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Recent advancement in hybrid nanofluids used in flat plate solar collectors and future prospects

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Abstract:

Hybrid nanofluids are developed by combining conventional fluids with various nanoparticles in specific proportions. This study gathers and analyses recent research published between 2020 and 2024 on the application of hybrid nanofluids in solar collector energy systems. It examines the types of nanoparticles, nanoparticle loading, and system design. The findings demonstrate that the performance of flat plate solar collectors (FPSCs) can be significantly enhanced by employing hybrid nanofluids. With a maximum friction factor of 1.14 times that of water, the Nusselt number (Nu) increased by 21.24% at a 0.16% nanoparticle loading. At 0.3 vol.% nanoparticle concentration and 60°C, increases in Nu, heat convection, and friction factors were observed at 18.7, 39.33, and 19%, respectively. The exergy performance of the panel improved by 40.5, 36.9, 33.2, and 29.6% with hybrid nanofluids at concentrations of 0.3, 0.2, 0.1 and 0.05 vol.% and Reynolds numbers (Re) of 1414, 1674, 1774, and 1892, respectively. This study offers several recommendations to further enhance the overall performance of FPSCs and maximise energy absorption, promoting broader adoption of hybrid nanofluids.

Keywords: **energy systems, flat plate, future prospects, hybrid nanofluid, solar collector.**

Classification numbers: **2.1, 2.3**

1. Introduction

Fossil fuels, the cornerstone of industrial activity, release substantial amounts of CO_2 and other toxic pollutants into the atmosphere, contributing to global warming. This phenomenon leads to severe weather events, rising sea levels, and a myriad of environmental challenges [1, 2].

Renewable energy sources offer a sustainable alternative to fossil fuels, providing a clean and essential option for addressing the growing global energy demand without compromising environmental health [3, 4]. The widespread adoption of photovoltaic cells and solar technologies paves the way for a sustainable future while ensuring ecological balance [1, 5].

Solar collectors and concentrators are specialised devices designed to convert solar radiation into thermal energy. Among these, FPSCs are cost-effective and environmentally friendly systems that harness solar energy for heating purposes [6]. Coolants such as oil, ethylene glycol, water, and air are used to absorb and transfer heat from FPSCs. Researchers are also exploring solar system storage solutions to improve thermal efficiency [7, 8].

To further improve flat plate solar collector (FPSC) thermal efficiency, researchers are investigating the use of nanofluids-mixtures of traditional fluids with nanoparticles (1-100 nm in size) [9, 10]. Nanofluids have been shown to significantly improve thermal conductivity, enabling superior heat transfer in various applications, including thermal exchangers, radiators, condensers, and solar storage systems [11].

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Many technical systems employ nanofluids as heat transfer media, including thermal exchangers, radiators, condensers, and solar storage units. These approaches fall within the broader category of passive heat transfer methods. S.U.S. Choi, et al. (1995) [11] demonstrated that nanofluids exhibit significantly higher thermal conductivities compared to traditional fluids, enabling more efficient heat transmission.

At low concentrations ranging between 0.05 and 1%, Y.R. Sekhar, et al. (2012) [12] Experimentally evaluated the conductivity of H_2O and Al_2O_3 nanofluids. The effects of nanoparticle loading, thermal conductivity, frictional influence, and flow characteristics of nanofluids were also studied by Y. Xuan, et al. (2003) [13]. Their findings indicated that the friction coefficient and viscosity are directly proportional to the loading of Al_2O_3-water in heat exchangers. This relationship was further investigated by J. Albadr, et al. (2013) [14], who explored the forced convection and flow characteristics of nanofluids.

E. Natarajan, et al. (2009) [15] compared the thermal properties of nanofluids with those of conventional fluids, while Z. Said, et al. (2015) [16] utilised TiO_2 nanofluids and polyethylene glycol dispersions in their investigations. Y. Xuan, et al. (2000) [17] examined heat transfer in nanofluids and proposed several methods for developing heat transfer correlations. V. Khullar, et al. (2012) [18] researched the use of nanofluids in solar water heaters, focusing on concentrating types, and provided a quantitative evaluation of the environmental benefits of these systems as alternatives to fossil fuel-based technologies.

In practical experiments, A.S. Shareef, et al. (2015) [19] analysed the effects of incorporating Al_2O_3 nanofluids into FPSCs, revealing enhanced system performance. T.P. Otanicar, et al. (2010) [20] reported that the use of nanofluids in absorption systems could improve collector performance by up to 5%. Moreover, experiments conducted by other researchers [21-23] have demonstrated significant improvements in the hydraulic efficiency of FPSCs when nanofluids are utilised. These findings suggest that optimising nanofluids could lead to the development of ideal formulations for various applications [24, 25].

A comprehensive review by L.S. Sundar, et al. (2021) [26] discussed the thermo-physical properties, applications in solar collectors with fluid movement, and the production of hybrid nanoparticles and nanofluids. Similarly, A.S.F. Mahamude, et al. (2022) [27] examined cutting-edge hybrid solar energy system applications across different types of solar collectors. W.S. Sarsam, et al. (2015) [28] conducted an in-depth analysis of the impact of nanofluids in FPSC systems.

Although numerous review studies have investigated the application of hybrid nanofluids in solar collector units, there remains a need for further research to assess recent advancements from 2020 to 2024. Such studies would provide valuable insights into cutting-edge innovations in hybrid nanofluids for FPSC systems. Consequently, this research aims to evaluate the thermal properties, efficiency attributes, and practical feasibility of these advanced units for real-world applications.

2. Cutting-edge innovations in hybrid nanofluids used in flat plate solar collector systems

2.1. Hybrid nanofluids boost flat plate solar collectors efficiency

O.A. Hussein, et al. (2020) [29] prepared hybrid nanofluids for use as coolants in FPSC by suspending multi-wall carbon nanotubes (MWCNTs) and graphene nanoplatelets (GNPs) with hexagonal boron nitride (h-BN) in distilled water. Several advanced techniques, including high-resolution transmission electron microscopy (HRTEM), field emission scanning electron microscopy (FESEM), energy-dispersive X-ray spectroscopy (EDX), ultraviolet-visible (UV-Vis) spectrum analysis, Fourier transform infrared (FTIR) spectroscopy, and X-ray diffraction (XRD), were employed to analyse the shape and structure of the nanofluids. Fig. 1 illustrates that using hybrid nanofluids as an absorption medium with a flow rate of 4 l/min improved the thermal performance of the solar collector by up to 86%.

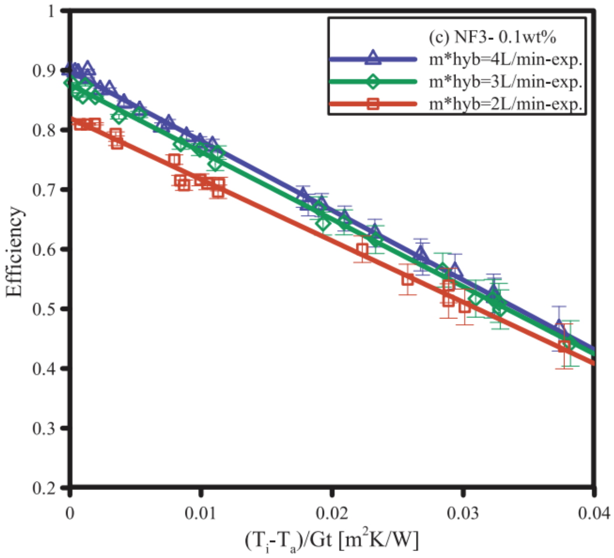


Fig. 1. Effect of hybrid nanofluid flow rates on flat plate solar collectors' efficiency [29].

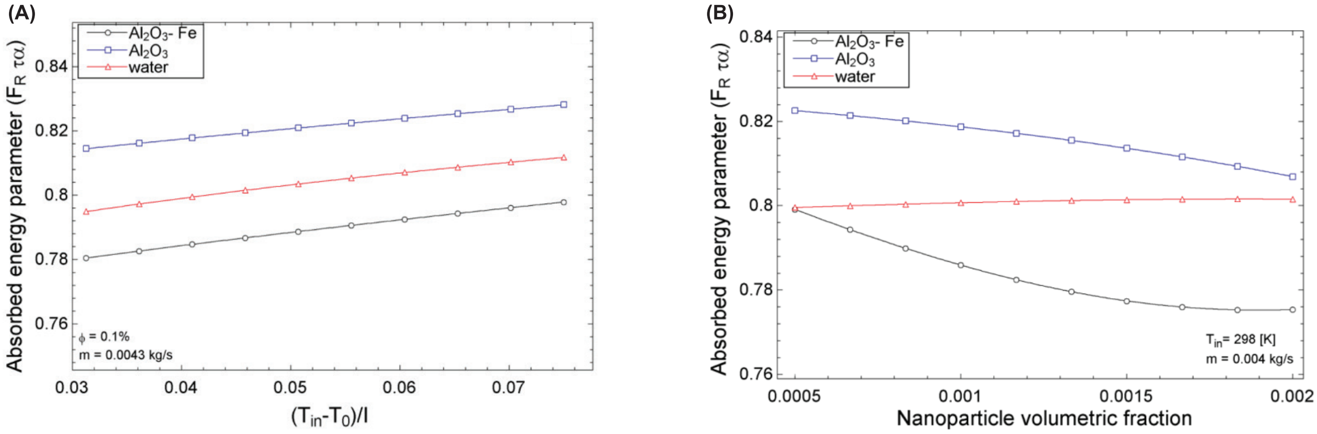


Fig. 2. Influence of temperature and nanoparticle volumetric fraction on absorbed energy [30].

