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Review Article

The role of hybrid nanofluids in optimizing parabolic trough concentrator performance: A comprehensive review

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ABSTRACT

This review evaluates the potential of hybrid nanofluids to enhance the efficacy of PTCs, which are a critical component of solar thermal systems. The study aims to critically evaluate the efficacy of hybrid nanofluids, developed by integrating two or more nanoparticles within a base fluid, to enhance the thermal efficiency and heat transfer properties of PTC systems. The purpose is to inspect augmentation in HNF formulations, assess their thermophysical characteristics, and evaluate experimental and computational research of their utilization in PTCs. The fundamental issues that must be determined are stability, compatibility with heat transfer systems, and economic efficiency. This review integrates latest findings to explain the advantages and disadvantages of hybrid nanofluids, recognizes existing research shortcomings, and recommended prospective routes for their inclusion into solar energy technologies. The Al_2O_3-MWCNT/H_2O hybrid nanofluid with a volume fraction of 0.04% provides the ultimate thermal efficiency enhancement, which is 197.1%. Maximum enhancement in Nusselt number is 14% using Cu-Mgo/water hybrid nanofluid at a 2% volume fraction. It is also noted that the exergy efficiency increases by 71.255% when using Al_2O_3-WO3/Therminol VP1hybrisd nanofluid at a volume fraction of 4%. The originality of this research dwells in its detailed examination of hybrid nanofluids particularly designed for PTC applications, filling a void in the existing literature by proposing a integrated framework for grasping and utilizing their advantages. The results highlight the transformative potential of hybrid nanofluids in enhancing solar thermal technology and delineate future research avenues for optimizing their implementation in practical systems.

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INTRODUCTION

The world is tackling an incomparable energy calamity, impelled by the growing requirement for energy and the declining supplies of fossil fuels. Fossil fuels, such as coal, oil, and natural gas, have been the main sources of energy for the last hundred years. They power homes, businesses, and transportation [1]. But their extensive utilization has had solemn consequences on the environment, like higher

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emissions of carbon, climate change, and air pollution. These are now major global issues. As fossil fuel reserves dwindle and environmental degradation escalates, a coordinated global initiative has emerged to shift towards more sustainable, clean and renewable energy sources [2]. Solar, wind, and hydroelectric power are some of the most promising alternatives to fossil fuels. Solar energy is especially promising because it is widely available and has little effect on the environment [3]. Figure 1 illustrates the shift from fossil fuels to renewable energy sources.

Solar energy is a massive, unused resource that can be utilized to produce electricity, heat, and cool things down. It arrives straightaway from the sun's radiation, which is a renewable and infinite source of energy that can be transformed into usable forms with technologies such as photovoltaic (PV) panels and concentrated solar power (CSP) systems [4]. CSP systems, which use mirrors or lenses to focus sunlight onto a receiver, have acquired plenty of concentrations because they can produce huge amount of electricity, even in places where there is plenty of direct sunlight. Construct a solar thermal systems perform superior, CSP technologies such as PTCs, dish-stirling systems, and central tower receivers have been implemented to augment the system's capacity to absorb heat [5].

A PTC is a highly efficient solar thermal system widely used in CSP plants for electricity generation, industrial heating, and desalination [6]. The various application of PTC is shown in Figure 2. It utilizes a parabolic shaped reflector, which is normally comprised of polished aluminum, concentrate sunlight onto a linear receiver tube that is positioned at the focal line. The shape of the reflector ensures that entering solar radiation is concentrated the receiver tube. The tube is layered with a specific absorber coating that augments energy absorption and reduces heat loss through infrared radiation. For minimizing convective losses furthermore, the receiver tube is bounded by a glass envelope with a vacuum layer to maintain the heat inside. A heat transfer fluid (HTF), like synthetic oil, molten salt or pressurized water, moves through the receiver tube to gather the concentrated heat. This heat goes to a heat exchanger, where it can be used to make steam that runs turbines in a Rankine cycle [7].

The system proceeds the sun's path all day utilizing a single-axis tracking system. This ensures the reflector in the optimal site and the optical efficiency highest, which is normally between 60% and 75%. PTCs are designed to operate at temperatures between 300°C and 400°C and can acquire as high as 80 times more concentrated. This allows them to achieve the high thermal performance required for extensive energy applications. The concentration ratio, which is the ratio of the aperture area to the cross-sectional area of the absorber, directly affects how well the system works and how hot it gets [8].

PTCs have many benefits, like being able to grow and work well in areas with a lot of radiation, but there are still problems to solve. These include high capital costs because mirrors, tracking systems, and receiver coatings need to be very precise. They are also sensitive to optical alignment and work less well in diffuse sunlight [9]. Research is focused on making receiver materials better, making HTFs that are more thermally stable, and making it easier for TES systems to work together so they can run all the time. Regardless of these challenges PTCs are a firmly established and dependable technology that is essential for policies to utilize more renewable energy and for planetary exertions minimize greenhouse gas emissions [10].

Figure 1. Transition from fossil fuels to renewable energy sources.

Nanotechnology has opened up new ways to improve the performance of HTFs in the last few years. This has led to the creation of nanofluids. Nanofluids are made by mixing nanoparticles (usually less than 100 nm in size) with a base fluid. These nanoparticles usually made from materials like metals, metal oxides, or carbon nanotubes, significantly improve the thermal properties of the base fluid [11]. Different types of nanomaterials used to enhance the performance of PTC are shown in Figure 3 [12]. Nanofluids can substantially boost the efficiency of heat exchange in systems such as PTCs by augmenting the thermal conductivity and heat transfer coefficients. Even so, single nanoparticle suspensions frequently indicate constraints concerning stability, enhancement of thermal conductivity, and overall efficiency at higher concentrations [13].

Figure 2. Various applications of PTCs.

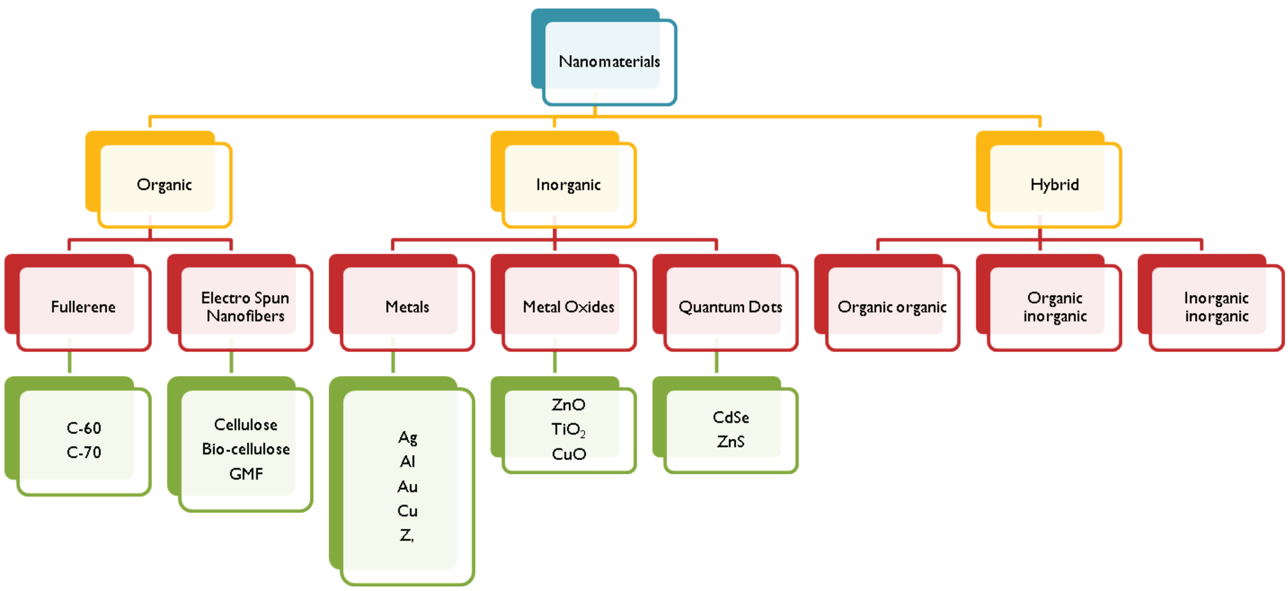

Figure 3. Different types of nanomaterials used to enhance the performance of PTC.

