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A Review on Potential Applications of Nanofluids in Solar Energy Systems

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Abstract: -

The use of nanofluids, a sophisticated type of liquid combination containing a modest concentration of solid particles smaller than a nanometer in suspension, is a field that is just a little more than two decades old. This review paper's goal is to look at how nanofluids are used in solar thermal engineering systems. The researchers chose solar energy as an alternate energy source because of the scarcity of fossil fuels and environmental concerns. Therefore, improving the effectiveness and performance of solar thermal systems is crucial. The majority of the earlier research on the use of nanofluids in solar energy has focused on their use in solar collectors and solar water heaters.

Keywords: Nanofluids, Solar energy, Efficiency, Economic and environmental considerations, Challenges

1. Introduction

Many industrial operations, including electricity generation, heating or cooling processes, chemical processes, and microelectronics, depend on common fluids including water, ethylene glycol, and heat transfer oil. These fluids can't achieve large heat exchange rates in thermal engineering devices due to their comparatively poor thermal conductivity. Utilizing ultra-fine solid particles dispersed in regular fluids to increase their thermal conductivity is one technique to get over this barrier. A nanofluid is a suspension of nanoparticles (1–100 nm) in a regular base fluid. In 1995, Choi coined the phrase "nano fluid" [1]. In comparison to suspensions containing millimeter- or micrometer-sized particles, nanofluids exhibit greater stability, rheological characteristics, and much higher thermal conductivities.

Numerous researchers have recently examined, both experimentally and conceptually, how nanofluids might improve heat transmission in thermal engineering systems. The thermophysical parameters of nanofluids, such as their thermal conductivity, viscosity, density, and specific heat capacity, have also been calculated using a range of production techniques, features, and models [2–9]. The effects of nanofluids on flow and heat transfer in natural and induced convection in various systems have also been described by certain researchers [10–13]. Since heat transfer intensification is crucial to many industrial sectors, including transportation, power generation, micro manufacturing, thermal therapy for cancer treatment, chemical and metallurgical sectors, as well as many others, the improved thermal behaviour of nanofluids may serve as the foundation for a significant innovation.

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The utilisation of solar energy has had a notable advantage recently. The usage of fossil fuels will be limited in the future due to predicted shortages as well as environmental concerns. Therefore, the hunt for alternate energy sources is driven. As the cost of fossil fuels keeps going up, this has grown in popularity. In only one hour, the sun provides the earth with more energy than the entire globe uses in a year. The majority of solar energy applications are profitable, and modest systems for personal use only need a few kilowatts of electricity [23,24]. It is crucial to use solar energy for a variety of purposes and to modify the energy to create solutions.

As a result, the focus of this analysis is on how nanofluids affect solar collector efficiency as well as the financial and environmental implications of using these systems. There is also a study of further uses for nanofluids in solar stills, solar cells, and thermal energy storage. Future research in this area is also suggested in several ways. Furthermore, the current difficulties with applying nanofluids to solar energy applications are explored. Finally, the authors would like to point out that far less is known about the use of nanofluids in solar energy applications compared to the thorough references on nanofluids cited above. As this is the first systematic review work on this topic, it is important to offer as detailed an explanation as possible.

2. Applications of nanofluids in solar energy

First, the effectiveness, cost, and environmental implications of using nanofluids in collectors and water heaters are examined. As these factors can decide whether nanofluids can improve solar system performance, certain studies on thermal conductivity and optical characteristics of nanofluids are also briefly addressed.

2.1 Collectors and solar water heaters

Solar collectors are a specific type of heat exchanger that convert solar radiation energy into the transport medium's internal energy. These gadgets take in solar radiation, transform it into heat, and then transmit that heat to a fluid running through the collector (often air, water, or oil). The energy gathered is transferred from the working fluid to the hot water or space conditioning equipment immediately or to a thermal energy storage tank, where it may be extracted for use at night or on overcast days [26]. The most often used solar energy equipment is solar water heating. The nanofluid-based solar collectors are examined from two perspectives, as was described in the introduction. These devices are examined from an efficiency standpoint in the first, and from an economic and environmental standpoint in the second.

