A Review of Hybrid Nanofluids: Emerging Trends and their Role in Enhancing Parabolic Trough Concentrators Performance

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https://doi.org/10.5109/7363508

出版情報：Evergreen. 12 (2), pp.1250-1275, 2025-06. 九州大学グリーンテクノロジー研究教育センター
バージョン：

A Review of Hybrid Nanofluids: Emerging Trends and their Role in Enhancing Parabolic Trough Concentrators Performance

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(Received January 14, 2025; Revised April 21, 2025; Accepted April 28, 2025)

Abstract: The article examines how hybrid nanofluids can significantly improve the efficiency of PTC used in solar thermal energy applications. The aim is to evaluate recent advancements in hybrid nanofluids, focusing on their thermophysical properties and their impact on PTC efficiency. The objective is to provide a comprehensive analysis of thermal, optical, and rheological characteristics, identify research gaps, and propose future directions for optimizing PTC performance. By incorporating a mixture of different nanoparticles into a single base fluid, hybrid nanofluids achieve enhanced thermal properties and more efficient heat transfer than single-particle nanofluids, achieving thermal efficiency improvements of up to 2.8% in PTCs and 197% in solar collectors. Notably, Al_2O_3/water nanofluid at 3% concentration increased thermal efficiency by 28%, from 40.8% to 52.4%. The novelty lies in integrating nanoparticle functionalization, surfactant-assisted stabilization, and passive techniques like turbulators to enhance stability and exergy efficiency. Challenges such as long-term stability, viscosity-related pressure drops, and scalability are addressed, offering insights for sustainable solar energy harnessing and green hydrogen production.

Keywords: hybrid nanofluid; heat transfer enhancement; nanoparticles stability; parabolic trough concentrator; solar thermal energy; thermal conductivity

1. Introduction

As we are moving into the new era of technology, solar energy acts as a good source of energy that can be harnessed for utilization in many works like industrialization and urbanization, daily human life, heating of water, thermal energy depots, photovoltaic cells, etc. on earth. Solar energy is such energy that is made from the rays of sunlight, able to produce heat, cause chemical reactions, or create electricity. It is renewable and therefore a green source of energy[1]. The Sun is an extremely powerful and broad energy source that is free of cost received by the sun. The impact of sunlight on Earth's surface is moderately low. Our only concern is how we can utilize this heat energy for various useful functions like electricity, heating water, etc. As we all know, solar rays can't be harmful during their development and life-cycle gives a clear justification for not having carbon content in solar power than other fuels. In earlier days, the most common way of utilizing energy from the sun was through photovoltaic (PV relates to the creation of electric current at the interaction of two substances when it brings to light) cells, which are also called solar cells. The function of PV cells is only that light can be reflected, soak up, or pass along a cell. The PV cell is obtained from semiconductor material; the "semiconductors" are the conductors that allow electricity to pass partially in a material or we can say medium through which passage of electricity has been made[2]. Many distinct semiconductor materials are used according to their application in PV cells. But nowadays, we use many other technologies to utilize sunlight. Currently, nano-technology has taken a crucial role in multiple fields of heat transfer operation and touched exceptional progression in the energy utilization technique. The first Heat Transfer Nanofluids were created by Choi[3]. Nanotechnology is an application or use of Nanofluid in a certain technique. The term "nano" is related to 1 billionth of a meter or 10-9 m in Figure1.

An innovative class of heat transfer fluids known as hybrid nanofluids has been innovated to enhance PTCs' thermal effectiveness. By dispersing multiple kinds of nanoparticles within a single base fluid, hybrid nanofluids achieve improved thermal properties, including greater conductivity, stability, and heat transfer performance than

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conventional nanofluids. These developments result from the use of nanotechnology, which disperses solid particles with sizes varying from 10 to 100 nm in base fluids to create fluids with remarkable thermal properties[4]. This method improves heat transfer and energy distribution while simultaneously lowering the size and energy usage of heat transfer equipment. By addressing significant heat transfer constraints, hybrid nanofluids are being used in PTCs to increase solar thermal systems' efficiency[5]. This paper explores the most recent advancements in hybrid nanofluids, highlighting their function in maximizing PTC performance and examining the difficulties in putting them into practice to realize their full potential.

In 2023, the world's energy consumption hit a record high, mostly due to the highest rise among industrialized nations. Despite growing attempts to incorporate renewable energy, fossil fuels still accounted for 84% of the global energy mix, making them the dominating energy source. According to the Statistical Review of World Energy, this constant dependence on conventional energy sources is a major factor in the rising CO2 emissions, which for the first time in 2023 surpassed 40 gigatons. The main cause of these emissions is the burning of fossil fuels, underscoring the urgent need to address global warming. In Figure 2[6], patterns highlight how vital it is to quicken the switch to sustainable energy sources in order to satisfy rising demand and lessen the effects of climate change.

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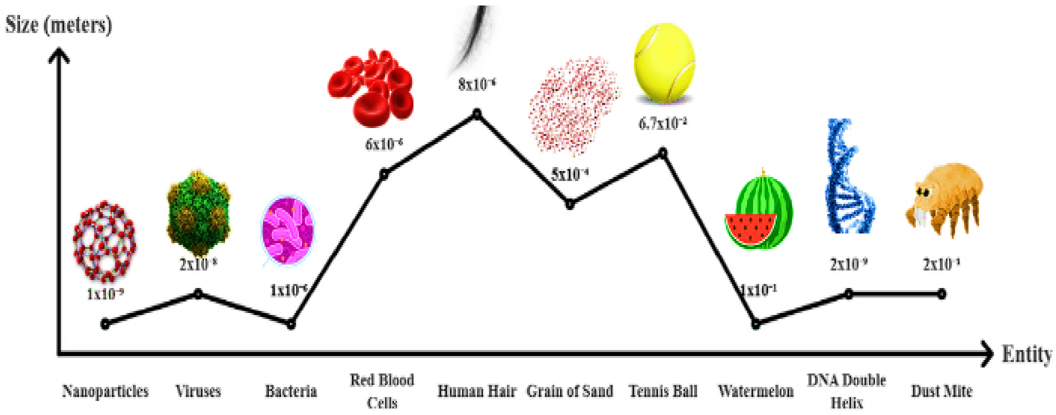

Fig. 1: Size comparison of nanoparticles and other entities

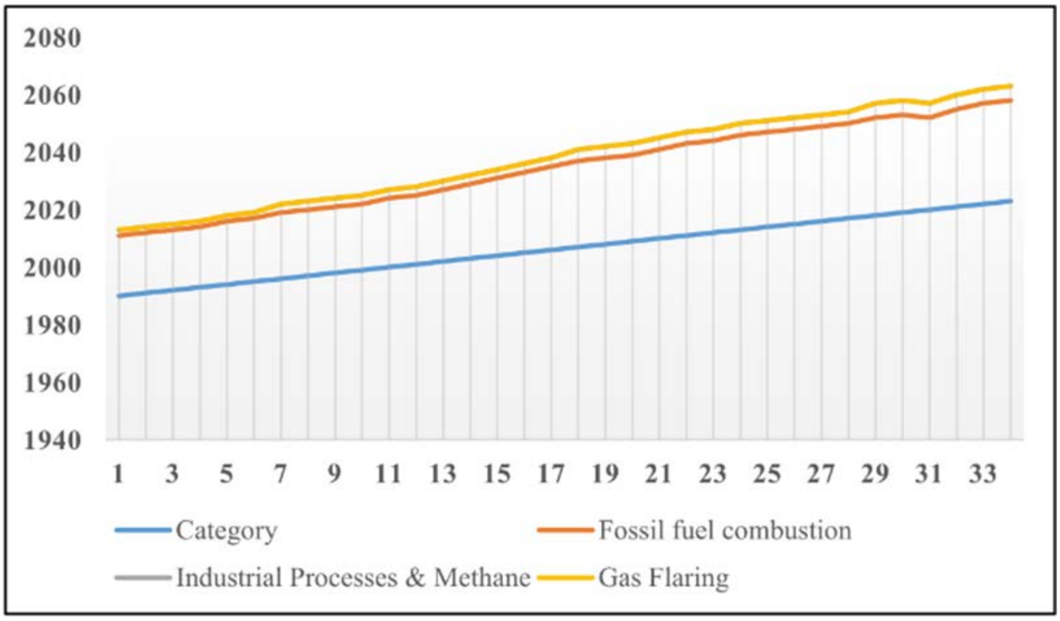

Fig. 2: Global energy-related greenhouse gas emissions[6]

Solar energy can be utilized by a gadget that converges as well as concentrated solar radiation from the Sun known as Solar Concentrator[7]. This solar energy gets absorbed by this collector and then transferred to a nanofluid for further function in the solar collector. Nanofluids are modern heat-carrying fluids that work as a substitute for normal base fluids to raise the exceeding heat transfer operation by the agglomeration of nanoparticle substances that shows the ability of higher thermal conductivity[8]. Solar thermal concentrators can achieve improved performance by utilizing nanofluids, which are known for their exceptional thermal conductivity properties[9][10].

The possibility of employing nanofluids in a range of solar applications has been established by several studies and current research is investigating novel nanomaterials and formulations that may enhance their efficacy even further[11)12)13)14)]. The industry might undergo a transformation with the incorporation of nanofluids into commercial solar energy systems, rendering solar power a more economical and efficient means of meeting global energy demands.

By combining different types of nanoparticles, hybrid nanofluids improve heat transfer efficiency in PTC, resulting in superior thermal conductivity and heat transfer efficiency. Recent studies have demonstrated the efficacy of various hybrid nanofluid compositions in augmenting the performance of PTCs. For instance, Moosavian et al.[15)] examined the utilization of MWCNT/Fe_3O_4 nanoparticles as additives to the heat transfer fluid Syltherm 800. Their findings indicated that incorporating 4% by volume of Fe_3O_4 resulted in a 2.5% increase in the useful energy rate absorbed by the system. This enhancement underscores the potential of hybrid nanofluids to improve energy capture and conversion in solar collectors. In another study, Singh et al.[16)] conducted a comprehensive assessment of PTCs utilizing hybrid nanofluids. They explored the combination of hybrid nanoparticles consisting of Al_2O_3 and TiO_2 at a 3% volume concentration. The results revealed substantial enhancements in thermal efficiency, with increases observed for various base fluids: Syltherm 800 (1.1%), Therminol VP1 (1.243%), Therminol 66 (1.04%), and Dowtherm (0.2%). Additionally, the HTC experienced significant boosts, ranging from 156.63% to 250% depending on the base fluid used. The integration of passive techniques, such as employing turbulators within the receiver tubes, has also been explored to further augment heat transfer rates in PTCs. Khetib et al.[17)] numerically investigated the combined effect of magnetic hybrid nanofluids and innovative hybrid turbulators. Their study demonstrated that using a hybrid turbulators with a pitch ratio of 1, at a Reynolds number of 20,000 and a nanoparticle volume fraction of 3%, resulted in optimal exergy efficiency. This approach highlights the potential of combining passive and active methods to achieve superior thermal performance in solar collectors. Furthermore, Al-Oran and Lezsovits[18)] examined the performance of a PTC under the climatic conditions of Budapest using a hybrid nanofluid composed of alumina (Al_2O_3) and tungsten oxide (WO_2) based on Therminol VP1. According to their simulation results, using a hybrid nanofluid with a 4% volume concentration yielded significant improvements, boosting the Nusselt number and HTC by 138% and 169%, respectively. As a result, the system's thermal and exergy efficiencies saw respective gains of 0.39% and 0.385% under operating conditions of 600 K temperature and a flow rate of 150 litres per minute. Hybrid nanofluids significantly enhance PTC performance by improving thermal conductivity and heat transfer. Combined with passive techniques like turbulators, they further optimize efficiency, advancing sustainable solar energy systems.