Hybrid nanofluids have come up as a new way to deal with these problems. Hybrid nanofluids are a type of nanofluid that mixes two or more types of nanoparticles into a base fluid. This makes them even better at conducting heat and staying stable than regular nanofluids [14]. Various nanoparticles performing together in hybrid nanofluids can enhance heat transfer, fluid flow, and efficiency of energy conversion. This renders them excellent for high effectiveness utilizations like PTCs in solar thermal power generation. In comparison with fluids comprised of only one type of nanoparticle, hybrid nanofluids might possess enhanced heat transfer properties, fewer heat loss, and more stable heat transfer behaviour over time [15].

Hybrid nanofluids have numerous possibilities to build PTCs perform better, but there are still plenty of hurdles that need to be resolved. These incorporate the optimization of nanoparticle amalgamations, the stability and dispersion of nanoparticles within the base fluid, the impact of various operational situations on performance, and the long-term resilience of hybrid nanofluids in practical applications [16]. Additionally, the facility of reliable testing methodologies and execution models for hybrid nanofluids in parabolic trough systems persists to be a subject of active research. Table 1 shows a summary of review articles that have already been published about using nanofluid in PTC. Figure 4 shows how many research articles have been published on the subject according to the Scopus database.

While several reviews have focused on the role of nanofluids in thermal PTC systems which are shown in Table 1 and a lot of research has been performed on the utilization of nanofluid in PTC, there is a lack of a comprehensive review dedicated to hybrid nanofluids specifically for PTC applications. Key research gaps include:

- Most reviews concentrate on single-component nanofluids, with insufficient discussion on the synergistic effects of hybrid nanofluids in PTC systems.
- There is limited assessment of the optimization methods for hybrid nanofluids, such as nanoparticle selection, stability enhancement, and process parameters.
- A relative analysis of hybrid nanofluids versus traditional nanofluids in PTC applications is missing
- Research often ignores the economic and long-term operational viability of hybrid nanofluids for commercial-scale PTC systems.
- Existing literature does not adequately capture or analyze the temporal trends in the use of hybrid nanofluids for PTC systems.

The goal of this review article is to give a full look at how hybrid nanofluids can improve the performance of parabolic trough concentrators. It will explicitly analyze emerging utilization for hybrid nanofluids, their thermal and flow characteristics, and how they can improve the performance of solar thermal system. The primary aim of this review is to sequentially examine the current innovation in hybrid nanofluid research and their utilization in PTCs. The benefits and limitation of utilizing HNF in solar PTC is also discussed. This review will also look at the different ways to make hybrid nanofluids more stable and easier to spread, which are two of the biggest problems that need to be solved before they can be used widely in business. This review is new because it focuses on how to use hybrid nanofluids in parabolic trough concentrators. Large scale solar power generation has got more attention, but its performance can still be enhanced by utilizing modern nanofluids in an optimal way. This article aims to contribute to the ongoing development of hybrid nanofluids as a key technology for improving the efficiency and performance of solar thermal power

Table 1. Summary of previously published review articles on the utilization of nanofluid in PTC

Ref. no.	Type of nanofluid	Summary of review
[17], 2018	Mononanofluid	The purpose of the study is to assess the techniques for improving thermal efficiency in PTCs.
[18], 2019	Mono nanofluid	Numerous parameters, including the kind of base fluid, nanoparticles, volume fraction, and nanoparticle size, have been studied about PTC effectiveness.
[19], 2020	Mono nanofluid	A review of the various HTFs utilized to improve the PTC's thermal efficiency and storage capacity is conducted.
[20], 2021	Hybrid nanofluid	Using hybrid nanofluid, previous and present research on PTC has been evaluated.
[21], 2022	Mono/Hybrid nanofluid	A thorough descriptive evaluation of the uses of mono/hybrid nanofluids in solar thermal collectors with those of other fluids is provided.
[22], 2022	Mono nanofluid	Examines nanofluids in 100–300 °C parabolic-through systems.
[23], 2022	Mono nanofluid	The most effective way to enhance PTC effectiveness is to combine turbulators with nanofluids.
[24], 2022	Nanofluid, nano-PCM	The impact of PCM and nano-PCM on the solar PTC's thermal efficiency was examined.
[25], 2023	Mono/Hybrid nanofluid	The purpose of this paper is to examine how increasing PTC performance is influenced by mono and hybrid nanofluid flowing with various turbulence promotors.
[26], 2023	Mono nanofluid	The use of nanofluid in solar PTC results in economic, environmental, and energy savings.
[27], 2023	Hybrid nanofluid	The investigation shows that using hybrid nanofluids as HT inside the absorber tube of the PTC can enhance its thermal and optical characteristics.

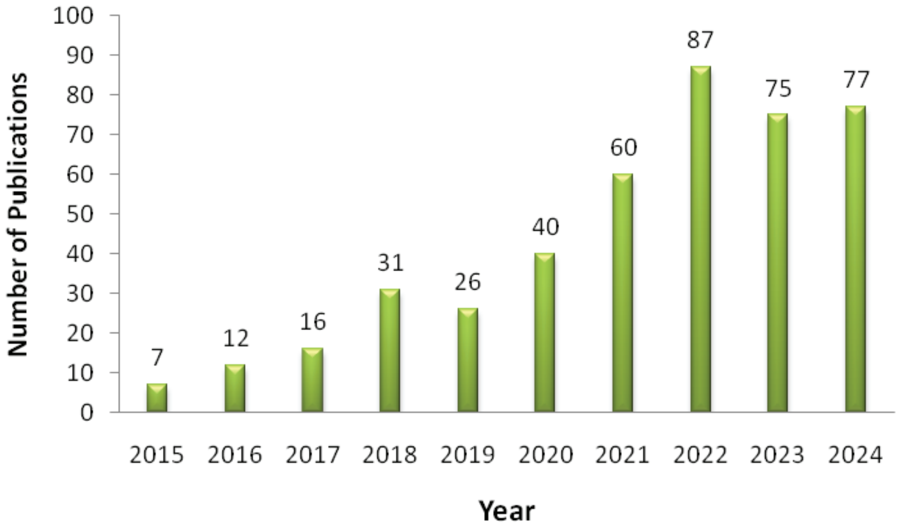

Figure 4. Research articles published on the application of nanofluid in PTC as per the Scopus database.

systems by providing an in-depth analysis of the current state of the art and identifying potential areas for future research.

Hybrid Nanofluid: Preparation, Stability and Thermophysical Properties

Hybrid nanofluids are advanced thermal fluids made by mixing two or more types of nanoparticles with a regular base fluid like water, ethylene glycol, or oil. The different base fluid and nanoparticles used in the preparation of hybrid nanofluid is shown in Figure 5. This new method uses the unique thermal, electrical, and mechanical properties of different nanoparticles, like metals, metal oxides, carbon-based materials, or ceramics, to make nanofluids that work better than traditional single-component

Figure 5. Different base fluid and nanoparticles used in the preparation of hybrid nanofluid.

nanofluids [28]. Hybrid nanofluids are mainly fascinating since they have superior thermal conductivity, enhanced heat transfer rates, and better stability. Mixing distinct kind of nanoparticles collectively can induce properties that are outstanding for ensured utilization, such as electronic cooling, car engines, solar thermal systems, and industrial heat exchangers. A hybrid nanofluid composed of graphene oxide and Al_2O_3, for example, has the high thermal conductivity of graphene and the high stability of Al_2O_3 in dispersion [29]. Also, optimizing the size, shape, concentration, and surface functionalization of the particles is very important for reducing agglomeration and improving the performance of hybrid nanofluids. Their adaptability includes renewable energy systems, where they improve the performance of solar collectors and geothermal systems by absorbing and transferring energy better [30]. The various base fluids and nanoparticles used in the formation of hybrid nanofluid are illustrated in Figure 5. Yet, there are challenges to resolve, though, like enhancing production costs, long-term stability problem, and the feasible health and environmental impact of nanoparticles. Even with these challenges, research is still being performed to produce hybrid nanofluids work effectively, cost minimum, and elevate for the environment. This creates them a better option for cutting edge heat transfer technologies [31].

Preparation of Hybrid Nanofluid

Single-step technique

The single-step method for making nanofluids combines the making and spreading of nanoparticles into a base fluid at the same time. This means that separate nanoparticle synthesis and spreading are no longer necessary. This method usually uses chemical vapor condensation (CVC) or physical vapor condensation (PVC), and it often uses a cooling medium to keep the nanoparticles in the fluid [32]. The single-step method's main benefit is that it reduces the amount of particle agglomeration, which makes the nanofluid more stable and even. Also, by holding the nanoparticles unbroken, it reduces the hazard of pollution and enhances the thermal properties of the produced nanofluid. Albeit this technique has these advantages, it may have obstacles with scalability and compatibility with some base fluids, subject to how it is produced [33,34].