2.1.1 Efficiency of nanofluid-based solar collectors

The efficiency of a low-temperature nanofluid-based direct absorption solar collector (DAC) with water and aluminium nanoparticles as the working fluid was theoretically studied by Tyagi et al. [27]. Fig. 1 depicts a schematic of the direct absorption collector. This collector is adiabatic because the upper side is coated in glass and the lower side has good insulation. The following equation can be used to determine the collector's efficiency:-

$$\eta = \frac{useful\ gain}{available\ energy} = \frac{\dot{m}c_p(\overline{T}_{out} - \overline{T}_{in})}{AG_T} \quad (1)$$

The change in collector efficiency as a function of particle volume percentage (%) was displayed by Tyagi et al. [27], where the volume fraction ranges from 0.1% to 5%. (see Fig. 2). Their findings demonstrated that adding nanoparticles to the working fluid significantly improves efficiency even at low nanoparticle volume fractions. They claimed that the inclusion of nanoparticles causes a rise in the attenuation of sunlight passing through the collector, which results in an improvement in collector efficiency. Adding additional nanoparticles is not advantageous since the efficiency practically remains constant for volume fractions larger than 2%.

In the case when the volume percent is equal to 0.8%, Tyagi et al. [27] also looked at the impacts of nanoparticle size on the collector efficiency. The findings showed that efficiency rises marginally as nanoparticle size increases (see Fig. 3).

Otanicar et al. [28] studied the impact of several nanofluids (carbon nanotubes, graphite, and silver) on the functionality of a micro scale direct absorption solar collector both experimentally and statistically (DASC). Fig. 4 presents the design of the experimental setup together with the collector's dimensions. Using Eq. 1, Fig. 5 illustrates how collector efficiency varies with volume fraction for various materials (1). In a typical collector arrangement, solar energy is absorbed on a black plate surface. The DASC statistics are contrasted with this configuration.

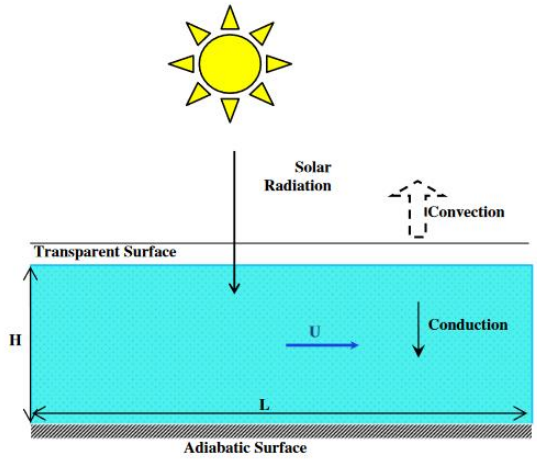

Fig. 1. Schematic of the nanofluid-based direct absorption solar collector (Reprinted from Tyagi et al. [27], with permission from ASME).

In a vacuum tube solar collector, He et al. [30] examined the light-heat conversion properties of two nanofluids, water-TiO_2 and water-carbon nanotube (CNT), in both sunny and overcast weather. The experimental findings indicate that the CNT-H_2O nanofluid with a weight concentration of 0.5% has extremely good light heat conversion properties. The temperature of the CNT-H_2O nanofluid is greater than that of the TiO_2-H_2O one due to the CNT-H_2O nanofluid's improved light-heat conversion properties. Accordingly, using the CNT-H_2O nanofluid in a vacuum tube solar collector is preferable than using TiO_2-H_2 O.

The effects of an Al2O3/water nanofluid on the effectiveness of a flat-plate solar collector were experimentally examined by Yousefi et al. [34]. They looked at the impacts of two distinct weight fractions of the nanofluid, 0.2% and 0.4%, using particles that were 15 nm in diameter. They also investigated the impact of using Triton X-100 as a surfactant on efficiency. In Fig. 10 and Table 1, respectively, the flat-plate collector's photograph and specs are shown.

