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Thermal performance enhancement of solar collectors by nanoparticles and magnetic field: a review

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HIGHLIGHTS

- This review presents the role of magnetic fields and nanoparticles in improving solar system heat transfer performance.
- Research shows applying a magnetic field to ferrofluids enhances thermal conductivity and performance.
- Studies reveal nanoparticle size and volume fraction directly influence ferrofluid thermal performance.
- Hybrid nanofluids like Al_2O_3-Cu, Al_2O_3-TiO_2, and ZrO_2-SiC exhibit superior thermal and exergetic performance.

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ABSTRACT

The implementation of nanoparticles in solar thermal conversion devices has long been a challenge. Consequently, employing ferrofluids combined with magnetic fields has been an intriguing investigation. The magnetization of magnetic nanoparticles, which noticeably enhances the thermal conductivity of ferrofluid, is one of the principal effects of the magnetic field. Given that the compelling behavior of ferrofluid in the presence of external magnetic fields supplied by either permanent magnets or current-carrying wire as the primary source of magnetic field and the significant effect of this combination on the thermal performance of solar devices, the current review focused on introducing research involving various collections of nanoparticles, ranging from solid metal to metal oxide and hybrid nanoparticles, and demonstrating their effect on the thermal conductivity. Based on the literature, results indicated that in particular cases, by applying a magnetic field in the range of 0.02-1T via permanent magnet and in the presence of hybrid nanoparticles Mn-Zn Fe_2O_4/H_2O for 0.5 vol%, the highest improvement in the obtained efficiency of the thermal is about 47%. Contemporary, the best performance of 74% was obtained for 4 vol% of Fe_3O_4/Terminol 66 ferrofluid under a 500 G magnetic field supplied by current carrying wire.

1. Introduction

Fossil fuel utilization is often regarded as a prominent global challenge in the present era. From the last century until now, humans have employed different types of fossil fuels. Generally, people use oil derivatives as fuel for their cars, personal generators at home, and, most importantly, for heating domestic water during the winter. One of the main keys to solving or reducing dependence on the usage of fossil fuels is employing renewable energy knowledge. Because of its long-term viability, solar energy has gained widespread acceptance as a clean and dependable heat source for various energy systems. Various strategies for capturing this important thermal heat have been devised, including using numerous solar collectors. Solar collectors are widely recognized as the primary appliances for developing a strong, cleaner production strategy (CPS) focusing on environmental sustainability, operations, recycling, and maximal heat loss removal [1]. The major challenge for solar energy implementation is determining how to improve the efficiency of the solar collectors [2]. It is possible to accomplish this by modifying the collector assembly and developing a new technique that would improve thermal performance. Numerous articles proposed diverse ideas. For instance, Balakin et al. [3], described a multiphase CFD model for DAC, and they considered the process of thermomagnetic convection in the collector using a magnetic nanofluid. Abdulmunem et al.[4], experimentally studied the impact of including embedded longitudinal fins within paraffin wax on the energy and exergy efficiency of the solar air collector in the climate of Baghdad governorate. Jalil and Salih [5], investigated how changing the paraffin wax's thermal characteristics affected the operation of a double-glazed window that was treated with it in the hot summer Baghdad climate. Karamallah and Abed [6], experimentally studied the effect of particle size and stability of Al_2O_3-H_2O nanofluid on heat transfer through a horizontal pipe. On the other hand, Safarzadeh et al. [7], analyzed expanded energy and entropy generation for a

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helically coiled pipe by employing Fe_3O_4, magnetic field, and micro fin tube. Hamza and Aljabair [8], considered the increase of heat transmission in a horizontal circular tube utilizing a hybrid nanofluid (CuO, Al_2O_3/distilled water) equipped with a conventional twisted tape. Aydin et al. [9], experimentally investigated the thermal performance of $NiFe_2O_4$ in a thermosiphon heat pipe with the use of a current-carrying wire to generate the magnetic field. Also, Fadhil et al. [10], investigated phase change material (PCM), which is useful for thermal storage and was used as a column obstruction to improve thermal performance. Xia et al. [11], presented a novel design scheme for the solar flat plate collector (SFPC) with porous metal blocks on the inner wall of the absorber. Zhao et al. [12], proposed a novel strategy for cascadingly using solar collectors with multiple concentration ratios in one collector loop to reduce optical losses and improve the overall performance of the PTC system.

Although water and thermal oils are currently frequently employed as heat transfer mediums in solar collectors, their limited heat conductivity as base fluids is considered a disadvantage [13]. Nanofluids are being considered by numerous researchers as a potential replacement for traditional working fluids in solar collectors because of their high heat conductivity (see Figure 1). As it display enhanced thermal conductivity approximately to base fluids due to the elevated heat transfer occurring within the fluid as an result of the presence of nanoparticles. Consequently, nanofluids have a rather high heat transmission rate [14]. The word nanofluid refers to the suspension of particular volume concentrations of nanoparticles in certain fluids while the entire nanofluid remains stable and no nanoparticle precipitation occurs [14]. Because of the moderate economic efficiency of solar appliances, solar energy overpriced fossil fuels [15]. Investigating solar devices working fluid is one of the most effective ways to improve the efficiency and performance of these systems. Furthermore, metal particle nanofluids are used to increase solar devices' thermal performance [16]. Although utilizing nanofluids elevates pressure drop [14], it enhances solar system exergy and thermal efficiency [17]. Three primary approaches for improving collectors' effectiveness are changing the contact surface so more heat transfers to the collector's absorber, coating the absorber so more solar radiation can be absorbed, and adding nanoparticles to the working fluid to make it more thermally conductive [18]. Nanofluids are regarded as a recently developed and improved working fluid type due to superior properties such as improved thermal conductivity (k), increased stability, and so on [19]. Researchers have been inspired to examine the impact of many passive and active factors that can control the phenomena of thermal convection of nanofluids, such as system geometrical configuration, the nature of the medium within which natural convection occurs, internal or external excitations, and nanofluid thermo-physical properties, among others, using various techniques to measure thermal system efficiency [20].

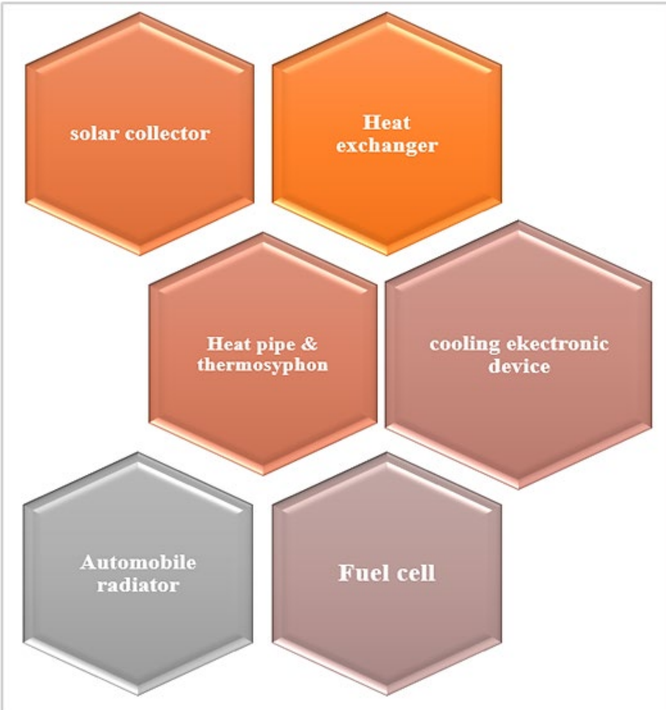


Figure 1: Several possible applications of nanofluid

The presence of nanoparticles in the working fluid increases its absorptivity, which is related to the process of numerous absorptions of the scattered radiation caused by particles. The optical properties, size, and shape of the nanoparticles, besides the base fluid optical properties, determine how much their incorporation improves the working fluid optical properties [21]. However, any fluid containing medium, large, or even nano-sized particles can pose significant challenges in exploitation, such as pipeline erosion, increased pressure drop, channel blockage, and limiting practical usage [22]. As demonstrated in some of the reviewed studies, caution must be observed when replacing pure fluids with nanofluids. It has been shown that exceeding the limit in the volume percentage of nanoparticles reduces heat transfer due to increased viscosity. Furthermore, some disadvantages have been identified with metal-based nanofluids, such as their low physical and chemical instability, which may impair their thermal performance. Some researchers have also shown that non-metallic nanoparticles have higher thermal efficiency than metallic nanoparticles. However, this finding requires further investigation [23]. Despite these well-known shortcomings, the fact that nanofluids positively enhance convective heat transfer makes them valuable in thermal systems, and there is a lot of experimental research on their properties and uses [22].

Nanoparticles interacting and colliding with each other raise the flow turbulence intensity, transition surface, and turbulence. These fundamental physical phenomena significantly improve the working fluid's heat transfer performance [24]. In addition to the heat conduction, the higher the surface area and turbulence intensity, the better the convective heat transfer performance. The presence of nanoparticles in the fluid leads to a decrease in the thickness of the boundary layer at the surfaces. This is one of the elements that contribute to the enhancement in convective heat transfer when nanofluids are used [25]. Another advantage of using nanofluid is that it reduces convective as well as radiative losses due to improved heat transmission between the absorber plate and the nanofluid [26]. Underlying mechanisms and strategies can be uncovered to improve these nanofluids' properties by researching the effect of magnetic fields on their rheological properties, stability, convective heat transfer, and thermal conductivity. This knowledge will contribute to efficient heat transfer systems' new designs, the discovery of new applications for magnetic nanofluids, and the advancement of nanofluid-based technologies [27]. The enhancement of heat conductivity is a key issue of research in the field of magnetic nanofluids, as the impact of an external magnetic field on the conductive properties of magnetic nanoparticles has been intensively explored in recent decades [28]. Many review articles discussed the applications and properties of nanoparticles, and others included information on how magnetic nanoparticles work. However, in the present article, a general discussion on the impact of the magnetic field by its different applications, including (a permanent magnet, current-carrying wire…etc.) has been implied, considering the impact and most recent finding of the combination of magnetic field on ferrofluid and solar applications.

