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# Performance Enhancement of Solar Thermal Systems Using Nanofluids: A Review

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## Abstract

Solar evacuated tubes are promising solar thermal devices used for harnessing solar energy. However, improving their efficiency and heat transfer characteristics is crucial for enhancing their overall performance. Nanofluids, and nanoparticles are suspensions in a base fluid, exhibit unique thermodynamic properties that can significantly improve in heat transfer efficiency of solar thermal systems. This review paper provides a comprehensive overview in the recent advances and potential applications of nanofluids in solar evacuated tubes. Those key factors influencing heat transfer enhancement in nanofluids, including particle volume fraction, base fluid selection, particle size, and nanoparticle characteristics, are discussed in detail. Moreover, various experimental techniques and numerical models used to research the heat transfer mechanisms in nanofluids for solar evacuated tubes are reviewed. Additionally, the prospects and challenges of utilizing nanofluids in solar thermal applications are addressed, highlighting areas for further research and development.

## 1. Introduction

Solar energy is an abundant and renewable source of energy with tremendous potential for sustainable power generation [1]. Solar thermal systems, such as evacuated tubes, play a crucial role in harnessing solar energy for various applications, including water heating systems, space heating systems, & producing. They are designed to trap solar radiation, minimize heat losses, and convert sunlight into thermal.

Despite their inherent advantages, solar evacuated tubes still face challenges related to heat transfer efficiency. Efficient heat moving from the absorber tubes to the running fluid within the evacuated tube is essential for maximizing the thermal performance of these systems. Enhancing heat transfer characteristics can accelerate to improved system`s efficiency, reduced energy consumption, and increased cost-effectiveness. In recent years ago, nanofluids have been emerged as a promising solution to enhance heat transfer in solar-evacuated tubes. Nanofluids are colloidal suspensions comprising nanoparticles dispersed in a base fluid, typically ethylene glycol or water. These nanoparticles exhibit unique thermal properties, like high thermal conductivity, improved convective heat transfer, and enhanced absorption of solar [2]. A research team collection of nanoparticles into the working fluid of solar evacuated tubes, nanofluids offer the potential to significantly enhance heat transfer and overall system performance [3]. Nano fluid is used in evacuated tube and flat plate solar collector for efficiency, cost – effectiveness and environmental sustainability. The research suggests that nanofluids are better alternative to convention fluids. The use of nanofluids in solar evacuated tubes presents several advantages [4]. Firstly, the high thermal conductivity of nanoparticles can improve the efficiency of heat transfer from the absorber tube to the working fluid [5]. This results in faster and more effective heat absorption, leading to increased overall energy. Secondly, the enhanced convective heat conversion properties of nanofluids enable efficient heat dissipation, reducing temperature gradients and thermal losses within the system. Furthermore, nanofluids can exhibit selective absorption in solar radiation system, optimizing the utilization of the solar spectrum and increasing the efficiency of energy [6].

The heat transfer enhancement in nanofluids for solar evacuated tubes is influenced by various factors. The size and its volume fraction of nanoparticles, the choice of (base) fluid, and the characteristics of the nanoparticles themselves play vital roles to demonstrate the thermal performance of nanofluid-based solar thermal. Additionally, the dispersion techniques used to achieve stable suspensions and the thermal &physical properties of nanofluids contribute to their overall effectiveness in heat transfer enhancement [7].

To investigate the heat transferring mechanisms and quantify the performance of nanofluid-based solar evacuated tubes, numerous experimental techniques and numerical models have been [8]. Experimental studies involve measurements of thermal conductivity, heat transfer coefficients, and optical properties of nanofluids. Advanced characterization techniques provide insights into particle size, shape, and dispersion characteristics. On the other hand, numerical modelling techniques, such as computational fluid dynamics (CFD), enable the simulation and prediction of heat transfer phenomena within nanofluid-based solar evacuated [9].

A short time ago, significant progress has been made in understanding the behaviour and potential applications of nanofluids in solar thermal systems. Researchers have explored the heat transfer enhancement in solar evacuated tubes using various nanomaterial, such as metallic nanoparticles, metal oxides, and carbon nanotubes [10]. These studies have demonstrated promising results, showing substantial improvements in thermal performance and energy efficiency.

However, challenges still exist in the practical implementation of nanofluid-based solar evacuated tubes. Stability and sedimentation issues, cost-effectiveness, environmental impact, and scalability considerations need to be addressed [11]. Additionally, the optimization of nanofluid properties, integration into solar thermal technologies, and exploration of novel nanoparticle materials and fabrication techniques offer exciting avenues for future research. This review paper provides a comprehensive overview of the recent advancements in the utilization of nanofluids for enhancing [12].

