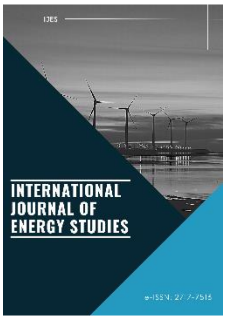
INTERNATIONAL JOURNAL OF ENERGY STUDIES

e-ISSN: 2717-7513 (ONLINE); homepage: https://dergipark.org.tr/en/pub/ijes



Review Article

Int J Energy Studies 2023; 8(3): 581-600

DOI: 10.58559/ijes.1299104

Received : 18 May 2023
Revised : 23 June 2023
Accepted : 05 Aug 2023

Recent advances in solar thermal system involving nanofluid utilization: A mini review

Edip Taşkesen[a*] , Rüzgar Üren[b]

[a] Faculty of Engineering, Department of Energy Systems Engineering, Sirnak University,Şırnak, Türkiye, ORCID: 0000-0002-3052-9883
[b] Graduate School of Education, Energy Science and Technologies, Sirnak University,Şırnak, Türkiye, ORCID: 0000-0002-0313-9337
*(*Corresponding Author:edip.taskesen@sirnak.edu.tr)*

Highlights

- Enhanced heat transfer efficiency.
- Optimal nanoparticle selection.
- Stability and longevity.
- Direct absorption of solar radiation.

You can cite this article as: Taşkesen E, Üren R. Recent advances in solar thermal system involving nanofluid utilization: A mini review. Int J Energy Studies 2023; 8(3): 581-600.

ABSTRACT

Nanofluids are fluids that contain nanoparticles that improve thermal characteristics. The thermal efficiency of systems that use nanofluids is higher than that of systems that use water as the working fluid. Solar thermal energy and systems, nanofluids and their structures, nanofluid integration into solar thermal systems, and the positive and negative consequences of nanofluid usage in these systems were all addressed in this study, emphasizing the importance of their integration. This study describes a study on using nanofluids in solar thermal systems. This research aims to examine the potential benefits of employing nanofluids, such as increased efficiency and lower prices. Furthermore, the study demonstrates that using nanofluids can reduce the size of the solar collector required to achieve the same performance level, which can lead to a decrease in the overall cost of the solar thermal system. This study's results indicate that using nanofluids in solar thermal systems can significantly enhance efficiency and reduce costs. However, further research is needed to fully explore the benefits and limitations of using nanofluids in solar thermal systems.

Keywords: Nanofluids, Solar thermal systems, Solar energy, Renewable energy sources, Nano-sized particles.

1. INTRODUCTION

With the growth of the world population and the increasing demand for resources such as oil and coal and the fact that it is no longer sufficient to meet its negative environmental impacts, the purpose of the use of renewable energy sources is increasing. Solar energy is getting more and more attention worldwide as it is a sustainable and clean energy source. Solar energy use is applied in various fields, from electricity generation to warming systems. In this context, solar thermal systems are an effective technique used to obtain heat energy by collecting solar energy. However, the efficiency and performance of solar thermal systems emerge as a subject that needs to be continually improved [1, 2, 3].

Solar systems are technologies used to generate electrical energy using solar rays. These systems are thermally divided into two main groups, Photovoltaic (PV) and the Sun. While photovoltaic systems convert solar rays directly into electrical energy, Solar Thermal systems convert solar energy into heat energy and generate electrical energy with this heat energy. Solar systems are increasingly preferred worldwide and are considered an environmentally friendly, economical, and sustainable energy source. Solar systems are used in homes, businesses, industrial facilities, and even in space. Although the number of solar systems varies according to their usage areas, there are millions of systems worldwide.

Photovoltaic systems are defined as systems made of semiconductor materials that directly generate electricity from sunlight using solar panels. The system operates by allowing the sunlight falling on the panel to free electrons in the photovoltaic cells, creating an electric current. With the help of an inverter, this electric current becomes usable and is synchronized and connected to the electric grid or a storage system (Figure 1 & Figure 2) [4, 5].