Two-step technique

The two-step method is a popular way to make hybrid nanofluids because it is easy and cheap. A extensive depiction of the two-step method for hybrid nanofluid production is illustrated in Figure 6. There are two important steps to this method: first, creating nanoparticles, and then extending them out in a base fluid. In the first step, chemical, physical, or mechanical techniques are used to produce particular nanoparticles, such as metal oxides, carbon-based materials, or metallic compounds. The next step is to stir these pre-assembled nanoparticles into a base fluid, such as water, ethylene glycol, or oil, to make the hybrid nanofluid [35,36]. At this stage, surfactants or ultrasonication are usually used to ensure that the particles are uniformly disperse and do not adhere collectively, leading to the fluid more stable. This technique permits you select and mix distinct nanoparticles to alter the thermal and rheological characteristics of the hybrid nanofluid for assured use [37,38].

The two-step technique for producing hybrid nanofluids is outperforming the one-step technique since it provides you more control over how nanoparticles disperse. This process produces nanoparticles first and then mixes them with a base fluid to ensure they are uniformly and stably scattered. This enhances the thermal properties and stops agglomeration, which is a complication with the one-step method.

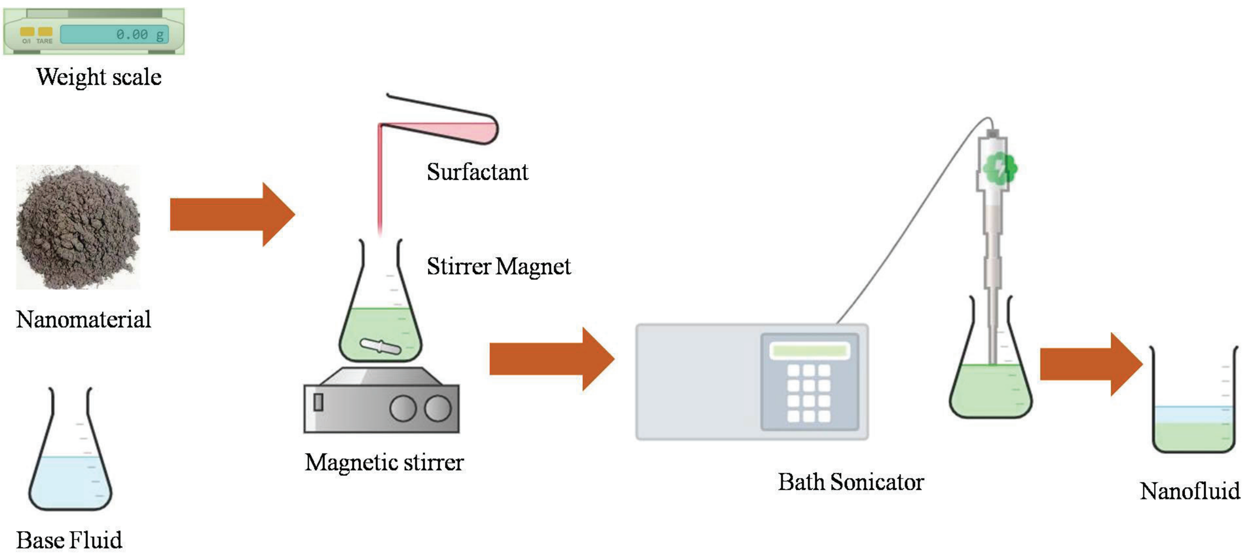

Figure 6. Two-step method for the preparation of hybrid nanofluid.

Stability of Hybrid Nanofluid

For hybrid nanofluids to perform better in applications such as heat transfer, energy systems, and biomedical uses, they must be stable. Stability refers that nanoparticles to remain uniformly distributed in the base fluid over time, without settling, clumping collectively, or generating clusters [39]. The stability of hybrid nanofluids is influenced by the type and size of the nanoparticles, the properties of the base fluid, the amount of nanoparticles, and the utilization of surfactants or stabilizing agents. Miniature nanoparticles with uniform shapes usually make things more stable since they do not adjust so much [40]. The pH of the nanofluid is also very significant since it alters the surface charge of the nanoparticles, which retain them from adhering collectively by including electrostatic repulsion. Ultrasonication and the utilization of emulsifiers are other technique that enhances stability by splitting up agglomerates and making particles disperse better [41]. If you enhance these factors properly, hybrid nanofluids will be more stable with time and work better with regard to thermal and rheological properties. The distinct methods to enhance the stability of hybrid nanofluid are illustrated in Figure 7.

Asadi et al. [42] conducted a DLS test to examine the stability of CuO – TiO_2/H_2Ohybrid nanofluid. Through the DLS test, the average diameter of the nanoparticles in relation to the laser beam intensity can be determined. The larger particles therefore diffract more intensely. The test findings indicate that the particles' nano-dimensions are present in the base fluid and that agglomeration has not taken place. The particles' maximum mean diameter is around 43 nm.Siddiqui et al. [43] conducted an investigation on the dispersion stability of the Cu-Al_2O_3 hybrid nanofluid for a range of mixing ratios 0.3: 0.7According to their findings, a mixing ratio greater than 0.5:0.5 causes quick settling because of its elevated settled velocity. For mixing ratios under 0.5:0.5, stability is less reliant on zeta potential.

Thermophysical Properties of Hybrid Nanofluid

The thermophysical properties of hybrid nanofluids are essential in settling their efficacy and relevance for various heat transfer systems. Thermal conductivity is the key of these properties since it has a direct impact on how effectively heat transfers through a material [44]. Adding more than one type of nanoparticle with different thermal properties greatly improves the thermal conductivity compared to regular nanofluids. This improvement is due to the combined nanoparticles working together in a way that different thermal transport mechanisms, like phonon scattering and electron transfer, work together [45]. Yet to enhance this, you must attentively optimize things such as the concentration, size, shape, and dispersion of the nanoparticles. An optimal balance ensures that the

Figure 7. Techniques to improve the stability of hybrid nanofluid.

thermal performance is at its best without aching other properties such as viscosity, density, specific heat, and stability [46].

To fully utilize hybrid nanofluids in practical uses, these thermophysical properties must be optimized collectively. For example, hybrid nanofluids with superior thermal conductivity and reduce viscosity can develop solar thermal systems excellent at absorbing heat and transforming it into energy [47]. Stable hybrid nanofluids make sure that industrial cooling or electronic cooling systems work well even when the temperature is high. Recent improvements in computational modeling and experimental methods make it possible to accurately measure these properties. This lets researchers customize hybrid nanofluids for certain applications [48]. The ongoing development of hybrid nanofluids continues to address challenges like economic feasibility and environmental impact, driving their adoption across diverse industries. Consequently, the investigation of their thermophysical properties continues to be a vibrant and consequential field of study, offering the potential for substantial progress in heat transfer technology [49]. Figure 8 shows the different factors that affect the thermophysical properties of the hybrid nanofluid.

Thermal Conductivity

The thermal conductivity of HNF is a critical factor that influences how efficiently they can transmit heat. It is investigated by different parameters mutually depends on each other. When metallic nanoparticles like Cu, Ag, or Al_2O_3 are mixed with carbon-based materials like graphene or CNTs, they can work together to improve thermal conductivity because their thermal properties work well together. [50]. The nanoparticles concentration is crucial due to intensified concentrations often make thermal conductivity exceptional by developing multiple paths for heat to transfer through. Yet, excessive loading can produce the viscosity higher and lead to particles to stick collectively, which reduce efficiency [51]. The heat conduction of nanoparticles also depends upon its size and shape. Another important parameter is temperature. Higher temperatures make nanoparticles accelerate and with more kinetic energy, which facilitates disperse thermal energy [52]. The stability of nanoparticles in the fluid has a significant impact on thermal conductivity. A stable distribution ensures that heat is transmitted evenly, while aggregation reduces performance [53].

Other aspects that can influence the nanoparticles' thermal conductivity, the resistance between nanoparticles and the base fluid, and process to produce. The dispersion stability of nanofluid is enhanced by ultrasonication and surfactant. The thermal conductivity of HNF also depends upon different parameters such as r specific heat capacity, density, and viscosity, which all affect convective heat transfer rate [54]. Due to enhancement in these properties, HNFs can acquire their full potential for

Figure 8. Variables influencing thermophysical properties of hybrid nanofluid.