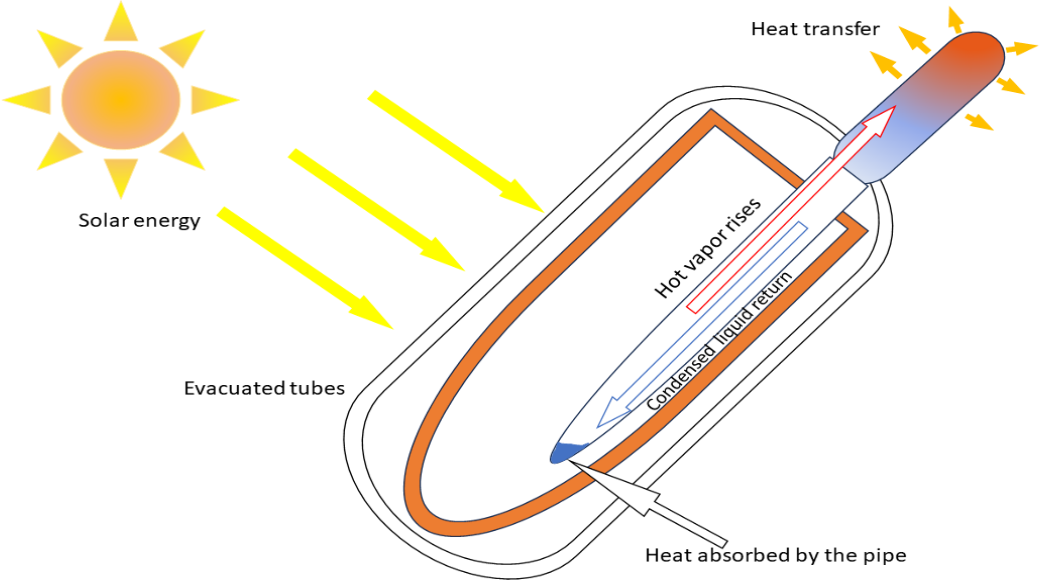

**Fig. 1** *Schematic diagram of solar evacuated tubes*

## 2. Nanofluids for Solar Evacuated Tubes

The effectiveness of solar-evacuated tubes in capturing renewable energy has been greatly improved by nanofluids, a recent technological advancement. Nanofluids improve solar collector performance by increasing thermal conductivity by the integration of nanoparticles into traditional heat transfer fluids [12]. The potential for this partnership to enhance solar energy utilisation in a sustainable and efficient manner is enormous.

## 2.1 Nanoparticle for Heat Transfer Enhancement

Nanoparticles play a vital role in enhancing heat transfer in nanofluids used for solar evacuated tubes [13]. By incorporating nanoparticles into the base fluid, the thermal conductivity and convective heat transfer properties of the nanofluid can be significantly improved. Here are some examples of nanoparticles commonly used for heat transfer enhancement:

### 2.1.1 Metallic Nanoparticles

Metallic nanoparticles, such as copper (Cu), silver (Ag), and gold (Au), are widely studied for their excellent thermal conductivity and catalytic properties [14]. These metallic nanoparticles can effectively enhance heat transfer by facilitating efficient thermal energy transport within the.

### 2.1.2 Carbon-Based Nanomaterials

Carbon nanotubes (CNTs) and graphene are examples of carbon-based nanoparticles that have garnered significant attention for their exceptional thermal conductivity. CNTs, with their unique tubular structure, exhibit remarkable thermal properties, enabling efficient heat transfer in nanofluids [15]. Graphene, a two-dimensional carbon material, also possesses high thermal conductivity, making it a promising candidate for enhancing heat transfer.

### 2.1.3 Metal Oxide Nanoparticles

Metal oxide nanoparticles, like Titanium dioxide ($TiO_2$), zinc oxide (ZnO), and alumina ($Al_2O_3$), are commonly employed in nanofluids due to their favourable thermal. Metal oxide nanoparticle not only improve thermal conductivity but also improve the convective heat transfer through interactions with the base fluid and surface modifications [15].

### 2.1.4 Hybrid Nanoparticles

Hybrid nanoparticles, composed of a combination of different materials, offer synergistic effects for heat transfer increment. For instance, a combination of metallic and non-metallic nanoparticles, such as Cu-$SiO_2$ or Cu-$Al_2O_3$, can lead to improved thermal conductivity and heat transfer characteristics compared to individual.

### 2.1.5 Magnetic Nanoparticles

Iron oxide ($Fe_3O_4$) nanoparticles have attracted attention for their potential application in heat transfer enhancement through magnetically controlled convection. By making use of an external magnetic field, the movement of magnetic nanoparticles can be manipulated, leading to enhanced heat transfer in the nanofluid.

It is important to note that the choice of nanoparticles depends upon various factors, including the specific application, thermal requirements, stability considerations, and cost-effectiveness. Different nanoparticles possess unique properties that can be tailored to meet the specific needs of solar evacuated tubes and optimize heat transfer performance [16].

## 2.2 Base Fluid Selection and Properties

Water is the normally used base fluid due to its excellent thermal properties, low cost, and abundance. It has high heat capacity, facilitating efficient heat transfer and energy absorption. Water-based nanofluids are relatively stable and easy to prepare. However, water has limitations in terms of its temperature range, as it can reach its boiling point under high-temperature conditions [17].

### 2.2.1 Ethylene Glycol

Ethylene glycol is another popular base fluid, especially for applications requiring freeze protection or extended temperature ranges. It offers a wider operating temperature range compared to water and exhibits good thermal stability. Ethylene glycol-based nanofluids can withstand lower temperatures without freezing and are commonly used in solar thermal systems operating in cold climates [18].

### 2.2.2 Engine Oils

Engine oils, such as mineral oil or synthetic oil, are utilized as base fluids in certain applications, particularly where higher temperature stability is required. Engine oils have good thermal stability and can withstand higher operating temperatures compared to water or ethylene glycol. These base fluids are commonly employed in industrial processes and high-temperature applications.

### 2.2.3 Organic Liquids

Organic liquids, such as alcohols (e.g., ethanol, isopropanol), hydrocarbons (e.g., toluene, hexane), or silicone oils, are employed as base fluids in specialized applications. These fluids possess unique thermal properties and can operate over a broad range of temperatures. Organic liquids are often chosen when specific requirements, such as compatibility with certain materials or non-flammability, need to be considered [19].