Yousefi et al. [34] conducted the experiments using a schematic setup shown in Fig. 11. Their findings are as follows:

1. The efficiency of the solar collector with 0.2% weight fraction (wt.) nanofluid is greater than that with water by 28.3% (see Fig.).
2. For a wide range of the reduced temperature parameter (Ti / Ta)/G T, the efficiency of collector with 0.2% wt.% nanofluid is higher compared to 0.4 wt.% (see Fig. 12).
3. Using surfactant leads to a 15.63% enhancement of the efficiency.

Later, Yousefi et al. [35] investigated the effects of water-Multi wall carbon nanotubes (MWCNT)-Water nanofluid on the effectiveness of the flat plate collector using the same experimental setup as their earlier work [34]. They noticed that:

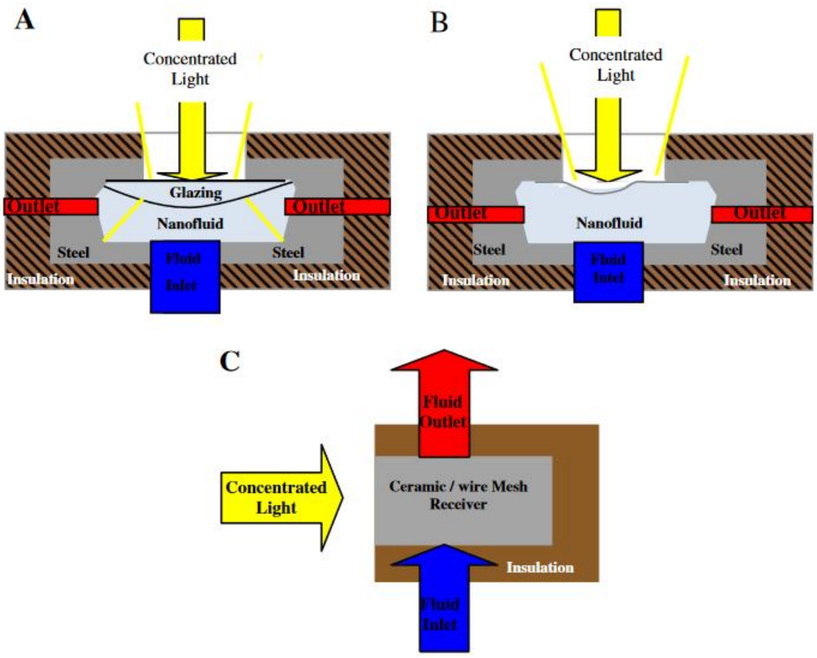

Fig. 2. (a) Conceptual design of a nanofluid concentrating collector with glazing. (b) Conceptual design of a nanofluid concentrating collector without glazing. (c) Conceptual drawing of a conventional power tower solid surface absorber (Reprinted with permission from Taylor et al. [29]. Copyright 2011, American Institute of Physics).

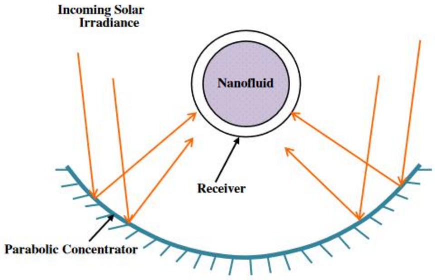

Fig. 3. Schematic of nanofluid-based concentrated parabolic solar collector (NCPSC) (Reprinted from Khullar et al. [33], with permission from ASME).

1) The efficiency of the collector by using of MWCNT–water nano fluid without surfactant is remarkably increased for 0.4 wt.% nanofluid, whereas with 0.2 wt.% the efficiency reduces compared to water as the working fluid.
2) For 0.2 wt.% nanofluid, using surfactant increases the efficiency of the collector compared to water.