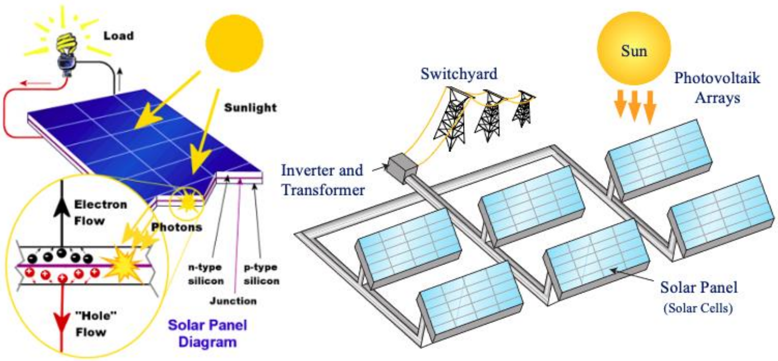


Figure 1. The basic principle of photovoltaic solar power plant [6, 7].

Thermal energy systems use mirrors or lenses to focus sunlight on a receiver that heats a liquid such as water or oil. The heated liquid is then used to produce steam that pushes the turbines to generate electricity. Thermal energy systems can also be divided into two types: Concentrated Solar Power (CSP) and Solar Water Heating (SWH) systems.

CSP systems use mirrors or lenses to concentrate sunlight on a small area, which warms a liquid to extremely high temperatures. The heated liquid is then used to produce steam that pushes the turbines to generate electricity. CSP systems are typically used in large-scale power plants (Figure 2).

SWH systems use solar collectors to heat water, which is then used for domestic or commercial purposes such as heating and cooling. SWH systems are typically used in residential and commercial buildings (Figure 3).

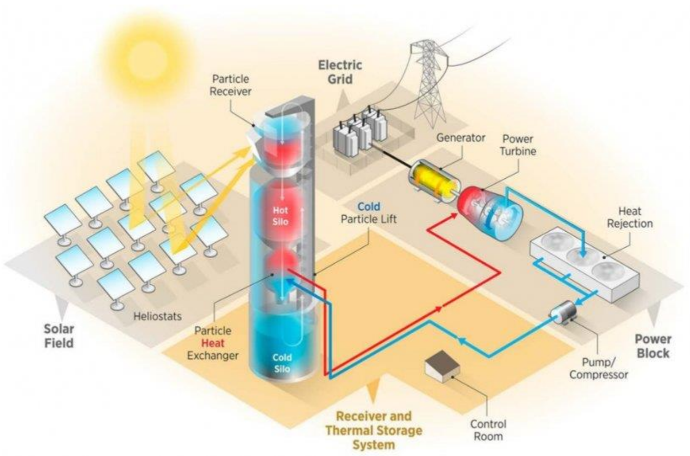


Figure 2. The basic principle of concentrated solar power (CSP) systems [8].

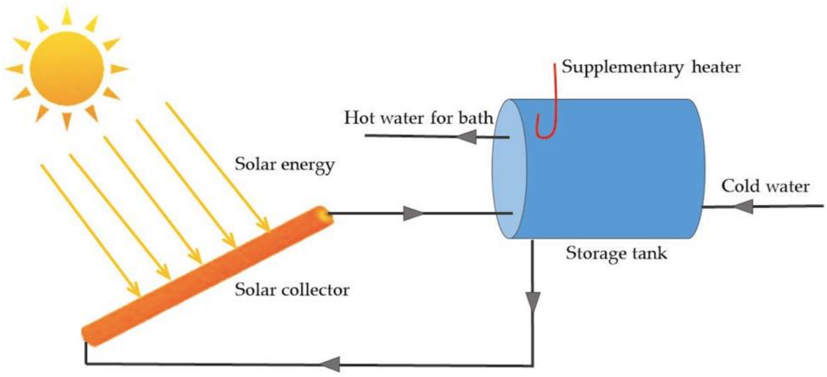


Figure 3. The basic principle of solar water heating (SWH) systems [9].

As illustrated in Figure 4, thermal energy systems produce power from heat by using different working fluids or water. In these devices, integrated steam turbines or heat engines run on a heated fluid caused by solar radiation. This can be accomplished with or without concentration by utilizing focusing techniques such as parabolic dishes or Fresnel mirrors. Because solar energy is an infinite resource, it qualifies as a renewable energy source, making it ecologically benign and with the potential to cut energy costs, making these systems extremely lucrative. Solar thermal systems will be one of the study's focal points.