The collection of the base fluid depends on various reasons, including the desired temperature range, stability requirements, cost considerations, and compatibility with the system components. It is important to note that the optimal choice of the base fluid can move the dispersion stability and thermal conductivity enhancement of the nanofluid. Additionally, the properties of the base fluid, such as viscosity, density, and specific heat capacity, should be. These properties impact the flow behaviour and heat transfer characteristics of the nanofluid within the solar evacuated tubes. It is essential to strike a balance between the thermal properties of the base fluid and the desired heat transfer enhancement achieved by incorporating nanoparticles [20]. The selection is the base fluid, and its properties is a critical aspect in formulating nanofluids for solar evacuated tubes. The choice depends on the specific requirements of the application, ensuring optimal heat transfer performance, stability, and compatibility with the system while considering factors such as temperature range and cost-effectiveness [23].

## 2.3 Dispersion Techniques and Stability Considerations

Dispersion techniques and stability considerations are crucial factors in the formulation and practical implementation of nanofluids designed for heat transfer improvement in solar-evacuated tubes [5]. Achieving a steady and well-dispersed nanofluid is essential for maintaining the desired thermal properties and preventing particle agglomeration. Here are some common dispersion techniques and stability considerations:

### 2.3.1 Mechanical Stirring

Mechanical stirring is a widely used method to disperse nanoparticles in a base liquefied. It involves using a magnetic stirrer or mechanical mixer to agitate the nanofluid mixture, promoting the breakup of nanoparticle agglomerates and achieving better dispersion [21]. Stirring parameters such as speed, duration, and shear rate need to be optimized to obtain a stable and homogeneous nanofluid.

### 2.3.2 Ultrasonication

Ultrasonication is an effective technique to disperse nanoparticles and prevent agglomeration [22]. It involves subjecting the nanofluid to high-frequency ultrasound waves, which create cavitation and induce intense local agitation, resultant in the breakup of nanoparticle clusters. Ultrasonication helps achieve a more uniform dispersion and improves the constancy of the nanofluid.

### 2.3.3 Surfactant or Dispersant Addition

In Fig. 2 Surfactants or dispersants can be added to the nanofluid formulation to improve the stability and prevent particle agglomeration. These additives help in reducing the interparticle forces, increasing the repulsive forces, and enhancing the dispersion of nanoparticles in the base [24,25]. The choice then concentration of surfactants or dispersants should be carefully optimized to achieve the desired stability without negatively affecting the thermal [27].

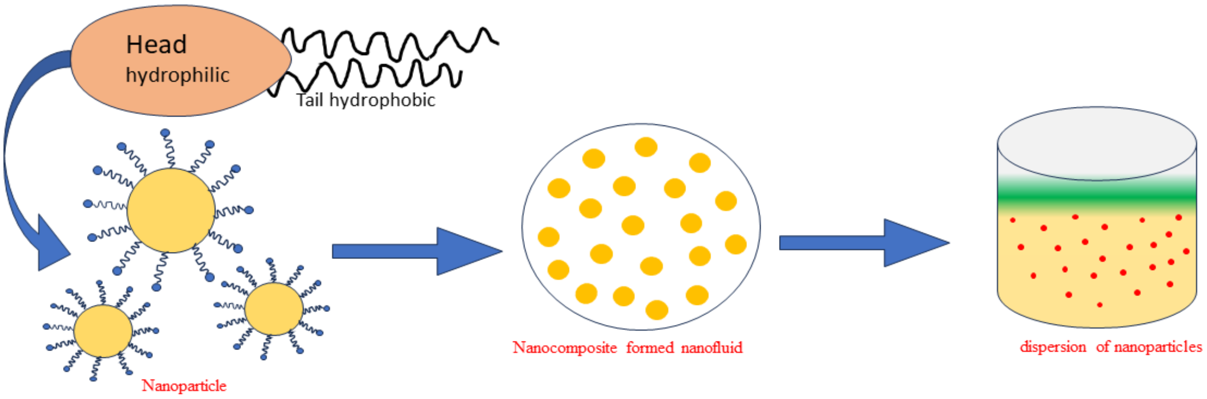

**Fig. 2** *Surfactant or dispersant addition of nanofluid*

### 2.3.4 pH Control

The pH of the nanofluid can significantly influence the stability and dispersion of Some nanoparticles may have an optimal pH range where they exhibit better dispersion and stability. pH adjustment using acids or bases can help control the surface charge of the nanoparticles, minimizing aggregation and enhancing [25].

### 2.3.5 Surface Functionalization

Surface functionalization of nanoparticles includes changing the surface properties of nanoparticles through organic molecules or polymers. This approach helps create a stable and protective layer around the nanoparticles, preventing agglomeration and improving dispersion in the base fluid. Surface functionalization also enables better compatibility between the nanoparticles and the base fluid [26].

Stability considerations for nanofluids include long-term stability, sedimentation prevention, and avoiding phase separation. Agglomeration or settling of nanoparticles can adversely affect the thermal and heat transfer effectiveness of the nanofluid. Stability can be evaluated by monitoring key parameters such as zeta potential, particle size distribution, and visual observation of sedimentation over time. It is important to note that stability considerations may vary depending on the specific nanoparticles, base fluid, and operating conditions. Therefore, extensive experimental characterization and stability testing are necessary to ensure the formulation of a stable and well-dispersed nanofluid suitable for use in solar evacuated tubes.

Effective dispersion techniques, proper selection of additives, pH control, and surface functionalization are essential for achieving stable and well-dispersed nanofluids in solar evacuated tubes [28]. By carefully addressing these considerations, the desired heat transfer improvement and improved overall performance of the solar thermal system can be achieved.