The potential of nanofluids for application in solar energy systems is investigated in the following through the examination of their optical characteristics and thermal conductivity. Reviewing the optical characteristics of gold nanoparticles was Link and El-[37] Sayed's focus. They focused on the shape and size dependency of the photothermal and radiative characteristics of gold nanocrystals. The size and form of the nanoparticle has a significant impact on the optical characteristics of a nanofluid, according to Khlebtsov et alinvestigation .'s [38] into the relationship between gold and silver nanoparticle size, shape, and structure.

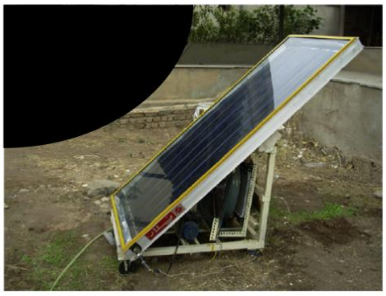

Fig. 4 Flat-plate collector used by Yousefi et al. (Reprinted from Yousefi et al. [34], with permission from Elsevier).

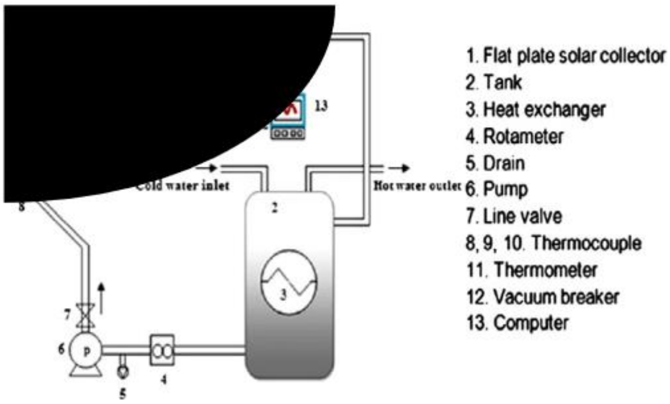

Fig. 5. Schematic of the experiment used by Yousefi et al. (Reprinted from Yousefi et al. [34], with permission from Elsevier)

Table 1: The specifications of the flat-plate collector (Reprinted from Yousefi et al. [34], with permission from Elsevier).

Specification	Dimension/value	Unit
Occupied area	200 × 94 × 9.5	cm
Absorption area	1.51	m^2
Weight	38.5	kg
Frame (Al6063 extruded)	–	–
Glass (float)	$t = 4$	mm
Header pipe (Cu)	Ø22, $t = 0.9$	mm
Connector riser pipe to absorber sheet (Cu)	Ø10, $t = 0.9$	mm
Absorption sheet:	–	–
Thermal emission:	7	%
Solar absorption:	96.2	%
Coating method:	Vacuum magnetron sputtering	–

For solar energy applications, Sani et al. [39] presented the optical characterisation of a novel fluid made of ethylene glycol and single-wall carbon nanohorns. They came to the conclusion that, in comparison to pure base fluid, carbon nanohorns might significantly improve sunlight absorption. The outcomes are contrasted with those of fluids suspending carbon-black particles, which are more typical carbon forms. They discovered that for a particular application, the spectral properties of nanohorn are significantly more advantageous than those of amorphous carbon. This finding demonstrates how employing carbon nanohorn-based nanofluids in thermal solar devices improves system efficiency and compactness. The potential of single-wall carbon nanohorn nanoparticles with water and glycol as two separate base fluids was studied by Mercatelli et al. [40,41]. Due to the fact that SWCNH particles only scatter only 5% of the total extinction, their experiments revealed that these nanofluids are excellent candidates for direct absorption solar devices. Mercatelli et al. [42] used a straightforward spectrophotometric method in another study to calculate the spectrum scattering albedo of SWCNHs/water nanofluid. The potential of using an aluminum/water nanofluid in direct absorption solar collectors was recently examined by Saidur et al. [43]. They came to the conclusion that an aluminum/water nanofluid with a 1% volume fraction greatly increases solar absorption, making it an excellent choice for a direct solar collector. Despite the fact that particle size has no bearing on the extinction coefficient of nanofluid, they recommended using nanoparticles with a minimum size of 20 nm in order to achieve Rayleigh scattering. They also discovered that the volume percent has a linear effect on the extinction coefficient. To increase the effectiveness of liquid-based solar receivers seeded with carbon-coated absorbent nanoparticles, Lenert and Wang [44] and Lenert [45] integrated theoretical and experimental studies.

