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Review

A Review of Enhancement of Thermal Performance of Flat–Plate Solar Collectors through Nanofluid Implementation

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Abstract

Nanofluids have found widespread practical applications in heat transfer, including cooling oils for diverse uses like automobile radiators, solar and nuclear power systems, biomedical devices, ventilation, heating, air conditioning, refrigeration, engine cooling, and transformers. Extensive scientific studies have investigated the impact of exotic fluids when combined with traditional heat transfer fluids, revealing that this combination enhances heat transfer performance beyond that of conventional working fluids. Collectively, these studies demonstrate the impressive heat transfer abilities of nanofluids. To optimize the efficiency of flat plate solar collectors, a comprehensive approach integrating theory and experimentation is essential. The results of such research highlight that increasing both the mass flow rate and concentration of nanofluids can lead to significant efficiency improvements, with potential enhancements ranging from 20% to 85%. The aim of this article is to present scientific achievements in the field of the implementation of nanofluids to increase the thermal performance of flat-plate solar collectors.

Keywords: nanofluids, solar collector, flat plate, thermal performance, solar energy

1. Introduction

To meet the heating requirements of various industrial processes, flat-plate heaters are employed, operating at temperatures below 150 °C. These solar collectors have the remarkable capacity to elevate the working fluid's temperature by 30 to 100 °C above the ambient environment. The underlying principle involves harnessing the sun's radiation and efficiently transferring it to the working fluid flowing through the collector's tubes. In pursuit of improved thermal efficiency, nanofluids have emerged as promising candidates for solar collector fluids or operating fluids, offering the potential for significant energy and cost savings.

The advantages of renewable energy systems, such as reduced pollutants, have become increasingly vital as pollution worsens and the depletion of fossil fuels accelerates. Consequently, there is an urgent need for alternative, clean, and cost-effective energy sources (Ali et al. 2023; Berkache et al., 2022; Hussein et al. 2014; Kalogirou, 2004; Natarajan & Sathish, 2009; Qader et al., 2023). Addressing these challenges, Yousef et al. (2012) conducted a study on a 2 m^2 flat solar collector, augmenting its performance through the use of MWCNT-H_2O nanofluids. By varying the mass flow rate (ranging from 0.0167 to 0.05 kg/s), nanofluid concentration (ranging from 0.2 vol% to 0.4 vol%), and nanoparticle diameter (10 to 30 nm), they achieved a remarkable 83% increase in the efficiency of the flat solar collector.

Dutta et al. (2019) investigated magnetohydrodynamic natural convection and entropy generation in rhombic enclosures filled with Cu-water nanofluids. Numerical simulations cover various Rayleigh (*Ra*) and Hartmann (*Ha*) numbers, along with enclosure inclinations and nanofluid volume fractions. Findings reveal that magnetic fields notably affect heat transfer at high *Ra*, while the interaction of Hartmann number and nanofluid fraction influences thermal behavior and entropy generation. Same researcher investigates the impact of natural convection using Cu-water nanofluid in a twodimensional recto-trapezoidal enclosure for absorber plate fin applications. The enclosure has an inclination angle of 60°, with cold temperature maintained on the vertical walls, a hot temperature at the bottom, and an adiabatic top wall. Numerical simulations, utilizing finite element methods, analyze streamlines, isotherms, and heat transfer rates across a range of Rayleigh numbers ($10^3 \leq Ra \leq 10^6$) and solid volume fractions ($0 \leq \varphi \leq 0.1$) of Cu-water nanoparticles. Results reveal intensified streamlines at higher Rayleigh numbers for greater nanoparticle volume fractions, demonstrating heat transfer rate enhancements of over 20% at $Ra = 10^6$ and 30% enhancements using Cu-water nanofluid at $Ra = 10^3$ (Dutta & Biswas, 2019).

These findings underscore the immense potential of nanofluids to revolutionize solar collectors, offering a pathway towards more efficient and sustainable energy utilization. As research in this area progresses, nanofluids hold the promise of playing a pivotal role in our transition towards a cleaner and greener energy future.

2. Models of useful energy gain (Q_u) and efficiency of the flat–plate solar collectors (FPSC)

The most basic prerequisite for studying the thermal performance of flat plate solar collectors through nanofluid implementation model. This model's mathematical formula was reported in publications of (Ali et al., 2023; Hussein et al., 2014; Vijayakumaar et al., 2013) and it is as follows:

The density and specific heat capacity can be estimated as:

$$\rho_{\mathrm{nf}} = (1-\varphi)\rho_{\mathrm{w}} + \varphi \times \rho_{\mathrm{p}} \tag{1}$$

$$C_{\mathrm{P_{nf}}} = \frac{(1-\varphi)\left(\rho c_{\mathrm{p}}\right)_{\mathrm{w}} + \varphi(\rho c_{\mathrm{p}})_{\mathrm{p}}}{(1-\varphi)\rho_{\mathrm{w}} + \varphi \times \rho_{\mathrm{p}}} \tag{2}$$