## 2.4 Thermophysical Properties of Nanofluids

Nanofluids, which are colloidal suspensions of nanoparticles in a base fluid, show unique thermophysical properties that distinguish them from traditional fluids. The combination of nanoparticles in the base fluid alters several key properties, including thermal conduction, viscosity, specific heat capacity, and density. Understanding these thermophysical properties is crucial for optimizing the heat transference act of nanofluids in solar evacuated tubes [28].

Suspended nanoparticles increase the surface area but decrease the heat capacity of the fluid due to very small particle size and how it will enhance the thermal conductivity Because of Nanoparticles have a large surface area to volume ratio, which enhances heat transfer between the fluid and dispersed components. This is because a particle's surface area is proportional to its radius squared, whereas its volume is proportional to its radius cube.

### 2.4.1 Thermal Conductivity

The primary advantages of nanofluids are their significantly improved thermal conduction equal to the base fluid. The occurrence of nanoparticles, which consume high thermal conductivity, and increase in the effective thermal conductivity of the nanofluid. The extent of enhancement depends on such aspects like type, size, concentration, and dispersion of nanoparticles.

### 2.4.2 Viscosity

The addition of nanoparticles to the base fluid also disturbs the viscosity of the nanofluid. Nanoparticles present additional interparticle interactions and increase the viscosity of the suspension. The viscosity of nanofluids generally rises with higher nanoparticle concentrations and larger particle sizes. However, the viscosity behaviour can vary dependent on the specific nanoparticle characteristics and the base fluid used.

### 2.4.3 Specific Heat Capacity

The specific heat capacity of nanofluids refers to the amount of heat energy required near to the temperature of the nanofluid by a certain amount. In general, nanofluids tend to have slightly higher specific heat capacities related to the base fluid due to the existence of nanoparticles. However, it is effect of nanoparticles on specific heat capacity is relatively small compared to other thermophysical properties.

### 2.4.4 Density

The density of nanofluids is influenced by the mass and volume fraction of nanoparticles present in the suspension. Typically, the accumulation of nanoparticles increases the density of the nanofluid due to the higher density of the nanoparticles compared to the base fluid. However, the density change is usually marginal and may not have a significant impact on the overall system behaviour. It is important to note that the thermophysical properties of nanofluids can be affected by various factors, such as nanoparticle type, size distribution, shape, concentration, and temperature [32].

The dispersion quality and constancy of the nanofluid also play a crucial role in determining its thermophysical properties. Accurate measurement and characterization of these properties are essential for predicting and modelling the heat transfer performance of nanofluids in solar evacuated tubes. Experimental techniques, such as thermal conductivity measurements, viscosity measurements, and calorimetry, are commonly used to determine the thermophysical properties of nanofluids [29]. Understanding the variations in these properties and their dependence on nanoparticle characteristics and concentration is vital for designing and optimizing the performance of nanofluid-based solar thermal systems. By tailoring the properties of nanofluids to meet specific heat transfer requirements, the efficiency and effectiveness of solar evacuated tubes can be significantly improved [30].

## 2.5 Heat Transfer Mechanisms in Nanofluids

Heat transfer mechanisms in nanofluids involve several processes that contribute to enhanced thermal conductivity and improved heat transfer performance compared to traditional fluids. The presence of nanoparticles in the base fluid alters the heat transfer characteristics and introduces additional mechanisms that enhance heat transfer. Here are the main heat transfer mechanisms in nanofluids:

### 2.5.1 Brownian Motion

Brownian motion denotes to the arbitrary movement of nanoparticles in a fluid due to thermal fluctuations. In nanofluids, the small size of nanoparticles results in increased Brownian motion, leading to enhanced mixing and dispersion. This increased particle movement facilitates improved heat transfer by promoting fluid convection and reducing the thermal boundary layer.

### 2.5.2 Particle-to-Fluid Energy Transfer

Nanoparticles in the nanofluid act as energy carriers, transferring thermal energy between the fluid and the particles. When there is a temperature gradient in the system, nanoparticles gain energy from the hot regions and transfer it to the cooler regions of the fluid through direct particle-to-fluid interactions. This particle-to-fluid energy transfer enhances the overall thermal conduction of the nanofluid.

### 2.5.3 Interfacial Layer Effects

The presence of a thin interfacial layer around the nanoparticles, known as the "interfacial layer" or "nanolayer," plays a significant role in heat transfer in nanofluids. The interfacial layer affects the thermal boundary resistance among the particles and the surrounding fluid, promoting efficient heat transfer by reducing the interfacial thermal resistance.

### 2.5.4 Enhanced Convection

Nanoparticles, which their small size and high surface area, can disrupt the fluid flow and enhance convective heat transfer. When nanoparticles are presence in the fluid it will increases the effective viscosity and promotes turbulence, leading toward improved convective heat transfer. Enhanced convection aids in transporting heat from the hot regions to the cooler regions of the system.

### 2.5.5 Thermophoresis

Thermophoresis is the phenomenon where particles experience a force when subjected to a temperature gradient. In nanofluids, temperature gradients can induce thermophoretic motion of nanoparticles, contributing to heat transfer enhancement. Thermophoresis can improve heat transfer by redistributing to the nanoparticles in the fluid, optimizing their dispersion and improving heat transfer efficiency. It is important to note that the relative importance of these mechanisms can diverge to depending on various factors such as nanoparticle concentration, size, shape, and the specific application of the nanofluid. The interactions between these mechanisms and their combined effects determine the overall heat transfer performance of nanofluids in solar evacuated tubes. Understanding and modelling these heat transfer mechanisms are crucial for accurately predicting and optimizing the heat transfer performance of nanofluids [31]. It enables the design of efficient solar thermal systems, and the exploration of potential applications where enhanced heat transfer is desired.