1.1. Factors Already Known about Utilization of Nanofluid in PTC

Hybrid nanofluids, which are composed of two or more different nanoparticles in a base fluid, have shown improved thermal conductivity and heat transfer capabilities when compared to single nanoparticle nanofluids and conventional fluids.

Research has indicated that the utilization of hybrid nanofluids in PTCs improves heat absorption and transfer properties, leading to a higher output temperature and increased efficiency.

When using hybrid nanofluids, the fluid's viscosity tends to rise which may result in higher pumping power needs. When evaluating a PTC system's total energy efficiency, this component is essential.

Several techniques have been studied to increase stability and stop agglomeration over time, including the use of surfactants and surface modifications of nanoparticles.

Preliminary economic analyses indicate that the utilization of hybrid nanofluids consequence long-term cost reductions because of increased efficiency.

Studies reveal that the fluid's capacity to effectively absorb and hold onto solar energy is greatly influenced by the size, shape, and kind of particles present.

1.2. Objective and Scope the Study

This paper's goal is to look at current developments and trends in the application of hybrid nanofluids for solar thermal energy systems' parabolic trough collectors. The study intends to close important research gaps to maximize the utilization of hybrid nanofluids for increased efficiency and sustainability while offering a thorough understanding of their thermal, optical, and rheological features and their influence on PTC performance. The main aspects of hybrid nanofluids, including their thermal, optical, and rheological qualities, are reviewed in this work along with an assessment of how they affect PTC system performance in different operational scenarios. It analyzes the trade-offs between stability, viscosity, and thermal efficiency and evaluates how these affect energy usage and system performance as a whole. The paper reviews recent life cycle evaluations and cost studies and looks into the economic and environmental effects of employing hybrid nanofluids in PTCs. Furthermore, it proposes future research initiatives to increase efficiency and sustainability of PTC systems by identifying significant research gaps in areas including long-term stability, ideal nanoparticle compositions, and sophisticated synthesis procedures. A summary of the previously published review papers related to nanofluid and hybrid nanofluid applications in PTCs

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after 2020 is systematically presented in Table 1. The selection of literature has been carried out to ensure the inclusion of the latest advancements, methodologies, and key findings in this domain. It is noteworthy that the majority of comprehensive review studies have emerged prominently during the years 2020 to 2024, reflecting the growing research interest and evolving developments in hybrid nanofluid-based PTC systems. This trend signifies a progressive shift toward exploring advanced heat transfer fluids for solar thermal applications. The studies incorporated from the post-2020 period emphasize critical aspects such as thermophysical enhancement, exergy improvement, stability issues, and environmental sustainability. Furthermore, the inclusion of any older studies is justified based on their significant contribution to the fundamental understanding of nanofluid behavior, benchmark thermal models, or pioneering experimental work that laid the foundation for subsequent research. Thus, Table 1 provides a comprehensive and chronological mapping of existing review works, ensuring both technical relevance and research continuity within the rapidly evolving field of nanofluids in PTC applications.

Table 1: Summary of a previously published review paper on a related subject after 2020

Ref.	Review detailed
[19], 2020	The paper examines nanofluids and suggests SiC-TiO_2 hybrid nanofluids as a way to improve the thermal and rheological characteristics of machining processes.
[20], 2021	The study examines hybrid nanofluids, covering their synthesis, thermophysical characteristics, and heat transfer applications. It also discusses present issues and potential future research areas.
[21], 2022	The assessment cites difficulties such as pressure loss and high friction factors, as well as gaps in the optimization of surfactants and mixing ratios for hybrid nanofluids.
[22], 2023	The paper compares hybrid and mono-nanofluids, looks at how various kinds, concentrations, and depths of water-based nanofluids improve solar still production, and outlines future research possibilities.
[23], 2024	The paper addresses issues including viscosity and pressure drop while providing an overview of hybrid nanofluids and highlighting their production, thermophysical characteristics, and advantages in heat transfer applications.
[24], 2024	In order to fill in gaps in the literature and direct future research, the paper covers developments in hybrid nanofluids with an emphasis on mathematical models, classifications, and their applications in the solution of flow issues.

1.3. Gap that Needs to be Addressed

Information on how different nanoparticle amounts, shapes, and carrier fluids influence the overall heat transfer efficiency in PTCs.

Several investigations have examined the trade-offs between elevated thermal conductivity and elevated viscosity, with the goal of identifying the best particle kinds and concentrations to reduce viscosity effects while optimizing thermal performance.

Insufficient research has been done on the creation of sophisticated hybrid nanofluids with high heat conductivity and low viscosity, which would need less extra pumping power.

Very little is known about the hybrid nanofluids' long-term stability in PTC applications, particularly when they are constantly exposed to high temperatures and strong sun radiation.

Insufficient thorough cost-benefit analysis that accounts for manufacturing costs, possible environmental risks, and long-term maintenance costs in addition to efficiency advantages.

1.4. Novelty of the Study

This review advances the application of hybrid nanofluids in parabolic trough concentrators (PTCs) by comprehensively analyzing their thermophysical enhancements beyond conventional mono-nanofluids. It examines the synergistic effects of metal oxides, carbon-based, and magnetic nanoparticles on key parameters such as thermal conductivity, specific heat capacity, viscosity, and convective heat transfer coefficients. Unlike previous studies, which primarily focused on individual nanofluids, this review integrates insights into nanoparticle functionalization, surfactant-assisted stabilization, and base fluid optimization to improve dispersion stability and thermal performance. Additionally, it explores hybrid nanofluid interactions with passive augmentation techniques, including twisted tape inserts and porous media, to enhance convective heat transfer and exergy efficiency. By synthesizing recent experimental and numerical findings, this study identifies research gaps related to long-term stability under prolonged thermal cycling, the influence of Brownian motion and thermophoresis on hybrid nanofluid heat transfer, and the scalability of hybrid nanofluids for industrial solar thermal applications. The insights provided serve as a foundation for advancing PTC performance and developing next-generation solar energy harnessing technologies.

2. Parabolic Trough Concentrator

In today's world, there are many techniques or systems available to harness solar rays that can produce solar power.

Solar Concentrators are categorized into two categories shown in Figure3; (i) non-concentrating concentrators and (b) concentrating concentrators. In regards to this, a PTC is used for the motive of solar power units. A parabola is a set of points (or we can say curve) where all points are equidistant from a fixed line or point when any point is drawn on it. A parabolic trough concentrator avails the same concept. The main function of concentrated solar power (CSP) technology is that it utilizes focused sun beams onto a specified surface (known as a heat absorber). A heat absorber is nothing but it is a kind of tube that is infused with a heat relay fluid, which grabs the heat well, such as fabricated oil, water, ethylene glycol, etc[25].

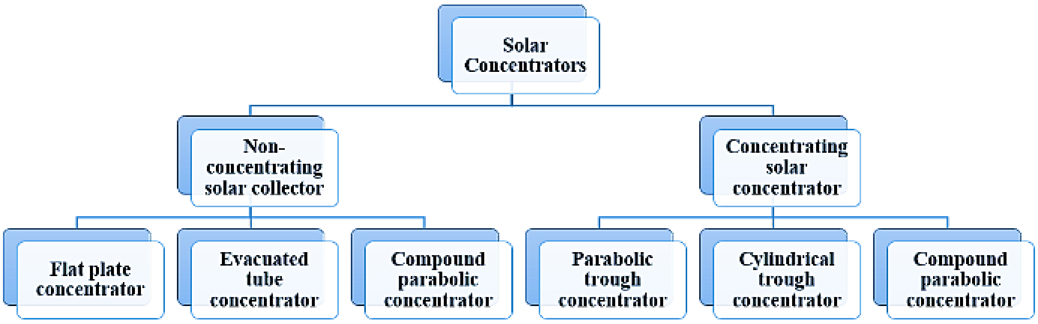

Fig. 3: Classification of solar concentrator

A PTC is a kind of solar concentrator that reflects solar radiation onto its focal line towards an absorber tube to increase the temperature of the nanofluid inside it as illustrated in Figure 4. Due to its single-tracking ability, all the radiations collapse parallel to its axis[26]. This system increases the efficiency of absorbing heat through the heat absorber by some percent which is extremely high in comparison to solar direct energy concentrator systems that have less adaptability[27]. The temperature creation in PTC is obtained to be surpassing in contrast to FPC because of the fact of its less absorber exterior surface area. The normal temperature of heat-transferring fluid passing through the heat absorber can be obtained up to 200°C. The heat absorber soaks up heat continuously from the feeder (trough) which enhances the efficiency of PTC[28]. To understand this method, we take the steam generator function which spins a generator and generates electricity by steam on a rotating steam turbine that rotates a shaft hence, mechanical work is obtained that will be converted to electricity. The working fluid soaks up heat from the sun rays that are coming from the reflected surface (trough) which leads a working fluid to be super-hot in the pre-heater system in the steam power plant; hence temperature fluid reaches up to 390°C. Then working fluid will facilitate a heat exchanger to heat water for the proper functioning of a working fluid in a steam turbine that will go around in the heating system and convert water into steam. This steam expands the turbine blades which results in a rotation of the turbine. After operating the turbine, the steam is reused to be liquefied in the condenser and pumped to a boiler which is to be recycled over and over till it can be used in the power production systems[29].

A similar function relates to the working nanofluid in PTC as shown in Figure 4[30], which also gets reused and again gains heat energy from the trough then it is used for transferring its heat to water. A classic solar concentrator field accomplished various parallel rows of PTC set and oriented along a north-south axis in such a way that it follows the sun's east-to-west motion during the day. This configuration enhances the duration for which solar reflectors can effectively absorb solar radiation and makes sure that the sun is consistently concentrated on the absorber tube which increases the efficiency of PTC. Different layers on the heat-absorbing tube permit a boost in solar radiation concentration and the utilization of an evacuated glass envelope framing the pipe as well. Thus, it shrinks heat losses to the ambient[30]. The main concern in PTC comes in the election of an efficient working fluid that can run within the absorber tube in a standard way. The rate of heat transfer is likely to rise with a more conductive fluid. Currently, Due to their superior thermal conductivity, nanofluids are utilized in PTC, where they capture solar heat while flowing through the receiver tube[31]. This harvested heat energy can be effectively utilized across various applications, ranging from industrial processes to power generation, depending on the specific requirements. The possibility of hybrid nanofluids to improve the effectiveness and performance of PTCs is explored in the next section.

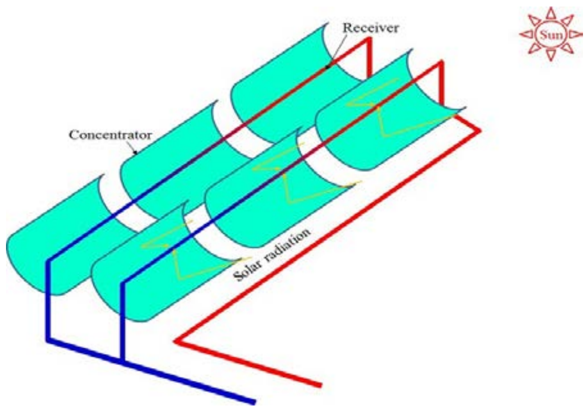

Fig. 4: Schematic arrangement of PTC[30)]

3. Hybrid Nanofluid and Their Preparation Technique

3.1. Hybrid Nanofluid

The demand for enhanced thermal and physical characteristics in advanced fluids has driven the development of hybrid nanofluids. Hybrid nanofluids are obtained by bounding two distinct kinds of nano-particles in the single or same base fluid. To gain higher physical properties affected by elevated temperature, optical, physicochemical, and linguistic properties from hybrid nanofluids. These fluids are the best alternative to simple (or general) nanofluids due to some basis for instance, vast absorption span, large thermal conductivity, lower extinction, moderate pressure drop, low frictional losses and pumping power in comparison to single or mono-nanofluids[32)33)]. Different kinds of hybrid nanofluids with base fluids are illustrated in Figure 5.