The useful energy gain (Q_u) of the FPSC determined by:

$$Q_u = \dot{m} * Cp_{\mathrm{w}} * (T_{\mathrm{ws.co}} - T_{\mathrm{ws.cin}}) = \tau\alpha * I(t) * A_{\mathrm{sc}} - U_{\mathrm{L}} * A_{\mathrm{sc}} * \left(T_{\mathrm{pm}} - T_{\mathrm{a}}\right) \tag{3}$$

where $\dot{m}$, Cp_{w} $T_{\mathrm{ws.cin}}$ and $T_{\mathrm{ws.co}}$ are fluid mass flow rate, fluid specific heat, fluid inlet the solar collector and fluid outlet from the solar collector, respectively. τ is transmittance coefficient of cover glass, α is the absorption coefficient of the absorbent plate, $I(t)$ is solar radiation intensity instantious, A_{sc} is the flat plate solar water collector area, U_{L} is total heat loss coefficient, T_{pm} is absorption plate mean temperature, T_{a} is ambient temperature.

The hourly efficiency, η_{sc}, for the flat plate solar water collector is (Dutta et al., 2019):

$$\eta_{sc} = \frac{Q_u}{I(t) * A_{\mathrm{sc}} * \Delta t} * 100\% = F_{\mathrm{R}}\tau\alpha - F_{\mathrm{R}}U_{\mathrm{L}}\left(\frac{T_{\mathrm{ws.cin}} - T_{\mathrm{a}}}{I(t)}\right) \tag{4}$$

where F_{R} is heat removal factor, and Δt is time period.

In a study conducted by Vijayakumar et al. (2013), a carbon nanotube (CNT) nanofluid with a diameter of 1 nm and varying weight proportions (0.6%, 0.5%, and 0.4%) was applied to an area-based solar collector with a deployed area of 0.34 m^2. The data from this investigation revealed a significant 39% increase in efficiency during a focused effort at 0.5%.

Another controlled experiment, carried out by Chaji et al. (2013), involved the utilization of TiO_2 nanofluid mixed with water as the base fluid with a diameter of 20 nm. Various ratios of weight (0.3%, 0.2%, 0.1%, and 0%) and volumetric flow rates of 36, 72, and 108 dm^3/h were employed on a 1 m^2 flat solar collector as shown in Figure 1. The introduction of nanoparticles in this setup resulted in a commendable 15.7% boost in collector efficiency, particularly at a flow rate of 108 dm^3/h.

On a flat solar collector with an area of 0.67 m^2, Zamzamian et al. (2014) investigated Cu nanofluids mixed with ethanol, featuring diameters of 10 nm. The volumetric concentrations ranging from 0.2% to 0.3%. At specific flow rates of 0.016-0.050 kg/s and a concentration of 0.3 vol%, the highest efficiency was obtained, highlighting the favorable impact of these conditions on the collector's performance.

Additionally, Nasrin and Alim (2014) conducted an experiment involving nanoparticles of various sizes (Al_2O_3, CuO, and TiO_2) mixed with distilled water for a 1.51 m^2 solar collector as shown in

Figure 2. Three different concentrations of nanoparticles (0.2 vol%, 0.4 vol%, and 0.8 vol%) were used, along with a mass flow rate of 4 kg/min, creating a laminar flow environment. The results of the experiment indicated that enhancing the rate of heat transfer is greatly facilitated when nanoparticles are uniformly dispersed throughout the base liquid. These research endeavors demonstrate the immense potential of nanofluids in enhancing the efficiency of solar collectors, offering valuable insights into optimizing energy utilization and promoting sustainable practices.