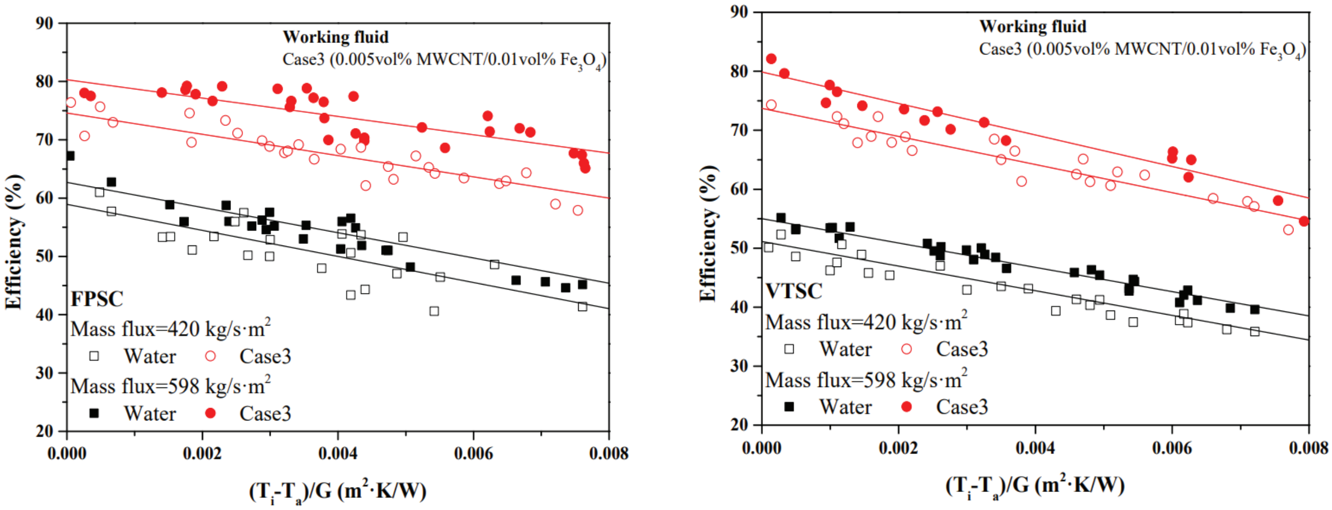
E.C. Okonkwo, et al. (2020) [30] conducted a thermal analysis of FPSCs operating with both simple and hybrid nanofluids. Their findings revealed that the best absorbed-energy parameter, which increases with temperature for all tested working fluids, was observed in Al_2O_3-water nanofluid. Fig. 2 demonstrates that nanoparticle loading significantly affects the absorbed thermal energy across all working fluids.

2.2. Nanofluid enhancement of solar efficiency

M. Lee, et al. (2020) [31] assessed the performance of FPSCs and vacuum tube solar collectors using H_2O and MWCNT/Fe_3O_4 hybrid nanofluids as active working fluids. Compared to FPSCs, vacuum tube solar collectors treated with MWCNT/Fe_3O_4 binary nanofluids exhibited a substantially higher efficiency boost and maintained optimal performance under various boundary conditions (Fig. 3).

Improving FPSC efficiency was also the focus of numerical research by S.P.A. Yegane, et al. (2020) [32]. Using the Darcy-Brinkman model to characterise the flow field of binary nanofluids within collector channels, their study incorporated metal foam within the tubes. The results showed that, with constant nanoparticle volume proportions, a combination of Cu and Al nanoparticles with equal concentrations outperformed pure alumina nanoparticles in terms of thermal exchange. Conversely, pure copper nanoparticles exhibited negligible variation. Additionally, as pore density increased from 10 PPI to 45 PPI, the collector's comprehensive performance ratio improved from 0.445 (at 0.85 porosity) to 0.487 (at 0.95 porosity).

Q. Xiong, et al. (2021) [33] investigated the thermal effects of binary nanoparticles in FPSCs, focusing on their properties, heat transfer performance, applied temperatures, and spatial distribution. Their modelling employed a two-stage approach, revealing that high nanoparticle loading



Flat plate solar collector

Vacuum tube solar collector

Fig. 3. Comparison of flat plate solar collector and vacuum tube performance with varying working fluid flow rates [31].

was concentrated near the lower section of the system at low Reynolds numbers (Re). This phenomenon was attributed to the mitigation of thermophoretic effects by high porosity, thermal energy, conductivity, and thermophoretic parameters.

V.P. Kalbande, et al. (2021) [34] highlighted the advantages of binary nanofluids in FPSCs for heat storage units. They tested a solar system with integrated heat storage and analysis capabilities using a hybrid nanofluid composed of CuO+Al_2O_3/water as the heat transfer fluid (HTF). Their research anticipated high thermal efficiency in energy storage devices employing stainless steel vessels and hybrid nanofluids. Comparative studies against traditional solar collector types demonstrated superior performance with binary nanofluids in FPSCs. Stainless steel heat storage systems using FPSCs were heated to a peak temperature of 87°C (Fig. 4).

2.3. Binary nanofluids for efficiency gains

In their investigation of hybrid nanofluids, A.K. Alzahrani, et al. (2021) [35] examined the absorption and potential thermal energy storage capabilities of an inclined plate solar collector. The study focused on hybrid nanofluids composed of MgO, CuO, and MWCNTs (MWCNTs) used as a base solvent instead of water. The key physical properties related to heat transmission, absorption, and emission of solar radiation were demonstrated (Fig. 5). The study revealed that the nanoparticle volume fraction significantly enhanced the efficiency of solar radiation capture and transport. Furthermore, as the nanoparticle loading increased, the rate of heat transmission also rose.

The researchers identified a relationship between the Schmidt number (Sc) and the concentration profile $\Phi(\eta)$, noting that an increase in Sc reduced $\Phi(\eta)$. The Schmidt number, commonly defined as the ratio of mass diffusion to momentum diffusion, influences this phenomenon. Fig. 6 shows that at high Sc values, momentum diffusion dominates over mass diffusion.

L.S. Sundar, et al. (2021) [36] evaluated the heat transfer performance, thermal convection, and friction coefficient of an FPSC using H_2O and nanodiamond-cobalt oxide binary nanofluids as coolants. At a mass concentration of 0.15% and a temperature of 60°C, the maximum increases in thermal conductivity and viscosity were recorded at 18 and 46%, respectively. The findings demonstrated a maximum friction factor penalty of 1.13 times that of water, with the Nusselt number (Nu) increasing by 21.23% at a nanoparticle loading of 0.15%. Under these conditions, the thermal efficiency of the collector reached 59%, compared to 48% with water alone.

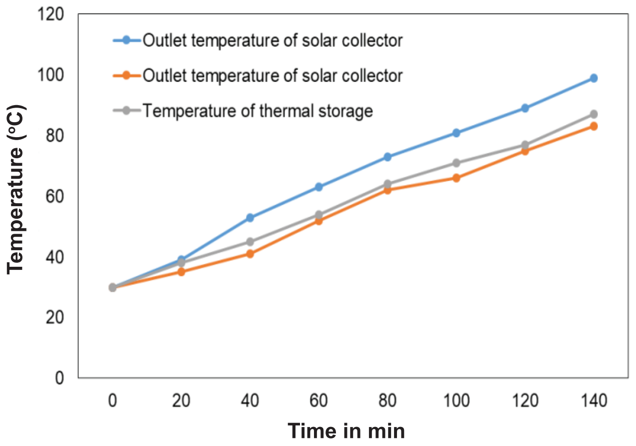


Fig. 4. Flat plate collector inlet and outlet temperature vs. time and thermal energy storage performance [34].

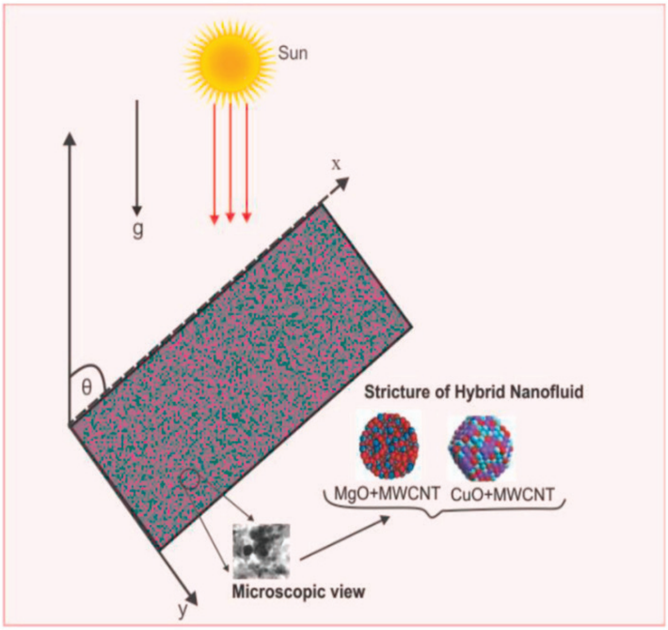


Fig. 5. Schematic of solar collector absorption [35].

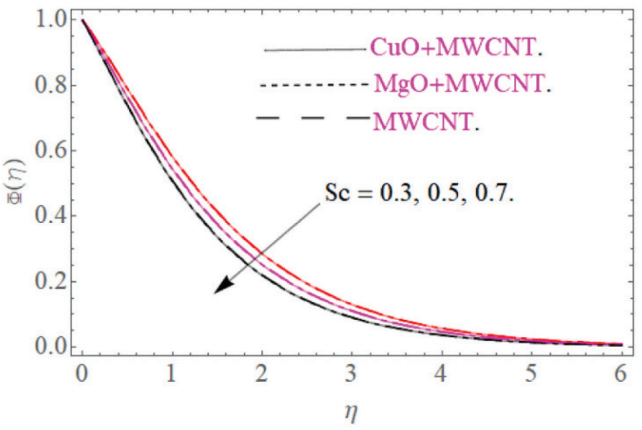


Fig. 6. Effect of Sc variation on Φ(η) (concentration profile) [35].

M. Lee, et al. (2021) [37] conducted theoretical research using various nanofluids to analyse the performance of three distinct solar collector designs. The study employed hybrid nanofluids containing highly effective nanoparticles, such as MWCNT, CuO, and Fe_3O_4, to assess solar collector efficiency. The results indicated that hybrid nanofluids composed of MWCNT/CuO or MWCNT/Fe_3O_4 outperformed other combinations, with FPSC, vacuum U-channel, and heat pipe systems showing efficiency improvements of 2-3% compared to 0.05% MWCNT nanofluids.