Table 2. Thermal conductivity of hybrid nanofluid

Ref. no.	Hybrid nanofluid	Volume fraction	Enhancement in thermal conductivity
[55]	F-MWCNTs–Fe_3O_4/EG	0 % to 2.3%	30% at 50°C and 2.3% vol. fraction
[56]	Cu-Ag/Ar	-	69.72% at 50% Cu-Ag
[57]	Zn – Fe_2O_4 /H_2O	0.5%	11.8% at 80°C
[58]	MWCNT – Cu/H_2O	0.05% to 0.6%	30.38% at 50°C and 0.6% vol. fraction
[59]	TiO_2 -CNTs/ H_2O	0.1% to 0.2%	20.5% at 25° C
[60]	CNT-SiO_2/Water	0.1% to 1%	26.29% at 1% Vol. fraction

thermal conductivity, leading to them useful for cooling systems, heat exchangers, and energy storage. Research and innovations are still examining the ideal integrations and conditions for augmenting thermal performance. Table 2 shows how different hybrid nanofluids have better thermal conductivity.

Viscosity

The viscosity of hybrid nanofluids is an important factor that affects how they flow and how well they transfer heat. The type, size, shape, and concentration of the nanoparticles used all play a role. Higher concentrations of nanoparticles usually make thermal conductivity better, but they can also make viscosity worse, which means that pumping requires more energy [61]. The interaction between different types of nanoparticles in hybrid nanofluids makes things more complicated because their combined effects can either make viscosity changes worse or better. The viscosity is also greatly affected by the properties of the base fluid and the quality of the dispersion of the nanoparticles [62]. Using surfactants and functionalizing the surface are two examples of proper stabilization techniques that help keep the dispersion even and stop agglomeration, which can make the viscosity go up. Temperature also affects the viscosity of HNFs since with increment in temperature viscosity reduces. To take full advantage of HNFs in real life applications, it is essential to determine the proper balance between superior thermal conductivity and viscosity that is operationally simple [63]. Table 3 shows a summary of the most recent research on the viscosity of hybrid nanofluid.

Specific Heat

The specific heat capacity of hybrid nanofluids, which is an important property for storing energy and moving heat, depends on the kind and amount of nanoparticles and how they interact with the base fluid. The addition of nanoparticles usually lowers the specific heat capacity of a hybrid nanofluid because most nanoparticles have a lower specific heat than base fluids like water or ethylene glycol [69]. But the amount of nanoparticles used and their type will affect how much the reduction happens. Hybrid nanofluids, which mix distinct kind of nanoparticles, may observe the optimal balance by using the distinct thermal properties of the nanoparticles to their benefit and mitigating the adverse effect on specific heat [70]. Innovative stabilization methods also ensure that nanoparticles are uniformly distributed, that maintains the thermal behaviour reliable. The reduction in specific heat seems to inferior, but it is generally equalized by the significant enhancement in thermal conductivity, which causes hybrid nanofluids superior at transferring heat in various situations [71]. The current research on specific heat of hybrid nanofluid is summarized in Table 4.

Table 3. Current research on the viscosity of hybrid nanofluid

Ref. no.	Hybrid nanofluid	Volume fraction	Enhancement in viscosity
[64]	CeO_2-Cu/H_2O, Al_2O_3-Cu/ H_2O, TiO_2-Cu/ H_2O, SiO_2-Cu/ H_2O	0.5% to 3%	58.8% at 3% vol. fraction for CeO_2-Cu/H_2O
[65]	ZnO-MWCNTs/engine oil	0.125% to 1%	45%
[42]	CuO-TiO_2/water	0.1% to 1%	Maximum viscosity is 1.74 mPa·s. at 1% vol. fraction and 25° C
[66]	MgO-MWCNTs/H_2O and EG	0.025% to 0.8%	43.47%
[67]	SiO_2- graphite/Water	0% to 2 %	36.12% at 3% vol. fraction and 15° C
[68]	MWCNTs- SiO_2/20W50	0.05% to 1%	171%

Table 4. Current research on the specific heat of hybrid nanofluid

Ref. no.	Hybrid nanofluid	Volume fraction	Decrement in specific heat (Cp)
[72]	CuO + MWCNT, MgO + MWCNT, and SnO_2 + MWCNT (80 to 20weight mixture ratio) and DI water base fluid	0.25% to 1.5%	Maximum 15.09% for MGO-MWCNT/DI water at 1.5 vol. fraction and 25° C
[73]	Al_2O_3 - ZnO/water	0.33% to 1.67%	30.12%
[74]	Aqueous graphene oxide - Al_2O_3	0.05% to 2%	7% at 2% vol. fraction and 20° C
[75]	Al_2O_3 – Si_2O_3/water	0% to 3%	18.38%

PERFORMANCE OPTIMIZATION OF PARABOLIC TROUGH CONCENTRATOR USING HYBRID NANOFLIUD

A parabolic trough concentrator is a solar thermal device that is made to focus and use solar energy in the best way possible. There are three main parts: a parabolic reflector, a receiver tube, and a system for tracking. The line diagram of PTC is shown in Figure 9. The parabolic reflector is a curved mirror that collects sunlight and focuses it onto the receiver tube, which runs along the reflector's focal line. There is a heat transfer fluid inside the receiver tube that collects the concentrated solar energy. The tube is usually wrapped in glass to keep heat from escaping. The tracking system makes sure that the PTC stays in line with the sun all day, which helps it capture the most solar energy [76,77]. The way it works is by bouncing sunlight off the parabolic mirror and onto the receiver tube, where the fluid absorbs the concentrated heat. Then, the hot fluid is sent to a heat exchanger or used directly in applications like making electricity, heating buildings, or removing salt from water. The PTC's thermal performance is better because of this combination of precise focus, efficient absorption, and active tracking [78].

Utilizing a hybrid nanofluid to enhance the performance of a PTC is a significant advancement for solar thermal energy systems and optical efficiency. The PTC enhances efficiency of heat transfer, decreased heat loss, and enhanced energy conversion rates by utilizing hybrid nanofluids that are composed of distinct nanoparticles those agugment thermal properties. These fluids delivered excellent result of producing the working medium's thermal conductivity and specific heat capacity superior, which makes it preferable at absorbing and preserving solar energy. This enhancement makes PTC systems more effective for wide range applications since they work effective in a wider range of environmental situations. The technique further aids to utilize solar energy in certain ways that is excellent for the environment, which implies reduced reliance on convectional energy sources.

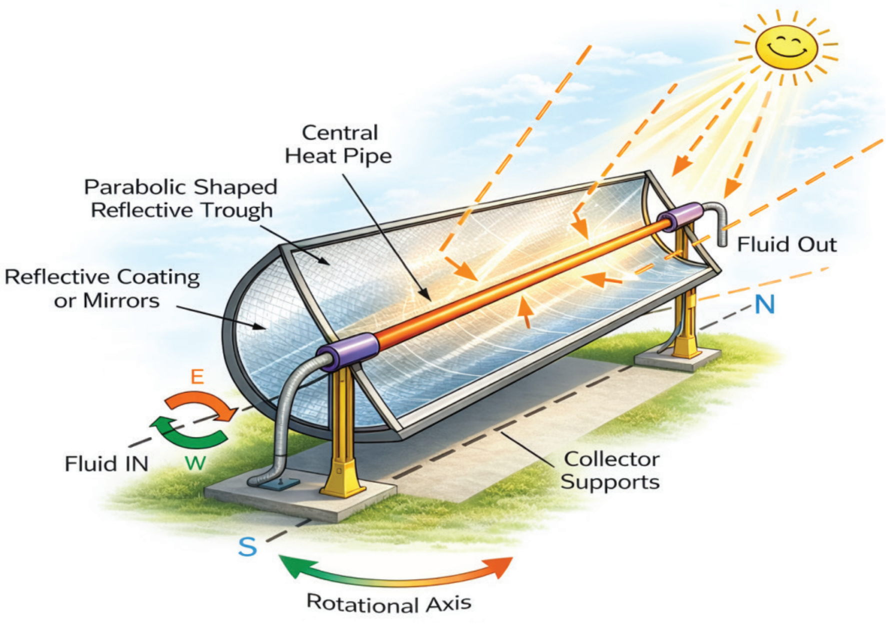

Figure 9. Parabolic trough solar concentrator.