Eventually, the main objective of this study is to review researches that has been investigated and undertaken in this domain, considering the performance of magnetic fields as well as nanoparticles in enhancing the thermo-hydraulic and the heat transfer rate overall performance of solar systems. The nanoparticle and magnetic field effects will be studied on four different types of solar collectors: Flat plate water collectors, parabolic trough collectors, direct absorption water collectors, and U-tube water collectors.

2. Magnetic nanoparticles in solar collectors

Several studies and articles have focused on using nanofluids to improve convective heat transfer throughout the last decade. The availability of innovative synthesis procedures and excellent characterization tools enabled the use of such materials in a wide range of applications. With these nanoparticles, the selected fluid can have better convective, boiling, and thermal conductivity [29]. Such studies often investigate the impacts of particle volume fraction, type, and size added to a particular base fluid, which might also be an important variable to investigate [30]. Nanofluids are colloidal dispersions of solid, inorganic particles having a minimum of a single dimension ranging from 1 to 100 nanometers. They are suspended in a base fluid, which is commonly a liquid. They are much known as nano aerosols in the case of a gas base fluid. As a result, nanoparticles have adaptable and favorable thermal, mechanical, electrical, and magnetic properties [31], making them suitable for various engineering applications. These features are changeable due to the nanoparticles' material, size, concentration, morphology, and the base fluid's chemical composition, different shapes of nanoparticles between blade, platelet, cylinder and more has been shown in Figure 2. On the nanoscale, small particles exhibit altered or completely new characteristics compared to their individual-constituent and bulk-material equivalents [32].

The term "nanofluid" dates back about 25 years, and numerous attempts at energy regulation have been made to enhance the capacity of solar systems simultaneously because of their thermo-optical features. These qualities can be increased by changing the size and form of the nanoparticles in a certain base fluid [33]. Nanoparticles with a large surface area and compact size have a high heat-handling capacity. The performance characteristics of nanofluids are determined by HTC (heat transfer coefficient), Nusselt number, Reynolds number, and Prandtl number; these parameters are critical in improving the performance of nanoparticles [34]. Various types and applications of nanoparticles have been shown in Table 1.

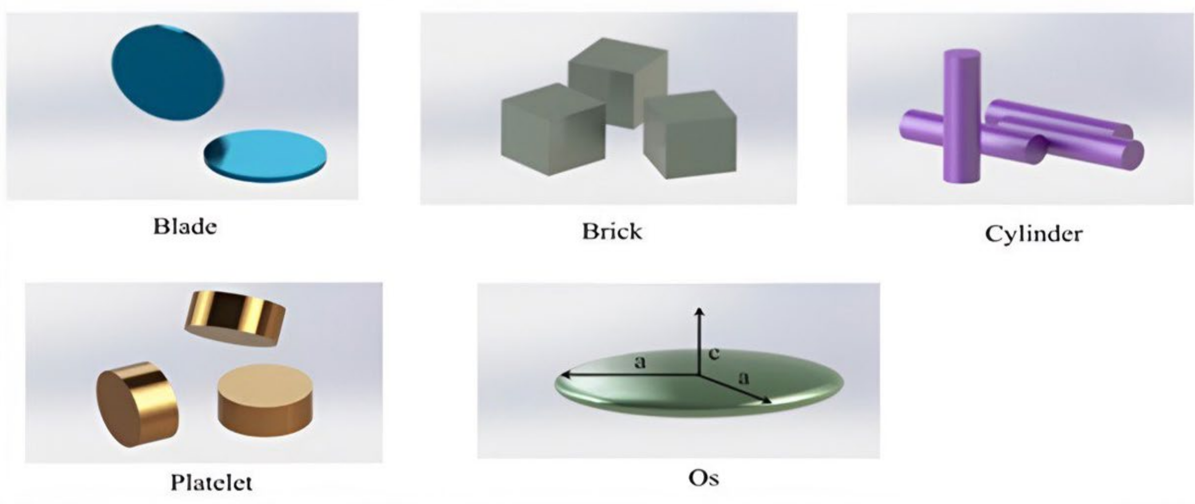


Figure 2: Different types of nanoparticles [35]

Table 1: Types of nanoparticles and applications

Nanoparticles	Main types	Applications
Metal NP	Fe, Au, Cu, Ag, Ti, Al,….etc.	Photovoltaic, biomedicine,…etc.
Metal oxide NP	ZnO, Al_2O_3 , TiO_2 , SiO_2, Fe_2O_4,….etc.	Energy storage, catalysis,…etc.
Hybrid NP	[Al_2O_3, Cu], [TiO_2,Al_2O_3], [ZrO_2, SiC],….etc.	Solar applications, sensors,…etc.

Various studies have been conducted on nanofluids incorporating metallic and nonmetallic nanoparticles. The current review article primarily summarizes theoretical, numerical, and experimental studies on all classic forms of nanoparticles employed as circulating fluids in absorbers. In addition, this section considers the physical objects that led to an increase in the thermal efficiency of solar collectors as a result of individual key factors, including nanoparticle type, size, vol/wt concentrations, mass/volume flow rate, radiation intensity, absorber slope angle, and many other combined arrangements. Furthermore, the purpose is to accurately classify the finest type of nanofluid in the SCs among the examined nanofluids [36]. A literature summary of the researchers and their remarks on employing nanoparticles is shown in Table 2.

2.1 Solid metal nanoparticles

Metal nanoparticles (such as gold, silver, or copper) may show a single or several abrupt absorption peaks due to the effect of the non-resonant lightning rod. This rod is responsible for the irregularity in nanoparticle geometries and produces absorption cross-sections many times larger than their physical cross-section [37].

Xu et al. [38], used a new volume fraction-thermal lattice Boltzmann method to numerically study the two-phase natural convection of Cu-water nanofluid in a square cavity. The impact on streamlines, isotherms, and the Nusselt number of the changing nanoparticle volume fraction at various Rayleigh numbers and starting nanoparticle volume fractions are investigated in this review. According to the findings, a large Rayleigh number causes a reduction in the Nusselt number along the side walls, whereas a small number has a reverse impact on certain regions of the side walls. When nanofluids are employed, especially at high nanoparticle concentrations, the efficiency increases significantly due to an increase in Brownian motion. Sultan et al. [39], explored the impact on the ETSC's thermal efficiency of using nanofluids (Cu (30 nm) + DW) as the working fluid. When using distilled water alone at the same volume concentration and different volume flow rates, the percentages of improvement for (Cu (30 nm) + DW) were (2.41%, 4.36%, 5.43%). Still, when using a 5% volume concentration and different volume flow rates, the percentages of improvement were (15.326%, 16.96%, and 19.98%, respectively) reported by the researchers.

2.2 Metal oxide nanoparticle

Metal oxide nanoparticles, on the other hand, are rarely employed as volumetric absorption solar nanofluids due to their large scattering cross-sections. Numerous researchers have tried to enhance the real applications of solar collectors, and recent contributions have been made to developing, designing, and testing various configurations using different types of working fluid. When it comes to heat transfer applications, nanofluids provide an alternative that could greatly improve thermal performance. In their study, Majeed et al. [40], assessed the thermal performance of ETSC. The use of nanoparticles in DI has been enhanced by two nanomaterials: aluminum and aluminum oxide. Based on their findings, employing nanoparticle metal greatly improved efficiency, whereas using oxide metal resulted in lower efficiency owing to the nanomaterial's higher thermal conductivity. A solar collector's efficiency and the rate of heat transmission were both improved by manipulating the size and type of nanoparticles used. The performance of the heat sink is affected by the addition of nanoparticles to paraffin, which changes its thermophysical properties.

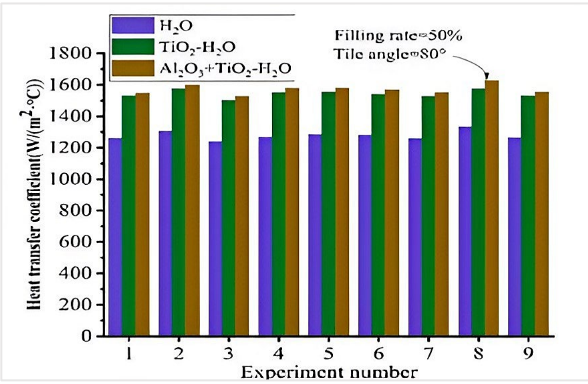
During the fusing process, the PCM absorbs heat from the bricks before it enters its interior, thereby reducing the temperature. This is done by utilizing its high latent fusion heat. For application in hot climes, Abbas et al. [41], supplied the thermal analysis of the Iraqi construction wall, which has mortar layers and brick containing PCM. The model depicts a composite wall made of two layers of mortar and bricks. The wall has cylindrical holes that may be filled with PCM (TW), PCM mixed with nano (TWN), or mortar (NTW) to create a home wall. The findings demonstrate that 4.7 °C and 4.4 °C reductions in peak inner surface temperature may be achieved by utilizing pure PCM and nano-augmented PCM, respectively. Jalil et al. [42], studied the impact of incorporating nanoparticles Al_2O_3 into PCM on heat sink cooling performance. It was discovered that the temperature can be reduced to 18 °C using the working heat sink in conjunction with PCM. Alumina outperforms all other commonly used nanoparticles when combined with PCM. It was found that by adding a small amount of nanoparticles (2%), the heat sink's performance can be enhanced. When nanoparticles are added to a heat sink, not only does the sink's temperature fall, but the convection effect is reduced, and conductivity is increased.