From Figure 5, the nanoparticles which have higher thermal conductivity along with metallic and non-metallic particles can be utilized as a supplement for the formation of nanofluid by mixing into the base fluid. We can examine the tremendous heat transfer characteristics from Newton's law of cooling given by Eq. 1[34)].

$$Q = hA\Delta t \tag{1}$$

Nanofluids are specialized for increasing the heat transfer rate (Q) by enhancing the heat transfer coefficient due to convection (h) for an unchanging area of heat transfer (A) and difference of temperature (Δt) due to having better thermal conductivity. Whenever the nano-sized rigid particles are blended in the base fluid then, one by one particle shrinks and unstrings an electron at the junction of the base fluid on agglomeration and possesses electrically charged.

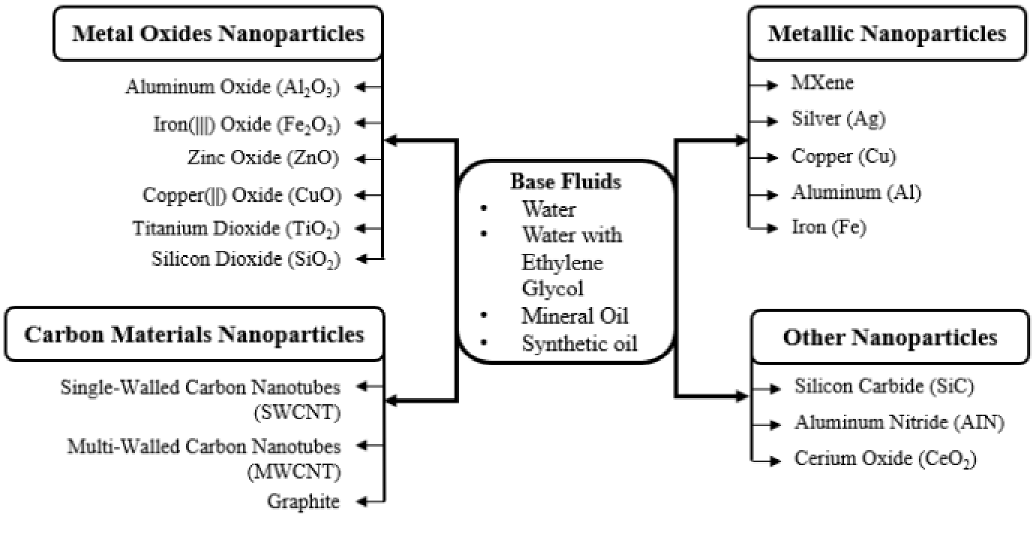

Fig. 5: A Plot of various base fluids and nanoparticles

Brownian motion, which plays a significant role in improving thermal conductivity by increasing small relocation because of the exchange of heat within solid particles throughout their impact, is achieved when Vander Waals' repellent forces in the stable nanofluid grow greatly in comparison to the attracting forces within the particles[35)36)].

An analysis comparing hybrid nanofluids with mono-nanofluids in PTC applications highlights key differences in their benefits and drawbacks. Single-nanoparticle fluids, known as mono-nanofluids, have been extensively studied for their capacity to improve thermal conductivity and elevate heat exchange efficiency in PTC systems. However, studies have shown that hybrid nanofluids, formed by combining two or more different nanoparticles, often exhibit superior thermophysical properties due to the synergistic effects between different particles. For instance, hybrid nanofluids such as Ag-Al_2O_3 or CuO-TiO_2 dispersed in base fluids like Syltherm 800 have demonstrated higher thermal conductivity (up to 15–25% enhancement) and improved convective heat transfer coefficients compared to mono-nanofluids. Despite these advantages, hybrid nanofluids also exhibit higher viscosity and friction factor, leading to increased pumping power and potential pressure drop penalties, which are less prominent in mono-nanofluids. Additionally, stability issues such as agglomeration and sedimentation are more challenging in hybrid nanofluids due to the presence of multiple particle types with different densities and surface properties. Therefore, while hybrid nanofluids offer greater potential for improving thermal efficiency in PTCs, their application requires careful optimization of nanoparticle selection, concentration, and stabilization techniques to minimize drawbacks related to flow resistance and long-term stability.

3.2. Hybrid Nanofluid Preparation Technique

Nanoparticles are fabricated and blended in the base fluid in one step utilizing each perspective, and this perspective obeys the bottom-up scheme[37)]. The single-step techniques associated with making and mixing nanoparticles into the base fluid, in a single process at the same time. This technique avoids depot, drying, transportation, and dispersion which improve the mixing of nanoparticles in the base fluid while agglomeration is minimized. The formation of residuals type points towards the partial reactions between base fluid and nanoparticle. That's the biggest limitation of the single-step technique[38)]. Kumar et al.[39)] used a straightforward, one-step method to reduce copper sulphate with fructose to create copper nanofluids. By using sodium laurel sulphate, the solution phase synthetic approach produced copper particles whose size was constrained to nano dimensions. They examined how various factors influenced the creation and distribution of Cu nanoparticles within the base liquid, which was made up of a 1:1 combination of ethylene glycol and water. It was discovered that the resultant nanofluid had enhanced thermal conductivity and was extremely stable. It was found that the method used to produce stable nanofluid dispersions for heat transfer purposes is simple, cost-effective, and versatile across various material types.

The 2-step technique is mostly used for the formation of nanofluids. In this technique, sol-gel nanoparticle powder is prepared first. Then, this prepared powder is blended with the base fluid by using ball milling and high-shear mixing. Figure 6[40)] presents the basic steps of making nanofluid by a two-step technique. This two-step technique is more beneficial, as this procedure is used in the formulation of nanofluids on an industrial level. But, the limitation of this technique is the accumulation of particles. For this limitation, detergents are added to it to avoid surface tension. However, this limitation indicates to use of a single-step composition technique[41)].

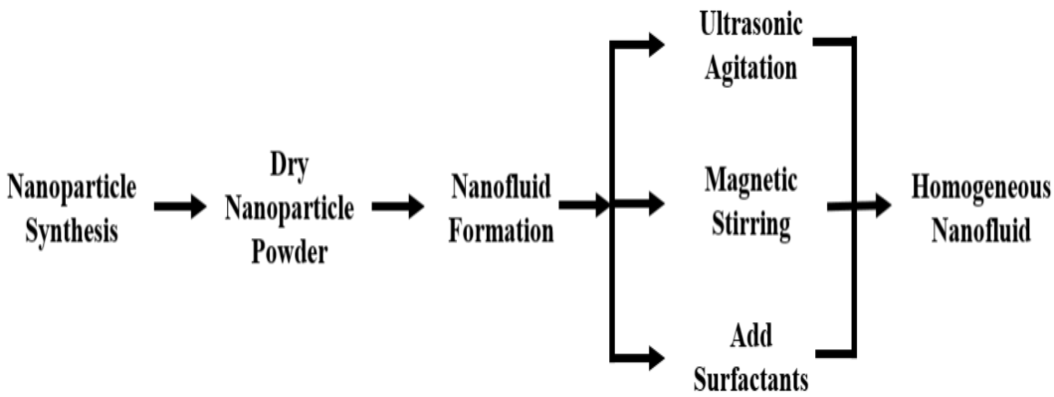

Fig. 6: Steps for two-step technique

Kshirsagar et al.[42)] prepared a biodegradable-based hybrid nanofluid by using a two-step method. With palm oil serving as the base fluid and sodium dodecyl sulphate (SDS) acting as a surfactant to preserve fluid stability, SiC and TiO_2 were utilized as nanoparticles. The study involved samples of palm oil combined with SiC, featuring nanoparticle volume fractions varying from 0.1% to 0.3%, palm oil mixed with TiO_2, also at different nanoparticle volume fractions and a blend of palm oil with both SiC and TiO_2. The results indicated that the SiC-palm oil and SiC-TiO_2-palm oil mixtures, as eco-friendly hybrid nanofluids, showed enhanced surface properties and chemical makeup. At volume concentrations of 1%, 2%, and 3%, a rise in the zeta potential values was found. In machining processes, the eco-friendly hybrid nanofluid formulations, consisting of palm oil combined with 1% volume SiC and TiO2, and palm oil with 2% volume SiC, exhibited enhanced physical, thermal, and rheological properties, as well as improved stability.

4. Stability and Hybrid Nanofluid Properties

4.1. Stability of Hybrid Nanofluid

For a nanofluid to last longer, stability is one of the most crucial factors. Hybrid nanofluids consist of multiple types of nanoparticles dispersed within a base fluid, such as water or oil. Due to their property clutter thus they lose their potential to transfer heat[43)]. The stability of nanofluids acts as an important property for the most suitable nanofluids that can reform their thermophysical properties for tactics. Chemical (addition of surfactant, surface treatment, and pH regulation) and physical (ultrasonic agitation, homogenization, and ball milling) methodologies were generated to enhance the durable stability and thermal properties of the nanofluids[44]. Figure 7 illustrates methods to increase stability through interactions between and within the particulates surrounding a liquid, creating two opposing forces: (i) Vander Waals forces that cause particles to be stirred up to one another and form clusters before being detached from the base fluid and falling to the bottom surface, and (ii) the electrical dual layer repulsive forces that cause particles to be separated from one another over electrostatic repellent forces[45)46)].

Aich et al.[47] sought to boost the performance of concentric counter flow heat exchangers through experimental improvements in the stability of graphene based nanofluids. The synthesis and characterization of graphene suspensions were emphasized, with a focus on assessing the dispersion characteristics of the materials in water, ethanol, acetone, and dimethyl formamide (DMF). XRD, DSC, and FTIR were used to analyze the graphene powder in detail. Next, graphene suspensions were made and combined evenly with the use of an ultrasonic vibrator and a magnetic stirrer. The analysis verified that the kind of solvent had a major impact on the suspensions' solubility and stability. In contrast to those in acetone, solutions of rGO in water, ethanol, and DMF showed exceptional long-term stability. The best solvent for creating the thermal transfer fluid turned out to be water. At $\varphi = 0.5\%$ concentration, the addition of graphene led to an approximate 48.15% increase in conductivity, while the highest thermal efficiency was achieved at volume fraction 0.35% and a discharge of 3 liter/min. In addition, it is best to steer clear of larger concentrations at lower flow rates in order to preserve ideal thermal efficiency.

The sustained consistency of nanofluids is vital for preserving the thermal performance of PTCs during prolonged operation. Nanofluids, engineered by dispersing nanoparticles into base fluids, are known to enhance thermal conductivity and, consequently, improve the thermal performance of PTCs. However, the practical application of nanofluids faces significant challenges related to particle agglomeration and sedimentation. Over time, nanoparticles tend to cluster and settle, leading to a degradation of the nanofluid's uniformity. This sedimentation can cause clogging in the absorber tubes, resulting in increased pressure drops and reduced heat transfer efficiency. Research indicates that this instability may reduce the thermal efficiency of PTCs, as the non-uniform dispersion of nanoparticles adversely affects the fluid's thermophysical properties[48]. Furthermore, the accumulation of nanoparticles on the inner surfaces of PTC components can lead to fouling, which impairs heat absorption and increases thermal resistance. This not only reduces the system's efficiency but also necessitates frequent maintenance, thereby elevating operational costs. Ensuring the stability of nanofluids is, therefore, essential to prevent such issues and to sustain the enhanced heat transfer capabilities that nanofluids offer. Research indicates that stable nanofluids can improve the effectiveness of thermal systems, emphasizing the importance of developing formulations that resist agglomeration and sedimentation. To address these challenges, it is imperative to focus on advanced synthesis methods that promote long-term dispersion stability, such as the use of appropriate surfactants and surface modification techniques[49]. Additionally, real-time monitoring of nanofluid stability and the development of standardized testing protocols are vital to ensure consistent performance. By overcoming stability-related limitations, the full potential of nanofluids can be harnessed, leading to significant improvements in the long-term operational efficiency of PTCs.