Enhancement in Thermal Efficiency

The utilization of hybrid nanofluids as working fluids has formed PTCs considerably more thermally efficient. Hybrid nanofluids are constituted of two or more kinds of nanoparticles suspended in a base fluid. They have superior thermal conductivity, enhanced specific heat capacity, and improved convective heat transfer. These features make it simpler for energy to be absorbed and curtail on heat loss. The thermal efficiency of PTCs can be significantly enhanced by optimizing the size, composition, and concentration of the nanoparticles and preserving the flow conditions appropriate. This leads to better performance and longer-lasting solar thermal systems [79]. The parameters that affect the thermal efficiency of PTC are shown in Figure 10. The summary of enhancement in the thermal efficiency of PTC using a hybrid nanofluid is shown in Table 5. The thermal efficiency of PTC is calculated by Eq. 1.

$$\eta = \frac{mc_p\left(T_{out} - T_{in}\right)}{A_{ap}G} \quad (1)$$

Minea and El-Maghlany [80] showed that each of the hybrid nanofluids under consideration had an increase in Nu. When compared to the base fluid, the Cu-MgO hybrid exhibits the largest rise in mean Nu at 2% volume fraction, with a surge of over 14%. For certain hybrids, nevertheless, the rapid viscosity increase resulted in a large pressure drop punishment. The 2% Ag-MgO-water hybrid nanofluid provides the highest efficiency of the trough collector, and its efficiency increases as Re increases. Bellos and Tzivanidis [81] investigated the thermal performance of PTC using hybrid nanofluid mentioned in Table 5 at constant volume concentration. The ultimate outcomes show that the hybrid nanofluid can increase thermal efficiency by up to 1.8%, whilst mono nanofluids can only increase thermal efficiency by up to 0.7%. The variation of thermal efficiency enhancement with varying inlet temperature is shown in Figure 11. The huge Nusselt number boost for the hybrid nanofluid situation, which is roughly 2.2 higher than the corresponding value for working with plain oil, is the basis for this enhanced thermal efficiency augmentation.

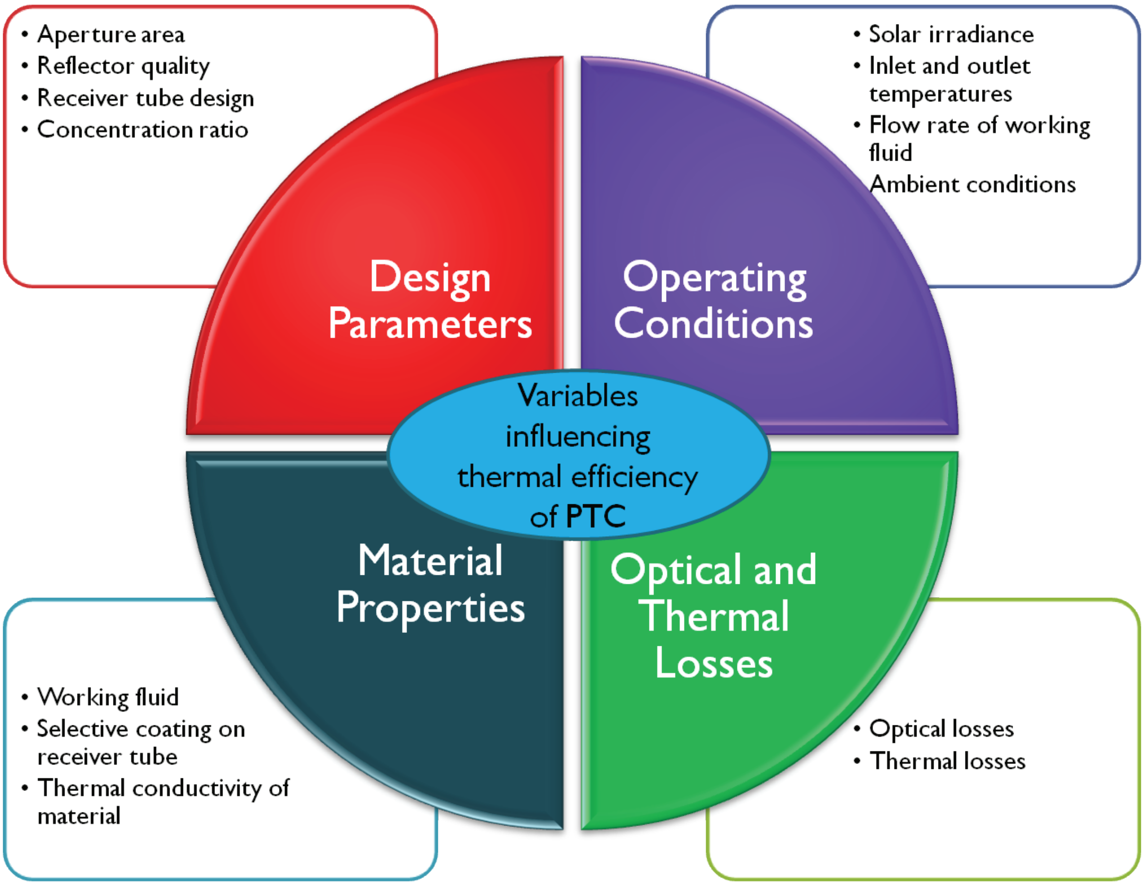

Figure 10. Variables influencing thermal efficiency of PTC.

Table 5. Summary of Enhancement in the thermal efficiency of PTC using hybrid nanofluid

Ref. no.	Hybrid nanofluid	Volume fraction	Enhancement in thermal efficiency/parameters
[80], 2018	Cu-MgO, Ag –MgO, GO-Co_3O_4, Al_2O_3-Cu	0.05% to 2%	14% enhancement in Nu for Cu-MgO at 2% vol. fraction
[81], 2018	Al_2O_3-TiO_2/Oil	constant	1.8% enhancement in thermal efficiency
[82], 2020	Al_2O_3-CuO/DI	0.01% to 0.5%	Maximum 31% enhancement in thermal efficiency
[83], 2020	Al_2O_3-CeO_2/ Syltherm 800, Al_2O_3-CuO/ Syltherm 800	4%	The maximum exergy enhancement occurred using Al_2O_3-CeO_2 reached 1.03%
[84], 2021	1.5% MWCNT – 1.5% TiO_2/ therminol-VPI	3%	Maximum 5.27% enhancement in thermal efficiency
[85], 2021	Al_2O_3-MWCNT/water	0.04%	Maximum 197.1% enhancement in thermal efficiency
[86], 2021	Ag - ZnO, Ag -TiO_2, Ag –MgO (base fluid Syltherm 800)	1% to 4%	Maximum 31% enhancement in convective heat transfer coefficient using Ag-MgO nanofluid at 4% volume fraction
[87], 2021	Al_2O_3-WO_3/Therminol VP1	1% to 4%	Thermal efficiency was enhanced by 32.728% and exergy efficiency was enhanced by 71.255%
[88], 2021	Ag-SWCNT, Ag-MWCNT, Ag-MgO (base fluid Syltherm oil)	1% to 2%	Maximum 11.5% enhancement in thermal efficiency using Ag-SWCNT nanofluid
[89], 2022	90% SiO_2-10% MWCNT/ EG-water	0.5% to 1.5%	Maximum 14.27% enhancement in thermal efficiency
[90], 2022	Fe_2O_3-GO, Fe_2O_3-SiC, Fe_2O_3-TiO_2 (base fluid Syltherm 800)	0% to 2%	Maximum 18.51% enhancement in thermal efficiency using Fe_2O_3-GO nanofluid at 2% volume fraction
[91], 2022	MgO-Cu/water	1% to 3%	Maximum 24.16% enhancement in thermal efficiency at 3% volume fraction
[92], 2022	Al_2O_3-CuO/water	1%	Maximum 29.21% enhancement in thermal efficiency
[93], 2022	Cu-MWCNT/water	-	The maximum energy and energy efficiency that could be obtained was 65.5% and 36.6%, correspondingly.
[94], 2023	Ag-Al_2O_3, Ag-MgO, Ag-TiO_2, Ag-CuO, Cu-Al_2O_3, Cu-MgO, Cu-TiO_2, Cu-CuO (base fluid Syltherm 800)	1.5% to 4%	Maximum 2.8% enhancement in thermal efficiency using Cu-MgO/Syltherm800 nanofluid at 3% vol. fraction.
[95], 2023	CuO-SWCNT/water	2% to 6%	The highest PEC value, 1.22, is associated with a volume fraction of 6% and Re = 12,000.
[96], 2024	Graphene-Fe_3O_4/water	0.01% to 0.2%	Maximum 45.46% enhancement in thermal efficiency at 0.2% volume fraction
[97], 2024	MWCNT-Y_2O_3/DI water	0.01% to 0.1%	Maximum 44.24% enhancement in thermal efficiency at 0.1% volume fraction