2.3 Hybrid nanoparticles

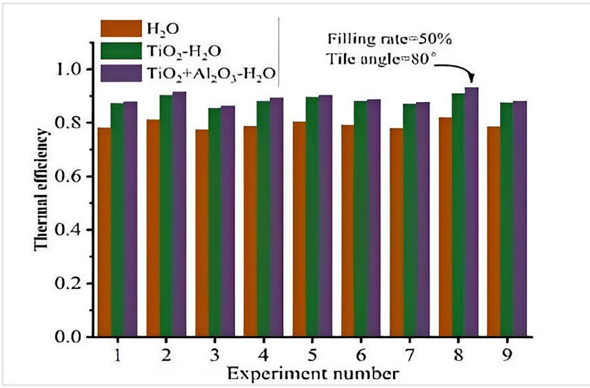
The industrial and technological sectors are finding it increasingly challenging to keep up with the increasing fuel and energy demands caused by a growing population. Researchers and professionals in the field have placed a premium on investigating the practicality of renewable energy sources, particularly solar power. In recent years, there has been a significant increase in investment, and studies have focused on examining both the advantages and disadvantages of employing nanofluids in solar-powered systems. When working with CuO nanofluid at increasing volumetric concentrations, the issue of relatively heavy nanoparticles settling down became more problematic compared to Al_2O_3 nanofluid. Salman et al. [43], conducted experiments to determine the effect on the thermal efficiency of an ETSC with an inner cylindrical coil located in a vertical tank utilizing a hybrid nanofluid consisting of aluminum and distilled water. A range of 15, 30, and 45 $l/h.rm^2$ were used to test the performance of ETSC with water and a hybrid nanofluid of aluminum and aluminum oxide. The results demonstrate the potential of (Al+ Al_2O_3) hybrid nanofluids as working liquids in an ETSC for converting solar radiation into thermal energy by absorbing heat.

However, among solar energy systems, U-tube SCs play a crucial role in domestic water heating. A solar power system can reduce emissions of Co_2 and So_2 by balancing off the high energy demand of water heating. Yıldırım and Yurddas [44], assessed the thermal efficiency of a U-tube whole system ETSC system in consideration of this. A variety of nanoparticle types were included in mono- and hybrid nanofluids at varying volume fractions, and their thermal and hydrodynamic behaviors were studied using the finite volume approach. The thermal performance of the system was found to be superior when Cu-H_2O nanofluid was employed in the analysis. The fluid in the system circulates quicker as the ratio of SiO_2 nanoparticles in the nanofluid increase and, hence, make a lesser contribution to thermal performance than Cu nanoparticles.

Adding nanoparticles to the typical working fluid of closed two-phase Thermosyphon Solar Collectors (TPCTs) can improve their heat transfer performance. However, it is important to maintain good rheological qualities while doing so. Xu et al. [45], analytically examined the impact of specific variables, like nanoparticle concentration and operational parameters, on the TPCT thermal performance in Figure 3. Consequently, the TPCT was treated with a mixture of spherical TiO_2 nanoparticles that exhibited excellent rheological properties and rod-shaped Al_2O_3 nanoparticles that exhibited outstanding thermal conductivity. The optimal heat transfer performance of the TPCT was reached with an 80° inclination angle while using $Al_2O_3 + TiO_2 - H_2O$ nanofluid as shown in Figure 3 (a) below, as it displays the comparison of different working fluids. Moreover, the highst thermal efficiency were acheived at a 0.6% nanoparticles volume concentration of $TiO_2 + Al_2O_3 - H_2O$, and a 50% filling ratio as shown in Figure 3 (b).



(a)



(b)

Figure 3: Comparison of different working fluids (a) equivalent heat transfer coefficient, (b) thermal efficiency [45]

Elshazly et al. [46], studied the thermal performance of SCs loaded with MWCNT, Al_2O_3, and a 50:50 mixture of the two materials. For all three composite fluids tested, the MWCNT provides the highest efficiency results. Findings from this study support the idea of replacing half of the MWCNTs with safer and more cost-effective ones. Al_2O_3 which increases efficiency by 26% at 1.5 L/m, 29% at 2.5 L/m, and 18% at 3.3 L/m, respectively. Ajeena et al. [47], dispersed ZrO_2-SiC particles in distilled water (DW) produce the hybrid nanofluid used in this study. The performance change of the collector is identified by using the nanofluid in an SFPC (Figure 4). Experimental results demonstrated that, when subjected to a nanofluid, the solar collector system outperformed the system-based distilled water in terms of energy and exergy efficiency. Therefore, the thermal efficiency is increased by 31.64% after the inclusion of nanofluids. The system achieved its highest exergy efficiency improvement of around 28.31% at a concentration of 0.1%.

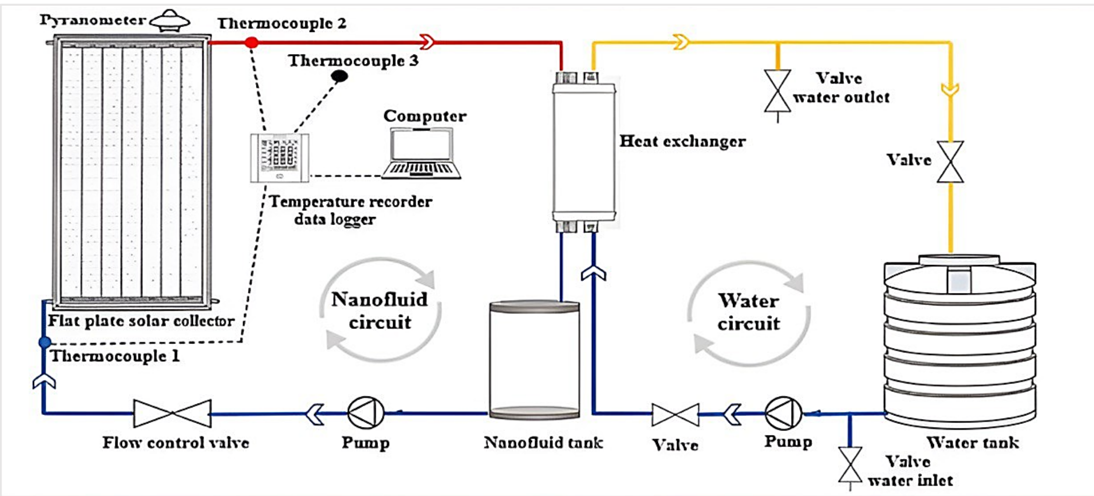


Figure 4: Schematic view of the experimental system [47]

Table 2: Literature summary of the researchers and their remarks by employing nanoparticles

Resch. Meth.	Base fluid	Nano particle	Concet.	Type of SC	Notable findings	Ref.
Num.	H_2O	Cu	1-5%	Square cavity	An increase in Brownian motion causes the efficiency to rise sharply with increasing nanoparticle concentrations.	[38]
Exp.	DI	Cu	1,3,5%	ETSC	Compared to DI, employing Cu as the working fluid of ETSC improves its thermal performance, particularly at high inlet temperatures.	[39]
Exp.	DI	Al, Al_2O_3	1-5%	ETSC	Combining nanomaterials with distilled water at varying concentrations enhanced the practical heat gain for two distinct nano-fluids.	[40]
	PCM	Al_2O_3	-	-	Demonstrate that 4.7 °C and 4.4 °C reductions in peak inner surface temperature may be achieved by utilizing pure PCM and nano-augmented PCM, respectively.	[41]
Exp. & Num.	Air	Al_2O_3	2%	Heat sink	When coupled with PCM, alumina performs better than any other nanoparticle that is frequently utilized.	[42]
Exp.	DI	Al,Al_2O_3	1-5%	ETSC	Max efficiency of 24.89% with a nanofluid mass flow rate of 45 l/hr.m2 and nanoparticles of 5% vol.	[43]
Exp. & Num.	H_2O	SiO_2, Cu	0.01-0.05%	ETSC	Compared to water, nanoparticles improve thermal capability by as much as 15%.	[44]
Exp.	H_2O	TiO_2 Al_2O_3	0.1-0.5%	TPCT	Adding Al_2O_3 to TiO_2 improves TPCT's thermal performance even more, according to the data.	[45]
Exp.	H_2O	MWCNT, Al_2O_3	0.005-0.5%	SFPC	The efficiency is increased by 26%, 29%, and 18% when hybrid MWCNT/Al_2O_3 (50:50) is used.	[46]
Exp.	DI	ZrO_2 SiC	0.025-0.1%	SFPC	The system achieved its highest exergy efficiency improvement of around 28.31% at a concentration of 0.1%.	[47]

3. Impact of magnetic field on nanoparticles in solar collectors

Dispersing superparamagnetic nanoparticles (usually less than 20 nm in diameter) in base fluids like ethylene glycol, oil, water, etc., can create magnetic nanofluids, a novel type of heat transfer fluid. These nanofluids contain nanoparticles of metals like iron, nickel, and cobalt, as well as oxides of these elements like magnetite Fe_3O_4. Parameters such as the kind and percentage of nanoparticles, the direction, strength, and orientation of the applied field of the magnetic can affect the thermophysical properties of fluids. This action permits the applied external magnetic field to influence the flow and heat transfer processes [22]. The primary variation between flows under a magnetic field and ferrofluids is that in inflows under a magnetic field, the source of mobility and movement is related to an externally applied body force. In contrast, in ferrofluids, the ferrofluid magnetized particles can move close to one another and bring in force. As a result, when magnetic fields and ferrofluids are employed simultaneously, both internal and external body forces influence ferrofluid movement [48]. When the concentration of nanofluid in an SC is high (particularly in DASC), the receiver temperature distribution would be uneven [49]. However, employing a magnetic field enhances the mixing and causes vortex flow inside the tubes, as it notably changes the flow from a uniform free state to a swirling state, which prevents the deposition and adhesion of nanoparticles to surfaces or pipe walls. It is observable in several reports that operating conventional SCs with ferrofluid without using a magnetic field reduces the collector thermal efficiency heat transfer rate in comparison to utilizing pure water, and thus this inappropriate deliberation can be eliminated by using a magnetic field [50].