L.S. Sundar, et al. (2021) [36] conducted an Experimental study on the thermal performance of FPSCs using H_2O and nanodiamond-cobalt oxide binary nanofluids. Experiments were performed at mass concentrations ranging from 0.05 to 0.15% and volume flow rates between 0.56 and 1.35 l/min. At a concentration of 0.15% and 60°C, the thermal conductivity and viscosity increased by 15.71 and 45.83%, respectively. The friction factor penalty relative to water was 1.13 times, while the Nu increased by 21% at 0.16% loading. The thermal efficiency of the collector reached 59%, compared to 48% with water.

B. Saleh, et al. (2021) [38] analysed the thermal exchange, friction coefficient, and overall collector performance of FPSCs operating with natural convection using hybrid nanofluids containing MWCNT and Fe_3O_4. The hybrid nanoparticles were synthesised using in-situ growth and chemical co-precipitation techniques. Experiments were conducted with loadings between 0.05 and 0.3% and flow rates ranging from 0.1 to 0.75 l/min. At a loading of 0.3% and 60°C, thermal conductivity and viscosity increased by 29 and 51%, respectively, compared to water. At 0.3% loading, the Nu, thermal performance, and friction coefficient improved by 19, 40, and 19%, respectively, under peak solar radiation conditions. Using data collected at 1:00 pm with a Reynolds number (Re) of 1400, the heat transfer performance of the collector increased by 29% with 0.3 vol.% hybrid nanofluids (Figs. 7 and 8).

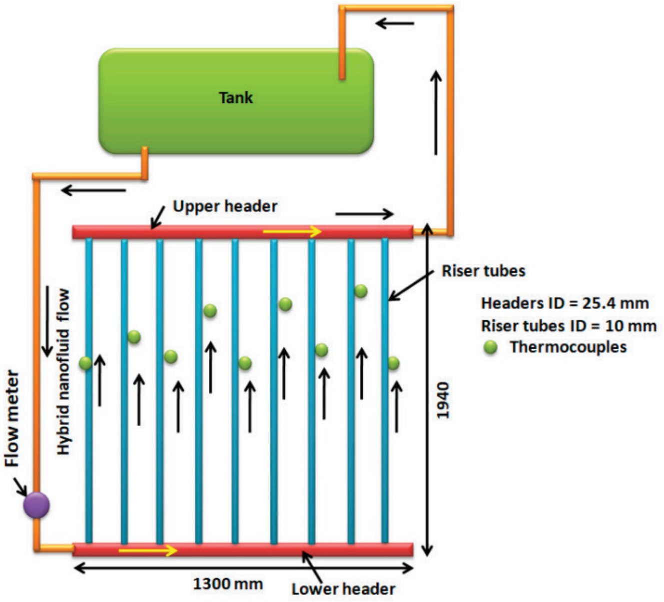


Fig. 7. Representation of free-circulation solar collectors [38].

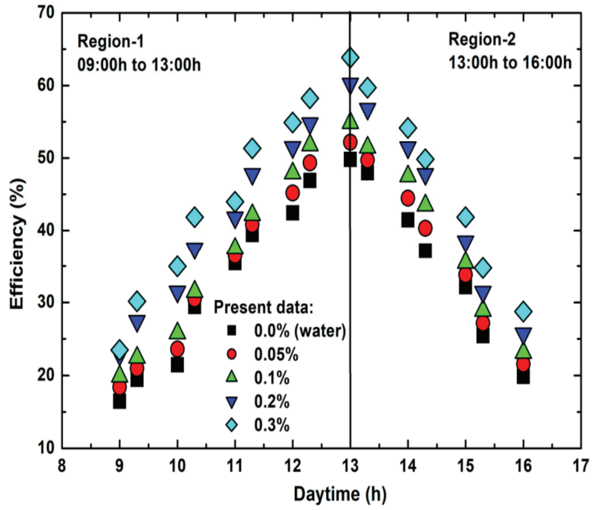


Fig. 8. Collector efficiency of water and hybrid nanofluids under daylight conditions [38].

2.4. MWCNT-Fe_3O_4 nanofluid: Solar efficiency

J. Mustafa, et al. (2022) [39] investigated the performance of an FPSC using a hybrid nanofluid composed of H_2O/Cu-Al to evaluate energy efficiency, visualise energy output, and assess environmental impacts. The study compared the results with those obtained using water, Al_2O_3 nanofluid, and H_2O alone. The Reynolds number (Re) ranged from 700 to 2300, with a nanoparticle concentration of 0.1%. The findings indicated that the hybrid nanofluid was the most effective operational fluid for the collector. The maximum improvement in power performance for the collector was 4.3% with hybrid nanofluids and 3.9% with mono nanofluids compared to water. The collector's performance was significantly superior with the hybrid nanofluid compared to the mono nanofluid containing Al_2O_3 and water. An environmental analysis showed that using the hybrid nanofluid reduced emissions of carbon dioxide by 29.15 kg, sulphur oxides by 0.0149 kg, and nitrogen oxides by 0.0255 kg compared to water.

Z. Said, et al. (2022) [40] employed hybrid nanofluids comprising MWCNT + Fe_3O_4/H_2O to study the heat transfer efficiency of FPSCs operating under free circulation conditions. The study achieved the highest heat transfer performance of 64% at a Reynolds number of 1415 and a nanoparticle concentration of 0.3%. The heat transfer coefficient increased by 26.3%, while the friction factor showed a slight penalty of 18.9%. The exergy performance of the collector improved by 40.51, 36.86, 33.21, and 29.56% at nanoparticle concentrations of 0.3, 0.2, 0.1, and 0.05%, respectively, with corresponding Reynolds numbers of 1413, 1674, 1774, and 1892. A new predictive model for thermal performance, friction coefficient, Nusselt number (Nu), and overall collector performance was developed using Experimental data, optimised through a Collaborative Boosted Regression Tree.

E. Elshazly, et al. (2022) [41] examined the heat transfer performance of FPSCs under controlled conditions using MWCNT, Al_2O_3, and a 50:50 hybrid of the two. The study evaluated various factors influencing efficiency, including solar intensity, nanoparticle loading, and flow rate. Four nanoparticle concentrations (0.5, 0.025, 0.01, and 0.005%) and three flow rates were tested. The results indicated that the 50:50 hybrid of MWCNT and Al_2O_3 improved efficiency by 26% at 1.5 l/min, 29% at 2.5 l/min, and 18% at 3.3 l/min. These findings suggest that replacing half of the MWCNTs with the more economical Al_2O_3 is beneficial. Increasing the fluid velocity and nanoparticle loading enhanced energy efficiency. At a constant flow rate, exergy performance improvements were recorded as 42.2% with MWCNT/water nanofluid, 40.5% with hybrid MWCNT/Al_2O_3 (50:50), and 34% with Al_2O_3/water nanofluid (Fig. 9).

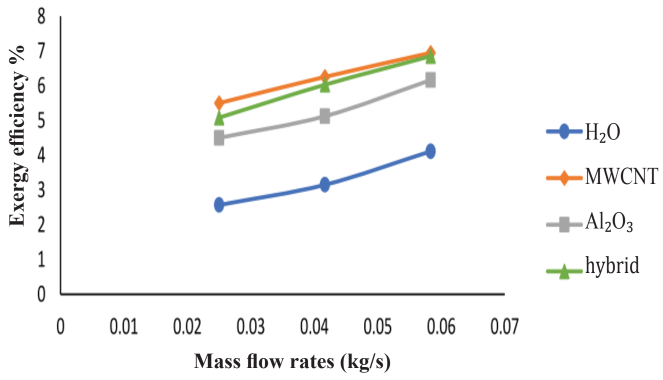


Fig. 9. Exergy performance of flat plate solar collectors at various mass flow rates [41].

Z. Said, et al. (2022) [42] further examined the thermal efficiency of FPSCs using a hybrid nanofluid containing MWCNT + Fe_3O_4/H_2O in an arid environment. The study recorded a notable 26.3% improvement in thermal performance, with a modest friction-induced pressure drop of 18.9%. Predictive models for thermal efficiency, Nusselt number, friction factor, and heat transfer effectiveness were developed using Experimental data. State-of-the-art machine learning algorithms, including XGBoost and boosted regression tree (BRT), were employed to optimise the models. Statistical techniques and Taylor diagrams confirmed the accuracy of these models. At a Reynolds number of 1413 and a nanoparticle concentration of 0.3 vol.%, the optimal conditions yielded a thermal efficiency of 63.84%.

To enhance the convective heat transfer coefficient (HTC), H. Nabi, et al. (2022) [43] utilised hybrid nanofluids and turbulence-inducing components in FPSCs. Using computational fluid dynamics (CFD) simulations, the study explored three configurations with identical pipe lengths. The first phase evaluated various turbulence-inducing elements, with CASE 3 exhibiting the best heat transfer performance, achieving a 31.31% higher thermal coefficient at Re 10, 000 and 31.06% at Re 8, 000 compared to the base case. The second phase used CASE 3 to test hybrid nanofluids and water, finding that SWCNT (Single wall carbon nanotubes)-CuO/H_2O hybrid nanofluids offered the best thermal coefficient. In the final phase, hybrid nanofluids with concentrations ranging from 1% to 5% were tested. The HTC increased by 8.79% at Re 4000 with a 5% concentration, which exhibited the most pronounced concentration-dependent effect (Fig. 10).