Khalil et al. [82] used a hybrid nanofluid for the enhancement of PTC effectiveness. Their findings showed that, when compared to basefluid, hybrid nanofluid enhanced the thermal efficiency of a typical PTC by 31%. Because of its increased heat transfer rate, sun trapping, and volumetric digestion, the direct absorption PTC was found to have a 19% better thermal efficiency gain than the standard PTC. Such bidirectional nanofluids have the potential to function in several solar thermal energy-based systems. Al-Oran et al. [83] used mono as well as hybrid nanofluid to ameliorate the energy and exergy of PTC. The variation of thermal efficiency, exergetic efficiency, Nusselt number and HTC with different nanofluids is shown in Figure 12. Using Al_2O_3-CeO_2 hybrid nanofluids increased thermal and energy efficiency by 1.09% and 1.03%, correspondingly, while increasing the Nu and HTC by 167.8% and 200.7%, correspondingly. Additionally, because they exhibit reduced pressure fall values, hybrid nanofluids have a greater benefit over mono nanofluids. Lastly, the evaluation of the efficiency variation influenced by the nanoparticle's thermal characteristics was shown at the optimal temperature of 575 K.

Khan et al. [84] used a hybrid nanofluid to evaluate the thermodynamic performance of PTC having convergent-divergent section. The study's findings show that using a changed design with hybrid nanofluids significantly enhances system effectiveness because of the formation of swirls and agitation that lower absorber surface

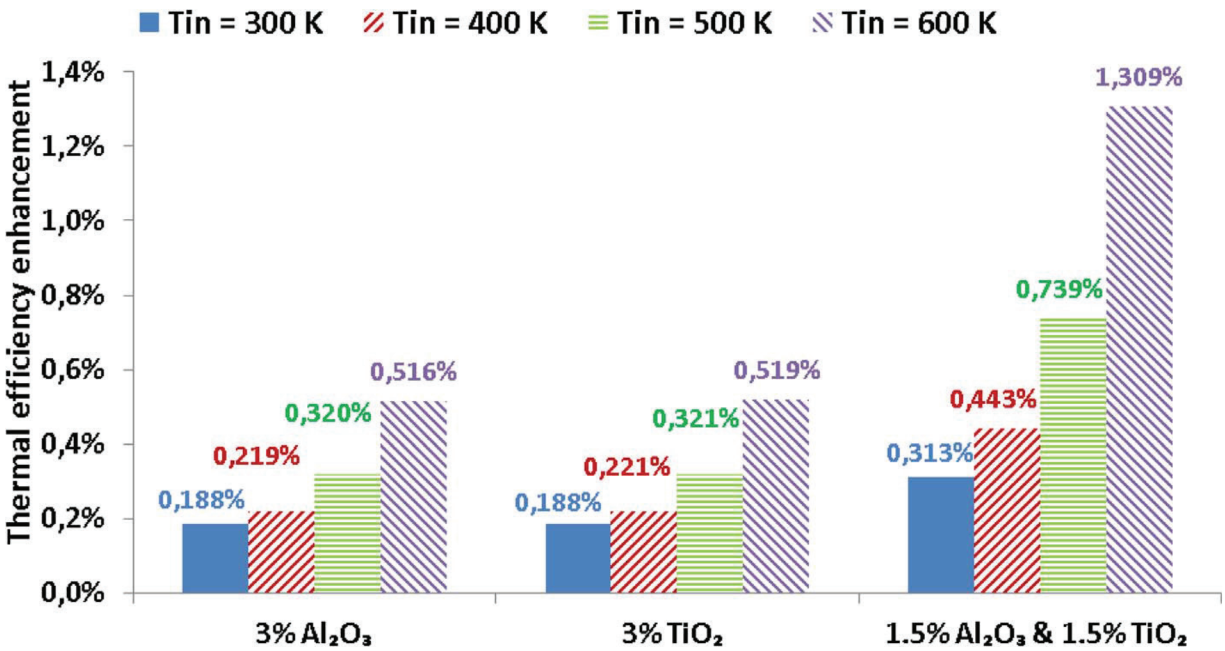

Figure 11. Variation of thermal efficiency enhancement with inlet temperature [From Bellos and Tzivanidis [81], with permission from Elsevier].

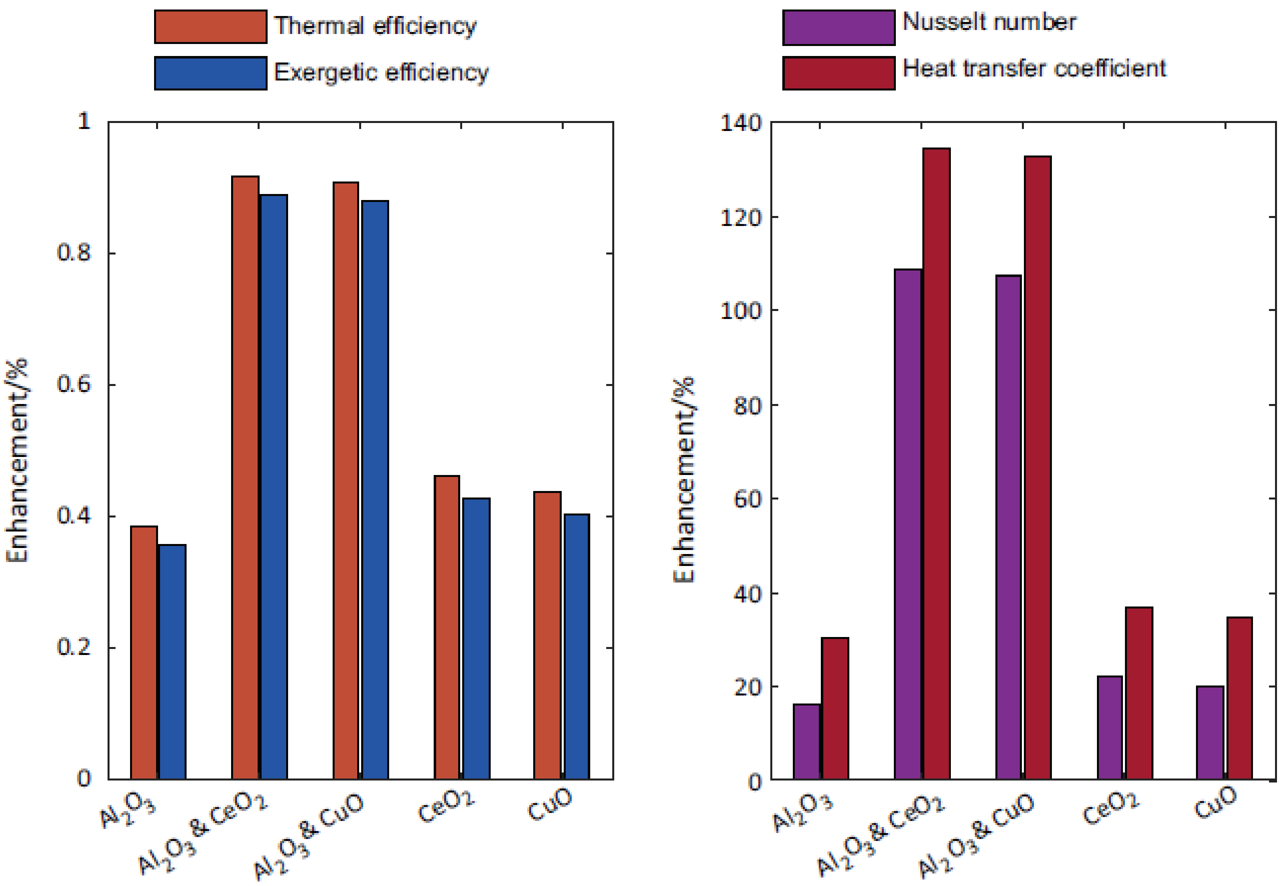

Figure 12. Variation of thermal efficiency, exergetic efficiency, Nusselt number and COH enhancement with different nanofluid [From Al-Oran et al. [83], with permission from Springer Nature].

temperature and, eventually, the loss of heat. In particular, the increase in thermal efficiency for the CD absorber tube with hybrid nanofluids varies between 3.61% and 5.27%, whereas for the smooth tube, it varies between 1.70% and 1.91%. Mashhadian et al. [85] ameliorate the environmental performance of DAPTC using hybrid nanofluid. Maximum enhancement in thermal efficiency was 197.1% using a hybrid nanofluid. The pressure drop in the absorber tube was measured, and the findings indicate that because of the low volume percentage, the pressure drop increase for hybrid nanofluids can be insignificant. Additionally, the nanofluid-based collector's water savings and releases of additional pollutants, like CO_2, were calculated. The findings show that switching to hybrid nanofluids from water can reduce CO_2 emissions and water use by up to 450.33 kg and 16.6 m3 per collector, correspondingly.