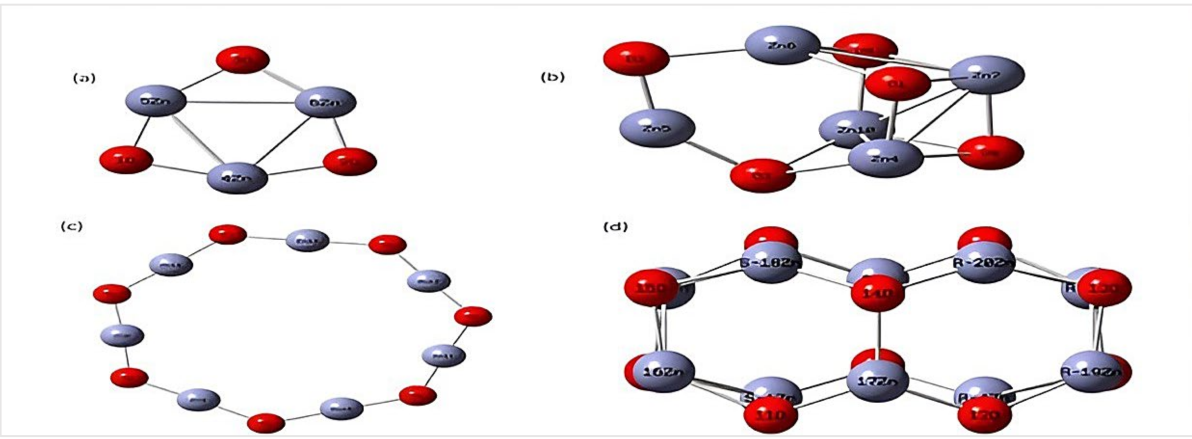


Figure 5: The geometry structure of Zn_nO_n cluster [51]

The interaction between a ferrofluid and a magnetic field induces magnetic moments in the ferrofluid due to the stimulation and orientation of the magnetic poles of the magnetic nanoparticles in the direction of the magnetic field. As a result, an increasing part of the body-force, known as body-force of the magnetic. The magnetic body force is significantly reliant on the magnetization of the nanoparticles and the value of the externally field of the magnetic applied. This effect produces the movement of the fluid, as a result the heat is transferred, controlled and regulated [52]. This effect will boost the thermal conductivity of fluid because of the chain-like bridges production as shown in Figure 5 that displays the Zn_nO_n cluster geometry, which is another phenomenon that have an observable effectiveness on the ferrofluid's. It is worth noting that this phenomena occurrence (the formation of chain-like bridges) is strongly relay on the direction of the magnetic field, and it might be dominant in homogeneous magnetic fields [53]. Magnetic field application using ferrofluid in SCs has become one of the most intriguing topics in recent years. The investigation of magnetic fields has been the focus of thorough examination on their effect on the efficiency of HEs operating with nanofluids. Using a magnetic field in two separate trials, it had examined the impact of particle size, type, and inclination angle [54, 55]. A linear link between magnetic field intensity and temperature rise has been demonstrated in other studies reporting on the relationship between Reynolds number, magnetic number, and heat transfer [56].

Figure 6: Ultrasonic types, (a) probe (b) bath [57]

The thermal conductivity increases as the nanoparticle's concentration increases, and this augmentation would be more prominent at larger concentrations. The form and distribution of chain-like clusters are responsible for this augmentation (Figure 5). It is common practice to physically separate clusters of nanoparticles using either ultrasonic baths that is shown in Figure 6 (a), or by the employment of probes as in Figure 6 (b). The ferromagnetic nanoparticle's effective attraction in nanofluids is dependent on magnetic energy, which is dependent on particle magnetic moments as well as thermal energy and distances, which is directly connected to temperature. In addition, thermal energy dominates when there is no magnetic field, and Brownian motion promotes particle movement. Nevertheless, the magnetic attraction is stronger than the thermal energy under the magnetic field, resulting in the creation of nanoparticle short chains in the applied magnetic field orientation [58]. The literature summary of the researchers and their remarks on employing nanoparticles and magnetic fields is shown in Table 2.

3.1 Permanent magnet and electromagnet coil

Considerable studies have concentrated on the flow and thermal performance of different magnetic fields and ferrofluids. As the solid volume fraction increases, the thermal conductivity of the nanofluid shows a remarkable improvement. An aqueous solution containing intrinsically magnetic quasi-crystalline Fe-Cu nanoparticles is employed by Alami et al. [59], to improve heat transfer (Figure 7). Transmission electron microscopy tests yielded sizes as small as 50 nm, confirming the outcomes of grain size reduction. Adding various quantities of nano-powder to deionized water to evaluate the effect of rotating magnetic agitation on heat transfer properties in a closed vessel. Results showed that transient heat transmission is up to 34.6% better after Fe-Cu nanofluid is added.

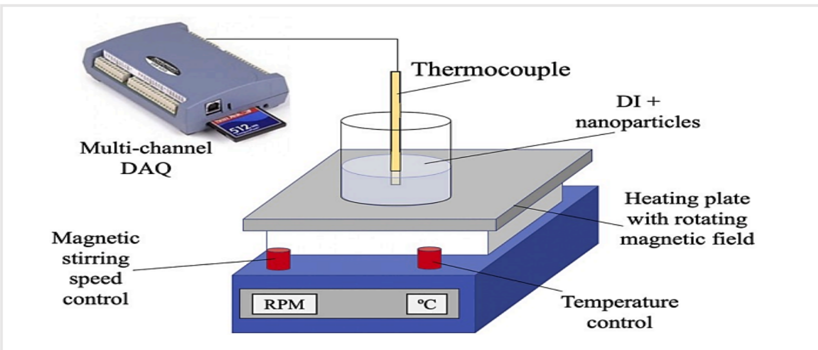


Figure 7: Schematic of the experimental set-up [59]

When a small magnetic field is applied, the Nusselt number increases as the magnetic field intensity increases, and the converse occurs when applying a high magnetic field. The bigger the particle mass percentage and the greater the density of the magnetic field, the higher the noticeable heat transfer. Fan et al. [60], investigated the hydraulic-thermal characteristics in corrugated tubes and various obstructers using Fe_3O_4-H_2O-AG nanofluids with various magnetic external fields. In addition, a unilateral source of magnetic field has a greater effect on heat transfer characteristics than a bilateral staggered magnetic field source. Moreover, a perforated turbulator in a corrugated tube improves heat transfer performance more than a non-perforated turbulator. The combination of nanofluids, perforated turbulator, and corrugated tube, and the magnetic field might greatly enhance heat transfer capacity more than the corresponding loss in flow pressure. A stronger magnetic field improves thermal efficiency and heat transfer in a system when the input heat flow and vol% are both high.

DASCs based on nanofluids are a promising new way to harness solar power as shown in Figure 8 (a) with a typical closed loop DASC. The agglomeration of nanoparticles and low-quality energy they produce, however, prevent their widespread use. Wang et al. [61], presented a novel approach to DASCs that makes use of magnetic nanofluids, Figure 8 (b). The results demonstrated that, with three sun irradiations, the maximum temperature can reach 98 °C, and that, with an external rotating magnetic field, the photothermal conversion efficiency can be enhanced by 12.8% at a concentration of 500 ppm. Meanwhile, the high-temperature, pure base liquids are sent to the heat exchanger, which not only prevents issues like corrosion and pipeline clogging but also lowers the flow resistance in the pipeline. Shojaeizadeh et al. [62], experimentally studied the benefit of utilizing Mn Zn Fe_2O_4/water ferrofluid was subjected to the effect of a set of permanent magnets producing a non-uniform magnetic field (Figure 9). Without a magnetic field; they were able to increase the efficiency of the collector when compared to water in the case study by a maximum of 48.54 % at 1.0 volume fraction and 0.033 kg/s mass flow rate. Adding a magnetic field also had the desired effect of a Kelvin body force, but only at higher volume fractions and lower flow rates. The ferrofluid manufacturing method is nearly identical to that of other nanofluids, and a well-stabilized ferrofluid can maintain its stability in the presence of a magnetic field.