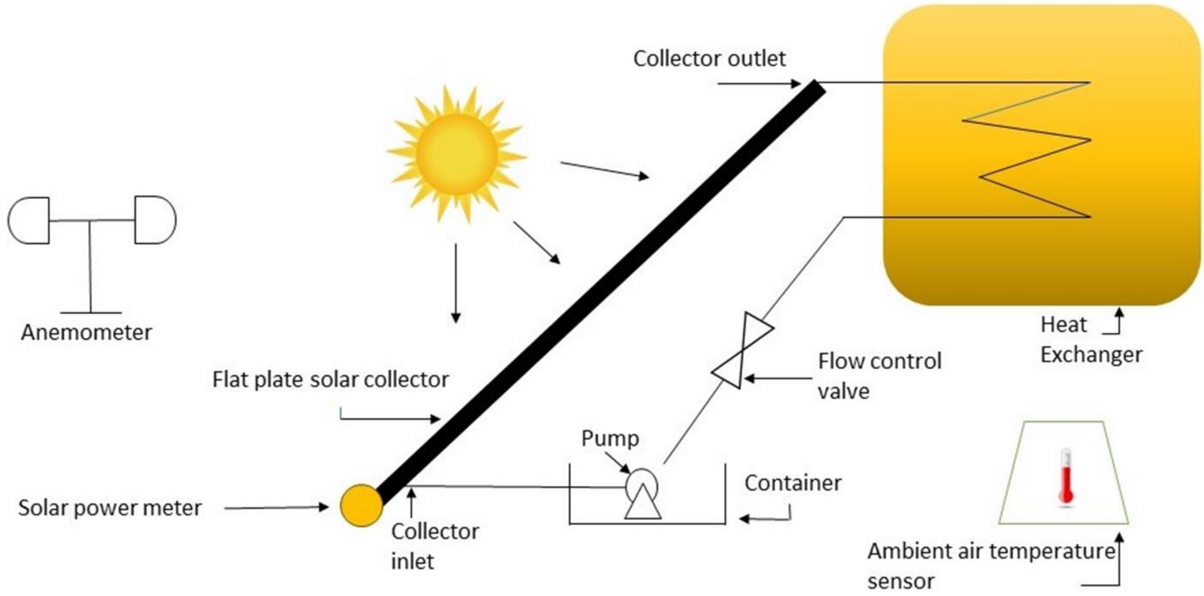

Fig. 1. The experimental set up schematic, prepared on the basis of Chaji et al. (2013).

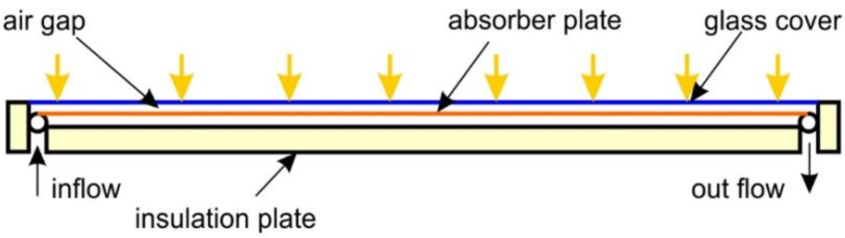

Fig. 2. The experimental set up schematic, prepared on the basis of Nasrin and Alim (2014).

The surface temperature gradient varies depending on the type of particle used, and copper particles exhibit a higher heat transfer rate compared to aluminum oxide and titanium oxide particles. The greatest improvement in efficiency, reaching 87.8%, is observed when using a combination of copper oxide and distilled water, surpassing the efficiency of distilled water alone by 52.5%.

Moghadam et al. (2014) examined the impact of CuO–water nanofluid in a flat-plate solar collector for domestic solar water heating. Nanofluid with 0.4 vol% CuO nanoparticles boosts collector efficiency by 21.8% compared to water alone at a 1 kg/min mass flow rate. The study suggests nanofluids can enhance thermal characteristics and improve collector performance in solar water heating systems.

During a separate experiment, a solar collector with an area of 2.184 m^2 was employed by Michael and Iniyan (2015). They have been used a CuO nanofluid with a diameter of 0.3-0.4 nm combined with water as the base fluid. The volumetric concentration was set at 0.05%, and the resulting efficiency of 57.98% at 0.1 kg/min for natural thermal load outperformed the forced thermal load.

Shojaeizadeh et al. (2015), researched on a 1.51 m^2 flat solar collector involving Al_2O_3 nanofluid mixed with distilled water, featuring a diameter of 15 nm and volumetric concentrations ranging from 0.090696 to 0.1423%, showed varying effects on combined energy by manipulating other factors. This study emphasized the potential for enhancing the available energy efficiency of nanofluids mixed with water.

Said et al. (2015) conducted an experiment on a solar collector with a flat surface area of 1.84 m^2 as shown in Figure 3. They utilized a TiO_2 nanofluid with a diameter of 21 nm and volumetric concentrations of 0.1% and 0.3%, employing a laminar flow with a mass flow rate of 0.5 kg/min. The percentage of efficiency increased by an impressive 76.6% compared to water as the base fluid, and the researchers used surfactants such as polyethylene clay and pentaethylene glycol (PEG) in the liquid.