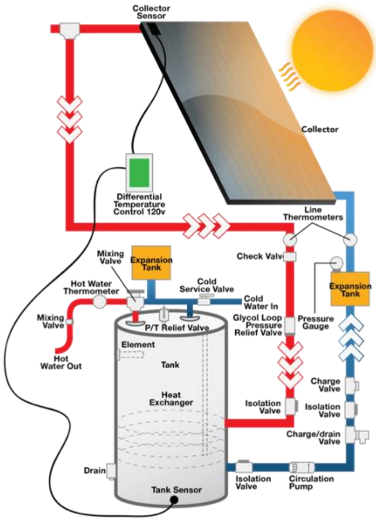


Figure 4. Schematic of the loop heater system [10].

Nanofluids are fluids in which nanoparticles (usually dispersed metal oxides or carbon-based materials) are liquid mediums. In solar thermal systems, nanofluids can absorb incoming sunlight more effectively and transmit heat, thereby increasing system efficiency. In general, however, nanofluids are considered a promising technology to increase efficiency in solar thermal systems [11].

Nanofluids are fluids in which particles on the nanometer scale are dispersed in a liquid medium. They are usually created using metal oxides or nanoparticles of carbon-based materials. The use of nanofluids in solar thermal systems has the potential to increase heat transfer efficiency. Thanks to the high thermal conductivity of nanoparticles, it is ensured that solar energy is absorbed and transmitted more effectively [9, 10].

Nanofluid is a term used in nanotechnology and is often used to refer to liquids consisting of nanometer size (10^{-9} meter) particles. These particles can alter the physical properties of liquids, for example (, increasing the viscosity, surface tension, thermal conductivity, etc.) can improve the performance of liquids. Nanofluids are used in many industrial applications, for example in the energy production, automotive, electronics, medical, and food industries [11]. In general, the thermophysical properties of (Figure 5) nanofluids are described as follows:

- Stability: Nanoparticles can disperse homogeneously in the liquid, providing stability.
- Optical Properties: Nanofluids exhibit optical properties based on the type of nanoparticles present, offering different responses to light and the ability to reflect light in various ways.
- Chemical Compatibility: The interaction between the nanoparticle and liquid components results in chemical compatibility.
- Additionally, two specific properties of nanofluids will significantly assist our study's progress:
- Fluidity: The mobility of nanoscale particles in the liquid can affect the fluidity of the nanofluid. After adding nanoparticles to the liquid, the characteristics of the liquid change, altering the viscosity of the resulting mixture and representing the fluid's internal friction resistance.
- Heat Transfer: Nanofluids exhibit higher heat transfer efficiency compared to traditional fluids. Particles in the fluid increase heat transfer by providing more surface area [11].

These properties play an important role in the heat transfer properties and performance of nanofluids [11].

Helically coiled tube heat exchangers are commonly used in various industrial applications to transfer heat between two fluids. The helical coil configuration provides a compact design with a large surface area, promoting efficient heat transfer. Several factors need to be considered to analyze the heat transfer and performance of such heat exchangers be considered. Here is an overview of the analysis process:

- Heat Transfer Analysis:
  - Heat Transfer Coefficients: Calculate the overall heat transfer coefficient (U) for the heat exchanger, which depends on the individual film coefficients and thermal resistances of the fluids inside and outside the coil.

- Log Mean Temperature Difference (LMTD): Determine the LMTD by considering the temperature difference between the hot and cold fluids at various points along the coil.
- Heat Transfer Rate: Calculate the heat transfer rate using the formula: Q = U×A×LMTD, where Q is the heat transfer rate, A is the heat transfer area, and LMTD is the log mean temperature difference.

- Performance Analysis:
  - Effectiveness: Determine the effectiveness of the heat exchanger, which is the ratio of the actual heat transfer rate to the maximum possible heat transfer rate.
  - Pressure Drop: Analyze the pressure drop across the helical coil to assess the flow resistance of the fluids. This involves considering the flow rate, tube diameter, coil geometry, and fluid properties.
  - Fouling Factors: Account for fouling effects on heat exchanger performance. Fouling can reduce heat transfer efficiency and increase pressure drop. Fouling factors depend on the nature of the fluids and the heat exchanger's operating conditions.
- Analysis Tools:
  - Computational Fluid Dynamics (CFD): Employ CFD simulations to model the fluid flow and heat transfer within the helical coil. CFD can provide detailed information about velocity profiles, temperature distribution, and pressure drop.
  - Experimental Testing: Conduct experimental tests using a scaled-down model or a prototype to validate the theoretical calculations and obtain empirical data for heat transfer and performance analysis.
- Optimization and Design Considerations:
  - Coil Geometry: Investigate different helical coil geometries (pitch, diameter, number of turns) to optimize heat transfer and minimize pressure drop.
  - Fluid Selection: Consider the properties of the fluids used, such as thermal conductivity, viscosity, and specific heat, to enhance heat transfer efficiency.
  - Flow Arrangement: Explore various flow arrangements (counterflow, parallel flow) to maximize heat transfer and effectiveness.