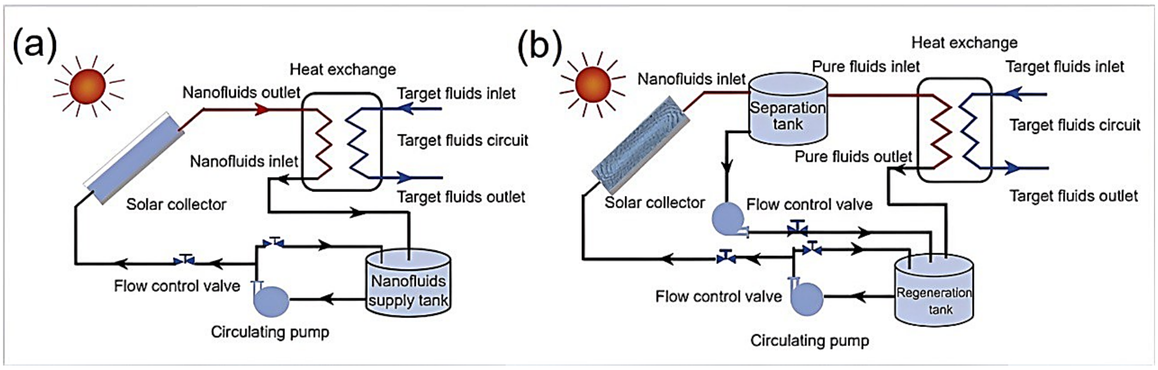


Figure 8: (a) Typical DASCs with a closed loop circulating nanofluid, (b) the proposed working mechanism model [61]

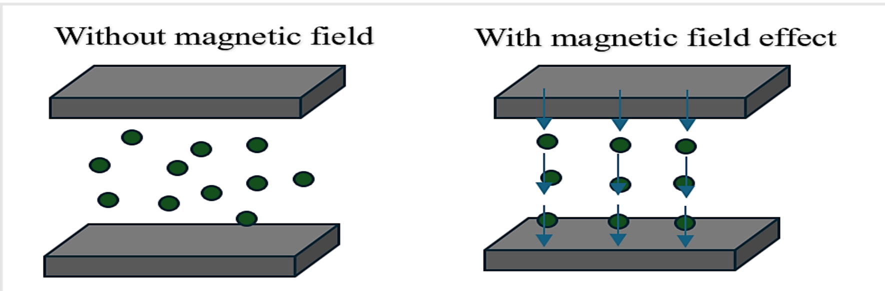


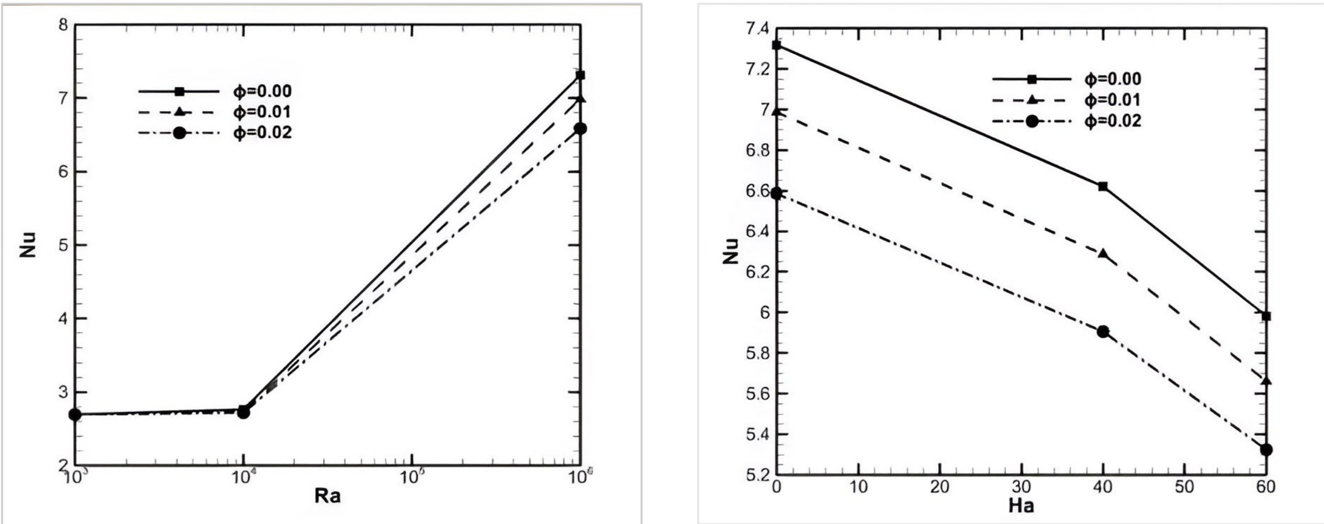
Figure 9: Internal distribution of ferrofluid particle without and with a magnetic field

The heat transfer coefficient increse as the intensity of the magnetic field increases. Furthermore, at thermal boundary layers, magnetic nanoparticles produced suitable magnetic connections, elevating the distribution of nanoparticles at the thermal boundary layer, which was thought to be the primary reason for the improvement in the nanofluid's overall thermal-hydraulic performance. Zhang and Zhang [63], investigated heat transfer and flow characteristics numerically under various magnetic field strengths, volume fractions, and magnetic field orientations. The magnetic field had a more noticeable effect on heat exchange in nanofluids with low flow rates than those with high flow rates. Moreover, there was a notable increase in the convective heat transfer coefficient and then a decline as the volume fractions of MNFs increased.

Multiple research projects demonstrated that it is crucial to optimize the nanofluid concentration to gain improved heat transfer ability and that it is critical to boost the thermal characteristics of a magnetic nanofluid. Lee et al. [64], experimentally investigated the influence of an external magnetic field on the CHT coefficient of $Co_{0.5}Zn_{0.5}\,Fe_2O_4$ nanofluid in a tube with constant heat flux. They concluded that there was an increase in the CHT coefficient as the nanofluid concentration increased. In addition, the pressure drop rose with the concentration of nanofluid and increased dramatically due to the magnetic field effect. The magnetic field impact resulted in the formation of a chain-like bridge agglomeration on the pipe's inner surface, causing a flow of fine turbulence and thereby raising the CHT coefficient. Some hybrid methods enhance convection and conduction mechanisms in the tubes while conserving more accessible solar energy. Cao et al. [65], focused on the sophisticated manipulation of a flat plate solar collector using microporous foam, revolutionary tubes, and nanofluid. They found that the combination of innovative tubes, nanofluid, and microporous fin considerably reduces the collector's maximum temperature. In optimal conditions, the designed collector's energy performance rises from 53.3% to 76.1%. The novel technique for manipulating the collector enhances exergy efficiency by 8.5%. Zhang and Ye [66], switched from water to a nanofluid comprising magnetic nanoparticles and zinc oxide. The risers were then subjected to magnetic fields of 100, 150, and 200 Oe. As the flow velocity increased, the efficiency improved due to the volume of nanoparticles that interacted with each other. The efficiency improved once the magnetic field was added; nevertheless, the flow rate had a peak for this circumstance, and after that peak, by increasing the flow rate, the efficiency declined. It is important to note that the pressure drop almost certainly leads to an increase in pumping power levels. Shojaeizadeh et al. [67], conducted experiments to study the impact of uneven magnetic field on the ferrofluid-based SFPC (Mn-Zn Fe_2O_4 /water) thermal performance. A series of permanent magnets was used to generate the magnetic field. It was concluded that the effect of the magnetic field on the collector efficiency improvement was raised by reducing the value of the mass rate of the different volume fraction scenarios. Additionally, they pointed out that when utilizing high-strength magnets, various disadvantages or challenges are evoked, for example, producing dune-like humps in the riser tubes at extremely strong magnetic fields. On the other hand, the developed pressure drops are caused by a combination of factors, including the relatively high viscosity value of the Mn-Zn Fe_2O_4 /water ferrofluid, which results in a maximum pressure drop compared to water, and the magnetic field, which results in the highest pressure drop compared to the ferrofluid case without the magnetic field.

Circumstantially, more research needs to be done into the mechanism and influence of the uniform magnetic field on the process of phase transition. He et al. [68], studied the mechanism and effect of solidification regulation using a uniform external magnetic field. They concluded that, the incorporation or dispersion of Fe_3O_4 nanoparticles in the liquid phase or solid speeds up the PW solidification. Under negative or positive magnetic fields, the non-uniformity of solid-phase formation rises or decreases with |B|, potentially affecting the efficiency of the entire energy release cycle and energy storage. In the existence of nanoparticles and a nonuniform magnetic field, other researchers studied the heat transport and melting process of PCM in a cylindrical area with various interior fins. Farahani et al. [69], computed the PCM's transfer of heat and MSP in cylindrical storage with different configurations of integrated internal fins in three dimensions. There is a strong relationship between the fin shape and the PCM melting point in the finned chamber. The existence of nanoparticles in the PCM considerably boosted its thermal conductivity and improved its MSP. The melting process was improved by applying a non-uniform magnetic field to the chamber's exterior walls.

Many studies use the Darcy-Brinkman Forchheimer method to model energy transit and liquid circulation, with the goal of studying how the Lorentz force affects the thermodynamic features of the system. A hybrid nanosuspension is studied in relation to magnetic fields as its entropy accumulates during thermal convection in an undulating hollow with an interior heated plate by Hamza et al., [70]. The Rayleigh number increases by around 300%, as shown in Figure 10 (a) that dispalys the performance of both Rayleigh and Nusselt numbers with various NP concentrations. On the other hand, the mean Nusselt number increases by about the same amount as in Figure 10 (b) that displays the relation between Hartman and Nusslet numbers with different nanoparticles concentrations. In comparison, the average skin friction parameter decreases by about 50% as the number of wall waves increases. At (N = 5), the parameter for the number of waves also achieves its maximum value, and the average Bejan number does the same.