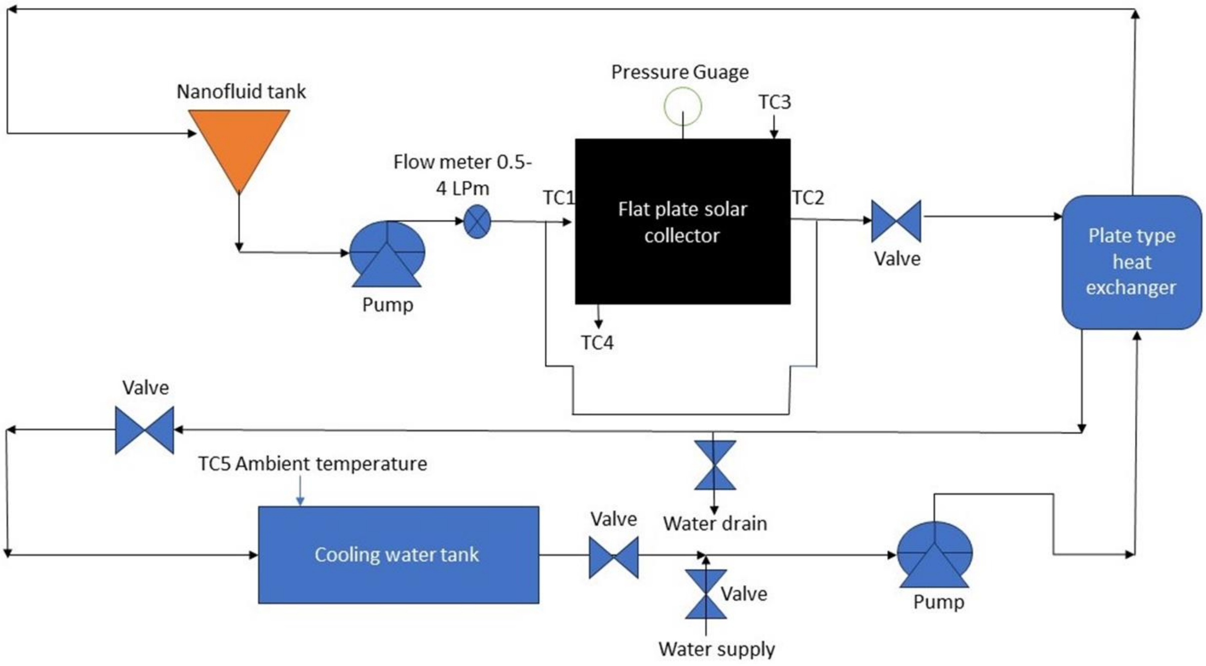

Fig. 3. Schematic presentation of the experimental setup, prepared on the basis of Said et al. (2015).

In the same year, Meibodi et al. (2015) conducted two experimental studies. The first study involved a flat solar collector of 1.59 m^2, using a nanofluid SiO_2/EG-water with a diameter of 10 nm and volumetric concentrations of 0.5%, 0.75%, and 1%. They operated with a turbulent flow and a mass flow rate of 2.7 kg/min. The results demonstrated a notable improvement in efficiency percentage, ranging from 4% to 8%, when compared to using water as the base fluid. In this study, the researchers utilized a flat solar collector with an area of 2 m^2, employing a SiO_2 nanofluid with a diameter of 10 nm and volumetric concentrations of 0.2%, 0.4%, and 0.6%. The flow condition was set to turbulent, and the mass flow rate was maintained at 3 kg/min. Remarkably, the findings revealed a substantial 23.5% increase in efficiency percentage as compared to using water as the base fluid.

Vakili et al. (2016) focused on enhancing the efficiency of solar collectors through a study on a 0.36 m^2 solar collector used for residential water heating. The results unveiled a noteworthy trend: the augmentation of collector efficiency in direct correlation to the increase in nanofluid weight fraction. Strikingly, the pinnacle of collector efficiency was achieved at the 0.015 kg/s flow rate, applying to both the base fluid and nanofluids alike. The efficiencies were quantified with exceptional precision: zero-loss efficiencies using nanofluids at weight fractions of 0.0005, 0.001, and 0.005 emerged at 83.5%, 89.7%, and 93.2%, respectively, while the base fluid yielded a comparatively modest 70% zero-loss efficiency.

Similarly, Verma et al. (2016) conducted an experiment on a 0.375 m^2 flat solar collector to investigate the impact of varying volumetric concentrations of MgO nanofluid mixed with water on the collector's efficiency. The results demonstrated a considerable 9.34% increase in heat efficiency at a concentration of 0.75% and a volumetric flow rate of 1.5 dm^3/min. Furthermore, the utilization of nanofluid as a base fluid resulted in a significant 32.23% improvement in the collector's availability efficiency at the same volumetric concentration and mass flow rate when compared to using water. Notably, the entropy generated at a concentration of 0.75 percent was lower, measuring 0.0611 W/K, as opposed to the concentration of 1.5 percent (0.071 W/K) with a flow rate of 0.1394 W/K.

