15. Rashidi MM, Nazari MA, Mahariq I, Assad MEH, Ali ME, Almuzaiqer R, et al. Thermophysical properties of hybrid nanofluids and the proposed models: an updated comprehensive study. Nanomaterials. Nov 2021;11(11):3084. doi:10.3390/nano11113084.
16. Wohld J, Beck J, Inman K, Palmer M, Cummings M, Fulmer R, et al. Hybrid nanofluid thermal conductivity and optimization: original approach and background. Nanomaterials. 2022;12:2847. doi:10.3390/nano12162847.
17. Borode AO, Ahmed NA, Olubambi PA, Sharifpur M, Meyer JP. Investigation of the thermal conductivity, viscosity, and thermal performance of graphene nanoplatelet-alumina hybrid nanofluid in a differentially heated cavity. Front Energy Res. 2021;9:737915. doi:10.3389/fenrg.2021.737915.
18. Maxwell JC. A treatise on electricity and magnetism. Clarendon Press; 1873. p. 616.
19. Yu W, Choi SUS. The role of interfacial layers in the enhanced thermal conductivity of nanofluids: a renovated maxwell model. J Nanopart Res. 2003;5(1):167–71. doi:10.1023/A:1024438603801.
20. Hamilton RL, Crosser OK. Thermal conductivity of heterogeneous two-component systems. Ind Eng Chem Fund. 1962;1(3):187–91. doi:10.1021/i160003a005.
21. Pak BC, Cho YI. Hydrodynamic and heat transfer study of dispersed fluids with submicron metallic oxide particles. Exp Heat Transf. 1998;11(2):151–70. doi:10.1080/08916159808946559.
22. Xuan Y, Roetzel W. Conceptions for heat transfer correlation of nanofluids. Int J Heat Mass Transf. 2000;43(19):3701–7. doi:10.1016/S0017-9310(99)00369-5.
23. Çolak AB, Yıldız O, Bayrak M, Celen A, Dalkilic A, Wongwises S. Experimental study on the specific heat capacity measurement of water-based $Al_2O_3$-Cu hybrid nanofluid by using differential thermal analysis method. Curr Nanosci. 2019;15(6):912–28. doi:10.2174/1573413715666191118105331.