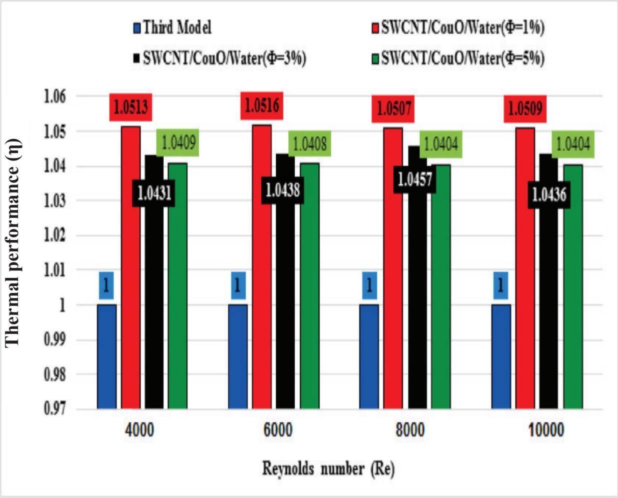


Fig. 10. Thermal performance of hybrid nanofluid concentrations at varying Reynolds numbers [43].

2.5. Boosting solar collector performance

K. Janardhana, et al. (2022) [44] investigated the operational efficiency of a FPSC-based water heater using a hybrid nanofluid composed of CuO and MgO nanoparticles as a coolant. The nanoparticle volume fraction was set at 0.2% (0.1% CuO and 0.1% MgO), and two distinct flow rates-0.017 kg/s and 0.034 kg/s-were employed. The study was conducted in April 2021 in North India (27.1767° N, 78.0081° E). The findings revealed that, compared to water, the use of hybrid nanofluids as a circulating fluid significantly improved the performance of the FPSC system. At a flow rate of 0.017 kg/s, the system's effectiveness increased by 43.3%, and the outlet water temperature was higher.

Y. Khetib, et al. (2022) [45] evaluated the thermal-hydraulic performance, energy, and exergy values of FPSCs using a two-phase model. The study examined the effects of incorporating turbulators with modified geometries and DWCNTs-TiO_2/H_2O hybrid nanofluids. The SIMPLEC algorithm, finite volume technique (FVT), and FLUENT software were employed for numerical simulations. In the turbulent flow regime, with Reynolds numbers (Re) ranging from 7, 000 to 28, 000 and nanoparticle loadings from 1% to 3%, the average Nusselt number (Nu) increased with higher Re and volume fraction (ϕ).

A.S.F. Mahamude, et al. (2022) [46] explored the use of graphene and waste cotton hybrid nanofluids to improve FPSC efficiency. The study proposed a composite of crystal nano-cellulose (CNC) and graphene as an alternative heat absorber. By comparing a 0.3% base fluid, 0.5% graphene, and CNC, as well as a 0.5% graphene-CNC hybrid at different temperatures, the researchers found that a 0.5% graphene-CNC hybrid achieved remarkable results. At 80°C, the hybrid nanofluid exhibited thermal conductivity 194% higher than ordinary nanofluid and was three times more viscous (Fig. 11).

M. Ahmed, et al. (2022) [47] studied the characteristics of H_2O-based working fluids reinforced with hexagonal boron nitride and carbon nanotubes (hBN/CNTs) in FPSCs. An optimal hybridisation ratio of 40:60 was achieved with CF-CNTs and hBN. Using volumetric flow rates of 2 to 4 l/min, thermal efficiency tests were conducted in accordance with the ASHRAE-93-2010 standard. The study revealed that the efficiency of FPSCs was enhanced by up to 87% when using 0.1% hBN/CF-CNTs at a flow rate of 4 l/min compared to traditional coolants (Figs. 12 and 13).

P.M.J. Stalin, et al. (2022) [48] investigated the thermodynamic performance of FPSCs using single and hybrid nanofluids. The results showed that the heat transfer efficiency increased by 6.6% when Zn-Fe_2O_4/H_2O hybrid nanofluids with 0.5% loading were used, and by 7.83% with Fe_2O_4/H_2O nanofluids. The highest energy efficiency of 80.1% was achieved at a flow rate of 0.1 kg/s. Exergetic efficiency improved by 8.24% when hybrids were used, compared to 5.36% for Fe_2O_4 nanofluids.

S.P.A. Yegane, et al. (2022) [49] employed entropy generation analysis to control the temperature of an FPSC. The study utilised porous metal foam to fill the collector channel and a hybrid nanofluid of Al_2O_3 and Cu with H_2O as the working fluid. The Darcy-Brinkman model was applied to describe nanofluid flow through porous metal foam. In the presence of a uniform magnetic field, the findings revealed that increasing nanoparticle loading reduced irreversibility at Re below 613. However, for strong magnetic fields and Re above 370, irreversibility increased with higher nanoparticle concentrations.

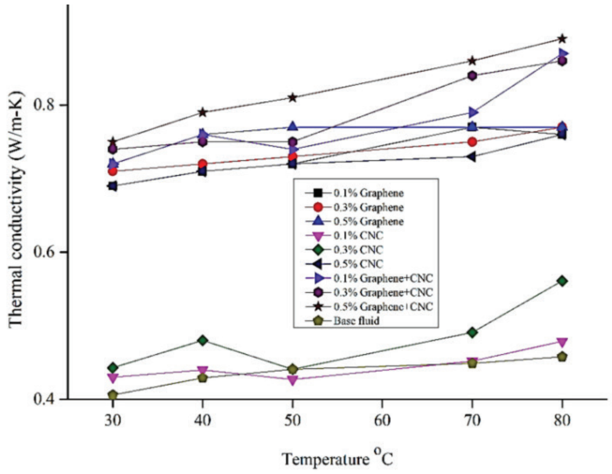


Fig. 11. Thermal conductivity of graphene and CNC-based hybrid nanofluids at varying temperatures [46].

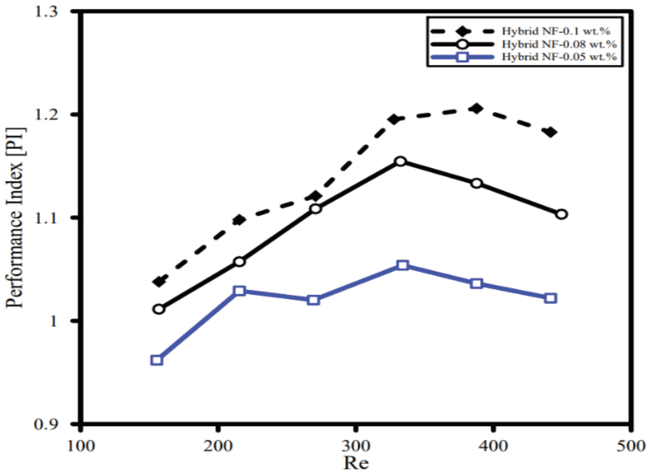


Fig. 12. Efficiency indices of H_2O-based hBN/CF-CNTs at various particle loadings and flow rates [47].

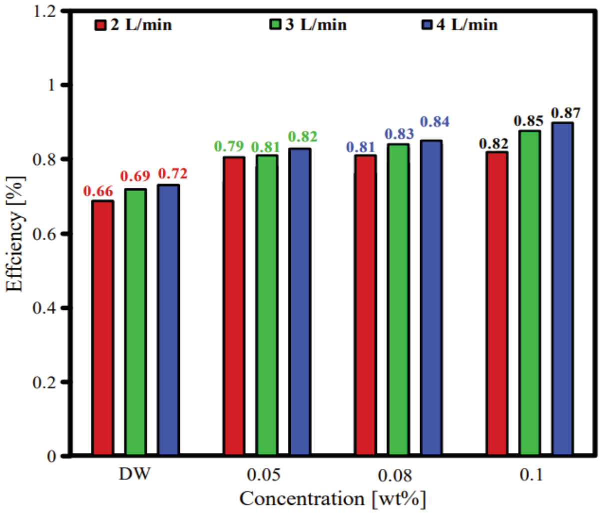


Fig. 13. Collector efficiency influenced by nanoparticle loading and flow rate [47].

A.M. Ajeena, et al. (2023) [50] studied the impact of nanofluids on FPSC performance. The study tested ZrO_2-SiC/DW hybrid nanofluids at mass flow rates of 0.025, 0.033, and 0.041 kg/s. The highest thermal performance of 75.21% was achieved with 0.1% loading at 0.041 kg/s. Heat transfer improved by 31.64% with nanofluids, and exergy efficiency increased with larger nanoparticles and higher loadings. However, mass flow rate was inversely related to exergy efficiency. The use of ZrO_2-SiC/DW hybrid nanofluids resulted in lower entropy generation compared to water (Figs. 14 and 15).

2.6. Numerical studies explore novel collector designs

E.S.R. Negeed, et al. (2023) [51] examined the effects of a novel turbulator with various geometric forms and a two-phase Cu-GO/H_2O hybrid nanofluid on the thermal-hydraulic, exergy, and energy efficiencies of a fluid power source converter (FPSC) operating under turbulent flow conditions. The results indicated that the thermal-hydraulic performance of the FPSC absorber tube was significantly enhanced when the turbulator was employed compared to a non-turbulated design. Heat transfer (HT) rates and pressure drop augmentation (Δp) were strongly influenced by increases in the turbulator's curvature angle (γ). Factors such as inlet velocity, nanoparticle volume fraction (φ), turbulator geometry, and FPSC boundary conditions were found to impact energy efficiency, which improved with increases in Re, φ, and γ.

J. Alsarraf, et al. (2023) [52] conducted numerical simulations of an FPSC with a spiral absorber channel. The FPSC geometry was created in SolidWorks, and computational domain and meshing were performed using Ansys software. The two-phase hydrodynamic fluid (HN) of MgO-MWCNT/Therminol VP-1 was simulated using the RNG k-ε turbulence model. Pitch ratios of the absorber channel ranged from 0.75 to 2.25, with nanoparticle volume fractions varying between 0 and 3% and Re values ranging from 9000 to 24,000. Additionally, a magnetic field of 20 to 140 Hartmann numbers (Ha) was applied. The results revealed that increasing Re and φ enhanced both thermal efficiency and pressure drop (Δp). When a spiral absorber channel with a pitch ratio of α=2.25 was used at φ=3% and Re=24, 000, the Nu and Δp improved by 122 and 310%, respectively, compared to a plain absorber tube.