Verma et al. (2017) conducted a research study aimed at enhancing the efficiency of solar collectors. They performed experiments on a flat solar collector with an area of 0.375 m^2, exploring various nanoparticles mixed with water at different concentrations and sizes. The volumetric concentration used in their study was 0.75%, with a mass flow rate of 0.025 kg/s, and the available energy was assessed. The research team found that employing TiO_2-H_2O, SiO_2-H_2O, CuO-H_2O, Al_2O_3-H_2O, Graphene-H_2O, and MWCNTs-H_2O as primary and subordinate liquids led to noteworthy improvements in thermal efficiency, showing percentage enhancements of 5.74, 6.97, 10.86, 16.67, 21.46, and 29.32, respectively, compared to water. Additionally, the entropy generated by the solar collector was lower for each of the mentioned combinations, ranging from 4.08% to 5.09%, from 8.28% to 12.64%, and from 16.97% to 23.4%.

In another study, Jouybari et al. (2017) evaluated the thermal efficiency of a 0.8 m^2 solar collector, aiming to enhance the collector's performance by using a SiO_2 nanofluid with a diameter of 7 nm mixed with a water-based carrier fluid. The researchers assessed three different nanoparticle concentrations (0.2%, 0.4%, and 0.8%) and a flow velocity of 1.5 kg/min to create a laminar flow environment. The study findings indicated that heat transfer was directly proportional to the nanoparticle concentration in the base liquid, and the type of particle used had a notable impact on the flat surface collector's performance. There was a notable 8% increase in productivity compared to using water as the base fluid. In another experiment, Sundar et al. (2018) conducted a study on a 2 m^2 flat solar collector with turbulent flow, utilizing Al_2O_3 nanofluid at 0.1% and 0.3% by volume, and a flow rate of 5 kg/s. This resulted in an impressive 18% efficiency increase in contrast to using H_2O as the primary medium.

Kiliç et al. (2018) evaluated the impact of a TiO_2 Triton X-100 nanofluid, with a 44 nm diameter, 0.2% volumetric concentration, and 2 kg/min mass flow rate, on the efficiency of a flat solar collector with an area of 1.82 m^2. According to their findings, the use of CeO_2 nanofluid in water, at varying mass flow rates and volumetric concentrations, can improve the performance of a flat solar collector by up to 34.43% compared to using water alone. Sharafeldin and Gróf (2018) discovered a linear relationship between the collector's thermal efficiency and the concentration of nanoparticles in the mass flow.

In another study by Tong et al. (2019), nanofluids with varying concentrations were used to assess their impact on the efficiency of a 2 m^2 flat solar collector. The best efficiency was achieved with a volumetric concentration of 0.1% Al_2O_3 nanofluid, resulting in a remarkable 21.9% efficiency rating. Moreover, the use of nanofluids, particularly with a volumetric concentration of 0.1 vol% Al_2O_3 or 0.5 vol% CuO, significantly increased the available energy by 56% and 49.6%, respectively, when compared to water as the base fluid. Additionally, the highest level of entropy was observed when using water, whereas the lowest was observed with a nanofluid containing 0.1 vol% Al_2O_3.

According to these findings, the incorporation of nanofluids into water can effectively enhance the performance of flat plate solar collectors, particularly with a 0.1% volumetric concentration of Al_2O_3 nanofluid. In an experimental study conducted by Choudhary et al. (2020) to optimize the performance of a 2.1 m^2 flat solar collector, they used ZnO nanofluid in EG&H Blend (ethylene glycol and water) with a 50 nm diameter and a volumetric flow rate of 30-150 dm^3/h. As the flow rate increased, the collector's thermal efficiency improved, reaching a maximum of 69.24% at a flow rate of 60 dm^3/h and a 1% volumetric concentration of nanofluid. This translated to a significant 19.24% boost in productivity compared to using distilled water alone.

Okonkwo et al. (2020) conducted an evaluation using single and hybrid nanofluids (Al_2O_3 and Al_2O_3-Fe) combined with water as the base fluid in a flat solar collector with a surface area of 1.51 m^2. The study revealed that nanofluid usage resulted in a more sensitive measurement of produced entropy compared to using water. The lowest percentage of entropy created was 5.541% W/K, and the highest percentage was 5.725% W/K, both achieved with nanofluid. Utilizing a nanofluid containing Al_2O_3 with a concentration of 0.1 vol% as the base fluid improved the thermal efficiency of the flat solar collector by 2.16%, while a hybrid nanofluid decreased it by 1.79%. However, the hybrid nanofluids were found to improve availability efficiency by 6.9% when compared to a single nanofluid.

To enhance the heat transfer process over a 3 m^2 area and increase efficiency, Alklaibi et al. (2021) conducted an experiment using a flat solar collector with a nanofluid containing diamond particles mixed with water as the base fluid. Different volume concentrations of 0.2, 0.4, 0.6, 0.8, and 1% were tested at a mass flow rate of 0.02 kg/s. The study found that using a 1 vol% concentration of nano-diamond fluid in water increased the flat solar collector's effectiveness by an impressive 69.8% compared to using water alone as the base fluid.