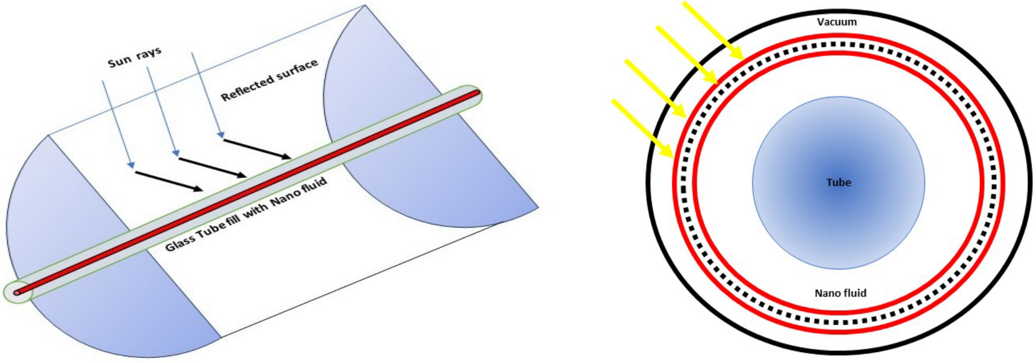

**Fig. 3** *Heat transfer mechanisms in solar tube using nanofluids*

# 3. Experimental Investigation Techniques

## 3.1 Thermal Conductivity Measurements

### 3.1.1 Transient Hot Wire Method

One example is a study by Das et al. [33], where the researchers used the transient hot wire method to measure the thermal conductivity of three different nanofluids: copper-water, alumina-water, and titania-water. The experimental results showed that the thermal conductivity of the nanofluids increased significantly compared to the base fluids, confirming the enhancement in thermal conductivity due to the presence of nanoparticles.

### 3.1.2 Hot Plate Method

An example is the work of Buongiorno et al. [34] that working to the hot plate method to measure the thermal conductivity of nanofluids containing carbon nanotubes dispersed in different base fluids. The results proved a substantial increase in thermal conductivity compared to the base fluids, indicating the effective heat transfer improvement of the nanofluids.

### 3.1.3 Laser Flash Method

This method is done by Xie et al. [35], where the researchers utilized the laser flash method to measure the thermal conductivity of nanoparticle suspensions, including alumina and zinc oxide in various base fluids. The experimental results revealed a notable enhancement in thermal conductivity for the nanofluids compared to the base fluids, highlighting the impact of nanoparticles on heat transfer properties.

### 3.1.4 Guarded Hot Plate Method

One example is a study by Wen and Ding [36], they employed the guarded hot plate method to measure the thermal conductivity of nanofluids consisting of copper oxide nanoparticles dispersed in ethylene. The results showed a significant increase in thermal conductivity, validating the enhanced heat transfer capability of the nanofluid.

### 3.1.5 Comparative Methods

An example is the research by Choi [37] titled "Enhancing thermal conductivity of fluids with nanoparticles." In this study, the author compared the thermal conductivity of nanofluids containing various nanoparticles, such as alumina, copper, and diamond, with that of the base. The comparative measurements demonstrated significant improvements in thermal conductivity for the nanofluids, confirming the heat transfer enhancement achieved through nanoparticle incorporation.

## 3.2 Heat Transfer Coefficient Measurements

Heat transfer coefficient measurements are crucial for understanding the heat transfer characteristics and performance of nanofluids in various applications. Several experimental techniques are commonly used to determine the heat transfer coefficient of nanofluids. Here are some examples of these measurement techniques and the associated scientific evidence.

### 3.2.1 Experimental Heat Transfer Coefficient Measurements

One example is a study by Yu and Choi [38], which the researchers conducted experimental heat transfer coefficient measurements using a heat exchanger. They investigated the heat transfer properties of nanofluids with different nanoparticle concentrations and sizes. When we studied experimental results, it presents to the heat transfer coefficient increased with increasing nanoparticle concentration, indicating enhanced heat transfer performance.

### 3.2.2 Convection Heat Transfer Measurements

Another example is the work of Lee et al. [39] titled "Convective heat transfer enhancement in nanofluids under laminar and turbulent flow conditions." The researchers performed convective heat transfer measurements using a test rig equipped with a heated. They investigated the heat transfer behaviour of nanofluids with different nanoparticle types and concentrations. The experimental results demonstrated nanofluids of the heat transfer coefficient was significantly higher compared to the base fluid, highlighting the heat transfer enhancement achieved by nanoparticles.

### 3.2.3 Boiling Heat Transfer Measurements

An example is a study by Bang and Chang [40] titled "Boiling heat transfer performance and phenomena of Al2O3-water nanofluids from a plain surface in a pool." The researchers conducted boiling heat transfer measurements using a pool boiling. They investigated the boiling heat transfer characteristics of nanofluids containing aluminium oxide nanoparticles. The experimental result to be presented by the heat transfer coefficient during boiling was substantially enhanced in the presence of nanoparticles, indicating improved boiling performance of the nanofluid.