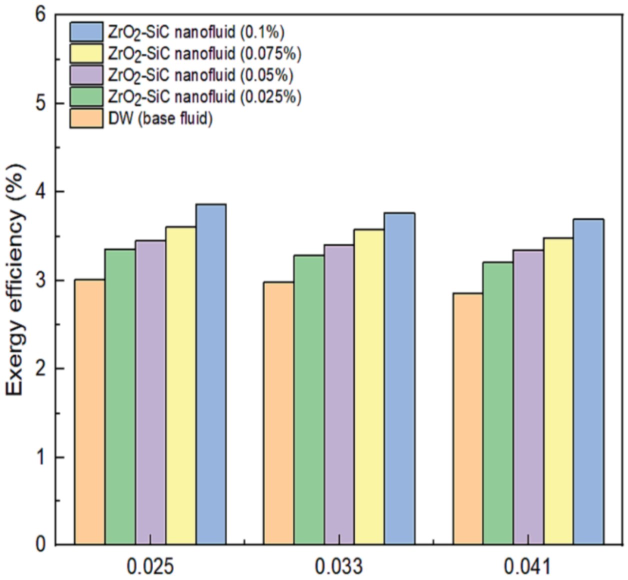


Fig. 14. Exergy efficiency of different loading ZrO_2-SiC/DW hybrid nanofluid flat plate solar collector against velocity [50].

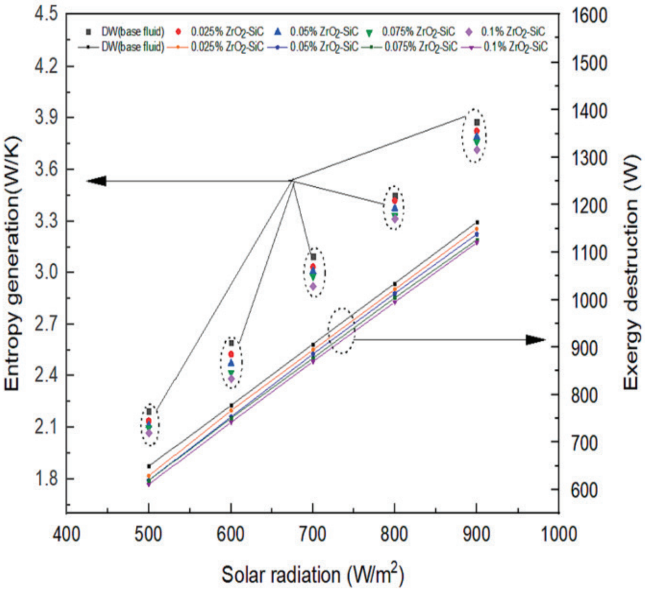


Fig. 15. Entropy generation and exergy destruction for ZrO_2-SiC/DW hybrid nanofluid and H_2O at varying solar energy [50].

N. Akram, et al. (2023) [53] synthesised Fe_3O_4 nanoparticles and polyethylene glycol 200 using a novel in-situ oxidation precipitation of ferrous hydroxide method. The thermo-physical properties, including thermal conductivity (TC), density, specific heat, and viscosity, were validated against existing correlations. At 0.1 wt.% and 35°C, TC, density, specific heat, and viscosity increased by 13.35, 0.06, 0.37, and 20.9%, respectively. Stability tests using UV-Vis spectroscopy and Zeta potential confirmed stability over 30 days. FPSC thermal performance was evaluated with ferrofluids at flow rates of 0.0133, 0.0200, and 0.0266 kg/s, input temperatures of 30 to 50°C, and nanoparticle concentrations of 0.025, 0.05, 0.075, and 0.1%. A 13.83% improvement in thermal efficiency was observed, with a maximum discrepancy of 8.33% between Experimental and numerical results derived from ANSYS-CFD simulations under identical conditions.

N. Azimy, et al. (2023) [54] employed a zigzag-shaped FPSC tube containing two working fluids: water and a hybrid nanofluid composed of fly ash and copper (80:20 vol.%) in water. Using 800 W/m² solar irradiation and laminar mixed convection, the study assessed the thermal and entropy characteristics of a solar system operating with these fluids. Increased coolant flow rates improved Nu by 33.33%, convective thermal performance by 41%, and friction entropy generation by 88%. However, higher flow rates also reduced outlet temperatures, friction factors, and thermal entropy generation. Larger nanoparticle concentrations significantly amplified thermal and friction entropy generation.

K. Mausam, et al. (2023) [55] Experimentally analysed FPSC-based solar energy harvesting systems (SEHs) using Cu-MWCNTs/H_2O hybrid nanofluids. Experiments utilised a grey relational analysis (GRA) optimised using an L27 orthogonal array with flow rates of 0.5, 1.0, and 1.5 lpm; inclination angles of 25, 30, and 35°; and solar intensities of 400, 600, and 700 W/m². A maximum instantaneous efficiency of 68.7% was achieved at a flow rate of 1.5 lpm, an inclination angle of 25°, and an intensity of 400 W/m². Compared to the previous year, greenhouse gas emissions were reduced by 21.42 kg.

O.A. Hussein, et al. (2023) [56] investigated the thermal and rheological properties of a hybrid nanofluid consisting of titanium dioxide (TiO_2) and chemically functionalised multi-walled carbon nanotubes (CF-MWCNTs) in water. A hybridisation ratio of 40:60 (CF-MWCNTs:TiO_2) was found optimal. Testing, conducted at flow rates of 2, 3, and 4 lpm following the ASHRAE-93-2010 standard, demonstrated that energy efficiency improved by 9% at low-temperature differentials and by 26% at high-temperature differentials compared to distilled water. At 0.1 wt.% and a flow rate of 4 lpm, the performance index reached 1.1, suggesting substantial energy efficiency benefits with minimal pressure drop.

R.M. Mostafizur, et al. (2023) [57] evaluated the performance of FPSCs using hybrid nanofluids consisting of CuO and MWCNT nanoparticles suspended in various base fluids, including water, ethylene glycol, methanol, radiator coolant, and motor oil (Fig. 16). Flow rates ranged from 1 to 3.5 l/min with nanoparticle volume fractions of 1%-3%. Among the fluids tested, CuO-MWCNT/water exhibited the lowest entropy production at all volume fractions and flow rates. CuO-MWCNT/methanol demonstrated superior heat transfer coefficients but lower exergy efficiency and higher entropy generation. The study also revealed that increasing the dead-state temperature reduced solar exergy due to diminished temperature gradients (Fig. 17).

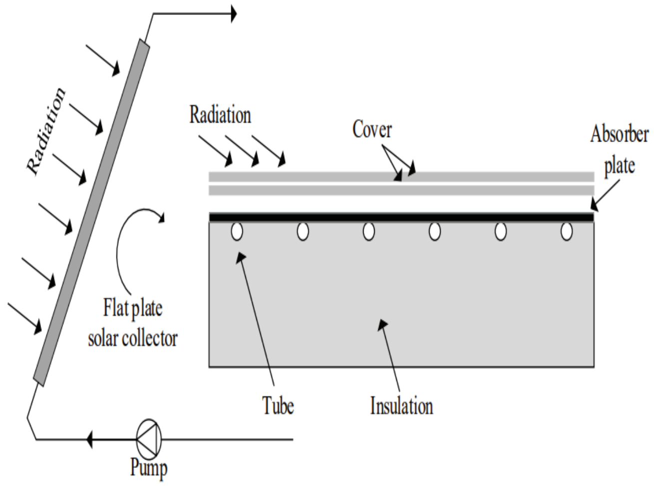


Fig. 16. Flat-plate solar collector schematic [57].

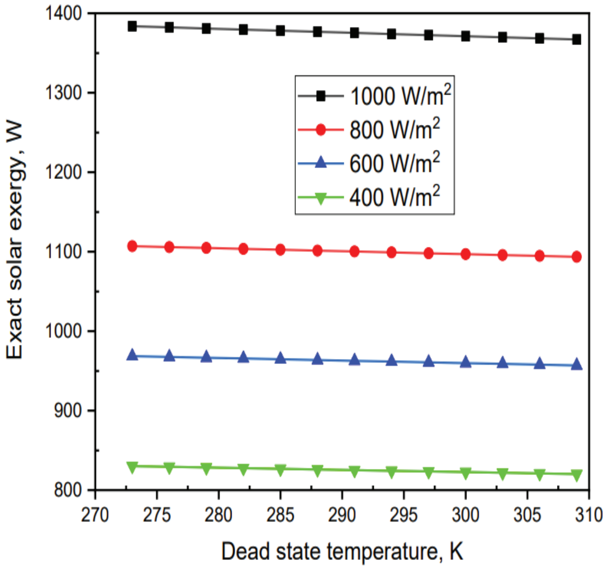


Fig. 17. Date state temperature affects solar exergy [57].

2.7. Sustainable solar collectors: Green nanofluid approach

A.I. Khan, et al. (2023) [58] developed a hybrid nanofluid by combining titania with silver nanoparticles in a composite structure, which was then dispersed in water. Thermal conductivity (TC) and dynamic viscosity were evaluated for 0.1 and 0.2 vol.% TiO_2-Ag/water, followed by simulations using regression models. Simulated mass flow rates ranging from 0.01 to 0.025 kg/s were analysed using the ANSYS CFD model for FPSC. The results showed that hybrid nanofluids at 0.1 and 0.2 vol.% increased the heat transfer coefficient by approximately 13 and 16.1%, respectively, compared to water at a flow rate of 0.01 kg/s. Energy efficiency improved by 0.85 and 1.03%, while exergy efficiency increased by 1.4 and 3.52% for the respective concentrations.

I. Harrabi, et al. (2023) [59] investigated the long-term performance enhancement of solar water heaters using basic and hybrid nanofluids, including copper oxide, magnesium oxide, and multi-walled carbon nanotube (MWCNT) nanofluids. FPSCs were simulated in transient systems under Tunisian climate conditions to address household energy demands. Results indicated that nanofluids significantly improved collector performance. Auxiliary energy consumption decreased by 47.6 and 60.9% with 0.2 and 0.6 vol.% TiO_2 in water, respectively, compared to water alone. With an annual output of 1294 kWh and a demand of 1998 kWh, the FPSC achieved a coverage rate of 65%. Replacing MgO with MgO-MWCNT nanofluids increased the solar fraction by 5.14%.