In the research by Hawwash et al. (2018), flat solar collectors with a surface area of 2.1 m^2 were evaluated, utilizing nanofluid Al_2O_3 with a diameter of 20 nm and a mass flow rate of 5.51 kg/min at volume concentrations ranging from 0.1 to 0.3% in distilled water. The study demonstrated that in the hot climate of Egypt, this research improved efficiency by 0.18% over water. The theoretical work was performed using ANSYS 17 program, and it was found that nanoparticles in the fluid reduced pressure, enhanced efficiency, and cooled the collector output. Two nanofluids were generated, one with TiO_2 and the other with Al_2O_3.

Farajzadeh et al. (2018) conducted a theoretical and experimental investigation to explore how nanofluids could enhance the efficiency of a flat 2 m^2 solar collector. Nanofluids with 20 nm particles and cetyltrimethylammonium bromide (CTAB) surfactant enhancer were used, with different volumetric flow rates (2.0, 2.0, and 1.5 dm^3/min) for different groups. The use of nanofluids instead of water increased the flat solar collector efficiency by 19%, 21%, and 26% for the respective flow rate groups. The study found that nanoparticle concentration had a positive effect on efficiency, with a 5% improvement. Both computational fluid dynamics (CFD) and numerical calculations yielded equivalent results, confirming the findings.

In the evaluation by Alawi et al. (2021), a flat solar collector with varying concentrations of graphene powder in distilled water was investigated. Different variables were assessed, such as mass flows (0.5, 1, and 1.5 kg/min), temperatures (30, 40, and 50 °C), and radiation intensities (500, 750, and 1000 W/m^2). The study consistently showed that mass flow increased heat transfer, circulation, and graphene nanoplatelets (GrNPs) percent. Nanofluids significantly influenced the thermal performance of flat-plate solar collectors, with CeO_2 nanofluid addition to varying mass flow rates and volumetric concentrations resulting in an efficiency increase of 34.43%. Flat solar collectors using nanofluids outperformed water-based ones, with efficiency improvements of 19%, 21%, and 26% for different flow rates. Concentrations of 0.075 wt.% and 0.1 wt.% at 0.025 kg/s achieved efficiencies of 13% and 12.5% respectively compared to water. MATLAB calculations were used to verify and validate the efficiency of the flat solar collector, demonstrating that introducing nanofluids led to an overall rise in efficiency in conjunction with water flow. Dutta et al. (2021) examines magnetohydrodynamic buoyancy-driven thermal energy transport within a copper-water nanofluid-filled quadrantal enclosure. The enclosure's base experiences constant temperature heating, while the vertical wall maintains a uniform cold temperature and the curved wall is insulated. Across the parameter range of $10^3 \leq$ Rayleigh number (Ra) $\leq 10^6$, $0 \leq$ Hartmann number (Ha) ≤ 100, and $0 \leq$ volume fraction of nanoparticles (ϕ) ≤ 0.05, the research indicates that the average Nusselt number increases with ϕ and decreases with Ha, particularly at higher Ra (10^5 and 10^6) values. Moreover, altering the enclosure's sector angle affects the heat transfer rate alongside Ra, ϕ, and Ha, emphasizing the combined role of geometry and influencing factors in heat transfer alterations.

Keerthi et al. (2022) investigates convective-radiative heat exchange with a radial-profile wet porous fin exposed to a hybrid nanofluid flowing at a constant velocity. The analysis considers various nanoparticle shape combinations and employs the mixture model to assess thermophysical attributes. By applying numerical techniques, the effects of multiple parameters on energy distribution, thermal gradient profiles, and thermal fin efficiency are graphically analyzed. Notably, nanoparticle volume fraction and shape factor significantly influence efficiency, with the highest value observed for the spherical-platelet combination, highlighting potential in extended surface technology enhanced by nanotechnology. Mohamad and Zelentsov (2022) employed a range of optimization techniques, starting from 1D simulations and extending to full 3D CFD simulations. These methods are also combined, utilizing a hybrid approach that integrates a 1D model with 3D tools.

3. Nanofluids

Nanofluids, composed of nanoparticles dispersed in base fluids, have emerged as a potential solution for enhancing the efficiency of flat plate solar collectors. By incorporating nanoparticles with high thermal conductivity, such as metal or oxide nanoparticles, these nanofluids can significantly enhance heat absorption and transfer within the collector, ultimately improving overall energy conversion. Various types of nanofluids, including metal-based (e.g., copper, silver), oxide-based (e.g., alumina, titania), and hybrid nanofluids, offer versatile options for tailoring the performance of flat plate solar collectors to specific operational conditions and requirements. Farhana et al. (2019) conducted a meticulous investigation aimed at evaluating the state of three distinct flow parameters concerning nanofluids and hybrid nanofluids as they traverse the internal header and riser tubes of a flat plate solar collector. The study employed CFD modeling, employing nanofluids such as Al_2O_3, TiO_2, and ZnO, as well as hybrid nanofluids like Al_2O_3+TiO_2, TiO_2+ZnO, and ZnO+Al_2O_3.