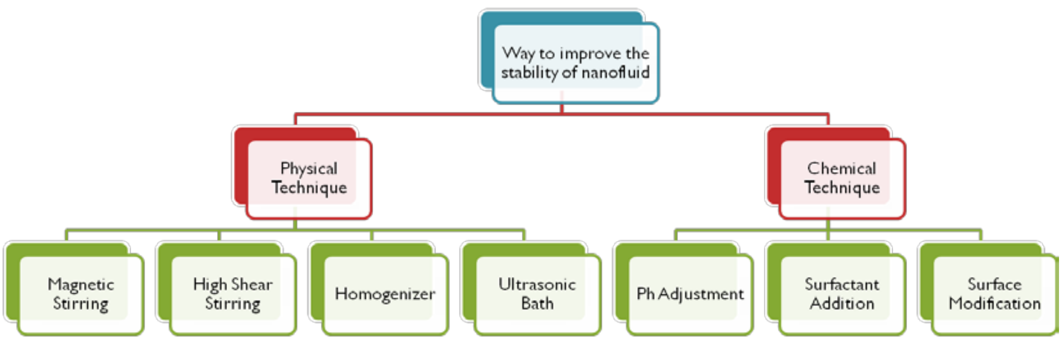

Fig. 7: Ways to improve the stability of hybrid nanofluid

4.2. Thermophysical Properties of Hybrid Nanofluid

The thermal conductivity (TC) of a fluid acts as an important property in its heat transfer ability. Nanofluids are deliberately high-grade to their base fluid due to the generation of the newest fluid with totally distinct thermophysical effects like thermal conductivity and many more[50]. The following describes the main thermophysical characteristics of nanofluids in Figure 8[51].

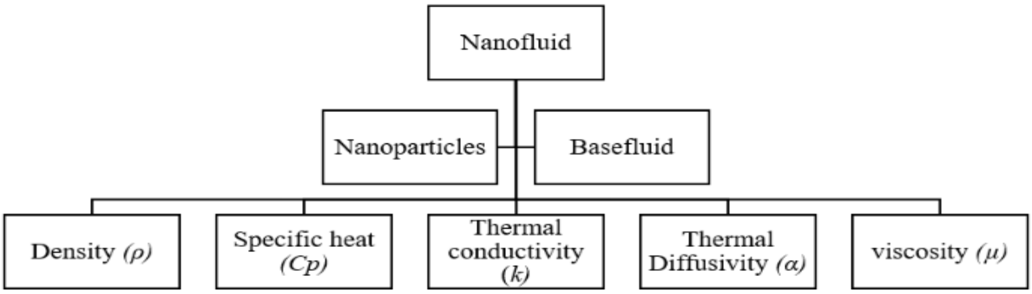

Fig. 8: Nanofluid thermophysical properties

4.2.1. Density

The density of a material is determined by its mass divided by its volume. In most experiments, the density of different materials changes with temperature and pressure is to be found. It will not affect solids and liquids but affect gases. In most nanoparticles, the reduced density of heated fluid causes an increase in temperature from the base to the top of the container holding nanofluids[52]. The effective density of nanofluids is a crucial property that gives direction to the nanofluid's application, but, has prevailed very less study among researchers. In regards to the effective density, a far-reaching model has been forecast for effective density properties[53]. The density of hybrid nanofluid is calculated using Eq. 2 as

$$\rho_{hnf} = \rho_f(1-\emptyset_2)\left[(1-\emptyset_1)+\emptyset_1\left(\frac{\rho_{s_1}}{\rho_f}\right)\right]+\phi_2\rho_{s_2} \qquad (2)$$

Where ρ_{hnf} is density of hybrid nanofluid, ρ_f is density of basefluid, $\emptyset_1$ and $\emptyset_2$ are Solid volume fraction of nanoparticles 1 & 2 and ρ_{s_1} & ρ_{s_2} solid density of nanoparticles.

Adun et al.[54] examined density effects by combining three different types of nanoparticles in the base fluid. The notion of ternary-hybrid nanofluids, which blend three distinct kinds of nanoparticles in a variety of mixing ratios, is fascinating but largely theoretical. It is crucial to optimize the mixing ratio for efficient heat transfer properties in energy-related applications. In this study, a novel $Al_2O_3/ZnO/Fe_3O_4$ ternary nanofluid is created, and its density is assessed. Three distinct mixing ratios (1:1:1, 2:1:1, and 1:2:1) were used in the creation of the nanofluid, with a volume fraction ranging from 0.5% to 1.25%. An explanation of the density prediction analysis is also included in this work. As a consequence, the maximum density is found to be 1165 kg/m^3 at a temperature of 25 °C and a volume per cent of 1.25%.

4.2.2. Specific Heat

The specific heat capacity of a nanofluid refers to the quantity of thermal energy required to raise the temperature of one gram of the fluid by one degree Celsius. This characteristic provides a reliable indicator of the nanofluids' rate of heat transfer. The specific heat capacity of the nanofluid is reduced as the concentration of nanoparticles in the fluid increases. The specific heat of hybrid nanofluid is calculated using Eq. 3 as

$$(\rho.C_p)_{hnf} = (\rho.C_p)_f(1-\emptyset_2)\left[(1-\emptyset_1)+\emptyset_1\frac{(\rho.C_p)_{s_1}}{(\rho.C_p)_f}\right] + \emptyset_2(\rho.C_p)_{s_2} \qquad (3)$$

Where C_p and C_P are specific heat at constant volume and constant pressure respectively.

Additionally, Zhou and Ni[55] found that the water-based alumina nanofluid's specific heat proportion decreased, and that the specific heat amount decreased uniformly as particle immersion increased. In this piece[56], the specific heat capacity (SHC) of a nanofluid consisting of 1.0% SiO_2 nanoparticles by mass and Melton Solar salt (MSS) was measured using DSC. The specific heat capacity of the nanofluid was found to be notably higher than that of pure MSS. In contrast to pure MSS, the nanofluid with 1.0% SiO_2 nanoparticles exhibited a 15.65% higher average SHC. Some published research with experimental evidence suggests that the creation of nanostructures following NP doping may raise the SHC of molten salt (MS) nanofluids. However, no comprehensive theoretical or computational research has been done to confirm the experimental results of MSS nanofluid.

4.2.3. Thermal Conductivity

This property plays a main role in the enhancement of the thermal conductivity among the nanofluids in comparison to normal fluids, which improves the heat transfer rate of a fluid. The nanoparticles have a higher thermal conductivity than their base fluid which will improve thermal conductivity on adding or mixing each other. The first correlation was developed by the Maxwell model in 1881, which is prone to finding the effective thermal conductivity of nanofluids[57]. The thermal conductivity of hybrid nanofluid is calculated using Eq. 4 as

$$\frac{K_{hnf}}{K_{bf}} = \frac{K_{s_2}+(m-1)K_{bf}-(m-1)\emptyset_2(K_{bf}-K_{s_2})}{K_{s_2}+(m-1)K_{bf}+\emptyset_2(K_{bf}-K_{s_2})} \qquad (4)$$

Where K_{hnf} & K_{bf} are the thermal conductivity of hybrid nanofluid & base fluid respectively. K_{s_2} & m are the thermal conductivity of solid particle and shape factor respectively.

Bijapur et al.[58] utilized two base fluids to distribute the nanoparticles: EG and a 60:40 blend of DI and EG. In order to increase TC values, optimization experiments were carried out using different stirring and measuring intervals. The findings demonstrated a 91.9% increase in TC over the base fluid EG when a 40 mW power source was supplied at a high volume fraction of NPs (i.e., 0.1 wt %). When compared to the base fluid DI-EG (60:40) at a concentration of 0.1 weight percent and a heating power of 80 mW, DI-EG-based nanofluids demonstrated improvements of up to 45%. These findings showed that adding NP significantly improved TC. Subsequent trials involved adjusting the temperature within the 30-80°C range, recording data at each 10°C rise. The results demonstrated a clear correlation with the TC values. At 80°C, the EG-based NFs exhibited increases of 77%, 111.49%, 139.67%, and 175% at nanoparticle dispersion of 0.01, 0.02, 0.05, and 0.1 weight percent, in that order.

4.2.4. Thermal Diffusivity

Thermal diffusivity measures how quickly heat disperses within nanofluids. It is the measurement of heat transfer in nanofluids. In regards to the effective thermal diffusivity of nanofluids, very few papers are being published. The method that is prone to identify the thermal diffusivity value of liquid is the thermal lens technique which is a very delicate method. This method is advantageous because it has an extremely high sensitivity, needs a small sample size, and is dependent on the thermo-optical effects of the solvent[59]. The thermal diffusivity of hybrid nanofluid is calculated Eq. 5 as

$$\alpha_{hnf} = \frac{K_{hnf}}{(\rho C_p)_{hnf}} \quad (5)$$

Pius et al.[60], describe how the improved thermal diffusivity and magnetic tunability of zinc ferrite nanofluids make them an excellent option for heat transfer fluids. The thermal diffusivity of the nanofluids was then assessed using the dual-beam thermal lens approach, revealing a three-fold increase over the thermal diffusivity of the basic fluid, water. Further experiments revealed that thermal diffusivity could be adjusted magnetically. It was determined that this increase was six times greater than what would have been seen without a magnetic field. By employing optical imaging and field emission SEM to study the nanofluid under a magnetic field, the research was enhanced, revealing the critical role of percolation due to nanoparticle aggregation, which is crucial for the magnetic tunability of thermal diffusivity.

4.2.5. Viscosity

Viscosity is a property of heat transfer fluid that resists the characteristics of transferring fluid heat among a nanofluid. Commonly, nanoparticle suspension in the liquid increases the fluid viscosity. The fluids are categorized into two groups; (i) Newtonian, and (ii) non-Newtonian. Newtonian fluids are those in which the shear stress of a fluid immediately correlates to the deformation rate at constant pressure and temperature otherwise it's called non-Newtonian[61]. The first efforts were made by Einstein using phenomenological hydrodynamic equations to determine the effective viscosity of suspensions of spherical matter[62]. The viscosity of hybrid nanofluid is calculated using Eq. 6 as

$$\mu_{hnf} = \frac{\mu_f}{(1-\emptyset_1)^{2.5}(1-\emptyset_2)^{2.5}} \quad (6)$$

Where μ_{hnf} & μ_f are the dynamic viscosity of hybrid nanofluid and base fluid.

Giwa et al.[63] have shown that, in comparison to its base fluid, the hybrid nanofluid greatly enhances both viscosity and thermal conductivity. The viscosity rose by 35.7%, improving its performance in applications involving heat control. Furthermore, higher temperatures increased electrical conductivity by 1676.4% while decreasing viscosity. The hybrid nanofluid is now much more appropriate for engineering applications where electrical and thermal characteristics are crucial thanks to these advancements.

4.3. Impact of Viscosity on Heat Transfer Efficiency

The viscosity of nanofluids significantly influences the heat transfer performance of PTCs. Elevated viscosity can lead to increased frictional losses and pressure drops, which may diminish the overall thermal performance of the system. For instance, Subramani et al.[64] observed that incorporating TiO_2 nanoparticles into deionized water enhanced the CHTC by up to 22.76%; however, this enhancement was attended by a rise in pressure drop due to increased viscosity. Similarly, Sivarman et al.[65] reported that SiO_2 nanofluids with smaller particle sizes (e.g., 20 nm) exhibited higher thermal efficiency enhancements (approximately 26%) compared to larger particles. This effect stems from the increased surface area relative to volume in smaller nanoparticles, which enhances thermal conductivity but also contributes to increased viscosity. Therefore, optimizing nanoparticle concentration and size is essential to balance the benefits of improved thermal conductivity against the drawbacks of increased viscosity and associated pressure drops in PTC systems. Additionally, elevated viscosity adversely impacts the Reynolds number and Nusselt number, which are key indicators of convective heat transfer performance. As hybrid nanofluids transition from laminar to turbulent flow regimes in receiver tubes, the shear-thinning or thickening behavior alters the boundary layer characteristics, influencing thermal energy absorption and fluid dynamics. These effects are especially relevant for solar thermal systems operating under varying solar flux and temperature gradients[66].