Ekiciler et al. [86] used a hybrid nanofluid mentioned in Table 5 to enhance the performance of the PTC receiver. Hybrid nanofluids significantly enhance thermal efficiency, demonstrating their effectiveness in utilizing solar energy. Among the tested fluids, the Ag–MgO/Syltherm 800 hybrid nanofluid with a 4.0 vol% concentration exhibits the highest thermal efficiency. However, at higher Reynolds numbers, the efficiency decreases due to increased pumping power requirements.Al-Oran and Lezsovits [87] used a hybrid nanofluid to enhance the performance of PTC at Budapest. During Budapest's warm climate, the highest possible energy and energy rates for HNFs were measured at noon and reached 32.728% and 71.255%, correspondingly, at the ideal temperature of 500 K. Mohammed et al. [88] used hybrid nanofluid for augmentation in heat transfer of PTC having receiver tube and conical turbulators. By employing Ag-SWCNT/Syltherm oil rather than pure Syltherm oil, the conical turbulators successfully increased their thermal endurance by 233.4%. It is determined that the PEC falls between 0.9 and 1.82. Both the exergetic and thermal efficiencies rose by 18.2% and 11.5%, correspondingly. The entropy production ratio and rate can degrade by up to 33.7% and 42.7%, respectively.

Khaledi et al. [89] used hybrid nanofluid to investigate the energy, exergy and hydraulic performance of PTC. The findings demonstrated that using HNFs increases thermal efficiency compared to the base fluid because they improve thermal characteristics and the Nu. Specifically, employing HNFs resulted in an ultimate thermal efficiency gain of 14.27% when contrasted with the base fluid. Additionally, the use of HNFs improved the energy efficiency. The appetite for pumping power is extremely low for the actual generation of the beneficial heat rate, as evidenced by the highest increase in pumping power utilizing HNFs of 9.72%. Mohammed et al. [90] used three different combinations of HNFs to investigate the performance of PTC thermohydraulically and thermodynamically. Using brick-shaped nanoparticles, the total PEC has been determined to be between 1.24 to 2.46. According to the findings, there was an 18.51% boost in thermal efficiency and a 16.21% rise in exergy efficiency. About 48.27% and 52.6%, correspondingly, are the highest reductions in the production of entropy rate and ratio. Khetib et al. [91] used a hybrid nanofluid to evaluate the energy as well as exergy performance of PTC using twisted turbulators. The findings showed that increasing the Re from 8000 to 32000 might increase thermal efficiency by 23.79% and exergy efficiency by 21.15%. Chakraborty et al. [92] evaluated the effect of hybrid nanofluid and elliptical insert on PTC performance. The design with an elliptical insert of 28 mm main diameter has the largest increase in both thermal efficiency as well as HTC, at 44.21% and 29.21%, correspondingly. Saray and Heyhat [93] used a hybrid nanofluid in PTC for 4E analysis. Their results revealed that a maximum of 40.44 GJ of energy can be saved as well and 59.03 KL of water can also be saved using HNF. The system achieves maximum exergy efficiency at 36.63% and energy efficiency at 65.47%, with the minimum energy production cost being $0.0195 per kWh.

Ajbar et al. [94] used eight different combinations of hybrid nanofluid as mentioned in Table 5 to investigate the thermal efficiency of PTC. The findings demonstrated that, when compared to base fluid, thermal efficiency might increase by up to 2.8% when hybrid nanofluids were used in the evaluation and by 1.6% on average within the tested operating circumstances. Esfahani et al. [95] evaluate the 4E performance of the PTC using a hybrid nanofluid. The heat transmission rate is increased by using a turbulator in the shape of a twisted strip in conjunction with a coil. The maximum increase in Nusselt number is noted 55% at a volume fraction of 2%. Al-Rabeeah et al. [96] used a hybrid nanofluid of different volume concentrations to evaluate the performance of PTC. Their results revealed that the maximum enhancement in thermal efficiency is 45.46% at 0.2% volume fraction. Al-Oran et al. [97] used a hybrid nanofluid to investigate the performance of PTC in Jordanian conditions. The results showed that water had a thermal efficiency of 19.32%, while 0.1% HNF had the highest thermal efficiency of 44.24%. Also, the highest optical efficiency got better as the concentrations went up. With 0.1% Vol, the highest efficiency of 45% was achieved.

Comparative Analysis of Hybrid Nanofluid versus Nanofluid for the Augmentation of their use in PTC

A comparative analysis of hybrid nanofluids versus nanofluids reveals that hybrid nanofluids offer superior thermal conductivity, heat transfer efficiency, and stability, making them more effective for enhancing parabolic trough concentrator (PTC) performance, despite their higher cost and viscosity. The comparative analysis is shown in Table 6.

Table 6. Comparative analysis of hybrid nanofluid versus nanofluid for enhancing their application in PTC

Parameter	Hybrid nanofluid	Nanofluid	Ref. no.
Composition	Mixing of two or more nanoparticles (e.g., Al_2O_3/Cu, CuO/Ag) in a base fluid (e.g., water, ethylene glycol)	One type of nanoparticle type (e.g., CuO, Al_2O_3, SiO_2) in a base fluid	[98,99]
Thermal Conductivity	15-50% enhancement in thermal conductivity than the base fluid	5-20% augmentation in thermal conductivity than the base fluid	[100,101]
Heat Transfer Efficiency	Compared to regular HTFs, the heat transfer rate can improve by 30 to 60%.	10-30% enhancement in heat transfer than the base fluids	[102,103]
Stability	Improved stability with zeta potential of >30 mV (using stabilizers)	Zeta potential is often less than 20 mV, which can cause problems with sedimentation and aggregation.	[104,105]
Viscosity	Higher viscosity (usually 10–25% more than the base fluid)	5–15% more viscous than the base fluid	[106,107]
Nanoparticle Interaction	Synergistic effects from several nanoparticles (for example, Al_2O_3 makes CuO more stable and helps it transfer heat)	Limited to the properties of a single nanoparticle, like high thermal conductivity but low dispersion stability	[108,109]
Cost	More expensive (2-3 times more than single-component nanofluids because they have two nanoparticles)	Less expensive (depends on the nanoparticle; usually 1–2 times the cost of the base fluid)	[110,111]
Operational Efficiency	25 to 40% more efficient at high temperatures (200 to 400 °C)	10-20% more efficient at lower temperatures (50–150°C)	[112,113]
Economic Feasibility	Higher initial cost, but possible savings in the long run with better operational efficiency and less maintenance	Lower initial cost, but less efficient at higher temperatures, which could mean losing energy.	[114,115]
Operational Durability	Better stablized over time with minimal reduction of quality (thermal stability > 300°C)	Chance of deterioration which might diminish performance over time (thermal stability < 250°C)	[116,117]

TECHNICAL AND PRACTICAL CHALLENGES OF HYBRID NANOFLUID USAGES IN PTC

Utilizing hybrid nanofluids in PTCs can enhance thermal efficiency in various manners, but it also has a lot of technical and practical challenges, as illustrated in Figure 13. A crucial concern is how stable hybrid nanofluids are. Gradually, nanoparticles can aggregate together and stabilize, which can suffer their thermal performance. Ensuring long-term stability in high-temperature conditions, which are common in PTC systems, is still a major challenge [118]. Also, nanoparticles can chemically interact with system materials and cause wear over time, which can lead to corrosion and erosion of metal parts. This is a risk that comes with compatibility with system materials [119]. Thermal and rheological properties make their use even more difficult. Hybrid nanofluids enhance thermal conductivity, but their enhanced viscosity can produce pumping power requirement higher, that might eliminate any energy savings [120].