Overall, analyzing the heat transfer and performance of helically coiled tube heat exchangers involves considering heat transfer coefficients, LMTD, heat transfer rate, effectiveness, pressure drop, and fouling factors, and utilizing tools like CFD and experimental testing. Optimization of coil geometry, fluid selection, and flow arrangement can help improve the performance of these heat exchangers.

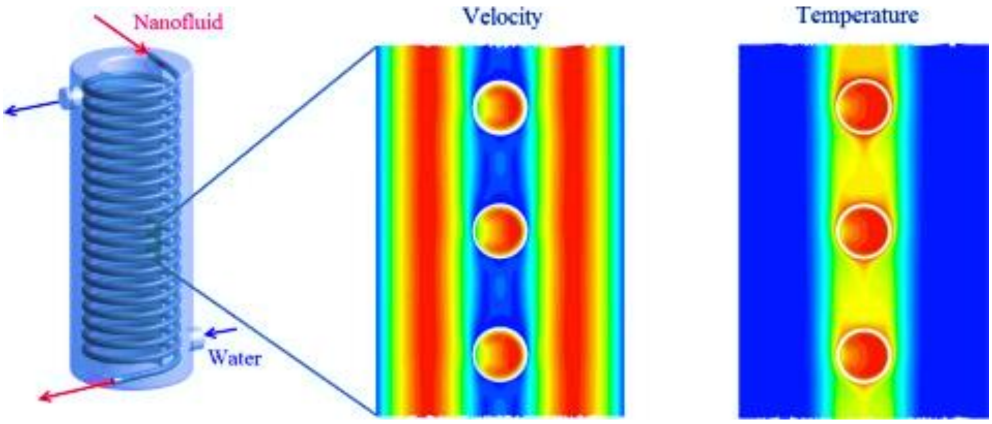


Figure 5. In helically coiled tube heat transfer and performance analysis [2].

Due to these properties, nanofluids are not only preferred in heat exchangers and cooling systems but also specifically selected for thermal energy storage systems [12]. With their unique characteristics, nanofluids represent the second focal point of this study.

This research aims to investigate the utilization of nanofluids as a fluid choice in solar thermal systems, considering their excellent heat transfer properties in addition to the clean and environmentally friendly nature of solar thermal systems.

2. SOLAR THERMAL ENERGY

Solar thermal energy is a method that uses the sun's energy to generate heat energy. The primary goal of these systems is to catch solar radiation and transform it into usable thermal energy that can be stored. Solar thermal energy is used in various applications, including water heating and steam generation for industrial processes, greenhouse heating, space heating, and home hot water production.

- There are two types of solar thermal systems: concentrating and non-concentrating solar thermal systems.
- Non-concentrating solar thermal systems collect solar radiation and store and utilize heat through a heat transfer fluid (usually a mixture of water or antifreeze). Solar energy is absorbed

through solar collectors, and the heat is used in different ways depending on the intended application.

- Concentrating solar thermal systems focus sunlight on a specific point using either parabolic troughs or Fresnel mirrors. The concentrated light heats a heat transfer medium (typically thermal oil [13]), and the generated heat is then converted into electricity. Concentrating solar thermal systems (Figure 6) are used in applications requiring high temperatures or electricity generation.
- The Stirling dish works as a kind of thermal energy system that generates electricity using solar energy. This system uses a solar-gathering dish, and the heat in this dish is converted into electrical energy using the Stirling engine. The solar tower uses a series of mirrors that focus solar energy and collects this energy at some point. The heat at this point is used to produce steam, and steam rotates the turbines, generating electrical energy. Stirling solar systems show (Figure 6-7).

Figure 6. A solar power tower covering an area of 1.21 km² and concentrating light using 10,000 mirrored heliostats [3].