5. Role of Hybrid Nanofluid in Solar Parabolic Trough Concentrator

The research related to the relevance of nanofluids is the talk of the hour. As the utilisation of nanofluids has increased, many investigations have been done on the development of nanofluids in solar concentrators. Many researchers have published reviews and short updates on the purpose of nanofluids in solar concentrators [67-72]. Still, a lot of research is required to enhance the stability of nanofluid and also to enhance the performance of trough concentrators using hybrid nanofluid. In this section role of hybrid nanofluid in solar concentrator is briefly discussed.

The lower-temperature nanofluids used in DASC were examined hypothetically by Tyagi et al[73]. They researched that nanoparticles of Al_2O_3 mixed with water (base fluid) which has a particle volume fraction of 0.1% to 5%) exploited the concentrator's effectiveness. In addition to altering the particle volume fraction, the glass cover transmissivity and concentrator height also revealed a slight improvement in the concentrator's effectiveness. Based on available research, PTC efficiency improved by 8% for volume fractions between 0.8% and 1.6%, with nanoparticle size having minimal influence on performance enhancement.

Another test was done by Hatamiet et al.[74] on a CPTC to report an increase in efficiency by using various nanofluids such as CuO_2, Fe_3O_4, TiO_2, and Al_2O_3. They examined several characteristics, including the sort of nanoparticle, its size, its concentration, and the effect of Rayleigh number (Ra) on Nusselt number (Nu). They discovered that the Cu nanoparticles shown in Figure 9 have a greater local and average Nu. They concluded that the Cu nanoparticle is better suited for use in nanofluid applications in PTC than whole nanoparticles, and they also reported that all of the properties rise in opposition to the Nusselt number as Cu nanoparticle volume concentration increases.

Recently, Paul et al.[75] described their investigational report on future-generation solar collectors (CSP) using NEILS as base fluids, their investigation described that thermal conductivity was increased by 5% subjected to the base fluid and ionic concentration. The heat capability of nanofluids using Al_2O_3 nanoparticles was increased by 23% to 26% in regards to utilizing silica nanoparticles and likewise, a 20% boost in convective heat transfer capability was also obtained. All research regarding nanofluid thermal conductivity and many other properties helps us in the development of solar concentrators as well as increases the rate of harnessing solar power. Ajbar et al.[76] use eight different hybrids to enhance the thermic effect of a parabolic trough concentrator. This experiment is executed with a model that succeeds in SNL's experimental data by utilizing purified Syltherm 800. The build-up model gives good experimental research with an approximate error of 1.9% and 2.3% to evaluate the outlet temperature and thermic effectiveness. They concluded that the higher thermic conductivity of the established nanoparticles was the cause of the high thermic conductivity of the hybrid nanofluids. They noticed that all of the studies using the hybrid nanofluids achieved a similar improvement in dynamic viscosity of 7.91% and an improvement in TC of roughly 9% over the pure Syltherm 800. The friction factor variation for the various hybrid nanofluids that have been compared to Syltherm 800 is shown in Figure 9. It has been discovered that as the Reynolds number rises, the fluid temperature and volumetric flow will raise as well, which lowers the friction factor of hybrid nanofluids.

The findings indicate that using hybrid nanofluids significantly increases the friction factor compared to the base fluid, Syltherm 800, across the entire range of Reynolds numbers, primarily due to enhanced fluid viscosity and particle–fluid interactions. This elevated friction factor directly implies higher pressure drops and consequently greater pumping power requirements in PTC systems. However, the decreasing trend of friction factor with increasing Reynolds number suggests that operating at higher flow rates can partially offset the increased frictional losses. Therefore, while hybrid nanofluids enhance thermal performance in PTCs, careful optimization of nanoparticle type, concentration, and flow conditions is essential to balance heat transfer benefits against the additional pumping power penalties.

As much research and experimental investigation have been done on the performance of hybrid nanofluids, one of the experimental studies was examined by Hamada et al.[77]. In this experimental study, they focused on enhancing the parabolic trough concentrator thermal power analytically. They build an analytical arrangement with the help of tracking solar radiation to increase absorptivity. They used TiO_2 nanofluid as the heat transmits fluid in the presence of a coated absorber tube and they utilize graphite to fill the ring within the absorber tube and receiver tube. The thermal efficiency of multiple setups is analyzed and collated with that of the reference one, and then a contrast of all setup's thermal efficiencies is built.

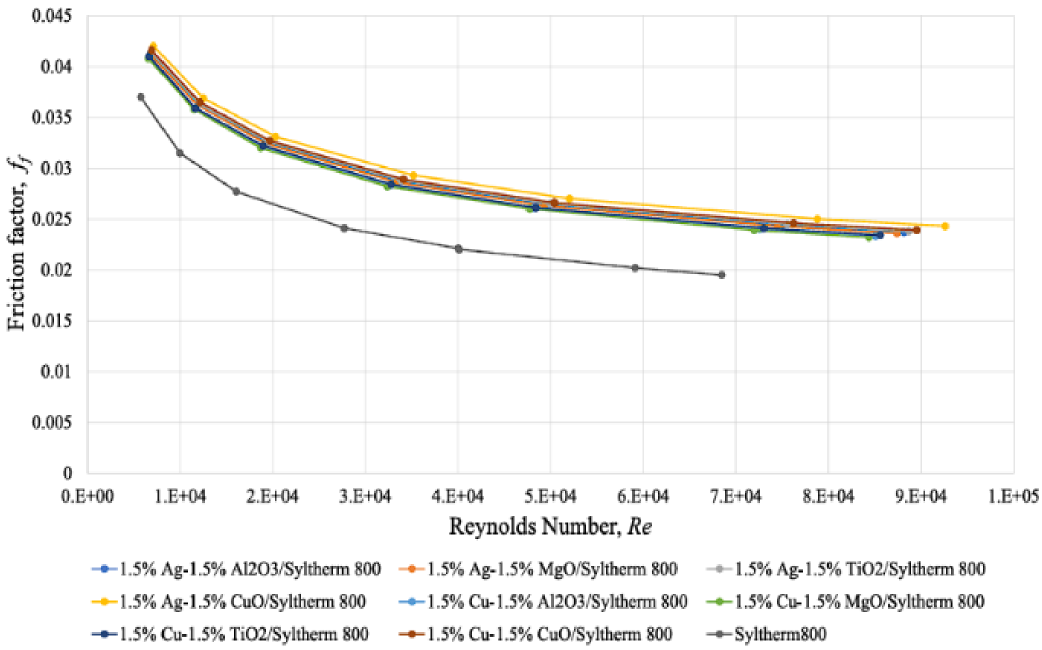

Figure 9: Contrast of friction factor's outcome of the hybrid nanofluids and syltherm 800 against Reynolds number[76)]

They investigated the temperature variation rise as the aforementioned system is altered, the outlet heated water temperature, and the thermal performance. Additionally, their findings revealed that the maximum enhancement in temperature variation for the G PTC is 82.5% greater than for the R PTC. The one advantage of G PTC is that it can be used throughout the entire day with almost the same effectiveness and this shows that it can be utilized effectively in any weather circumstances. Figure10 shows the moderate efficiency, outlet temperature (TW-out), inlet temperature (TW-in) and temperature difference (TW-out -TW-in) of all cases.

Hayati et al.[78)] have done an experiment on a parabolic trough concentrator receiver tube with elliptical fins that have dimples. They developed a C++ code to implement a non-uniform heat of flux on the receiver tube's outside while obtaining real-world operating conditions. Different types of nanofluid, such as mono and hybrid nanofluid with different volume fractions of nanoparticles were employed as a working fluid. They looked at the convective heat transfer rate property, exergy analysis, and entropy generation for the parabolic trough concentrator's plain and concave receiver tubes. Their experimental research revealed that when a receiver tube is moved without an elliptical concave fin, the minimum friction factor is 0.0314 and that it is exceptionally maximized by 49.68% for elliptical dimpled fins and increased by 8.6% for concave receiver tubes. The optimum fluid for their study was a hybrid nanofluid made of 1.5% Al_2O_3 and 0.5% TiO_2/Syltherm800, however, they still recommended the elliptical ratio of a: b=5:3. They also concluded that at this ratio Nusselt number was increased approximately 38% at Reynolds number 30000.

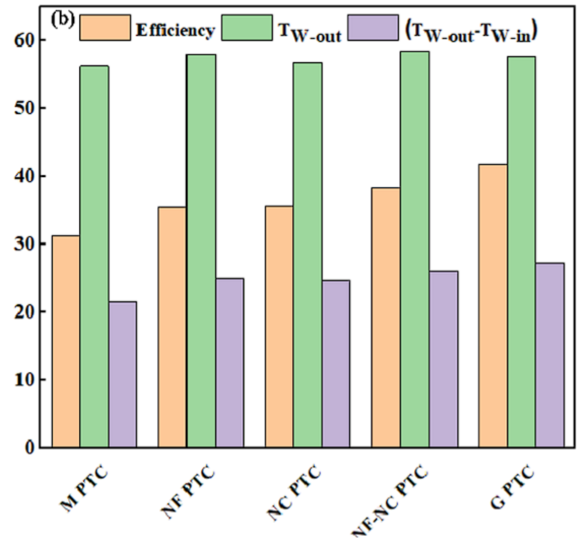

Fig. 10: Graphical representation of the moderate efficiency of all cases[77)]

Vahidinia et al.[79)] evaluated the use of hybrid nanofluid MWCNT-Fe_3O_4 /Therminol in PTC. They used this hybrid nanofluid in their study to evaluate a PTC's thermal, energy, economic, and environmental performance utilising smooth and flipper absorber tubes, and they found that it correlates with mono nanofluids. They continued to state that PTC has a 7.8 (m) length and a 5 (m) breadth. They found that substituting the base fluid with single or mixed nanofluids has minimal impact on the thermal efficiency of the PTC. Efficiency improves by up to 0.3% when employing a finned absorber tube rather than a plain one. Additionally, the energy efficiency dropped by 3.24% when the inlet fluid temperature increased from 400 to 600

(K).

Another study of hybrid nanofluids deals with the MWCNTs submerged in H_2O and a mixture of Al_2O_3, based on the environmental execution of a direct absorption PTC was done by Amirarsalan et al.[80]. In their performance analysis, they performed the spectrometric analysis which reveals that; since hybrid nanofluids offer superior optical effects than mono nanofluids and the base fluid, they will be more appropriate for usage in enhancing the DAPTC's thermal performance. Environmental studies and the ASHRAE 93–10 standard was used to examine the use of hybrid nanofluids, alumina nanofluids, and MWCNTs nanofluids in different volume fractions on a DAPTC thermal execution. They concluded some outcomes like in DAPTC fluid which has a higher extinction coefficient have higher thermal efficiency in DAPTCs. They also concluded that increasing the flow rate of heat transfer flow results in a decrease in the friction factor of fluids.

Mohamed et al.[81] analyzed the solar water pump using copper-gold/engine oil with hybrid nanofluid running in PTCs through which they investigated the thermal transfer real execution of the solar water pump in the existence of parameters like viscous effect, heat dissipation, and solar radiation as well as entropy investigation for Oldroyd-B fluid was also analyzed. They obtained numerical calculations for both mono as well as hybrid nanofluid. The variation in controlling parameters reports the variation in heat transfer, thermal conductivity and many other parameters.