2.1.2 Economic and environment considerations

Life cycle analysis is a recognised method for evaluating a product's economic and environmental effects [50]. The economic and environmental implications of nano-fluid-based collectors are discussed in this section. In Phoenix, Arizona, Otanicar and Golden [50] contrasted the environmental and financial benefits of utilising a traditional solar collector with those of a nanofluid-based collector. According to the economic study, the nanofluid-based solar collector has capital expenses and maintenance costs that are respectively \$120 and \$20 greater than those of a traditional solar collector (see Table 2). However, the fuel cost reductions per year, for both electricity and natural gas, are more than those of the traditional solar collector due to the higher efficiency and yearly solar fraction of the nanofluid-based solar collector. Furthermore, a nanofluid-based collector has a longer payback period than a traditional collector due to the higher cost of nanofluids, but at the conclusion of its useful life, it has the same life cycle savings.

2.2 Other applications

This section reviews further uses for nanofluids in solar energy systems, such as their use in thermal energy storage components, solar cells, and solar stills. It should be emphasised that there are very few documented efforts in this sector.

2.2.1 Thermal energy storage

The storage medium must have a high heat capacity and thermal conductivity in order to function as a typical solar thermal energy storage facility. Few materials, nevertheless, have these qualities and are suitable for use in high temperatures. Shin and Banerjee [52] recently revealed the abnormal improvement of high-temperature nanofluids' specific heat capacity. They discovered that silica nanoparticles added to alkali metal chloride salt eutectics at 1% mass concentration increased the nanofluid's specific heat capacity by 14.5%, making it a promising material for use in solar thermal energy storage facilities. Application of PCMs is one method of solar energy storage. The best PCM among the many ones on the market is paraffin because of its advantageous traits, such as high latent heat capacity, little super cooling, and inexpensive price. However, potential uses are severely limited by the material's intrinsically poor heat conductivity (0.21-0.24 W/mK) [53]. Wua et al[53] .'s numerical investigation of the Cu/paraffin nanofluid PCM melting processes. Their findings showed that the melting time might be reduced by 13.1% using 1 weight percent Cu/paraffin. They came to the conclusion that improving the heat transfer in a system for thermal energy storage using latent heat by adding nanoparticles is an effective strategy.

Table 2 Economic comparisons for conventional and nanofluid-based solar collectors (Reprinted with permission from Otanicar and Golden [50]. Copyright (2009) American Chemical Society)

Parameter	Conventional solar collector ($)	Nanofluid solar collector ($)
Independent costs	200.00	200.00
Area based costs	397.80	327.80
Nanoparticles		188.79
Total capital (one time cost)	597.80	716.59
Total maintenance (for 15 year life)	96.23	115.35
Total costs	694.03	831.94
Electricity cost saving per year	270.13	278.95
Years until electricity savings = costs	2.57	2.98
Natural gas cost saving per year	80.37	83.02
Years until natural gas savings = costs	8.64	10.02
Electricity price		
November_March (per kWh)	0.08	0.08
May_October (per kWh)	0.09	0.09
Daily service charge	0.25	0.25
Gas price		
Rate (per therm)	0.74	0.74
Monthly service charge	9.70	9.70

2.2.2 Solar cells

The effectiveness of such solar systems can be increased by cooling the solar cells. The cooling of the solar cells may be accomplished using nanofluids. The cooling of a silicon solar cell was modelled by Elmir et al. [54] using the finite element approach. They solved the equations using a Cartesian coordinate system, using the solar panel as an inclined hollow (with a slope of 30°). They conducted their investigation on an Al2 O3/water nanofluid, and they utilised the Wasp [55, 56] and Brinkman [56] models to determine the nanofluid's thermal conductivity and viscosity. They came to the conclusion that employing nanofluids improves the average Nusselt number, and as a result, the rate of cooling increases with increases in volume percentage, as seen in Fig. 3.