I.A. Khan, et al. (2023) [60] evaluated the energy and exergy performance of FPSCs using TiO_2-Ag/water nanocomposite fluids and TiO_2/water nanofluids. Thermal conductivity and viscosity were measured at various temperatures, with regression models developed for 0.1 and 0.2 vol.% concentrations. At 60°C, TC improvements for 0.2 vol.% TiO_2/water and TiO_2-Ag/water nanofluids were 10.9 and 18.1%, respectively. Simulations conducted with engineering equation solver (EES) showed that at a flow rate of 0.02 kg/s, energy efficiency increased by 0.5% and 1.27%, while exergy efficiency improved by 1.25 and 2.54% for TiO_2/water and TiO_2-Ag/water, respectively.

T. Huq, et al. (2023) [61] examined the stability and performance of graphene oxide (GO) and graphene nanoplatelet (GNP) hybrid nanofluids in FPSCs. The study demonstrated that higher GO concentrations enhanced stability, with sedimentation measurements indicating that a 50:50 GNP-GO ratio maintained 90% concentration after one month of static conditions. Under operational flow in a solar collector test rig, GNP alone lost over 80% concentration within one day, while the 50:50 GNP-GO sample retained 66% concentration after five days, achieving equilibrium. These findings suggest superior operational stability for hybrid nanofluids compared to single-component systems.

S. Singh, et al. (2023) [62] assessed the thermal efficiency of FPSCs using a hybrid nanofluid composed of Cu-MWCNTs in water. Experimental variables included flow rates of 0.5, 1.0, and 1.5 l/min; inclination angles of 25, 30, 35, 40, and 45°; volume concentrations from 0 to 0.4%; and irradiance levels of 400 W/m². A 3D numerical model created in Ansys fluent 15.0 mirrored the FPSC's geometry and employed the SST turbulence model. The optimal configuration (0.4 vol.%, 1.5 l/min, 45° inclination, and 400 W/m²) yielded a 79.74% increase in instantaneous efficiency, with a maximum 3.5% discrepancy between Experimental and numerical results.

M.A. Alfellag, et al. (2024) [63] explored the hydrothermal performance of FPSCs using nanocomposite fluids produced through a green synthesis method. The working fluid consisted of clove-treated MWCNTs and TiO_2 (CT-MWCNTs/TiO_2) in a 60:40 ratio dispersed in water. Parameters included flow rates of 0.3 to 1.2 l/min, heat flux intensities of 400 to 1000 W/m², and inlet temperatures of 30 to 45°C, with nanofluid concentrations ranging from 0.025 to 0.1 wt.%. At 0.1 wt.% and 1.2 l/min, energy efficiency increased by 20.6%, and exergy efficiency by 22.9%. Additionally, using the hybrid nanofluid reduced solar collector size by 20.5%.

O.A. Alawi, et al. (2024) [64] studied the hydrothermal characteristics of hybrid nanofluids in solar collectors using graphene oxide (GO) and GO/SiO_2 mixtures (50:50) with water. Concentrations ranged from 0.01 to 1 vol.%, with Reynolds numbers between 300 and 1500 and inlet temperatures of 30 to 60°C. Simulations revealed a maximum variance of 3.96-4.71% for the first validation and 4.32-6.45% for the second. The GO-DW nanofluid at 1% concentration and 30°C achieved the highest pressure drop (ΔP), energy efficiency (η_eng), and absorbed energy (Q_abs), with comparable results for GO/SiO_2-DW nanofluids.

2.8. Efficiency analysis of nanofluid heat exchangers in solar systems

By considering the impact of slip on a contracting Riga plate, N.A. Aminuddin, et al. (2024) [65] investigated the flow characteristics of a non-Newtonian hybrid nanofluid composed of glycerine ($C_3H_8O_3$) as the base fluid and graphene oxide (GO) and molybdenum disulfide (MoS_2) nanoparticles. Computational analysis was conducted using MATLAB's bvp4c program to examine the effects of various parameters on frictional force coefficient, local Nusselt number, entropy generation, rate distribution, and temperature profile. Results indicated that an increase in speed reduced the fluid temperature by 7.01 to 11.28% and 7.35 to 10.2% for cases involving thermal slip. The inclusion of graphene oxide enhanced fluid temperature by 4.13 to 10.22%, demonstrating its superior heat conduction capabilities.

L. Selvam, et al. (2024) [66] optimised the thermal performance of an FPSC by varying the flow rates of a hybrid nanofluid containing aluminium oxide (Al_2O_3), nickel (Ni), and their combinations at 0.1 vol.% in water. Flow rates of 0.028, 0.041, 0.055, and 0.068 kg/s were tested. Experimental analysis revealed that at higher flow rates, the hybrid nanofluid (Al_2O_3/Ni/water) delivered a coefficient of performance (COP) of 7.9, a heat transfer coefficient of 133.2 W/m²K, and exergy and thermal efficiencies of 72.8 and 22.9%, respectively. These results significantly outperformed those of water-operated FPSCs under similar conditions.

S. Wciślik (2024) [67] investigated the influence of the Nusselt number on efficiency (ε) and exergy efficiency (η_ex) in a chevron-type gasketed plate heat exchanger (PHE) integrated into a small solar system designed for single-family homes (Fig. 18). The heat exchanger utilised a TiO_2:SiO_2/ethylene glycol-distilled water (EG:DI) hybrid nanofluid at concentrations ranging from 0 to 1.5 vol.%. The Experimental flow rate on the hot water side ranged between 3 and 6 lpm, with the cold side input temperature set at 30°C and the hot side at 60°C. Analysis showed that the selected Nusselt number model had minimal impact on exergy efficiency, with a maximum discrepancy of 3.4% across concentrations. Discrepancies in exergy efficiency decreased as the Reynolds number increased, from 49% at Re=329 to 42% at Re=430. Fig. 19 illustrates that the Nusselt number improved by 10 to 32% when using nanofluids based on ethylene glycol compared to traditional fluids.

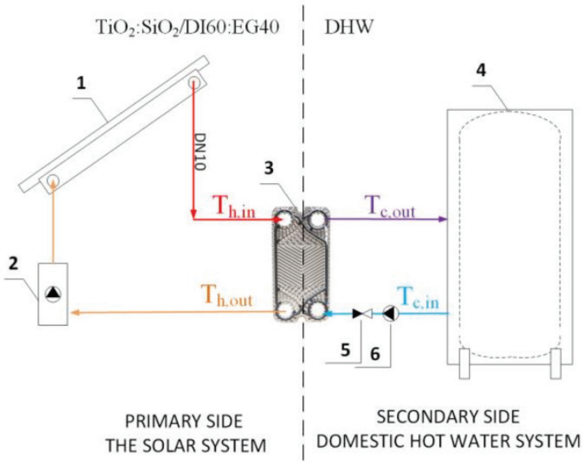


Fig. 18. Solar system hydraulics, plate heat exchanger, and operating conditions [67].

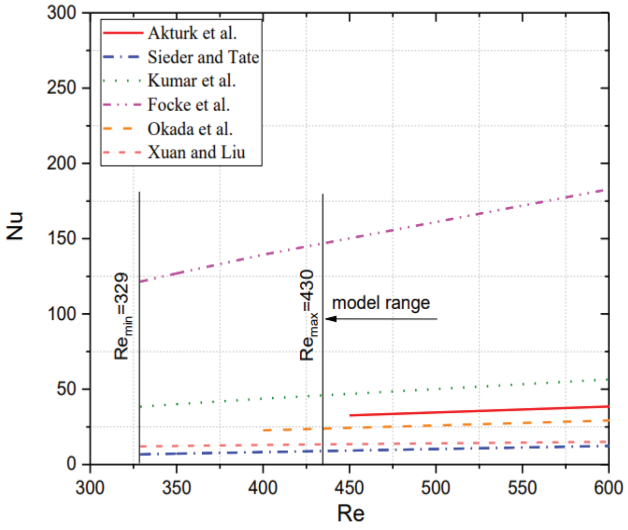


Fig. 19. Variation in Nusselt number of TiO_2:SiO_2/DI:EG hybrid nanofluid during PHE system flow vs Reynolds number at 0.5% vol. [67].

A summary of studies on the applications of hybrid nanofluids in FPSCs is provided in Table 1.

Table 1. A summary of studies related to applications of hybrid nanofluid in FPSCs.