In regards to the role of nanofluid in different applications of a compound parabolic concentrator as shown in Figure 11, the energy, hydraulics, and exergy were analyzed first time in a past study by Khaledi et al.[82] experiment. In this experiment, a CPC was constructed and built following specifications, and analytical thermal efficiency tests were then carried out on days with ideal conditions. In that experiment, they employed EG – H_2O base fluid with SiO_2/MWCNT hybrid nanoparticles (volume concentration varied from 0 to 10%). The final finding demonstrates that using hybrid nanofluids improves thermal characteristics and Nusselt number, increasing thermal efficiency more than utilizing the base fluid. Using hybrid nanofluids generally resulted in a 14.27% enhancement in thermal efficiency over the base fluid. Additionally, this resulted in a rise in energy efficiency. As a result, the maximum pumping power gain found with hybrid nanofluids was 9.72%, indicating that the net generation of the beneficial heat rate outweighs the desire for pumping power of the beneficial heat rate.

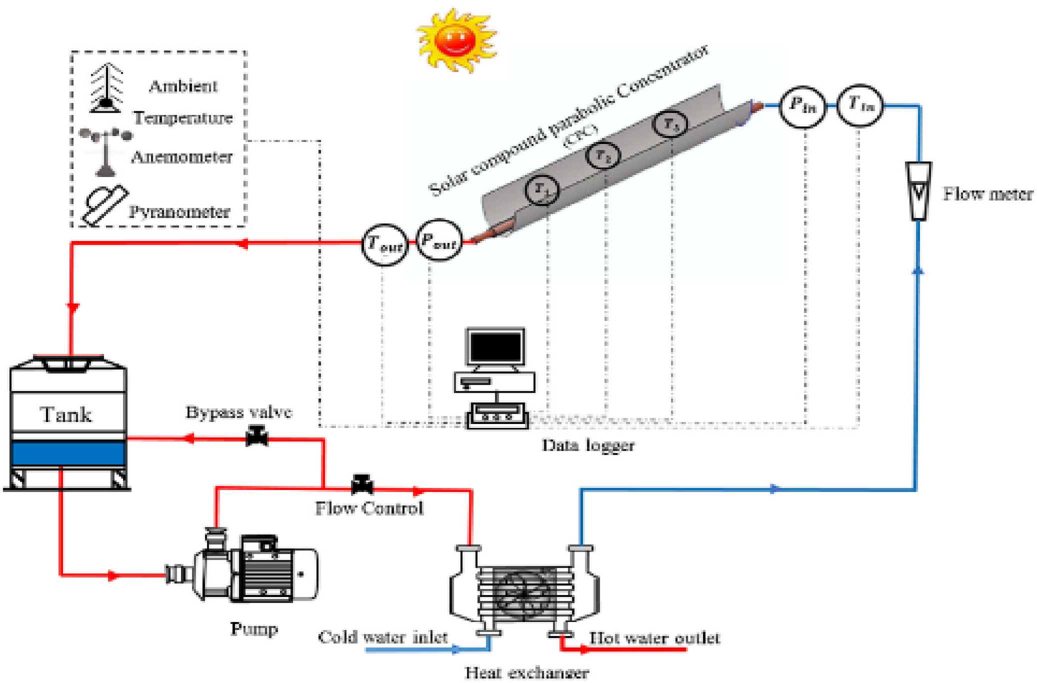

Fig. 11: Line diagram of CPC Experimental Set-up beneficial heat rate[82]

Adun et al.[83] examined the energy/exergy analysis of a Kalina cycle with a PTC that uses a ternary nanofluid as the HTF. The efficiency of the integrated Kalina cycle based on solar radiation absorption and the volume fraction of the nanofluids is assessed using a variety of nanofluids and compared to more conventional fluids like salt, thermal VP1 oil, and Dow Thermal oil. In conjunction with this experiment, they carried out a complex analysis to use a genetic algorithm to increase the system's overall energetic efficiency and the Kalina cycle's net power production. The findings indicate that the system's highest energy output was achieved by incorporating various nanoparticles in the experiment, with the power generated being measured. The $MgO-TiO_2$ ternary nanofluid has the maximum system exergy efficiency at a volume fraction of 0.01 and superior system energy and exergy efficiency at a volume fraction of 0.001 when compared to Al_2O_3-Fe nanofluid.

To improve the heat transfer efficiency of nanofluids, Farooq et al.[84] did a CFD analysis to compute the efficiency of PTC using two working fluids i.e. alumina and copper-oxide nanofluids. They kept different concentrations of 0.01% of a working fluid in the nanofluids. As they looked at the efficiency of PTCs in terms of mass flow rate, they found that Al_2O_3 nanofluids achieved the highest efficiencies of 13.1% at 0.0224 kg/s mass flow rate whereas CuO nanofluids recorded maximum efficiencies of 14.79% at the same flow rate. They advise raising the fluid's exit temperature by utilising the heat-absorbent metals copper and aluminium. Copper has a maximum output temperature of 311 K, while steel and aluminium appear at lower fluid exit temperatures of 307 K and 308 K. They also researched to determine the optimal length of the receiver tube given the temperature of the working fluid. They express in their calculations that adopting nanofluids as the working fluid in PTSC can boost the total thermal efficiency by up to 1% to 2%.

Oran et al.[85] conducted a second experimental demonstration on the performance of two comparable PTCs in Amman, utilizing distilled water and nanofluid as fluids to increase PTC performance against the weather. The mass flow rate was used as a constraint during the creation and testing of these two identical PTCs. Ceria was also used at four different volume fractions ranging (0.01% to 0.1%) in PTC. One of the PTCs was employed as a thermic fluid in water. The PTC's thermal efficiency was investigated for different concentrations of ceria nanofluid mixed with pure water, as well as for the production of nanofluids and stability tests. Their results showed that the maximum thermal efficiency was reached. From that variation, the concentration was raised to get the highest optical thermal efficiency. In other words, 47.7% was seen at 0.1% volume concentration. Once the experiment was finished, the noted results were compared to solid work simulations for various scenarios. Their results are quite precise, with exit temperature exceeding 0.10% and average thermal efficiency not exceeding 2.19%.

Nazir et al.[86] utilized a thermal plasma approach to create hybrid nanofluids (HNFs) containing ZnO-MgO nanoparticles in various base fluids, including motor oil, coconut oil, distilled water, and pristine coolant. The resulting HNFs demonstrated enhanced thermal conductivity, with the most significant increase observed in coolant-based HNFs, which exhibited a 19% improvement at 60°C as shown in Figure 12. Notably, the study found that the band gap of the HNFs decreased for coolant and engine oil-based HNFs while increasing for coconut oil-based HNFs. The results suggest that HNFs have tremendous potential as next-generation heat transfer fluids, particularly in optoelectronic devices such as solar cells, and highlight the importance of precise control over nanoparticle size to affect band gap and optimize performance.

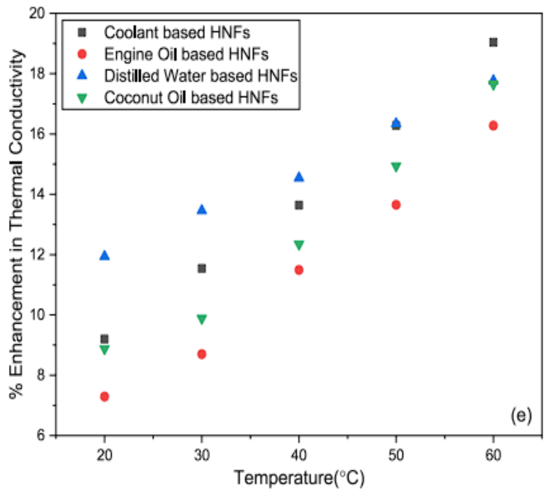

Fig. 12: Comparison of thermal conductivity of different base fluid-based hybrid nanofluids[86]

Mohammed et al.[87] conducted a 3D mathematical evaluation of various hybrid nanofluid types dispersed in a Syltherm 800 with varying nanoparticle concentrations (1.0% -2.0%) and different shapes (platelets, bricks, blades, and cylindrical) while submerged in a PTC setup with a central wavy booster. They looked at the difference in friction factors between Fe_2O_3-GO/Syltherm oil hybrid nanofluids and Fe_2O_3-GO /Syltherm oil, which has the lowest value. In contrast to thermal oil, hybrid nanofluids reduce the overall entropy creation, as stated by the second law of thermodynamics. For all of the volume concentrations, it appears advantageous to use a Reynolds number in their numerical analysis between 5000 and 80000. While dealing with a Re number greater than 80000 seems disadvantageous. By using brick-shaped nanoparticles in their numerical analysis, the overall thermal assessment standard is discovered to be between 1.24 and 2.46. The results show an 18.51% increase in thermal efficacy and a 16.21% increase in exergetic effectiveness. The entropy propagation ratio and rate can both decrease by a maximum of about 48.27% and 52.6%, respectively. Using hybrid nanofluids, they created a connection between the Nusselt number, thermal efficiency, and friction factor for PTC tubes with wavy boosters.

The importance of hybrid nanofluids in regulating mass and heat transfer phenomena is examined by Li et al.[88] The results show that hybrid nanofluids based on motor oil have better heat transfer properties than those based on water, and that hybrid nanofluids based on water have better mass transfer properties. Furthermore, hybrid nanofluids based on motor oil work better in endothermic processes, whereas hybrid nanofluids based on water have a noticeable influence on heat transfer in exothermic reactions. Additionally, when exposed to external pollution sources, water-based hybrid nanofluids show lower pollutant levels than engine oil-based hybrid nanofluids. These findings offer insightful advice on how to choose the best hybrid nanofluids for certain engineering uses.

Hanif et al.[89] use Ag–TiO_2 nanoparticles to enhance heat transmission in an inclined cavity. A unique feature of the study is the evaluation of the proposed thermal system's efficiency under the influence of magnetic fields and thermal radiation. The heat transmission capabilities of a conventional fluid, nanofluid, and hybrid nanofluid have also been compared. The FEM technique is applied to compute numerical results. The calculations are performed using a program called MATLAB. The temperature of the liquid rises noticeably when a magnetic field is appliedand thermal radiation is present. The rates of heat transmission increased to 2.5% and 1.6% with 4% vol. of Ag–TiO_2 and TiO_2, respectively. The ability of nanoparticles to transport heat is enhanced by the application of a magnetic field. Ag addition to TiO_2/H_2O nanofluid enhanced heat transfer rates by 0.4% when thermal radiation was applied and by 0.2% when it wasn't.

Zeid et al.[90] compare the thermal efficiency of FPSC and PTC in their study. FPSC and PTC are frequently utilized for domestic SWH applications. The effect of nanofluid on SWH systems was examined. The analysis's findings showed that PTSC operated more efficiently than FPSC. Two different types of nanofluids were used to test the PTSC and FPSC systems' performance. Water-soluble carbon nanotubes and ethylene glycol were employed. Ethylene glycol nanofluid considerably increased the average thermal efficiency of FPSC and PTSC systems to 64.1% and 80.6%, respectively. According to Figure 13, the FPSCs and PTSCs reduced their CO_2 emissions by 31.26 kg/day and 39.28 kg/day, respectively, when the ethylene glycol nanofluid was present. CO_2 emissions are noticeably lower as a result of solar collectors' clean, sustainable energy production.