(a) (b)

Figure 10: Average Nusselt number versus (a) Hartman number (b) Ra number at different values of volume fraction (φ) [70]

With their significance in understanding fluid mixing and mass transport phenomena, vortices attract the attention of numerous scientists when they examine any flow model. Researchers must explore vortices wherever they come across them since they are present in the natural world. Kai et al. [71], illustrated the complex physics of a Lorentz force that controls the rotation of nanoparticles and the components of the complicated structure of eddies inside the fluid flow of a hybrid fluid, including Ag and TiO_2 nanoparticles. Results show that when the magnetic fields are amplified, the degeneration of the two main vortices becomes immediately apparent as shown in Figure 11 (a). New vortices in the flow regime with varying NP intensities and rotational directions become apparent, as shown in Figure 11 (b) that displays the effect of NP concentration on the Nusselt number.

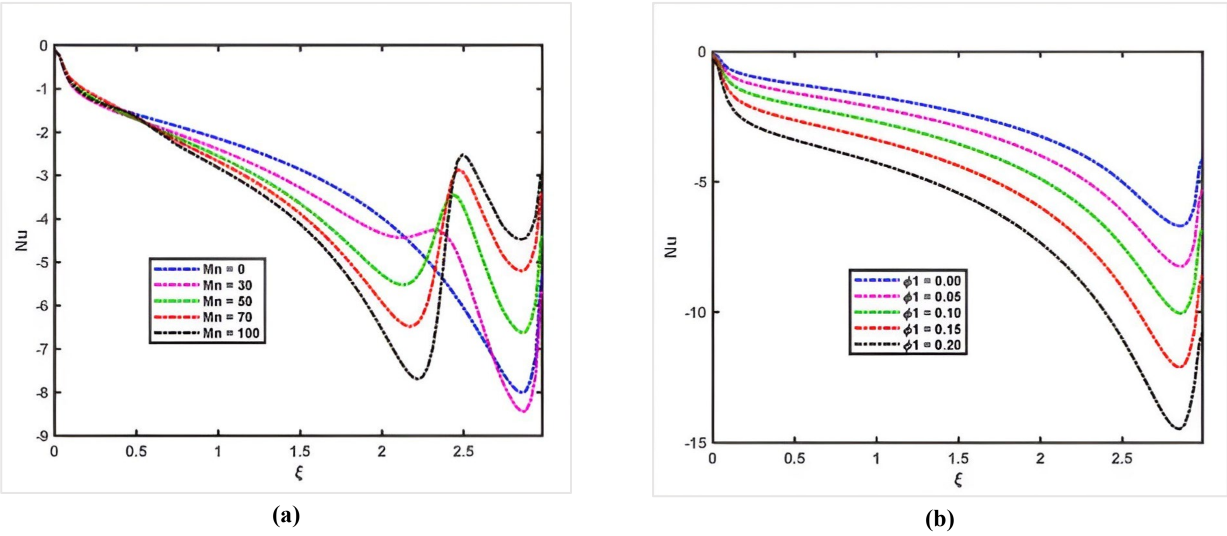


Figure 11: Dependence of Nusselt number with variation in (a) magnetic field, (b) nanoparticles concentration [71]

Numerical simulations, carried out by Halawa and Tanious [72], maximized the effect of the magnetic field on characteristics of heat transfer for Fe_3 O_4 magnetic nano-fluid. They evaluated that the N-N orientation of magnets positioned on the very top and bottom sides of the channel produced the best flow mixing and maximum Nu when compared to the S-S and N-S orientations. Up to a certain point, increasing the number of magnets resulted in an increase in Nu, output flow temperature, and pressure drop. The best magnet arrangement was achieved by aligning 10 pairs of magnets in N-N orientation. Under magnetic fields and orthogonal electrical, the flow of two immiscible fluids, electro-magneto-nanofluid and Newtonian fluid, was shown by Umavathi [73]. The equations were solved numerically by employing the finite difference method and the SOR method. They concluded that by increasing Gr, the energy and momentum in both zones were boosted. Increasing the Brinkman number accelerates the flow exclusively in the top part of the duct and increases the temperature curvature convexity. On the other hand, Alqahtani et al. [74], employed the Lattice Boltzmann method to investigate mixed, free numerically, and forced convection of nanofluid in a 2D rectangular enclosure. Under volumetric radiation, a magnetic field was applied to the container. They showed that an increase in radiation reduces the generated entropy but has no effect on the Bejan number. In the absence of radiation, entropy generation is greatest. Entropy generation decreases as enclosure height increases from 0.5 to 1, while total entropy generation increases as enclosure height increases.

Electric currents or magnetic materials can induce a vector field to change in space, providing a localized magnetic field. Applications of localized magnetic fields include quantum physics, magnetoencephalography, indoor localization, and the detection of magnetic anomalies. Ahmad et al. [75] numerically investigated the complex dynamics of a localized magnetic field using the one-phase model, examining its influence on the rotation of nanostructures and the formation of vortices within the tri-hybrid nanofluid flow regime (Figure 12).The spin of tri-hybrid nanoparticles, which induces the complex vortex structure in the flow regime, is found to be a product of the applied magnetic field. Finally, increasing the number of nanoparticles in the flow field raises Nu and CfRe, though the exact amounts and types of nanoparticles affected the results.

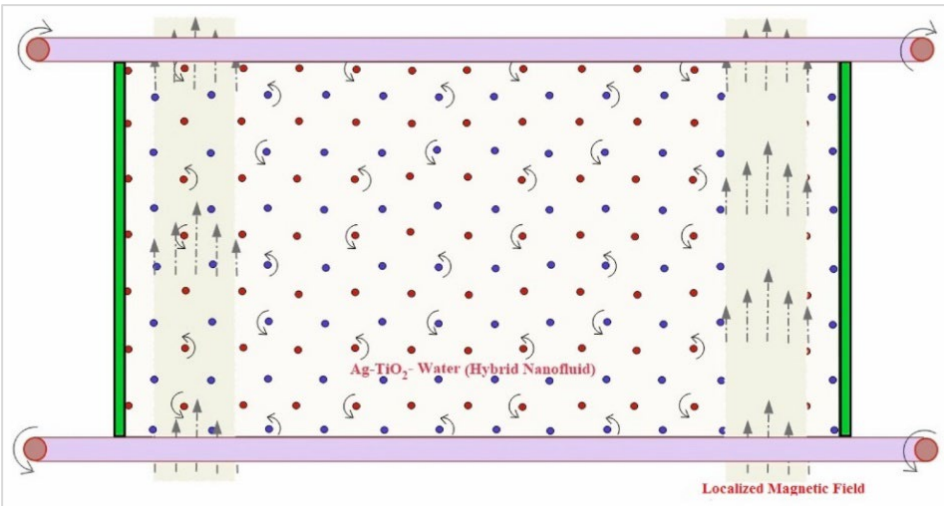


Figure 12: Physical diagram of the problem with straight arrows indicating the region of localization of magnetic field [75]

Because paraffin PCM has a low thermal conductivity, the researchers employed graphene oxide (high thermal conductivity) as a nanoparticle together with Fe_3O_4, the highest magnetic material on earth, in paraffin as a hybrid form. The design and construction of a new Stepped Solar Still (SSS) was carried out by Toosi et al., [76]. The SSS with PCM and hybrid NPCM were tested experimentally under an external magnetic field. When compared to lauric acid, palmitic acid, and sodium sulfate, paraffin as a latent heat storage system has a significant impact on the rate of SS productivity due to its acceptable melting point temperature, which is in the range of SS temperature. The use of this hybrid NPCM raised the SSS production rate by 75 Nanoparticles gather near the contact region of the tube due to the low thermal conductivity of the working fluid. Utilizing magnetic force enhances the convective heat transfer coefficient, diffusing the heat to the tube center, in which the thermal boundary layer gets disturbed, improving the fluid mixing and, in turn, leading to the augmentation of the convective heat transfer coefficient. The forced convection properties and friction factor of $CoFe_2O_4$-$BaTiO_3$/EG hybrid nanofluids flow in a tube with the presence of a magnetic field was investigated by Sundar and Ramana [77]. They concluded that thermal conductivity is increased by 7.76% and 16.8% at 1.0% vol. nanofluid and temperatures of 20 and 60 °C, respectively, as compared to the base fluid. As a magnetic field is applied, the Nusselt number of the nanofluid increases compared to when no magnetic field is applied. This study clearly shows that the Nusselt number of magnetic fluids increases with the influence of magnetic field and location.