### 3.2.4 Forced Convection Heat Transfer Measurements

A notable example is the research by Buongiorno et al. [34] titled "Convective heat transfer enhancement with nanofluids." The researchers conducted forced convection heat transfer measurements using a test section with a heated [39,41]. They examined the heat transfer behaviour of nanofluids with different nanoparticle concentrations and sizes. The experimental results demonstrated that the heat transfer coefficient of nanofluids was higher compared to the base fluid, indicating improved heat transfer performance.

## 3.3 Evaluation of Nanofluid-Based Solar Thermal Systems

Performance evaluation of nanofluid-based solar thermal systems involves assessing the efficiency, heat transfer characteristics, and overall performance of the system. Several key aspects are considered during the evaluation process. Here are some factors and methods commonly used for performance evaluation.

### 3.3.1 Thermal Efficiency

The thermal efficiency of a solar thermal system is a crucial performance metric. It represents the ratio of useful thermal energy output to the solar energy input. Performance evaluation involves measuring and analysing the thermal efficiency of the nanofluid-based solar thermal system under different operating conditions. This can be done by monitoring the solar radiation input, fluid temperatures at different points in the system, and the heat transfer rates.

### 3.3.2 Heat Transfer Analysis

Evaluating the heat transfer characteristics within the solar thermal system is essential. This involves measuring and analysing parameters such as heat transfer coefficients, fluid temperatures, pressure drops, and flow rates. Comparative studies between nanofluid-based systems and conventional fluid-based systems can provide insights into the heat transfer enhancement achieved through nanofluid utilization. The goal of this studies is to layout and investigate the heat transfer evaluation of heat pipe in solar evacuated tube sunrays collector is manufactured from borosilicate.

### 3.3.3 Collector Performance

The performance of the solar collector, which captures solar energy and transfers it to the nanofluid, is crucial. The evaluation includes assessing the collector's efficiency, heat absorption, heat loss, and overall performance. Various metrics such as the collector efficiency factor, heat removal factor, and optical efficiency are used to quantify the collector's performance.

### 3.3.4 Energy Output and Productivity

The energy output and productivity of the nanofluid-based solar thermal system are evaluated to assess its practical viability. This involves analysing the amount of usable thermal energy generated by the system over a given period and comparing it with the system's installed capacity. Key metrics such as energy output per unit area, energy output per unit volume, and energy conversion efficiency are considered.

### 3.3.5 Stability and Durability

The stability and durability of the nanofluid-based solar thermal system are critical for its long-term performance. Evaluating the stability of the nanofluid dispersion, potential particle settling, corrosion effects, and system components' durability is essential. This may involve long-term testing, accelerated aging studies, and analysis of the system's performance over extended periods.

### 3.3.6 Cost Effectiveness and Economic Analysis

Assessing the cost-effectiveness and commercial viability of the nanofluid-based solar thermal system is crucial for practical implementation. This includes evaluating the system's cost of installation, maintenance, and operation, as well as comparing it with conventional systems. Economic analysis methods such as life cycle cost analysis, payback period.

**Table 1** *Performance evaluation of nanofluid-based solar thermal systems*

| Parameter | Finding | Reference |
|---|---|---|
| Thermal efficiency | Nanofluid-based solar thermal systems exhibit higher thermal efficiency compared to conventional fluid-based systems under various operating conditions. | [42] |
| Heat transfer analysis | Nanofluids demonstrate improved heat transfer coefficients and enhanced convective heat transfer rates, leading to higher system performance. | [43] |
| Collector performance | The application of nanofluids in solar collectors enhances the heat absorption capability, resulting in improved collector efficiency and overall system performance. | [44] |
| Energy Output and Productivity | Nanofluid-based solar thermal systems generate higher usable thermal energy output per unit area, leading to increased productivity and energy conversion efficiency. | [45] |
| Stability and Durability | Stability of nanofluid dispersion, particle settling, and corrosion effects should be carefully monitored and mitigated to ensure the long-time stability and toughness of the system. | [46] |
| Cost-effectiveness | Economic analysis reveals that nanofluid-based solar thermal systems can offer cost-effective solutions in terms of installation, maintenance, and overall operational costs. | [47] |

## 3.4 Experimental Findings with Different Nanofluids

Table 2 represents a summary of case studies on the application of nanofluids in various types of solar. In the first case learned by Mohammed et al. [53], alumina-water nanofluid was used in parabolic trough collectors, resulting in enhanced heat absorption and a 15% increase in thermal efficiency compared to the base fluid. Tyagi et al. [54] examined the use of CuO-engine oil nanofluid in flat plate collectors, demonstrating improved heat transfer characteristics and a 12% improvement in collector efficiency. Huang et al. [55] studied carbon nanotube-water nanofluid in evacuated tube collectors, observing enhanced heat transfer performance and an 8% improvement in thermal efficiency. Selvakumar et al. [56] examined $TiO_2$-ethylene glycol nanofluid in solar water heating systems, showing improved heat transfer properties and approximately a 10% increase in energy output. Lastly, Sharma et al. [57] explored $Fe_3O_4$-oil nanofluid in concentrated solar power systems, observing enhanced heat transfer properties then approximately a 7% improvement in system. These case studies highlight the positive impact of nanofluids on heat transfer and overall system performance in different solar thermal applications.