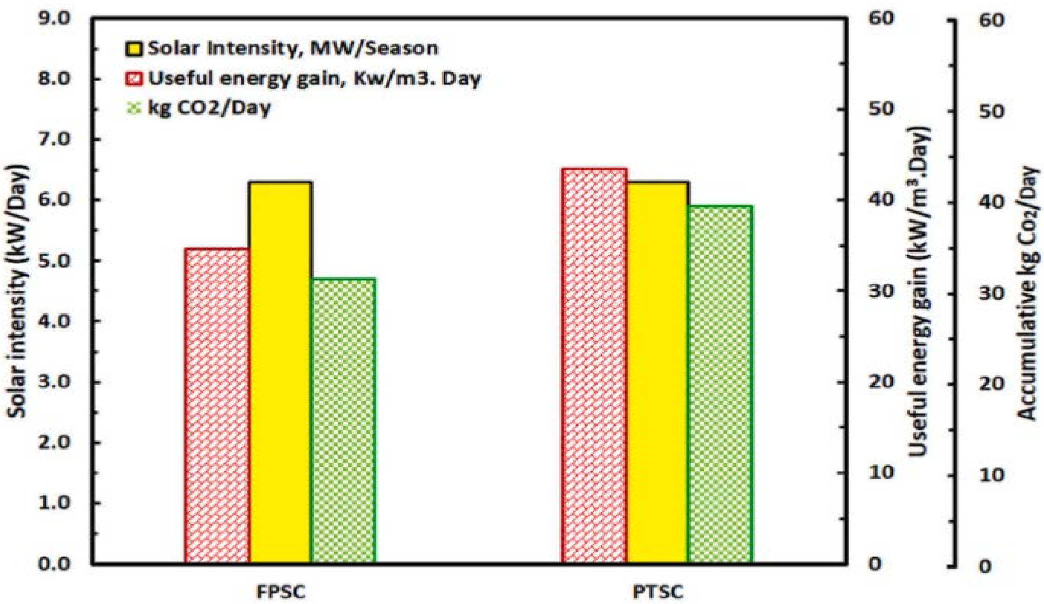

Fig. 13: Shows how different solar collecting systems can reduce CO2 emissions, and harvest freshwater daily[90]

Alhamayani et al.[91] centered on modeling the effectiveness of the PTSC after introducing Al_2O_3+TiO_2 to a variety of base fluids, including thermal oil and molten salts, in order to increase efficiency. Three thermal oils that are utilized as base fluids and have hybrid nanoparticles added to them. It is found that the inlet temperature has some bearing on the choice of base fluid. Thermal oils with intake temperatures ranging from 300 to 650 K have improved the PTSC's thermal and energy efficiency by approximately 0.99% and 0.59%, respectively, with the addition of Al_2O_3–TiO_2. Among thermal oils, Syltherm-800/Al_2O_3-TiO_2 has the highest energy efficiency of 24.1%. Slimani et al.[92] innovative-fluid PV/T system was created. A copper radiator was attached to the rear surface of the m-Si-PV module using a copper tube. The findings showed that their setup's overall efficiency achieved a value of 94.53%. The effect of cooling techniques on the effectiveness of Trombe walls fitted with PV technology was investigated by Abdullah et al.[93] The researchers looked at a variety of PV system configurations, such as water-cooled, air-cooled, and standard systems without cooling. They also looked at systems that combined air and water cooling. The water-based cooling system achieved the peak thermal efficiency of 39.81%

Abdulmajeed et al.[94] study investigated the effects of fluid air and water mass-flow rates on the thermal efficiency of two distinct types of PV/T systems. The power output of the PV modules has grown dramatically with the use of bi-fluid cooling techniques. The air-based PV/T system only achieves a thermal efficiency of 35.56%, whereas the bi-fluid system achieves a thermal efficiency of 64.57%.

Table 2 presents a summary of recent studies highlighting the efficiency improvements achieved using nanofluids and hybrid nanofluids in PTC systems, showcasing their enhanced thermal, electrical, and energy absorption performance.

Table 2: Reported Efficiency Improvements of Nanofluids/Hybrid Nanofluids in PTC Systems from Recent Studies

Ref. No.	Nanofluid Type	Nanoparticle Concentration	Efficiency Improvement (%)
[95], 2020	Al_2O_3-TiO_2	2 wt%	17.6
[96], 2021	CuO-water with PCM	0.4 wt%	76.34
[97], 2022	TiO_2/DI-H_2O	0.2 vol%	8.66
[98], 2023	Graphene oxide/SiO_2	-	9
[99], 2024	Cu- Al_2O_3	0.02 vol. fraction	12.2
[100], 2024	MWCNT/Fe_3O_4	4% volume of Fe_3O_4	2.5

6. Generation of Green Hydrogen via Carbon Capture and Water Splitting System

The development of green hydrogen production relies on PTCs, especially when combined with water-splitting and carbon capture technologies. PTCs provide the high temperatures required for the thermochemical reactions that produce hydrogen by directing sunlight onto a receiver tube. Concentrated heat makes it easier for water molecules to split into hydrogen and oxygen in water-splitting processes like thermochemical cycles, increasing efficiency. PTCs can also be used in solar-assisted carbon capture systems, which use thermal energy to renew solvents rich in CO_2 so that carbon dioxide can be captured and used later. By turning CO_2 into useful fuels, this integration not only increases overall energy efficiency but also helps lower greenhouse gas emissions. The viability of employing PTCs in solar-assisted carbon capture has been shown in recent research, underscoring their potential for use in sustainable energy applications[101].

Additionally, the stability and scalability of hydrogen production are improved when PTCs are combined with cutting-edge materials and storage systems. For example, adding thermal energy storage enables continuous operation, reducing the erratic nature of solar energy and guaranteeing a steady supply of hydrogen. To maximize efficiency and endurance, PTC systems must be designed and optimized, which includes choosing the right heat transfer fluids and receiver materials. The goal of ongoing research is to create environmentally benign and economically viable hydrogen production systems by enhancing the thermal performance of PTCs and combining them with cutting-edge carbon capture technology. A viable route to a sustainable hydrogen economy is the combination of PTCs, carbon capture, and water-splitting devices[102].

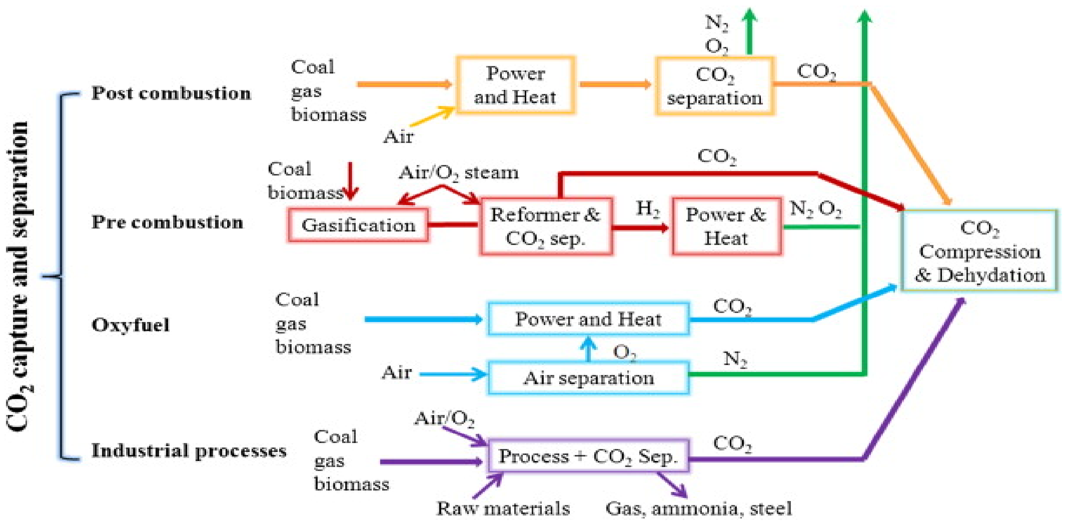

Fig. 14: CCS components and their effect on reducing greenhouse gas emissions[104]

According to recent studies[103], adding nanoparticles such as copper oxide (CuO) can raise the efficiency of solar-to-hydrogen conversion from 9.19% to 9.63%. This improvement is ascribed to the nanofluids' enhanced heat transfer and thermal conductivity. Furthermore, combining water splitting systems with carbon capture technologies improves the sustainability of hydrogen production. These hybrid systems reduce greenhouse gas emissions while simultaneously producing clean hydrogen by absorbing CO_2 emissions from industrial processes and using them in the water splitting reaction1. According to experimental data, a solar-powered hydrogen production system that used a CuO-based nanofluid and a Kalina cycle observed an improvement in hydrogen production from 0.669 kg/h to 0.702 kg/h. The potential of hybrid nanofluid systems to promote green hydrogen technologies and aid in the shift to a carbon-neutral future is highlighted by this experimental data.

CCS is a tried-and-true way to lower greenhouse gas emissions, improve industrial sustainability, and aid international efforts to tackle climate change by absorbing and permanently storing CO_2 emissions. This technology is especially important for reducing emissions from industries that are difficult to control, like chemical manufacture, cement production, and power generation. Capture, transport, and storage are the three main steps in the CCS process as shown in Figure 14[104]. For greater efficiency and environmental security, each step is backed by cutting-edge technologies and strict safety regulations.

At the capture step, CO_2 is extracted from industrial emissions using advanced technologies such as post-combustion, pre-combustion, and oxy-fuel combustion. These technologies use effective solvents, sorbents, and membranes to enhance capture efficiency while consuming the least amount of energy. After being captured, the CO_2 is compressed into a dense phase and transported to specified storage locations by rail, pipe line, or ship. During the storage phase, the compressed CO_2 is injected into deep geological formations such as saline aquifers, depleted oil and gas reservoirs, or unmineable coal seams to safely confine it. While cutting-edge methods like mineral carbonation offer long-term storage solutions by turning CO_2 into stable minerals, sophisticated monitoring systems guarantee the integrity of these storage locations. In order to actively remove CO_2 from the environment, CCS also supports negative emissions technologies like BECCS, which combines the production of biomass energy with CCS. The economic feasibility of CCS can also be increased by repurposing captured CO_2 for industrial uses such as improved oil recovery, the creation of synthetic fuel, and building materials. Notwithstanding obstacles like exorbitant expenses and energy requirements, continuous technological developments, encouraging laws, and international projects are establishing CCS as a key component of climate and sustainable energy plans[105][106][107].

Integrating Carbon Capture and Storage (CCS) with PTCs necessitates aligning the thermal energy output of PTCs with the specific temperature requirements of various CCS processes. PTCs are capable of generating heat transfer fluid temperatures ranging from approximately 100 °C to 400 °C, depending on the design and operational parameters. This temperature range is particularly suitable for certain CCS technologies. For instance, sorbent-based Direct Air Capture (DAC) systems operate effectively at temperatures around 100 °C, allowing the use of solar heat from PTCs to facilitate CO_2 adsorption and desorption cycles. Conversely, solvent-based DAC processes require higher temperatures, approximately 900 °C, which exceed the thermal capabilities of standard PTCs. However, advancements in PTC technology, such as the development of high-temperature heat transfer fluids and materials, have extended their operational range up to 823 K (approximately 550 °C), potentially bridging this gap. Moreover, the utilization of molten salts, known for their high thermal stability, has been proposed to capture CO_2 at elevated temperatures, aligning with the upper limits of PTC outputs. Therefore, the successful integration of PTCs with CCS processes hinges on matching the thermal output of the solar collectors with the specific temperature demands of the chosen carbon capture technology, ensuring both operational efficiency and economic viability[108][109].

The generation of green hydrogen through carbon capture and water splitting represents a pivotal advancement in sustainable energy technology. This process integrates carbon capture mechanisms with water electrolysis to produce hydrogen with minimal environmental impact. Water electrolysis, powered by renewable energy sources such as wind or solar, involves splitting water molecules into hydrogen and oxygen, achieving efficiencies up to 95% in advanced electrolyzers. Integrating carbon capture technologies further enhances the sustainability of hydrogen production. For instance, the KOH cycle has demonstrated energy efficiencies of 44.2% and exergy efficiencies of 67.66%. Additionally, integrating direct air capture of CO_2 with thermochemical water-splitting cycles has been explored to produce Syngas, a mixture of CO and H_2, offering a pathway to utilize atmospheric CO_2 for fuel production[110][111]. The environmental benefits of green hydrogen are substantial. Studies indicate that renewable electrolytic hydrogen production generates at least 50–90% fewer greenhouse gas emissions compared to fossil-fuel-based methods without carbon capture. This significant reduction underscores green hydrogen's potential in mitigating climate change impacts. Economically, the production cost of green hydrogen is influenced by factors such as electrolyzers efficiency, renewable energy availability, and carbon capture integration. Advancements in electrolyzers technology and supportive policies, like production tax credits, aim to reduce hydrogen costs to $1/kg by 2031. Such initiatives are crucial for enhancing the economic viability of green hydrogen[112].