3.2 Current carrying wire

Employment of the current carrying wire with the use of nanofluid has been applied from different perspectives. A solar thermal collector known as a parabolic trough has a mirror-lined interior and is straight in one dimension while curving in the other two like a parabola. One of the biggest obstacles to building and expanding parabolic trough solar thermal power plants is improving the collectors' thermal efficiency. Khosravi et al. [78], presented a numerical investigation using CFD to investigate the impact of magnetic field and ferrofluid on the performance of a PTSC with Fe sub 3 , O sub-4-Therminol66 ferrofluid as the working fluid. Furthermore, experiments were conducted both with and without a magnetic field, which was created using a current-carrying wire placed near the collecting tube. The highest performance was obtained with ferrofluid at 4 vol% in a magnetic field of 500 G, demonstrating the efficacy of both magnetic field and ferrofluid on collector performance. Researchers concluded that as the magnetic field intensity increases, it would boost the pressure drop within the system due to the occurrence of the mixing and disturbance in the hydrodynamic boundary layer. Additionally, increasing the ferrofluid viscosity would, in turn, increase the pressure drop, which is caused by the increase in the volume fraction. Bezaatpour and Rostamzadeh [50], came up with a novel and economical way to enhance the efficiency of an SFPC when operating in cold and windy conditions. The newly built collector had four rotary tubes and a magnetic field inducer to affect the nanofluid and save more energy. They concluded that a decline in the pressure drop occurred due to the use of the rotary tube as the rotation of the tube caused a non-zero velocity within the boundary, which in turn resulted in a lower fraction between the fluid flow and the tube surface. Moreover, the use of a magnetic field inducer and rotational pipes restored a maximum of 27.8% and 10.44% of the energy loss in the SFPC, respectively. Zhang et al. [79], investigated the performance of the PTSC (LS-3 solar collector) using a multiple-line dipole magnetic field and the Therminol®VP-1/Fe_3O_4 nanofluid. The magnetic field is created by cables carrying an electric current that is generated non-uniformly. They concluded that when a magnetic field is utilized, the boundary layer propagates, resulting in higher turbulent kinetic energy, and the tube's cross-sectional area experiences a secondary flow. Additionally, scientists proved that a disrupted flow with a relatively high-velocity area close to the current carrying-wire results from an uneven magnetic field. Dahmani et al. [80], examined the ferrofluid flow numerically in a PTSC absorber using a novel design for the current-carrying wire. The researchers investigated how the magnetic field impacts the hydro-thermal properties of ferrofluid flow. The periodic perturbation of the flow caused by the change in the direction of the Kelvin forces causes the spatial periodicity of the velocity profile for the periodic wire configuration scenarios. The influence of Mn decreases as Reynolds number increases due to an increase in inertial forces.

In the presence of magnetic fields, Cao et al. [81], examined the free convection of Fe_3O_4-water inside the porous enclosure. The FVM-based equations were solved using the SIMPLE algorithm technique (Figure 13). While the temperature of the outside wall remained constant, the interior wall was thought to be constantly moving. Two more walls act as thermal insulation and reflect radiation onto the inner semi-annulus. A coil that produces a magnetic field and carries electricity encircles the semi-annulus.

According to the data, the mean Nusselt number is directly related to concentration, magnetic number, and porosity. Conforming to the literature, the heat transfer enhancement of Fe_3O_4 ferrofluid, and flow characteristics of DT was investigated comprehensively by many researchers. Gürsoy et al. [82], analyzed the flow of a 1% ferrofluid under the influence of a magnetic field in a variety of conditions. More specifically, the forced convective heat transfer properties of Fe_3 O_4 ferrofluid running in smooth and dimpled tubes under a uniform magnetic field have been thoroughly examined. They showed that the maximum Nusselt number was obtained in both dimpled and smooth tubes at x/D = 20 magnetic field location and B = 0.3 T magnetic field condition. Alsarraf et al. [83], employed CFD to simulate an SFPC with a spiral absorber tube. A mixture model is employed to simulate MgO-MWCNT/Therminol VP-1 two-phase HN, and the RNG k-turbulence model is employed as the turbulent flow model. According to their findings, they evaluated that when nanoparticle concentration is 3% and Re = 24000, using a spiral absorber tube in an SFPC leads to a 121.11% increase in Nu compared to the SC with a basic absorber tube.

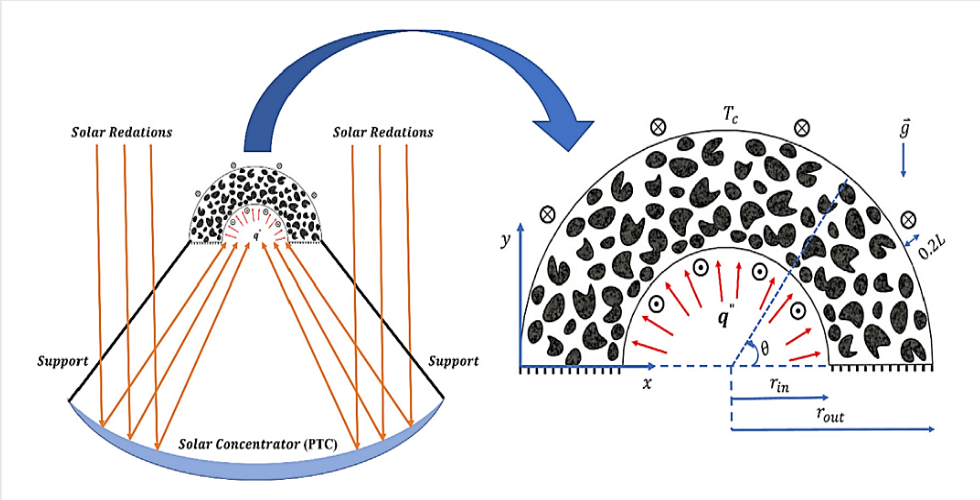
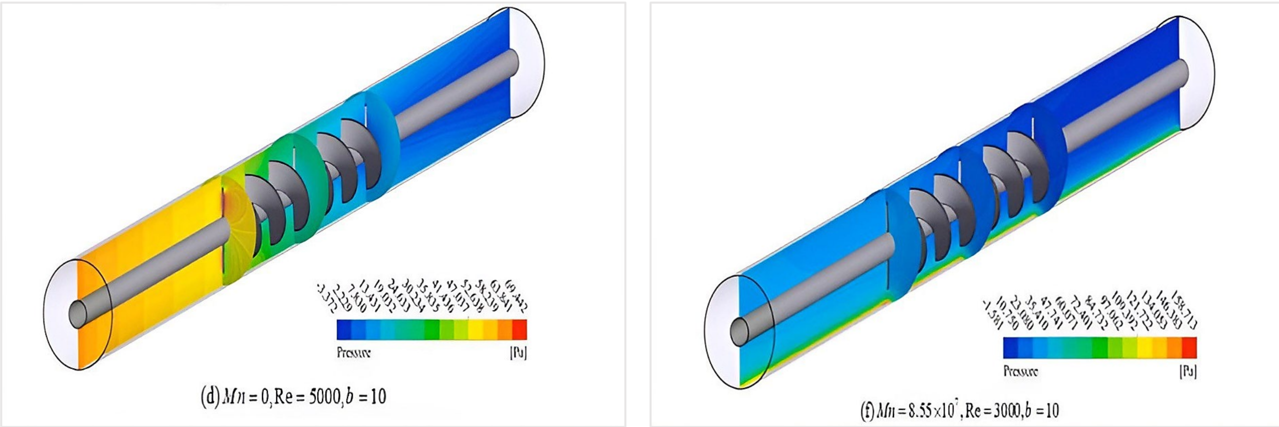


Figure 13: Physical and schematic model of the problem with boundary condition and magnetic coil [81]



(a) **(b)**

Figure 14: Pressure contours (a) without using magnetic field, (b) with applying magnetic field [84]

Gerdroodbary et al. [84], revealed the effect of varying MHD on the hydrothermal properties of a nanofluid-streamed screw heat exchanger as shown in Figure 14 (a and b) that displays the pressure contours of the screw HE without and with applying the magnetic field at different Reynolds number. A parallel wire is chosen as the source of the magnetic field for this reason. The FVM for controlling and coupling the pressure velocity is used to model the nanofluid within these exchangers. The results obtained are in good accord with the data from the experiments (Figure 15). According to their research, the skin friction of nanofluids increases at a rate far higher than the Reynolds number as the screw diameter increases. It was reported in previous articles that the working fluid thermal properties were controlled by the magnetic field using the magnetic properties of the magnetic NF, which was one of the easy ways to improve STEHP. Kim et al. [85], employed Fe_3O_4 NF will increase the working fluid STEHP in the deep receiver. Furthermore, the effects of various external magnetic fields on the temperature uniformity of Fe_3O_4 STEHP and NFs were explored experimentally. It was proved that the thermal conductivities of the Fe_3O_4 NFs were improved at all concentrations as compared to DI. Furthermore, good convective heat transfer within the working fluid enhances the receiver temperature uniformity, which can limit heat loss to the environment, hence improving the STEHP in the DASC. A literature summary of the researchers and their remarks on employing magnetic force and nanoparticles is shown in Table 3.

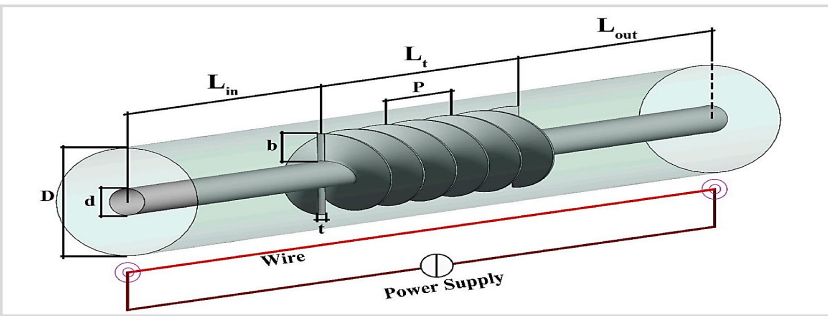


Figure 15: Screw heat exchanger in the presence of magnetic field [84]

Table 3: Literature summary of the researchers and their remarks by employing nanoparticles and magnetic field