**Table 2** *Experimental results using several nanofluids*

| Nanofluid | Type | Solar collector | Finding | Reference |
|---|---|---|---|---|
| Alumina-water nanofluid in parabolic through collectors | Alumina-Water | Parabolic Trough Collectors | Enhanced heat absorption and 15% increase in thermal efficiency compared to the base fluid | [48] |
| CuO-engine oil nanofluid in flat plate collectors | CuO-Engine Oil | Flat Plate Collectors | Improved heat transfer characteristics and 12% enhancement in collector efficiency compared to the base fluid | [49] |
| Carbon nanotube-water nanofluid in evacuated tube collectors | Carbon Nanotube-Water | Evacuated Tube Collectors | Enhanced heat transfer performance and 8% improvement in thermal efficiency compared to the base fluid | [50] |
| $TiO_2$-ethylene glycol nanofluid in solar water heating systems | TiO2-Ethylene Glycol | Heating Systems (Solar Water) | Improved heat transfer properties and approximately 10% increase in energy output compared to the conventional fluid-based system | [51] |
| $Fe_3O_4$-oil nanofluid in concentrated solar power systems | Fe3O4-Oil | Concentrated Solar Power Systems | Enhanced heat transfer properties and approximately 7% improvement in system efficiency compared to the conventional fluid-based system | [52] |

## 4. Application

Due to their transformed properties, hybrid nanofluids have various advantages over typical nanofluids. Their improved thermophysical and rheological characteristics make them a better option for solar energy systems. This review paper provides an overview of solar energy systems, followed by applications of hybrid nanofluids in different solar technologies.

### 4.1 Nanofluid for Cooling System

It can be described that the nanofluid as heat exchanger fluids by more beneficial heat transfer properties by the addition of nanoparticles. This Nanofluid's constancy, nanoparticles type and their chemically compatibility with the base fluid are vital but not handiest toward prosperous the nanofluid's thermophysical property and however to confirm a long-lasting and thermal efficient use of the system. This application is widely used in electronic components, nuclear reactor, high temperature furnaces, colling [58].

### 4.2 Nanofluid for Thermal System

This thermal system is renewable and sustainable energy system called Geothermal power. The predictable equal energy of geothermal electricity is around 42 million MW which is anticipated to ultimate for billions of years. Nanofluid can extract extra energy of geothermal and may produce extra power in Rankine [50]. The productivity of the device may remain enhanced in the use of nanofluid in geothermal boreholes and heat exchanger [48]. The electric efficiency (EE) of PVT (photovoltaic technology) systems is expanded with the aid of water spray cooling, water float through copper finned tubes, the use of reflector, moist absorbent and air waft within the optimized diffuser increased with the aid of 2%, 6%, 10%, 15% and 20%, [59].

### 4.3 Nanofluid as a Heat Exchanger

Recently, researchers are trying to increment onto the heat switching performance improvement in thermal heat exchanger using replacing conventional heat switch fluid with nanofluid. Carried out experimental and CFD (Computational fluid dynamics) analysis of CuO/water nanofluid in plate warmness exchanger. Now this research shows better thermal conduction of nanofluid. Because of the 0.9% extent fraction of nanoparticles, there was a 69.3% increase in the heat transfer coefficient while employing silver nanofluid in a twin pipe heat exchanger. Besides, compact heat exchanger become investigated the use of nanofluid.

### 4.4 Solar Stills

Small water desalination device combined with a Cu/water nanofluid solar collector as a heating supply. The system is comprised of a flat plate sun collector solar water heater, a blending tank, a flashing chamber, a helical heat exchanger [60]. The main method of desalination is the evaporation of seawater under extremely low-stress conditions, or vacuum. After then, the evaporating water condenses to produce sparkling water. The results of the simulation indicated that a key factor in boosting freshwater production and reducing costs is nanoparticle concentration.

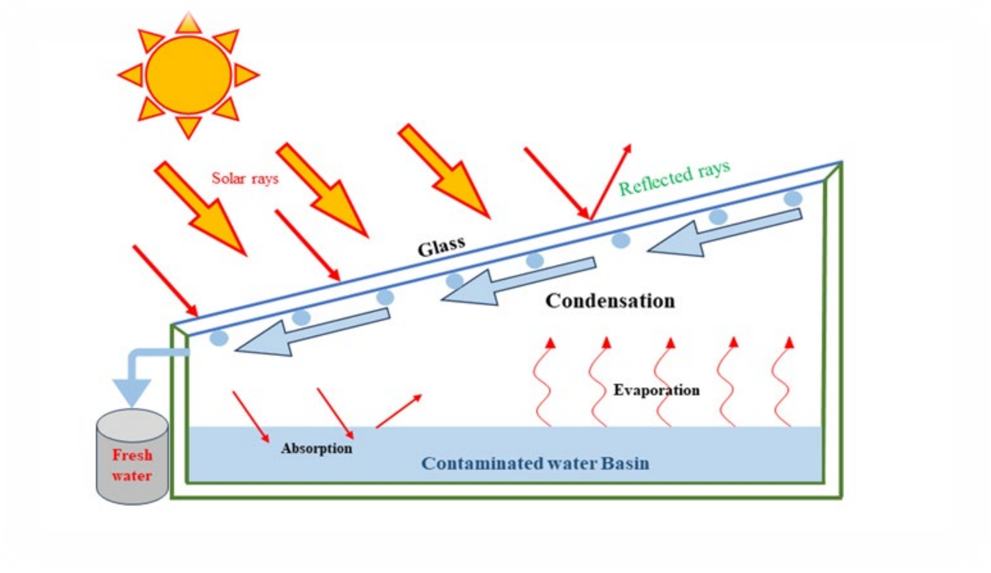

**Fig. 4** *Solar-powered water desalination devices*

For an example, $MnO_2$ nanoparticles addition onto the solar still increases the pace at which distilled water is produced. We can now analyse how using glass cooling and nanofluids can improve the performance of solar stills. Their findings demonstrated that despite this, solar productivity become stepped forward with the aid of 44.91% and 53.95% while the use of CuO and graphite micro-flakes, respectively. Further, the output yield was changed into stronger approximately 47.80% and 57.60% the usage of CuO and graphite nanoparticle [62].