Authors and year	Study type	Configuration of the solar still system	Composition of hybrid nanofluid	Concentration of nanofluid	Results and highlights
O.A. Hussein, et al. (2020) [29]	Experimental	FPSC with hybrid nanofluid.	Covalently functionalised graphene nanoplatelets (CF-GNPs) and functionalized MWCNTs (CF-MWCNTs) in pure water.	0.05, 0.08, 0.1 wt.%	Increases in the concentrations of nanoparticles led to an increase in the thermal energy gain, which in turn led to an increase in the temperature of the fluid outflow.
E.C. Okonkwo, et al. (2020) [30]	Experimental	FPSC with hybrid nanofluid.	Alumina-iron/water nanofluids.	0.05, 0.1, and 0.2%.	The usage of hybrid nanofluids did not result in a more effective thermal alternative to water; however, it did result in an increase in exergetic efficiency of 6.9%, which was much higher than the 5.7% improvement that was achieved by employing alumina-water nanofluids.
M. Lee, et al. (2020) [31]	Experimental	FPSC with hybrid nanofluids.	MWCNT/Fe_3O_4 Binary nanofluid.	0.005 vol.% MWCNT/0.01 vol.% Fe_3O_4.	The maximum efficiencies of the vacuum tube solar collectors and the FPSC both saw increases of 7.8 and 8.3%, respectively.
S.P.A. Yegane, et al. (2020) [32]	Experimental	FPSC with porous media.	Copper and alumina hybrid nanofluid.	Equal volume fraction.	The combination of copper and alumina with identical volume percent performs better than pure alumina nanoparticles when the volume fraction of nanoparticles remains constant. On the other hand, there is no noticeable difference between pure copper nanoparticles and the mixture.
Q. Xiong, et al. (2021) [33]	Numerical	Porous FPSC.	Ag-Al_2O_3 hybrid nanoparticles.	0.1%.	The use of hybrid nanofluid resulted in a reduction in the rate of heat transfer and a modest increase in the supply temperature when the Re value was very low.
V.P. Kalbande, et al. (2021) [34]	Experimental	FPSC with hybrid nanofluids.	Hybrid nanofluid of CuO+ Al_2O_3/water.	0.1%.	Through the use of hybrid nanofluid, it has been discovered that the FPSC is more effective than the other traditional type solar controller.
A.K. Alzahrani, et al. (2021) [35]	Numerical	Porosity of a Darcy-Forchheimer medium on top of a flat plate.	MgO, CuO with MWCNTs and water is used as a base solvent.	1, 2, and 3%.	The nanoparticle volume fraction brings about an increase in the efficiency with which solar radiation is captured and transported. While the value of the volume fraction continues to rise, the rate of heat transmission continues to increase.
L.S. Sundar, et al. (2021) [36]	Experimental	The FPSC uses low mass concentrations.	ND-Co_3O_4 hybrid nanofluid.	0.05-0.15%.	Comparing to water, the Nusselt number augmentation of hybrid nanofluid with a mass concentration of 0.15% is 21.23%, and the highest friction factor penalty is 1.13 times.
M. Lee, et al. (2021) [37]	Theoretical	Various types of solar collector.	MWCNT/CuO and MWCNT/Fe_3O_4 binary nanofluids.	0.05%.	An MWCNT/CuO binary nanofluid and a MWCNT/Fe_3O_4 binary nanofluid both exhibit efficiency increases in the range of 2-50%, 3-7%, and 2-4%, respectively, in flat plate, vacuum U-tube, and heat pipe solar collectors. This is in comparison to a 0.05 vol.% MWCNT nanofluid.
L.S. Sundar, et al. (2021) [36]	Experimental	A thermosyphon-equipped FPSC would be ideal.	The nanodiamond-cobalt oxide hybrid nanoparticles.	0.05-0.15%.	Comparing to water, the Nusselt number augmentation of hybrid nanofluid with a mass concentration of 0.15% is 21.23%, and the highest friction factor penalty is 1.13 times.
B. Saleh, et al. (2021) [38]	Experimental	Thermosyphon FPSC.	Multi-walled carbon nanotubes+Fe_3O_4 hybrid nanofluid.	0.05 to 0.3%.	At a concentration of 0.3 vol.% at a temperature of 60 °C over water, the Nusselt number, heat transfer coefficient, and friction factor are all increased by 18.68%, 39.22%, and 18.91% respectively.
J. Mustafa, et al. (2022) [39]	Experimental	FPSC with hybrid nanofluid.	Water/copper-aluminium hybrid nanofluid.	0.1%.	In comparison to other working fluids, the energy efficiency of the collector that uses hybrid nanofluid is higher. Furthermore, the highest increase that can be achieved by using mono and hybrid nanofluids in comparison to water is 3.86 and 4.23 percent, respectively.
Z. Said, et al. (2022) [40]	Experimental	FPSC with hybrid nanofluid.	MWCNT + Fe_3O_4/Water hybrid nanofluids.	0.3 vol.%, 0.2 vol.%, 0.1 vol.%, and 0.05 vol.% fractions.	The collector's exergy efficiency rose by 40.51%, 36.86%, 33.21%, and 29.56%, respectively, when it was operated with hybrid nanofluids with volume fractions of 0.3%, 0.2%, 0.1%, and 0.05%, and Re values of 1413, 1674, 1774, and 1892.
E. Elshazly, et al. (2022) [41]	Experimental	FPSC with hybrid nanofluid.	MWCNT, Al_2O_3, and hybrid MWCNT/Al_2O_3.	0.5, 0.025, 0.01 and 0.005%.	The use of hybrid MWCNT/Al_2O_3 (50:50%) results in an improvement in efficiency that is 26, 29, and 18% for 1.5, 2.5, and 3.3 l/m, respectively.

Authors and year	Study type	Configuration of the solar still system	Composition of hybrid nanofluid	Concentration of nanofluid	Results and highlights
Z. Said, et al. (2022) [42]	Experimental	FPSC with hybrid nanofluid.	MWCNT + Fe_3O_4/Water hybrid nanofluids.	0.05, 0.1, 0.2 and 0.3%.	The use of hybrid nanofluids led to a substantial improvement in the heat transfer coefficient, which was found to be 26.29%, despite the fact that there was a little loss owing to the factor of friction, which was 18.91%. Through the use of nanofluid with a concentration of 0.3 vol.% at Reynold's number 1413, the most favourable outcomes were achieved, resulting in a thermal efficiency of 63.84%.
H. Nabi, et al. (2022) [43]	Numerical	FPSC with hybrid nanofluid.	SWCNT-CuO/H_2O hybrid nanofluids.	1-5%.	One of the most significant effects of concentration was seen at Reynolds number 4000, when the concentration was 5%. This resulted in a rise of 8.79% in the HTC.
K. Janardhana, et al. (2022) [44]	Experimental	Water heater that uses FPSC.	CuO nanoparticles and MgO nanoparticles.	0.2 % (0.1 % CuO nanoparticles and 0.1 % MgO nanoparticles).	When compared to the use of water, the performance of the FPSH is improved when hybrid nanofluid is used as the circulating fluid for the solar collector. The hybrid nanofluid operated at a flow rate of 0.0167 kg/s, which resulted in a 43.3% increase in the efficiency of the FPSH.
Y. Khetib, et al. (2022) [45]	Numerical	Solar collector using a flat plate and innovative turbulators.	DWCNTs-TiO_2/water hybrid nanofluid.	1 to 3%.	An increase in the average Nusselt number may be achieved by increasing both the Re and ϕ. In the scenario where the value of ϕ is 3%, and the Re is increased from 7000 to 28000, the energy and exergy efficacies rise by 22.19% and 23.26%, respectively, for PR=4 and PR=1.
A.S.F. Mahamude, et al. (2022) [46]	Experimental	FPSC using hybrid nanofluids.	Nano-cellulose (CNC) and a graphene hybrid.	0.3% base fluid, 0.5% graphene, and CNC separately, as well as 0.3%, 0.5% CNC.	At an 80 ºC, the hybrid nanofluid has a conductivity that is 194% higher than that of the ordinary nanofluid. Furthermore, the hybrid nanofluid is 3.05 times more viscous than the basic fluid.
M. Ahmed, et al. (2022) [47]	Experimental	Hydrophobic dual-hybrid nanofluid solar collectors with flat plates.	hBN/CF-CNTs hybrid nanofluid.	0.1, 0.08, and 0.05%.	The collector efficiency was significantly improved by up to 87% when compared to the standard working fluid that was utilized in FPSC. This was accomplished by using 0.1 wt.% of hBN/CF-CNTs at a feed flow rate of 4 lpm.
P.M.J. Stalin, et al. (2022) [48]	Experimental	FPSC with hybrid nanofluids.	Zn-Fe_2O_4/water hybrid nanofluids.	0.1%.	The use of Zn-Fe_2O_4/water hybrid nanofluids with a particle concentration of 0.5% resulted in a 6.6% improvement in the thermal performance of the solar collector. On the other hand, the utilisation of Fe_2O_4/water nanofluids resulted in a 7.83% increase in the collector's thermal performance as compared to the utilisation of water being the working fluid.
S.P.A. Yegane, et al. (2022) [49]	Numerical	Solar collector with perforated flat plates.	Al_2O_3-Cu/water hybrid nanofluid.	0.1%.	When the magnetic field is strong, the dimensionless average total irreversibility is a decreasing function of nanofluid volume fraction for Reynolds values that are lower than 369.6. However, when the Reynolds value is greater than 369.5, the tendency would be the opposite.
A.M. Ajeena, et al. (2023) [50]	Experimental	FPSC with hybrid nanofluid.	ZrO_2-SiC/DW hybrid nanofluid.	0.025, 0.05, 0.075, and 0.1%.	The use of nanofluid resulted in a 31.64% improvement in thermal efficiency. A maximum improvement in the exergy efficiency of about 28.31% was achieved by the system while it was operating at a concentration of 0.1%.
E.S.R. Negeed, et al. (2023) [51]	Numerical	FPSC and a turbulator.	Cu-GO/water hybrid nanofluid.	1 and 4%.	φ, the velocity of the inflow, the geometric form of the turbulator, and the boundary conditions of the FPSC all have an impact on energy efficiency. Increasing the values of Re, φ, and γ resulted in an improvement in energy efficiency.
J. Alsarraf, et al. (2023) [52]	Numerical	Using a magnetic field, a FPSC is outfitted with a spiral absorber tube.	MgO-MWCNT/Therminol VP-1 HN.	$0\% < \varphi <$ to 3%.	Assuming a value of 3% for φ and a value of 24000 for Re, the use of a spiral absorber tube with a value of 2.25 for α results in an increase of 121.11 and 309.52% for the average Nusselt number (Nu_{ave}) and Δp when compared to the solar collector that utilizes a basic absorber tube.
N. Akram, et al. (2023) [53]	Experimental and numerical	FPSC with hybrid nanofluid.	PEG-Fe_3O_4 Hybrid nanofluid.	0.1%.	The use of hybrid nanofluids resulted in the greatest possible increase in thermal efficiency, which was 13.83%.
N. Azimy, et al. (2023) [54]	Numerical	The zigzag tube of a FPSC.	Fly Ash-Cu/water hybrid nanofluids.	80:20 vol.%.	The Nusselt number, the convection heat transfer coefficient, and the friction entropy production on working fluid pumps are all increased by about 33.33%, 41%, and 88%, respectively, when the flow rate is increased.