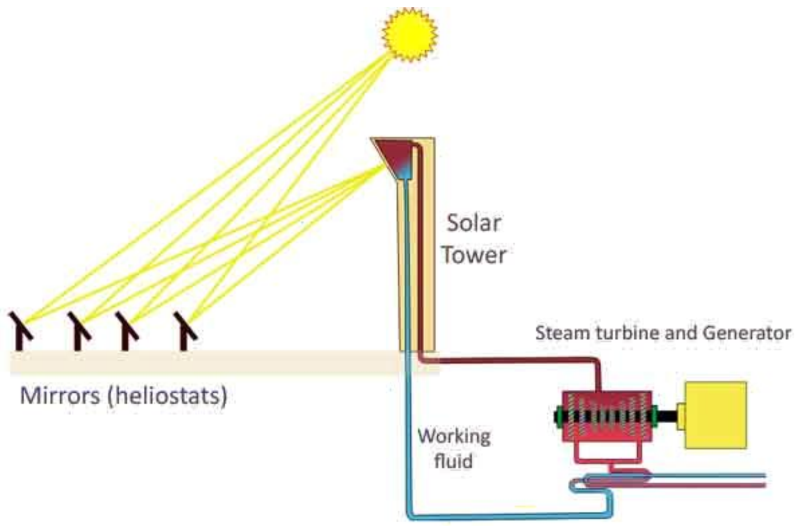


Figure 7. Stirling solar tower system [14].

2.1. Advantages of Solar Thermal Systems

Solar thermal systems are clean, environmentally friendly energy sources that help to reduce greenhouse gas emissions while supporting environmentally friendly energy generation. They can reduce their costs and save energy over their lifetime. They are often long-lasting and require little upkeep. Solar thermal systems are utilized in various applications, including hot water production, space heating, cooling, and many industries [15, 16].

2.2. Challenges of Solar Thermal Systems

The initial cost of solar thermal systems might be significant compared to alternative energy sources, limiting access for some consumers. Because solar energy is renewable, it is also dependent on the availability of sunlight, which can be difficult. While optimal functioning can be attained in areas with consistent sunlight, overcast or gloomy days, as well as interruptions in sunlight, can have an impact on energy output. Furthermore, low storage capacity and the requirement for vast installation sites are limitations [17, 18].

3. NANOFLUIDS

Nanofluids, colloidal suspensions of nanoparticles in a base fluid, exhibit altered thermophysical properties compared to the base fluid alone. The thermophysical properties of nanofluids can vary depending on factors such as nanoparticle material, concentration, size, shape, and the base fluid used. Here are some of the critical thermophysical properties that are affected by the presence of nanoparticles:

- Thermal Conductivity: One of the most significant advantages of nanofluids is their enhanced thermal conductivity. Adding nanoparticles can significantly increase the effective thermal conductivity of the base fluid. The extent of enhancement depends on factors like nanoparticle material and concentration.
- Specific Heat Capacity: Nanofluids generally exhibit slightly higher specific heat capacity compared to the base fluid. However, the increase is relatively small, and the properties of the base fluid primarily govern the specific heat capacity.
- Density: The addition of nanoparticles can slightly affect the density of the nanofluid. However, the change is typically negligible unless high nanoparticle concentrations are used.
- Viscosity: Nanofluids tend to exhibit higher viscosity compared to the base fluid, especially at higher nanoparticle concentrations. The increase in viscosity is attributed to the presence of nanoparticles, and it can impact the pumping power requirements and pressure drop in nanofluid systems.
- Stability: While not a thermophysical property per se, the stability of nanofluids is an essential characteristic. The dispersion stability of nanoparticles in the base fluid is influenced by factors such as the selection of stabilizing agents, nanoparticle surface charge, and surface functionalization.

It is important to note that various factors influence the thermophysical properties of nanofluids, and the specific properties can vary significantly depending on the nanoparticle type, concentration, and base fluid. Experimental measurements and theoretical models are used to determine the thermophysical properties of specific nanofluids under specific conditions.

Nanofluids [19, 20] are special fluids created by adding dispersed nano-sized particles in a liquid medium. They exhibit unique properties such as thermal conductivity, viscosity, fluidity, and heat transfer efficiency compared to traditional fluids. Particularly metallic or ceramic materials such as gold, silver, aluminum oxide, titanium dioxide, and copper nanoparticles are used. The inclusion of nanoparticles alters the properties of the base fluid [19] and imparts or enhances new characteristics, especially conductivity. By contributing to improving thermal properties, nanofluids enable better heat transfer of the fluid [21].