## 5. Challenges

### 5.1 Nanofluid Stability

The unresolved issue of nanofluid stability over an extended period limits the commercialization of nanofluids. For the nanofluid to have identical thermophysical characteristics, stability is essential. Van der Waals' appealing pressure and electric double-layer repulsive force are connected to nanofluid stability. To obtain a strong nanofluid, the electrical double layer repulsive force (EDLRF) needs to be greater than the Vander Waals attractive force. Most experimental investigations failed to mention the brief reaction of the nanofluids operating inside the solar thermal collector. The optical and thermal characteristics of nanofluids are also impacted by their stability, in addition to their thermal properties.

Solar radiation fluctuations, weather patterns, and energy demand variations are common causes of transient situations in solar thermal systems. When it comes to thermal difficulties, nanofluids are crucial because of how they improve heat transfer capabilities [46]. However, a crucial factor for long-term efficiency is their stability in the face of changing operating circumstances.

### 5.2 Nanofluid Viscosity

When addition of nanoparticle in nanofluid it will increase the viscosity of nanofluid. carbon nanotubes (CNT) based water nanofluid are the best example for more instance solar absorbing nanofluid which exhibits high viscosity despite the extremely small weight of the [60]. Now, the results very higher power required to pump to operates to the solar thermal. There are more efficient ways to increase the pump strength to achieve the desired thermal performance because this will raise the device's operating costs. Emphasizing entropy evaluation observations is necessary to support the use of nanofluids in solar collectors. Now, most of the research on entropy formation is theoretical aspects.

## 5.3 Inconsistent Results of the Researchers

Most research projects in review & research paper are indicated to increase the nanofluid's thermal performance operated to the solar collector becomes better as the addition of nanoparticle using various methods. Nevertheless, limited research has demonstrated that the thermal overall performance declines as soon as the specific particle loading is surpassed [61].

An example, Yousefi in this paper study says that when using 0.2 wt% MWCNT nanofluid, the flat-plate solar collector's efficiency is lower than when using water as the base fluid [62]. But after adding 0.4 wt% of carbon nanotube, the solar collector showed a noticeable improvement. The received consequences are primarily predicated on applying suspension without adding surfactant.

## 5.4 Solar Collector and its Design

Different types and its design of solar collector are also affecting the sedimentation of the particles, and this was studied by Colangelo et al. this paper indicates the maintaining a specific number of rates of mass flow of the liquid, one can deal with the sedimentation of the [63]. Thus, the design of the solar collector must be altered. Even though these authors introduced a new layout, extra comprehensive examine is still needed on this vicinity [64].

## 5.5 High Cost for Nanofluid

In future need High energy is the one of the most serious problems affect to the human. The rising requires of strength to provide welfare for humans has led specific nations to discover specific energy [65]. Nanofluid can be generated by many various approaches like one step or two step methods, but this method needed to more advanced and specific sophisticated equipment's and systems and that is the main challenge that high costing of produced nanofluid so that one of most drawbacks of nanofluid productions and its [66].

## 5.6 Complicated Production Process

Now, in single step method to produce nanofluid have often at the same time makes and disperse the nanoparticle into base nanofluid, but in two step approaches that makes producing nanoparticles and after that disappearing in the nanofluid's base. When using both of approaches, Nanoparticles are fundamentally created from approaches that include interactions or ion alternating process. Furthermore, it is difficult or impossible for separating the other ions and reactions from the base fluids [67].

The tendency of the nanofluid to aggregate into bigger particles when it produces the nanoparticles which limits good high surface area of nanoparticles now most research up have been restrained to sample sizes much less than some one hundred millilitres of nanofluid. This is elaborate in view that larger samples are required to trial many materials characteristics of nanofluids and, specifically, to evaluate their capability to be used in new programs.

In study, water heat exchange in a single phase using many nanoparticles; however, actual heat transfer processes have not yet been documented. however, when nanoparticles were placed at the boiling and condensed points of heat transfer, they even caused fouling on the floor of the heat transfer, which decreased HTCs [44].

## 6. Conclusion

Nanofluid use in solar thermal systems presents a viable approach for enhancing performance and efficiency. Through case studies and experimental findings, it has been proven that nanofluids offer improved heat transfer properties, enhanced thermal efficiency, and increased energy output compared to conventional fluid-based systems. The selection of appropriate base fluids and nanoparticles, along with careful dispersion techniques and stability considerations, are crucial for achieving optimal performance. However, further research is needed to address challenges such as long-term stability, cost-effectiveness, and scalability for large-scale implementation. Despite these challenges, nanofluids hold great potential for advancing solar thermal systems and contributing to the sustainable utilization of solar energy. Continued study and development efforts in this area will open the door for a widespread application of solar thermal systems based on nanofluids in the future.

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## Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

## Author Contribution

*The authors confirm contribution to the paper as follows:* ***study conception and design:*** *Jignesh Tank, Gaurav Jadav, Sandhya Dodia;* ***data collection:*** *Tanvi Dudharejiya, Mayur Vala, Pankaj Solanki, D.K. Dhurav;* ***analysis and interpretation of results:*** *J.H. Markna;* ***draft manuscript preparation:*** *Bharat Kataria. All authors reviewed the results and approved the final version of the manuscript.*

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