The modeling approach adopted a three-dimensional framework, utilizing the k-epsilon turbulence model configured with the Standard and Standard Wall Functions. The research maintained an absolute reference frame and a predetermined calculative intensity percentage throughout the modeling. The base fluid utilized in the study was water, with a consistent volume fraction of 0.1% for both nanofluids and hybrid nanofluids. The research methodology involved a single-phase viscous model accompanied by an energy equation. Three distinct design models (referred to as Model A, Model B, and Model C) were employed, featuring fixed inlet and outlet diameters. While the number of header tubes was consistently set at two, the number of riser tubes varied across three scenarios: two, seven, and twelve.

The findings from Farhana et al. (2019) study yielded noteworthy results. In Model B, both nanofluids and hybrid nanofluids experienced a considerable increase in maximum dynamic pressure, with approximately 48% and 16% increments, respectively. Furthermore, Model B showcased the most significant enhancement in velocity magnitude for both nanofluids and hybrid nanofluids. The study also highlighted that the highest turbulence kinetic energy was achieved in Model A (5.5%) for nanofluids and in Model B (18%) for hybrid nanofluids. Ultimately, Farhana et al. (2019) work underscored the superior performance of Model B when compared to both Model A and Model C.

These findings provide evidence that nanofluids have the potential to enhance solar collector performance. However, the choice of nanoparticle and model can impact the extent of improvement. The details of the finding from selected references are presented in Table 1.

Table 1. Summary of the main findings on analysis of thermal performance of solar collectors through nanofluid implementation

Reference	Type of the study	Nanoparticle type	Used liquid	Findings
Yousef et al. (2012)	Experimental	MWCNT	H_2O	Increased mass flow rate and nanofluid concentration resulted in an 83% improvement in the planar solar collector's efficiency.
Vijayakumar et al. (2013)	Experimental	CNT	H_2O	At a volume fraction of 0.5%, the results showed a 39% increase in efficiency.
Chaji et al. (2013)	Experimental	TiO_2	H_2O	The effectiveness of the solar collector rose in proportion to the volumetric rate of flow.
Zamzamian et al. (2014)	Experimental	Cu	C_2H_6O	Nanofluids boost collector efficiency and absorb power factor.
Nasrin and Alim (2014)	Experimental	TiO_2, CuO, Al_2O_3	H_2O	Copper oxide with distilled water had the largest efficiency gain (87.8%), while aluminum oxide and titanium oxide had lower numbers (71%). in contrast to pure water.
Moghadam et al. (2014)	Experimental	CuO	H_2O	The efficiency rate was 21.8% higher in comparison to water.
Michael and Iniyan (2015)	Experimental	CuO	H_2O	At flow rate of 0.1 kg/s, the solar collector is 57.98% efficient compared to a forced load.
Shojaeizadeh et al. (2015)	Experimental	Al_2O_3	H_2O	Change other parameters and increase nanofluids mixed with water energy efficiency to affect combined energy.
Said et al. (2015)	Experimental	TiO_2	H_2O	The results proved a 76.6% efficiency gain compared to when water was the starting point.
Meibodi et al. (2015)	Experimental	SiO_2/EG	H_2O	In contrast to working with water, in contrast to working with water, the findings revealed a percentage efficiency gain of 4-8%.
Meibodi et al. (2015)	Experimental	SiO_2	H_2O	Compared to water, efficiency was 23.5% greater.
Vakili et al. (2016)	Experimental	Graphene nanoplatelets	H_2O	A mass flow rate of 0.015 kg/s is optimal for the planar solar collector.
Verma et al. (2016)	Experimental	MgO	H_2O	The collector's heat efficiency increased 9.34% at flow rate 1.5 dm^3/min and 0.75% concentration.
Verma et al. (2017)	Experimental	(MWCNTs, graphene, CuO, SiO_2, TiO_2, Al_2O_3)	H_2O	Highest possible solar collector efficiency.
Jouybari et al. (2017)	Experimental	SiO_2	H_2O	The rate of heat transmission increased as nanoparticle concentration in the base liquid increased.