Nanofluids, which are a specialized fluid system formed by dispersing nanoparticles into a liquid medium, consist of three main components:

- Base Fluid: It is the fundamental component of the nanofluid and is typically composed of water, organic solvents, or certain oils [13]. The choice of base fluid affects the transport properties of the nanofluid, the thermal conductivity of the fluid, and the degree of homogenous dispersion of nanoparticles within the liquid.
- Nanoparticles: These are solid particles of nanometer size dispersed in the nanofluid. Their high surface area plays a significant role in influencing heat transfer and other properties.
- Stabilizing Agents: These substances are used to ensure homogenous nanoparticle dispersion and prevent sedimentation. Stabilizing agents prevent nanoparticles (Figure 8) from agglomerating with each other and maintain the stability of the nanofluid. With the help of stabilizing agents, nanoparticles remain continuously dispersed in the liquid, exhibiting the desired properties.

In Figure 8 only shows the CuO nanoparticles and not the nanofluid, then the statement in the text may be misleading or inaccurate. Without the presence of the nanofluid in the figures, it would not be possible to visually observe the effects of stabilizing agents on maintaining the stability of the nanofluid.

To clarify, stabilizing agents are typically added to nanofluids to prevent the agglomeration or settling of nanoparticles within the fluid. They provide a stabilizing effect by surrounding the nanoparticles and creating a barrier that hinders their interaction and clumping together. This helps maintain the dispersion of nanoparticles within the nanofluid, enhancing its stability.

In the context of the given statement, if the figures only show the CuO nanoparticles and not the nanofluid, it would not be visually apparent how the stabilizing agents are working to prevent agglomeration or maintain stability. To accurately assess the features and effects of the stabilizing agents, it would be necessary to observe the nanofluid itself, preferably through techniques such as transmission electron microscopy (TEM) or scanning electron microscopy (SEM) that allows visualization of the entire nanofluid.

Based solely on the information provided, the statement in the text may not be appropriately supported by the figures in Figure 8, as they only show the nanoparticles and not the nanofluid. It is vital to ensure that statements align with the visual evidence presented.

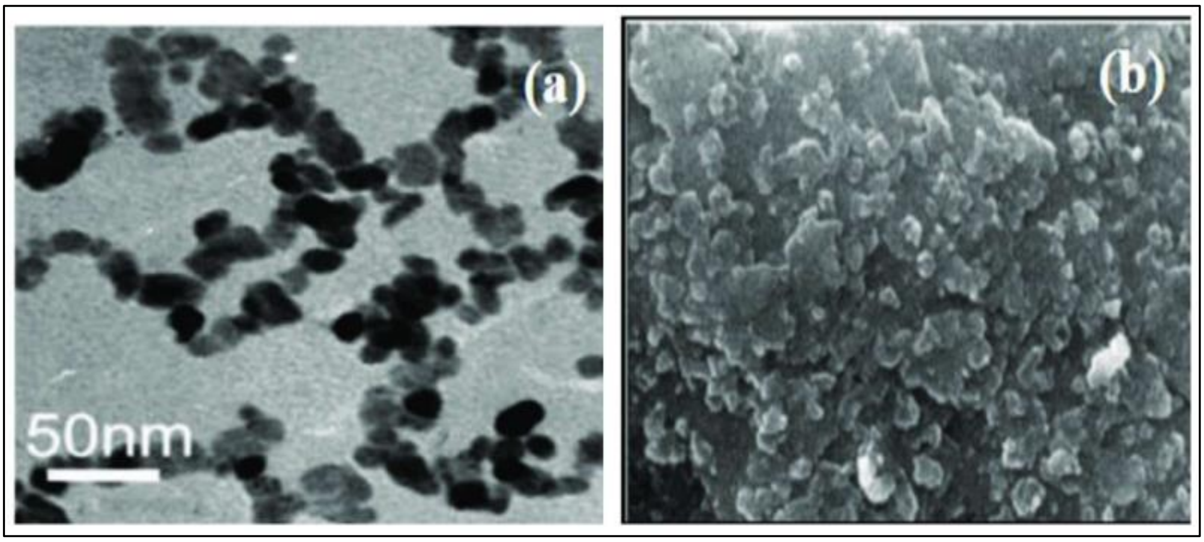


Figure 8. CuO nanoparticles using (a) TEM [22] and (b) SEM [23] (An Electron micrograph).