Another reason why widespread use isn't happening is because of the costs. Producing hybrid nanofluids is costly since it entails convoluted synthesis technique. Operational expenses also escalate since these fluids need unique equipment to control, preserve, and monitor them [121]. When shifting from laboratory experimentation to industrial utilization, there are more complications to resolve, such as keeping the nanoparticles uniformly dispersed and receiving the same performance from huge systems [122]. Environmental and safety concerns make things even harder. Nanoparticles are toxic, and hybrid nanofluids need to be thrown away properly, which means that strict rules and waste management plans must be followed [123].

Measurement and standardization make progress even harder because there aren't any standardized ways to test the thermal and rheological properties of hybrid nanofluids in real-world situations. Ensure that the findings are credible and can be iterative; their production must have quality control [124]. Additionally, including hybrid nanofluids to prevailing PTC systems frequently implies making costly design amendments, such as retrofitting pipelines and revalidating system parameters to enhance flow and heat transfer. These technical and practical difficulties emphasize the requirement for aimed research and innovation provides hybrid nanofluids a possible outcome for solar thermal applications [125]. To clearly perceive the capabilities of hybrid nanofluids in enhancing PTC system

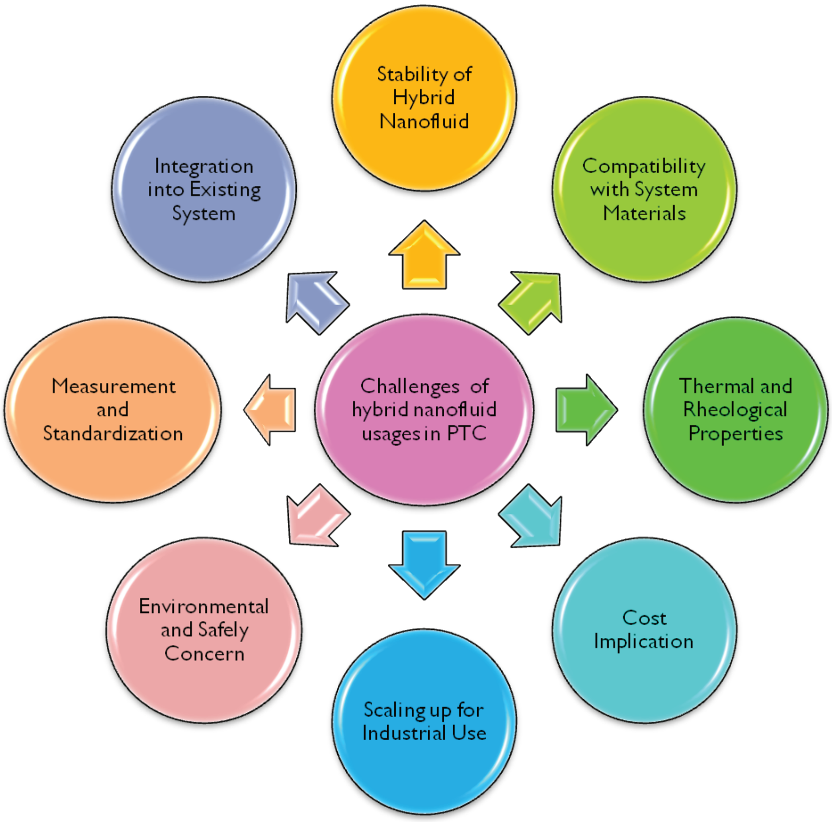

Figure 13. Challenges of hybrid nanofluid usages in PTC.

efficiency, it is essential to resolve these difficulties by making advancement in material science, finding economical methods to make them, and adding strong environmental protections.

Limitations of Hybrid Nanofluid in Enhancing PTC Efficiency

Hybrid nanofluids are very promising for improving the thermal performance of parabolic trough concentrators, but they are not widely used yet because of technical, economic, and environmental problems. To accomplish these works, we required to increase efforts in research and create new technologies to get around these difficulties. Limitations are mentioned below

- Nanoparticles in hybrid nanofluids agglomerate and sediment progressively, diminishing thermal performance
- Higher viscosity means more pumping power is needed, which cancels out any gains in energy efficiency.
- Nanoparticles can make parts of a system corrode and wear down.
- Hybrid nanofluids are costly since they are developed through complex synthesis processes.
- It is challenging to preserve nanoparticles uniformly distributed and their performance reliable in large scale system.
- The feasible contamination of nanoparticles and the challenges in eliminating them.
- Lack of standard methodologies for examining thermal and rheological characteristics in practical situations.
- Upgrading existing PTC systems to work with hybrid nanofluids can be costly.

CONCLUSION

Hybrid nanofluids are a potential new area of solar energy technology, particularly when it comes to making PTCs perform effectively. There are still certain challenges to resolve, but advancement in nanotechnology, material science, and thermofluid dynamics is advantageous. Utilizing hybrid nanofluids in PTC systems is in accordance with worldwide energy aims since it is a prolonged way to utilize more solar energy and depend less on fossil fuels. This review article pertains to following conclusion.

- Hybrid nanofluids greatly improve the thermal efficiency of parabolic trough concentrators by speeding up heat transfer rates. This makes them a good choice for solar thermal applications.
- The Al_2O_3–MWCNT/water hybrid nanofluid had the highest thermal efficiency increase of 197.1% at a volume fraction of 0.04%, and it also had a very small pressure drop.

- Hybrid nanofluids greatly improve the performance of convective heat transfer. For example, the Cu–MgO/water hybrid nanofluid at a 2% volume fraction had the highest Nusselt number improvement of 14%.
- Hybrid nanofluids significantly improve the exergy performance of PTC systems. For example, Al_2O_3–WO_3/Therminol VP-1 at 4% volume fraction achieved a maximum exergy efficiency improvement of 71.255%, which means that it uses energy better and is less irreversible than base fluids.
- Comparative analysis confirms that hybrid nanofluids provide 15–50% higher thermal conductivity and 30–60% better heat transfer efficiency than conventional nanofluids, though at the cost of 10–25% increased viscosity, emphasizing the need for optimized formulations to balance thermal gains and pumping power requirements.
- The review shows that hybrid nanofluids can have a big positive effect on the environment, such as reducing CO_2 emissions by up to 450.33 kg and saving 16.6 m^3 of water per collector. This shows that they are important for solar thermal energy systems that are low-carbon and sustainable.
- Comprehensive experimental studies and simulation models corroborate the theoretical advantages of hybrid nanofluids, providing insights into their practical applicability.
- Ensuring the stability and longevity of hybrid nanofluids remains a critical factor in their widespread adoption, necessitating additional research into anti-agglomeration techniques.

Future Research Direction

Future research should focus on augmenting hybrid nanofluid formulations, evaluating prolonged economic feasibility, exploring modern dispersion methods, and implementing extensive real world applications to evaluate hybrid nanofluid efficacy in practical PTC systems. Here are few realistic directions for future research:

- Identify the best composition of nanoparticles, concentrations, and base fluids for PTC applications to get the superior thermal performance and stability.
- Generate and enhance procedures to disperse hybrid nanofluids to ensure that they are more stable and homogeneous, which will ensure that they work the similarly over time in PTC mechanism.
- Inspect hybrid nanofluids at micro level and in the practical working PTC systems to observe how efficiently they work, how energy efficient they are, and how effectively they can be utilized on a larger scale.
- Evaluate the economic efficiency and extended operational sustainability of hybrid nanofluids, considering production cost, maintenance, and system endurance.
- Evaluating the aging impact, stability, and diminution of hybrid nanofluids under operational circumstances to ensure dependable and efficient performance over sustained periods.

NOMENCLATURE

A_{ap}	Surface area collecting solar energy or Aperture area (m^2)
C_p	Specific heat capacity (kJ/kgK)
G	Solar irradiance (W/m^2)
m	Mass flow rate of working fluid (Kg/s)
Nu	Nusselt number
Re	Reynolds number
T_{out}	Outlet temperature of the working fluid (K)
T_{in}	Intlet temperature of the working fluid (K)

Abbreviations

4E	Energy, exergy, economic and environment
CD	Converging-diverging
DLS	Dynamic light scattering
DAPTC	Direct absorption parabolic trough collector
DI water	Distilled water
EG	Ethylene glycol
HNF	Hybrid nanofluid
HTC	Heat transfer coefficient
PTC	Parabolic trough concentrator
PEC	Performance evaluation criterion

AUTHORSHIP CONTRIBUTION

All the authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the manuscript.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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