Table 1. *Cont.*

Reference	Type of the study	Type of nanofluid used	Used liquid	Findings
Sundar et al. (2018)	Experimental	Al_2O_3	H_2O	Compared to water, efficiency was 18% greater.
Kiliç et al. (2018)	Experimental	TiO_2 Triton X-100	H_2O	In contrast to working with water, the findings showed a 34.43% efficiency increase.
Sharafeldin and Gróf (2018)	Experimental	CeO_2	H_2O	Collector thermal efficiency is a function of the volumetric concentration of nano-particles and the mass flow rate.
Tong et al. (2019)	Experimental	CuO, Al_2O_3	H_2O	Nanofluids in water improved solar collector performance.
Choudhary et al. (2020)	Experimental	ZnO	mixed with a mixture of ethylene clay col with distilled	At flow rate of 150 dm^3/h, a flat solar collector's thermodynamic efficiency rises, and its exit temperature is 45.47 °C.
Okonkwo et al. (2020)	Experimental	Al_2O_3-Fe, Al_2O_3	H_2O	A hybrid nanofluid enhances the availability efficiency by 6.9% relative to the size of a single nanofluid.
Alklaibi et al. (2021)	Experimental	Diamond	H_2O	Nanofluid generated greater entropy than water.
Hawwash et al. (2018)	Theoretical and experimental	Al_2O_3	H_2O	Increased water nanoparticle concentrations enhanced solar collector efficiency and exit temperature.
Farajzadeh et al. (2018)	Numerical and experimental	TiO_2-Al_2O_3	H_2O	Nanofluids instead of water increased flat solar collector efficiency by 19- 26%. Nanoparticle concentration between 0.1 vol% and 0.2 vol% increases performance by 5%.
Alawi et al. (2021)	Theoretical and experimental	Graphene	H_2O	By raising volumetric concentration of GrNPs and fluid mass flow rate, heat transmission was improved. At 0.075 wt.% and 0.1 wt.%, the flat solar collector was 13% efficient, whereas at 0.025 wt.%, it was only 12.5% efficient.
Alim et al. (2013)	Theoretical	TiO_2, SiO_2, CuO, Al_2O_3	H_2O	CuO nanofluid potentially decreases entropy creation by 22.15% compared to water.
Farhana et al. (2019)	Theoretical	ZnO, TiO_2, Al_2O_3 and hybrid nanofluids ZnO+ ZnO, TiO_2+TiO_2, Al_2O_3+Al_2O_3	H_2O	Utilizing three scenarios: two, seven, and twelve of riser tubes to enhance thermal performance of flate plate solar collector

4. Conclusions

Numerous researchers have found that incorporating nanofluids in a solar collector can significantly enhance its efficiency, leading to the following improvements:

- Enhanced flow rate in a volumetric medium: when nanofluids are used as the working fluid in a solar collector, the flow rate within the collector increases. This increase in flow rate contributes to the overall improvement in the collector's efficiency.
- Increased efficiency with higher fluid concentration and absorbed power: as the concentration of nanofluids in the solar collector rises, along with the absorbed power factor, the efficiency of the collector is further improved. Higher concentrations of nanofluids lead to better thermal performance and energy absorption, resulting in enhanced overall efficiency.

By leveraging nanofluids mixed with water, researchers have identified these key factors that positively impact the efficiency of solar collectors, paving the way for more efficient and effective solar energy utilization.

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Przegląd Doskonalenia Wydajności Cieplnej Płaskich Kolektorów Słonecznych poprzez Zastosowanie Nanocieczy

Streszczenie

Nanociecze znalazły szerokie praktyczne zastosowanie w wymianie ciepła. Oleje chłodzące w tym oleje stosowane są w różnych zastosowaniach, takich jak chłodnice samochodowe, systemy energii słonecznej i jądrowej, urządzenia biomedyczne, wentylacja, ogrzewanie, klimatyzacja, chłodnictwo, chłodzenie silników i transformatorów. Celem szeroko zakrojonych badań naukowych było zbadanie wpływu egzotycznych cieczy w połączeniu z tradycyjnymi cieczami przenoszącymi ciepło, ujawniając, że ta kombinacja poprawia wydajność wymiany ciepła w porównaniu z konwencjonalnymi cieczami roboczymi. Badania wykazały imponujące zdolności przenoszenia ciepła przez nanociecze. Optymalizacja wydajności płaskich kolektorów słonecznych polega na kompleksowym podejściu łączącym metody teoretyczne oraz badania eksperymentalne. Wyniki takich badań podkreślają, że zwiększenie zarówno masowego natężenia przepływu, jak i stężenia nanocieczy może prowadzić do potencjalnej poprawy wydajności w zakresie od 20% do 85%. Celem tego artykułu jest zaprezentowanie osiągnięć naukowych w zakresie implementacji nanocieczy do zwiększenia efektywności cieplnej płaskich kolektorów słonecznych.

Słowa kluczowe: nanociecze, kolektor słoneczny, płaska płyta, sprawność cieplna, energia słoneczna