Authors and year	Study type	Configuration of the solar still system	Composition of hybrid nanofluid	Concentration of nanofluid	Results and highlights
K. Mausam, et al. (2023) [55]	Experimental	System for collecting solar energy using an FPSC.	Cu-MWCNTs/water hybrid nanofluid.	0.1%.	Using 1.5 lpm, 400 W/m^2, and 25 °, the hybrid nanofluid can improve the performance of SEHs by achieving a maximum instantaneous efficiency of 687%.
O.A. Hussein, et al. (2023) [56]	Experimental	FPSC with hybrid nanofluid.	TiO_2@CF-MWCNTs-DW hybrid nanofluid.	CF-MWCNTs: TiO_2 is 40:60.	Because of the incorporation of TiO_2/CF-MWCNTs into the working fluid, the energy efficiency of the collector was enhanced by roughly 9% and 26%, respectively, when the temperature difference was low and high.
R.M. Mostafizur, et al. (2023) [57]	Numerical	FPSC using various hybrid nanofluids.	CuO-MWCNT/water nanofluid.	1 to 3%.	Among the several nanofluids that were investigated, the CuO-MWCNT/water nanofluid demonstrated the highest level of success in terms of lowering the creation of entropy at volume fractions as well as volume flow rate.
A.I. Khan, et al. (2023) [58]	Numerical	FPSCs with hybrid nanofluids.	TiO_2-Ag/water hybrid nanofluid.	0.1 vol.% and 0.2 vol.%.	Comparing to water, hybrid nanofluids with 0.1 and 0.2 vol.% exhibited a maximum augmentation in the heat transfer coefficient of around 13 and 16.1%, respectively, when the feed flow rate is 0.01 kg/s.
I. Harrabi, et al. (2023) [59]	Experimental	Thermostatically flat plate solar water heater in a north African environment	MgO with MWCNT hybrid nanofluid.	0.2%.	A 5.14% increase in the solar percentage was deduced when MgO nanofluid-based nanoparticles were replaced with MgO nanoparticles that included MWCNT.
I.A. Khan, et al. (2023) [60]	Experimental	A solar collector that uses nanocomposite fluid and a flat plate.	TiO_2/water and TiO_2-Ag/water.	0.2%.	While the energy efficiency is improved by 0.5 and 1.27% for 0.2 vol.% TiO_2/water nanofluid and TiO_2-Ag/water nanocomposite fluid at 0.02 kg/s, the exergy efficiency was improved by 1.25 and 2.54%, respectively. Energy efficiency was also improved by 1.27%.
T. Huq, et al. (2023) [61]	Experimental	Flat plate solar thermal collector.	Combinations of graphene oxide (GO) and graphene nanoplatelets (GNP) form hybrid nanofluids.	50%:50%.	Over the course of five days of operation in the test rig, the sample that had a 50:50 ratio of GNP and GO maintained around 66% of its concentration. Furthermore, the concentration seemed to stabilise, achieving equilibrium, which suggests that there were no additional declines.
S. Singh, et al. (2023) [62]	Experimental and numerical	FPSC with hybrid nanofluid.	Nanofluid based on a combination of water and Cu-MWCNT nanoparticles.	0, 0.1, 0.2, 0.3, and 0.4%.	The instantaneous efficiency is improved by 79.74% when the volume is 0.4%, the flow rate is 1.5 lpm, the angle of inclination is 45°, and the intensity is 400 W/m^2.
M.A. Alfellag, et al. (2024) [63]	Experimental	FPSC with hybrid nanofluid.	CT-MWCNTs/TiO_2) nanocomposites	60 to 40%.	When compared to the base fluid, the largest improvement in energy efficiency (20.6%) and exergy efficiency (22.9%) was accomplished at a concentration of 0.1 wt.% and a flow rate of 1.2 lpm. Additionally, the use of a hybrid nanofluid resulted in a reduction in the size of the solar collector by 20.5%.
O.A. Alawi, et al. (2024) [64]	Numerical	Continuously heated FPSC.	Carbon dioxide/graphene oxide hybrid nanofluids (GO/SiO_2-DW).	Mixing ratio (50:50), the concentration range 0.01-1 vol.%.	When the input temperature was 30ºC, the GO-DW-1% displayed the greatest values for ΔP, η_{eng}, and Q_{abs}. In close proximity, the GO-SiO_2-DW-1% exhibited somewhat lower energy values.
N.A. Aminuddin, et al. (2024) [65]	Numerical	The Riga plate solar collector is compacting.	GO-MoS_2/$C_3H_8O_3$ hybrid nanofluid.	0.1%.	To transport heat into the fluid, graphene oxide has been shown to be a good conductor. This is demonstrated by the fact that it raises the temperature by a percentage that ranges from 4.13 to 10.22%.
L. Selvam, et al. (2024) [66]	Experimental	FPSCs with hybrid nanofluids.	Nanoparticles of Al_2O_3 and Ni suspended in water form a hybrid nanofluid.	0.1%.	The hybrid nanofluid, which is composed of Al_2O_3/Ni/water, has a greater thermal and exergy efficiency of 72.8 and 22.9%, a better heat transfer coefficient of 133.2 W/m^2 K, and a high coefficient of performance (COP) of 7.9 when subjected to high flow rates.
S. Wciślik (2024) [67]	Experimental	A gasketed plate heat exchanger of the Chevron type.	TiO_2:SiO_2/EG:DI hybrid nanofluid.	0 to 1.5% vol.	For Re=329, the difference between the values obtained within a given concentration is 49%. However, when the flow of nanofluid in the solar installation increases, the difference drops to 42% for Re=430.

3. Conclusions

The use of hybrid nanofluids has shown promising outcomes in enhancing the heat transfer performance of solar collector energy systems. It is crucial to understand that the enhancement ratio is influenced by various factors, including concentration, composition, solar radiation conditions, and Experimental setup.

This review aimed to collate and evaluate the most recent research published between 2020 and 2024 on hybrid nanofluids, with a particular focus on FPSC energy systems. The primary areas of focus were the physical construction of FPSCs, the composition and concentration of hybrid nanofluids, and the outcomes and observations from the studies. The following key findings were identified:

1. Increases in nanoparticle concentrations led to improved thermal energy gain, resulting in higher fluid outflow temperatures.

2. While hybrid nanofluids did not outperform water in thermal efficiency, they achieved a 6.9% improvement in exergetic efficiency, compared to 5.7% with alumina-water nanofluids.

3. A combination of copper and alumina nanoparticles at equal volume fractions outperformed pure alumina nanoparticles, but showed no significant difference compared to pure copper nanoparticles.

4. Hybrid nanofluids improved FPSC performance, making them more effective than traditional solar controllers.

5. At a mass concentration of 0.15%, hybrid nanofluids increased the Nusselt number by 21.23% with a friction factor penalty of 1.13 times compared to water.

6. Using 0.3 vol.% hybrid nanofluids at 60ºC increased the Nusselt number, heat transfer coefficient, and friction factor by 18.68, 39.22, and 18.91%, respectively.

7. Exergy efficiency rose by 40.51, 36.86, 33.21, and 29.56% for hybrid nanofluids with volume fractions of 0.3, 0.2, 0.1, and 0.05%, respectively, at corresponding Re values of 1413, 1674, 1774, and 1892.

8. The heat transfer coefficient improved by 26.29%, despite a minor friction factor penalty of 18.91%, when hybrid nanofluids were used.

9. Using hybrid nanofluids as circulating fluids in FPSCs improved performance by 43.3% at a flow rate of 0.0167 kg/s compared to water.

10. Incorporating 0.1 wt.% hBN/CF-CNTs at a flow rate of 4 lpm enhanced collector efficiency by more than 87% compared to the standard working fluid.

11. CuO-MWCNT/water nanofluids demonstrated the highest efficiency in reducing entropy production at varying volume fractions and flow rates compared to other nanofluids.

4. Critical issues and recommendations for future research

Although flat plate collectors (FPCs) are more reliable and cost-effective than concentrating collectors, they are less efficient in absorbing energy, especially in low-irradiation regions. Heat loss to the environment further reduces their overall thermal output, necessitating optimisation to minimise these losses. Additionally, stagnant fluid within collectors during low-demand periods, such as overcast days, can lead to overheating and potential damage. Prolonged exposure of absorber materials and glass to sunlight and weather may degrade system components, reducing long-term effectiveness.

Public education, innovative approaches to problem-solving, and continuous research are all essential components in the process of overcoming the limits and hurdles described above. The combination of better solar collector systems with hybrid nanofluids has the potential to make this solar concentration technology more applicable and less harmful to the environment. These limitations would be released as a result of this.

To address these challenges and further enhance the performance of FPSCs, the following recommendations should be considered:

1. Development of stable nanomaterials: Focus on creating nanomaterials with improved colloidal stability and specific surface area (SSA) for long-term usability in FPSCs.

2. Selective absorber coatings: Design coatings capable of capturing a broader solar spectrum while minimising heat re-radiation to improve thermal efficiency.

3. Material enhancements: Incorporate nanoparticles into collector materials to enhance light absorption and thermal conductivity, thereby boosting overall performance.

4. Transparent materials: Develop transparent materials that maximise solar input while reducing heat loss.

5. Phase change materials (PCMs): Integrate PCMs to store thermal energy during peak solar hours and release it later, increasing system flexibility and addressing stagnation issues.

6. Anti-dust coatings: Research coatings that resist dust and grime accumulation, reducing maintenance needs and improving long-term efficiency.

7. Cost reduction: Explore alternative materials and manufacturing methods to lower production costs while maintaining or improving performance.

8. Building-integrated solutions: Investigate integrating FPSCs into building materials (e.g., roofing) to create visually appealing, cost-effective solar energy solutions.

By addressing these critical challenges and pursuing the outlined research directions, FPSCs can become more efficient, cost-effective, and adaptable, making them a more attractive option for widespread adoption.

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COMPETING INTERESTS

The authors declare that there is no conflict of interest regarding the publication of this article.

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