4. INTEGRATION OF NANOFLUIDS IN SOLAR THERMAL SYSTEMS

Nanofluids are integrated into solar thermal systems by adding nano-sized particles in the fluid in the collectors where solar energy is collected. Adding these microparticles aids in the collection, storage, and efficiency improvement procedures [20, 24]. This contribution is made possible by increasing the heat conductivity of the fluid when the nanoparticles are uniformly disseminated within it. Materials with high heat conductivity [25] are generally preferred. Furthermore, consideration should be given to the materials' possible toxicity or corrosiveness, and safeguards should be made in this regard. The following are the existing approaches for incorporating nanofluids into solar thermal systems:

- Manual or automated addition of nanofluids to the fluid tanks in the collection collectors.
- Use of circulation pumps.
- Optimization of the system design to accommodate the use of nanofluids.

The benefits of using nanofluids in solar thermal systems can be listed as follows:

- Increased Energy Efficiency: The enhanced thermal conductivity resulting from including nanoparticles improves the energy efficiency [26] of solar thermal systems. This allows for more energy to be collected and utilized more effectively. Using nanofluids can enable solar energy systems to operate with reduced energy losses [25, 26].

- Improved Heat Transfer: The addition of nanoparticles increases the thermal conductivity of the fluid, enabling more efficient collection and storage of solar energy. This efficiency enhancement in heat transfer processes significantly elevates system performance [27, 28].
- Higher Temperature Endurance: The incorporation of nanoparticles enhances the fluid's ability to withstand high temperatures. This allows solar thermal systems to operate more stably at elevated temperatures [29, 30].
- Better Fluidity: The presence of nanoparticles can improve the fluid's flow properties, resulting in lower viscosity and better fluidity. This can lead to reduced energy consumption in the system and lower power requirements for pumping operations [31].
- Reduced Storage Space Requirement: The increased thermal conductivity of the nanofluid implies that a smaller volume is required to store the same amount of energy compared to pure fluid. This enables the design of more compact solar thermal systems [30].

The advantages of using nanofluids in solar thermal systems continue to include reducing dependence on fossil fuels and the associated environmental benefits, lowering thermal stress by reducing temperature gradients through high thermal conductivity to extend material durability and lifespan, preventing corrosion and sedimentation, potential economic advantages, as well as flexible design and application.

The use of nanofluids in solar thermal systems is not limited to water-based systems alone. Nanofluids can be developed on different base fluids (such as oils) and can be utilized in various application areas of solar thermal systems (Figure 9) [13].

Classification of Solar-Thermal Systems and Nanofluid Applications:

- Solar-Thermal Systems: Solar-thermal systems can be broadly classified into two main categories:
  a) Concentrated Solar Power (CSP) Systems: These systems use mirrors or lenses to concentrate sunlight onto a receiver, where a working fluid (such as water or a heat transfer fluid) is heated to produce steam and generate electricity.
  b) Solar Water Heating Systems: These systems capture solar energy to heat water for various applications, such as domestic hot water or space heating.
- Nanofluid Applications: Nanofluids, suspensions of nanoparticles in a base fluid, have various applications in heat transfer and energy systems. Some typical applications include:

a) Heat Transfer Enhancement: Nanofluids can be used to improve the thermal conductivity and heat transfer properties of heat exchangers, cooling systems, and thermal energy storage systems.
b) Solar-Thermal Systems: Nanofluids can be employed in solar-thermal systems to enhance the absorption of solar radiation and improve heat transfer efficiency.
c) Electronics Cooling: Nanofluids can be used for cooling electronic components by improving heat dissipation properties.
d) Engine Cooling: Nanofluids can potentially enhance the efficiency of engine cooling systems by improving heat transfer and reducing the size of heat exchangers.