The production of hydrogen from fossil fuels, including solid, liquid, or gaseous forms, primarily involves the generation of shifted Syngas, which predominantly consists of hydrogen (H_2) and carbon dioxide (CO_2). Figure 15[113] illustrates a typical pathway for hydrogen production integrated with CO_2 capture. Syngas production not only serves as a fundamental step in hydrogen generation but is also widely utilized in large-scale chemical syntheses such as ammonia and methanol manufacturing. For hydrogen production processes integrated with CO_2 capture, the Syngas processing stage must be enhanced by incorporating an additional separation unit to effectively isolate high-purity hydrogen and CO_2 suitable for transportation and storage. This separation results in three distinct process streams: purified hydrogen, purified CO_2, and an off-gas mixture containing residual components like H_2, CO_2, CO, CH_4, and N_2. Depending on the production route, gasification and autothermal reforming (ATR) utilize internal heat generated by partial oxidation of fuel within the reactor, while steam methane reforming (SMR) relies on external heating provided by the combustion of a separate fossil fuel stream in a reforming furnace, producing flue gas as a by-product.

In SMR-based systems, if CO_2 capture is confined solely to the Syngas stream, approximately 60% of the total CO_2 emissions from the overall process can be recovered. However, to achieve higher CO_2 capture efficiency, an additional post-combustion CO_2 capture unit is essential for treating the flue gas generated in the reforming furnace, thereby enhancing the overall carbon capture potential of the process[114][115].

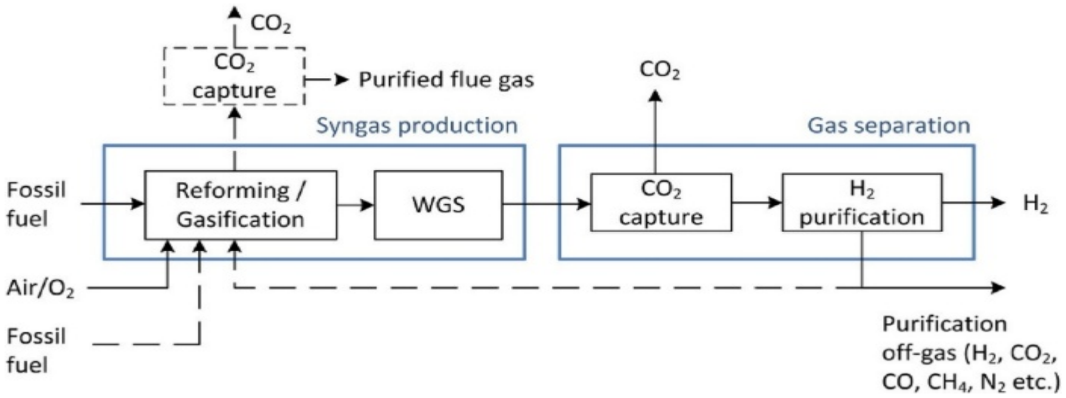

Fig. 15: A well-established fossil-based hydrogen production route with CO_2 capture, showing key processes and unit variations[113]

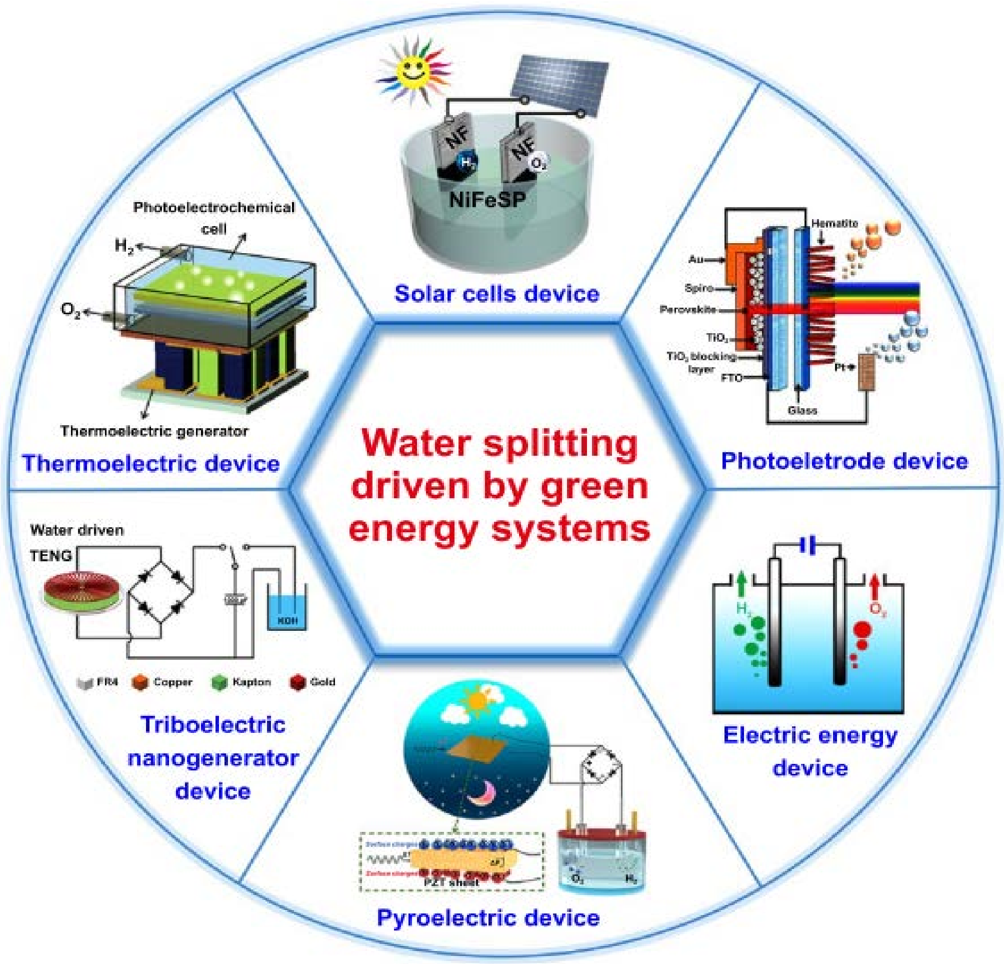

Fig. 16: Water splitting methods powered by various green energy sources[116)]

Alternatively, water splitting has emerged as a clean and promising route for green hydrogen production, where water molecules (H_2O) are decomposed into hydrogen and oxygen (O_2) using electrochemical processes. Recent advancements have focused on integrating hybrid nanofluid-based energy devices to enhance the efficiency of water splitting while reducing external energy consumption. Hybrid nanofluids, containing a mixture of nanoparticles with superior thermal, electrical, and optical properties, improve heat transfer and photothermal conversion in solar-assisted electrolysis systems. Devices such as photoelectrochemical cells, thermoelectric generators, solar cells, and triboelectric nanogenerators (TENG) utilize renewable energy sources like solar, wind, and tidal energy to drive water splitting processes efficiently with minimal or no external power supply as shown in Figure 16[116)].

These integrated hybrid systems not only improve hydrogen evolution reaction (HER) kinetics but also optimize energy harvesting from multiple environmental sources, thus offering a viable pathway for large-scale, sustainable green hydrogen production while addressing challenges related to energy consumption, system stability, and cost-effectiveness[117)].

7. Conclusion and Future Aspects of Research

This paper provides a comprehensive review of research and experimental studies conducted to harness solar energy through the use of parabolic trough concentrators (PTCs). Globally, efforts are being made to achieve maximum efficiency with PTCs. Numerous researchers have carried out experimental investigations, emphasizing enhancements in thermal conductivity and other properties by utilizing various types of nanofluids in PTC absorber tubes. Some studies have explored the use of hybrid and ternary nanofluids, as well as advanced compound PTCs. The utilization of hybrid nanofluids in parabolic trough collectors (PTCs), despite offering enhanced thermophysical properties, presents notable research limitations. Key challenges include long-term stability issues due to nanoparticle agglomeration and sedimentation, increased viscosity at higher concentrations leading to elevated pressure drops and pumping power, and complex flow behavior under variable thermal loads due to

Cite: V. Rathore, S. Gupta, "A Review of Hybrid Nanofluids: Emerging Trends and their Role in Enhancing Parabolic Trough Concentrators Performance". Evergreen, 12 (02) 1250-1275 (2025). https://doi.org/10.5109/7363508.

non-Newtonian characteristics. Additional concerns involve material compatibility, corrosion potential, and difficulties in large-scale preparation and dispersion. Experimental limitations such as high nanoparticle costs, lack of real-time monitoring tools, and absence of standardized testing protocols further restrict scalability. Overcoming these barriers through advanced functionalization techniques, surfactant optimization, and robust computational models is essential for practical deployment in solar thermal systems. The integration of hybrid nanofluids into PTCs significantly enhances solar thermal system efficiency by improving heat transfer and thermal conductivity. These advanced fluids have been shown to boost thermal efficiency by up to 2.8% in PTCs and up to 197% in solar collectors. Their applications extend beyond power generation to industrial process heating, desalination, and hybrid photovoltaic-thermal systems, where enhanced thermal management is crucial. The reviewed outcomes are highlighted as follows:

Utilizing appropriate nanofluids in Parabolic Trough Collectors (PTCs) can significantly enhance thermophysical properties and improve thermal efficiency. For instance, integrating Al_2O_3/water nanofluid at a 3% volumetric concentration increased thermal efficiency from 40.8% to 52.4%, marking an approximate 28% improvement.

Achieving stability in nanofluids is critical for PTC efficiency. While single-step techniques have been employed to produce hybrid nanofluids, complete prevention of nanomaterial agglomeration remains challenging, potentially affecting long-term performance.

The friction factor significantly influences the flow of nanofluids in absorber tubes. Improved flowability of hybrid nanofluids leads to higher heat transfer rates. For example, using CuO nanofluid at a 0.3% concentration resulted in a heat transfer coefficient of 172.3 W/m²K, enhancing thermal efficiency to 70.9%.

Hybrid nanofluids outperform conventional fluids by enhancing PTC efficiency. Studies have shown that employing hybrid nanofluids can lead to a 197% improvement in the thermal efficiency of solar collectors.

Exergy studies on hybrid nanofluids demonstrate reduced total entropy generation compared to traditional thermal oils, indicating improved system performance. For instance, utilizing CuO nanofluid achieved an exergy efficiency of 37.2%, surpassing that of conventional fluids.

Incorporating hybrid nanofluids in solar energy systems has been linked to significant improvements in green hydrogen production efficiency. Researchers have developed electrolysers with 95% efficiency, substantially reducing energy waste in green hydrogen production.

These advancements highlight the role of sustainable technologies in mitigating global warming and reducing carbon emissions.

Abbreviations

CPC	Concentrated solar power
CPTC	Concentrated parabolic trough collector
CHTC	Convective heat transfer coefficient
DASC	Direct absorption solar collectors
DAPTC	Direct absorption parabolic trough concentrator
ETSC	Evacuated tubes solar collector
EG	Ethylene glycol
Nu	Nusselt number
Ra	Rayleigh number
HTF	Heat transfer fluid
G PTC	Parabolic trough collector using graphite in the cavity
R PTC	Reference parabolic trough collector
M PTC	Modified parabolic trough collector
PV	Photovoltaic
PTC	Parabolic trough concentrator
MWCNT	Multi-walled carbon nanotube
SWCNT	Single-walled carbon nanotube
LCOE	Levelized cost of energy
SEM	Scanning electron microscopy
SNL	Sandia national laboratory
TC	Thermal conductivity
EDX	Energy dispersive x-ray
NEILS	Nanoparticle enhanced ionic liquids
FPC	Flat plate collector
SWH	solar water heating
CSS	Carbon capture and storage
BECCS	Bioenergy with carbon capture and storage

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