The thermophysical parameters of nanofluids should thus be calculated using temperature-dependent models in the future, or at the very least, more recent temperature independent models. For instance, the models and relationships described by Maiga et al. [57], Buongiorno [58], Nguyen et al. [59], Koo and Kleinstreuer [60], and Duangthongsuk and Wongwises [61] can be used to determine the viscosity of nanofluids. The relationships reported by Maiga et al. [57], Xuan et al. [62], Jang and Choi [63], Koo and Kleinstreuer [64], Chon et al. [65], Duangthongsuk and Wongwises [61], and Yiamsawasd et al. [66] may be used to calculate the thermal conductivity of nanofluids.

2.2.3 Solar stills

Due to both the fast population growth and the unchecked contamination of freshwater resources, there is an increase in the demand for potable water. 90% of infectious diseases in the poor world are caused by water-borne illnesses, according to the World Health Organization, which estimates that there are presently 2.8 billion people (or around 40% of the world's population) without access to clean drinking water [67]. Fresh water availability is increasingly important in dry, isolated areas of the world. Where solar energy is available in these areas, solar desalination devices can partially address the issue. The greenhouse gas emissions from the manufacturing of fresh water can be avoided by using solar stills [68]. Solar stills have been the subject of extensive investigation, and several techniques have been used to increase their production. According to a recent study by Gnanadason et al. [69], adding nanofluids to a solar still can boost production. Fig. 15 depicts the design of their experimental setup. They looked at what happened when carbon nanotubes (CNTs) were added to the water in a single basin solar still. Their findings showed that the efficiency is increased by 50% with the addition of nanofluids. They did not, however, indicate how much nanofluid was put to the water in the solar still. The economic viability of adding nanofluids to the solar still should be taken into account. According to certain literary works, adding colours to solar stills might increase their effectiveness. For instance, Nijmeh et al. [70] found that increasing the efficiency by putting violet dye in the water within the solar still. However, it is clear that nanofluids, particularly CNTs, are more expensive than dyes. As a result, employing nanofluids in solar stills may be challenging since, in this application, the nanofluids do not flow in a closed loop where they might be recovered.

3. Conclusion

In the last two decades, sophisticated fluids called nanofluids have evolved, which include nanoparticles. In several thermal engineering systems, nanofluids are employed to enhance system performance. An overview of nanofluid applications in solar thermal engineering was offered in this research. In some instances, the efficiency of solar collectors might be markedly improved by employing nanofluids, according to experimental and computational research. Naturally, it is discovered that employing a nanofluid with a greater volume fraction is not always the optimum choice (Yousefi et al. [34]). The best volume fraction should thus be determined by testing the nanofluids in various volume fractions. Additionally, differing conclusions on how particle size affects the effectiveness of the collectors may be seen in the theoretical research that are now accessible (see Refs. [27,28]). It might be worthwhile to do an experiment to see how particle size affects collector effectiveness. Additionally, it is established that several elements, such as adding surfactant to nanofluid and choosing an appropriate pH level for nanofluid, have an impact on the effectiveness of the collector. Previous research demonstrated that employing nanofluids in collectors reduces CO_2 emissions and results in yearly power and fuel savings from an economic and environmental perspective. The use of nanofluids in solar stills, solar thermal energy storage, and other reported uses is also discussed. It is also emphasised that in order to have a more precise forecast of the system performance while studying solar systems numerically (for instance, cooling solar cells), it is preferable to employ new thermophysical (temperature-dependent) models and two-phase mixture models for the nanofluid. This review demonstrates that the use of nanofluids in solar energy is still in its early stages.

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