The Benefit of Using Nanofluids: To provide a more accurate assessment of the benefits of using nanofluids, it would be helpful to have specific information on the context and application being discussed. Nanofluids can offer several advantages, such as:

- Enhanced Heat Transfer: The presence of nanoparticles in the fluid can increase thermal conductivity, resulting in improved heat transfer performance.
- Reduced Size and Weight: With enhanced heat transfer, smaller heat exchangers or cooling systems can be designed, leading to reduced size, weight, and potentially lower costs.
- Temperature Uniformity: Nanofluids can contribute to more uniform temperature distribution, minimizing hot spots or thermal gradients.
- Improved System Efficiency: By improving heat transfer efficiency, the overall performance of heat exchangers or thermal systems may be enhanced, leading to improved system efficiency.

Overall Efficiency of Solar-Thermal Systems: The term "overall efficiency" in the context of solar-thermal systems typically refers to the conversion of solar energy into useful output. It considers the efficiency of converting solar radiation to thermal energy and any subsequent conversion of thermal energy to electricity or other useful outputs.

The specific components of the overall efficiency may vary depending on the system configuration and application. In general, it encompasses thermal efficiency (conversion of solar energy to heat) and electrical efficiency (conversion of heat to electricity, if applicable). It does not typically include optical efficiency (conversion of sunlight to heat) or exergy efficiency (considering the quality of energy).

Figure 9. Nanofluid is a solar energy plant it works in progress plant that produces energy [32].

The challenges encountered during the application of nanofluids [30, 33, 34] and the recommended considerations can be stated as follows:

- Stability: It is crucial to achieve homogeneous dispersion of nanoparticles in the nanofluid. Stability issues such as particle sedimentation or agglomeration can adversely affect the performance of the nanofluid. Therefore, appropriate stabilization methods and dispersion techniques should be employed. pH adjustments can be made to ensure stability [35].
- Particle Selection: The selection of nanoparticles for nanofluids is of great importance. Factors such as particle material, size, density, and shape significantly influence the heat transfer properties of the nanofluid. Proper particle selection ensures the desired thermal performance [31, 34].
- Chemical Corrosion and Material Compatibility: The materials in the system where nanofluids are used must be compatible with the nanoparticles. Some nanoparticles can cause chemical corrosion or material degradation in the system. Material selection should be carefully conducted to assess the long-term effects of nanofluid usage [34, 36].

In addition, factors such as particle settling or accumulation leading to pump and clogging issues, the cost of fluid synthesis and stabilization, and the consideration of environmental impacts due to potential toxicity should be considered.

Disadvantages include the lack of sufficient studies on commercial viability, data gaps in the field due to insufficient research, the lack of formulation and design of customized nanofluids for specific applications and needs, and insufficient research on the integration of nanofluids into existing systems.

5. CONCLUSION

Solar thermal systems have great potential as a sustainable energy source. However, continuous development, research, and integration efforts are required to overcome certain obstacles, such as high costs, dependence on sunlight, and energy storage challenges. Continuity of research and development is crucial to overcome these challenges and ensure nanofluids' safe and effective use.

Understanding the properties of nanofluids and evaluating their potential concerning their unique characteristics plays a significant role in developing advanced technologies. Ongoing research and development activities will enable the use of nanofluids in various application areas by optimizing their properties.

- The preference for nanofluids in solar thermal systems will enhance the overall efficiency.
- Due to their high heat transfer coefficients when mixed with a fluid, nanofluids are the preferred choice in applications such as solar power plants, cooling systems, electronic devices, and industrial processes.
- Factors such as system design, costs, and application processes should be carefully considered and evaluated, along with the properties of nanofluids.

The benefits, significance, and potential of nanofluids in solar thermal systems demonstrate their broader perspective. However, it is vital to consider the fundamental challenges and costs associated with using nanofluids. Efforts are constantly being made to overcome these challenges through research, development, and integration.

NOMENCLATURE

PV Photovoltaic
CSP Solar power
SWH Solar water heating
LMTD Log mean temperature difference
CFD Computational fluid dynamics
TEM Transmission electron microscopy
SEM Scanning electron microscopy

ACKNOWLEDGMENT

Analyzes and comments made in this document belong to the authors. Article is not supported by any institution, company, and etc.

DECLARATION OF ETHICAL STANDARDS

The authors of the paper submitted declare that nothing which is necessary for achieving the paper requires ethical committee and/or legal-special permissions.

CONTRIBUTION OF THE AUTHORS

Edip Taşkesen: Writing - review & editing.

Rüzgar Üren: Analysis, Acquisition of data, Interpretation of data, Writing - original draft.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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