Resch. Meth.	Base fluid	Nano particle	Concet.	Mag. field	Strength	Type of SC	Notable findings	Ref.
Exp.	DI	FeCu	0.001, 0.01, 0.1%	PM	-	-	Transient heat transmission is up to 34.6% better after Fe-Cu nanofluid is added.	[59]
Anal.	H_2O	Fe_3O_4 AG	0.5%	PM	0-30 mT	Heat exchange system	Comparing Fe_3O_4-H_2O-AG nanofluids to DI water, their Nu value is 50.2% greater.	[60]
Exp.	Oil	Fe_3O_4 @C	50-500 ppm	PM	-600-600	DASC	The greatest viscosity of the working fluid was lowered by 21% at a concentration of 500 ppm at 95 °C.	[61]
Exp.	H_2O	Mn-Zn Fe_2O_4	0-0.5%	PM	0.02-1 T	SEETSC	Max improvements in thermal efficiency are 47.0%, and Nu boosts are 73.0% for the 0.5 vol% ferrofluid, respectively.	[62]
Num.	H_2O	Fe_3O_4	1-5 %	PM	0.01-0.09T	Rect. tube	When the magnetic field is perpendicular to the flow direction, there is an 8% rise in thermal performance.	[63]
Exp.	H_2O, EG	CoZn Fe_2O_4	0.2%	PM	750G	KD2-pro	A 2.64% rise was observed in the CHT coefficient when subjected to a 750 G magnetic field.	[64]
Exp.	H_2O	Fe_3O_4	2%	PM	-	SFPC	Energy efficiency increases by 22.8% and exergy efficiency by 8.5%.	[65]
Exp. & Num.	H_2O	ZnO	0.1-10%	PM	100-200 Oe	SFPC	The heating-generating power of magnetic nanoparticles is affected by magnetic field and frequency.	[66]
Exp.	H_2O	Mn-Zn Fe_2O_4	0-0.8%	PM	0-1 T	SFPC	As a magnetic field is applied, the collector efficiency can be increased by up to 52.15 % as compared to water alone.	[67]
Exp.& Num.	H_2O	Fe_3O_4	0-3%	HC	0-1.44 T	-	When subjected to positive or negative magnetic fields, the solid phase fraction and energy release of the cavity were found to be 29.2%, 19.23%, 4.6%, and 3.88% higher or lower, respectively, compared to paraffin.	[68]
Num.	H_2O	Al_2O_3	2.5-5%	PM	-	Tube	The melting process is enhanced when the magnetic field intensity is increased by around 16-57%.	[69]
Num.	H_2O	Ag, MgO	0-0.02%	PM	-	-	The average skin friction parameter decreases by about 50% as the number of wall waves increases.	[70]
Num.	H_2O	Ag, TiO_2	0-0.2%	PM	0-200 G	-	Along the bottom horizontal wall, Nu increases due to the Re. However, Nu takes on a zigzag pattern when the magnetic parameter is added.	[71]
Num.	H_2O	Fe_3O_4	0-3%	PM	0-1200 G	Rectangular channel	Compared to the design without the magnetic field, the average Nu increases from 16.44% to 24.46%.	[72]
Num.	W/Oil/ Blood	CuO, Al_2O_3, GO	0-0.1%	PM	-	-	The volumetric flow rate is reduced when nanoparticles and a magnetic field are present, but it is amplified when electric field, Gr, and Brinkman factors are considered.	[73]
Num.	H_2O	-	-	PM	-	Enclosure	Entropy generation in the enclosure was reduced as the Ha rose, particularly at higher heights, and BE dropped as the enclosure height increased.	[74]
Num.	H_2O	Ag Al_2O_3, TiO_2	0-0.2%	PM	$0 < Mn < 700$	-	A 99% rise in the (Nu) and a 46% increase in local skin friction (CfRe) are possible outcomes of a stronger magnetic field.	[75]
Exp.	H_2O	Fe_3O_4, GO	-	PM	-	SSS	The SSS output rate was increased by 75% when this hybrid NPCM was used.	[76]
Exp.	EG	Co Fe_2O_4 Ba TiO_3	0-1%	PM	0-4000G	-	When a magnetic field is present, Nu increases by around 72.33% and 68.95 %, respectively.	[77]

Table 3: Continued

Resch. Meth.	Base fluid	Nano particle	Concet.	Mag. field	Strength	Type of SC	Notable findings	Ref.
Num.	H_2O	Fe_3O_4Therminol 66	1-4%	CCW	0-500G	PTSC		[78]
Num.	H_2O	Fe_3O_4 Cu	2%	inducer	0-0.1 T	SFPC	In this comparison, there was a significant increase of 101% and 24% in the (PEC).	[50]
Anal.	H_2O	Fe_3O_4	0-0.04%	MLD	0-100G	PTSC	Adding Fe_3O_4 nanoparticles to Therminol® VP-1 will improve heat transfer and decrease exergy destruction.	[79]
Num.	H_2O	Fe_3O_4/Therminol 66	4%	CCW	-	PTSC	An irregular magnetic field causes a disrupted flow, with a fast-moving area close to the wire carrying the current.	[80]
Num.	H_2O	Fe_3O_4	0-0.03%	CCW	$0 < Mn < 8 * 10^7$	semi-annulus enclosure	Nu was improved by 32% when the volume fraction was increased from 0.01 to 0.03 in the high magnetic number.	[81]
Exp.	H_2O	Fe_3O_4	0.1%	CCW	0-0.3 T	Dimpled tube	A substantial 33.54% gain was determined for the dimpled tube's Performance Evaluation Criteria.	[82]
Num.	H_2O	MgO-MWCNT	0-3%	CCW	-	SFPC	Increasing Re from 9000 to 24,000 improves exergy efficiency by 36.14%	[83]
Num.	H_2O	Fe_3O_4	4%	CCW	-	Screw HE	The skin friction of nanofluids, caused by an increase in screw diameter, is significantly more than Re.	[84]
Exp.	H_2O	Fe_3O_4	0.05-0.1%	CCW	500G	DASC	When contrasted with DI-water, the STEHE that made use of an external dynamic magnetic field rose by 119.6 %	[85]

4. Conclusion

The primary objective of the present review is to accumulate, discuss, and summarize the recent available research involving different types of nanoparticles and their effect on the working fluid as well as the thermal performance of solar collectors. In addition, magnetic field effect on the ferrofluids had been discussed for both types of applications as permanent magnet and current carrying wire. The following findings have been drawn from the studies:

1) According to the studies within the literature, applying an external magnetic field to ferrofluids enhances their thermal conductivity, and increasing the magnetic field improves the ferrofluid's thermal performance efficiency by up to 55%. Moreover, based on the literature review, increasing the magnetic field to a certain limit will increase the pressure drop that would reach 1.87 kPa in different systems. While on the other hand, utilizing hybrid nanoparticles like $MWCNT/Al_2O_3$, in particular, systems increase the thermal efficiency by up to 30%.
2) The size and volume fraction of the nanoparticles have a direct effect on the thermal performance of the ferrofluid, as raising the volume percentage between 0.1-3% increases the thermal conductivity of the circulating fluid, which improves the thermal performance of the solar system. Nevertheless, increasing nanoparticle concentration prior to 3% in different cases will have an unfavorable influence on the thermal conductivity of the nanofluid due to an increase in fluid viscosity.
3) Compared to working fluids composed of single nanofluids, hybrid nanofluids such as (Al_2O_3Cu), ($Al_2O_3TiO_2$), and (ZrO_2SiC) etc. demonstrated superior thermal performance, as in many studies, the latter one enhances energetic efficiency by 2.59%. Noteworthy is that hybrid nanofluids were chosen for their ability to reduce production costs, increase collector thermal efficiency, and avoid the agglomeration of nanofluids.
4) Researchers substantiate that applying a magnetic field highly affects the thermal efficiency of the systems, as magnetic force leads to the augmentation of the convection heat transfer coefficient. On the other hand, increasing the former would lead to the incrimination of the pressure drop within the system, as the hydrodynamic boundary layer is disturbed, which would eventually negatively impact the thermal efficiency.
5) Additionally, nanofluids have a few disadvantages, the most noticeable of which are the agglomeration and cost associated with nanoparticles. Nevertheless, nanofluids have greater heat transfer capacities and many possible research destinations. Therefore, despite these drawbacks, they are one of the most explored subjects in the present literature.

List of Abbreviations

CCW	Current carrying wire	**NF**	Nanofluid
CFD	Computational fluid dynamic	**NPCM**	Nanoparticle phase change material
CNTs	Carbon nanotubes	**PCM**	Phase change material
DASCs	Direct absorb solar collectors	**PM**	Permanent magnet
DI	Distilled water	**PTSC**	Parabolic trough solar collector
GAHP	Gravity-assisted heat pipe	**PW**	Paraffin wax
GNPs	Graphene nanoplatelets	**RBF- BP**	Radial basis function- Backpropagation
HN	Hybrid nanofluid	**SSAs**	Specific surface areas
MNF	Magnetic nanofluid	**SOR**	Southwell over relaxation
MSP	Melting solidification process	**SPESS**	Solar power energy systems
MWCNTs	Multi-wall carbon nanotubes	**TAC**	Total annual cost
NEPCM	Nanoparticle-enhanced phase change material	**VAS**	Nanofluid-based volumetric absorption system

Author contributions

Conceptualization, **N. Dawood**, **J. Jalil** and **S. Faraj**; data curation, **N. Dawood**; formal analysis, **N. Dawood**; investigation, **N. Dawood**; methodology, **N. Dawood**; project administration, **N. Dawood**, resources, **N. Dawood**; software, **N. Dawood**; supervision, **J. Jalil**, and **S. Faraj**; validation, **N. Dawood**; visualization, **N. Dawood**; writing—original draft preparation, **N. Dawood**; writing—review and editing, **J. Jalil**, **S. Faraj**, and **N. Dawood**. All authors have read and agreed to the published version of the manuscript.

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

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