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A review of the applications of nanofluids in solar energy

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ABSTRACT

Utilizing nanofluids as an advanced kind of liquid mixture with a small concentration of nanometer-sized solid particles in suspension is a relatively new field, which is less than two decades old. The aim of this review paper is the investigation of the nanofluids' applications in solar thermal engineering systems. The shortage of fossil fuels and environmental considerations motivated the researchers to use alternative energy sources such as solar energy. Therefore, it is essential to enhance the efficiency and performance of the solar thermal systems. Nearly all of the former works conducted on the applications of nanofluids in solar energy is regarding their applications in collectors and solar water heaters. Therefore, a major part of this review paper allocated to the effects of nanofluids on the performance of solar collectors and solar water heaters from the efficiency, economic and environmental considerations viewpoints. In addition, some reported works on the applications of nanofluids in thermal energy storage, solar cells, and solar stills are reviewed. Subsequently, some suggestions are made to use the nanofluids in different solar thermal systems such as photovoltaic/thermal systems, solar ponds, solar thermoelectric cells, and so on. Finally, the challenges of using nanofluids in solar energy devices are discussed.

Contents

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1. Introduction

Common fluids such as water, ethylene glycol, and heat transfer oil play an important role in many industrial processes such as power generation, heating or cooling processes, chemical processes, and microelectronics. However, these fluids have relatively low thermal conductivity and thus cannot reach high heat exchange rates in thermal engineering devices. A way to overcome this barrier is using ultra fine solid particles suspended in common fluids to improve their thermal conductivity. The suspension of nano-sized particles (1–100 nm) in a conventional base fluid is called a nanofluid. Choi first used the term ''nanofluid'' in 1995 [1]. Nanofluids, compared to suspensions with particles of millimeter-or-micrometer size, show better stability, rheological properties, and considerably higher thermal conductivities.

In recent years, many researchers have investigated the effects of nanofluids on the enhancement of heat transfer in thermal engineering devices, both experimentally and theoretically. Researchers have also applied a variety of preparation methods, characteristics, and different models used for the calculation of thermophysical properties of nanofluids (i.e., thermal conductivity, viscosity, density, specific heat capacity) [2–9]. Some investigators have also summarized the effects of nanofluids on flow and heat transfer in natural and forced convection in different systems [10–13]. The enhanced thermal behavior of nanofluids could provide a basis for an enormous innovation for heat transfer intensification, which is of major importance to a number of industrial sectors including transportation, power generation, micro-manufacturing, thermal therapy for cancer treatment, chemical and metallurgical sectors, as well as heating, cooling, ventilation and air-conditioning. Nanofluids are also important for the production of nanostructured materials for the engineering of complex fluids as well as for cleaning oil from surfaces due to their excellent wetting and spreading behavior (Ding et al. [14]). Another application of the nanofluid flow is in the delivery of nano-drug as suggested by Kleinstreuer et al. [15].

Saidur et al. [16] reviewed the potential of nanofluids in the improvement of heat transfer in refrigeration systems. The authors concluded that more studies are required to find the reasons behind the considerable improvements in heat transfer whereas an insignificant increase in pressure occurs. Thomas and Sobhan [17] presented experimental studies on nanofluids, with emphasis on the techniques of measuring the effective thermal conductivity. Escher et al. [18] investigated the applications of nanofluids in cooling electronics. Recently, applications of computer simulations and computational fluid dynamics (CFD) used to model systems employing nanofluids were reviewed and analyzed by Abouali and Ahmadi [19] and Kamyar et al. [20]. Ahn and Kim [21] also published a review on the critical heat flux of nanofluids for both convective flow boiling and pool boiling applications. In another publication, Saidur et al. [22] reviewed the general applications of nanofluids in some fields such as cooling of electronics, heat exchangers, medical applications, fuel cells, nuclear reactors, and many more. They also mentioned briefly the applications of nanofluids in solar water heaters. They investigated challenges in using nanofluids, including an increased pressure drop and pumping power, long-term stability of nanoparticles dispersion, and the high cost of nanofluids.

In recent years, the use of solar energy has had a remarkable edge. The perceived shortage of fossil fuels as well as environmental considerations will constrain the use of fossil fuels in the future. Therefore, researchers are motivated to find alternative sources of energy. This has become even more popular as the price of fossil fuels continues to rise. The earth receives in just about 1 h more energy from the sun than that consumed by the entire world for 1 year. Most solar energy applications are financially viable while small systems for individual use require just a few kilowatts of power [23,24]. It is important to apply solar energy to a wide range of applications and provide solutions through the modification of the energy proportion, improving energy stability, increasing energy sustainability, and enhancing system efficiency [25]. This paper presents a review of former studies on the application of nanofluids in solar thermal engineering systems. The former works on applications of nanofluids in solar energy are mainly related to their applications in collectors. Therefore, this review mainly investigates the effects of nanofluids on the efficiency improvement of solar collectors as well as on economic and environmental considerations regarding the usage of these systems. Other applications of nanofluids in thermal energy storage, solar cells, and solar stills are also reviewed. Some suggestions also are made for future works in this field. In addition, the existing challenges of using nanofluids in solar energy applications are discussed. Finally, the authors wish to mention that in contrast with the comprehensive references on nanofluids mentioned above much less is known about the application of nanofluids in solar energy applications. It should be reiterated here that, as this is the first systematic review paper on this subject, it is desirable to provide as complete details as possible. However, in an attempt to reduce the overall length of the paper, without compromising the technical quality, only some very important questions for problems of practical applications have been briefly described.

2. Applications of nanofluids in solar energy

Initially, the application of nanofluids in collectors and water heaters are investigated from the efficiency, economic, and environmental aspects. Some studies conducted on thermal conductivity and optical properties of nanofluids are also briefly reviewed, because these parameters can determine the capability of nanofluids to enhance the performance of solar systems.

2.1. Collectors and solar water heaters

Solar collectors are particular kind of heat exchangers that transform solar radiation energy into internal energy of the transport medium. These devices absorb the incoming solar radiation, convert it into heat, and transfer the heat to a fluid (usually air, water, or oil) flowing through the collector. The energy collected is carried from the working fluid, either directly to the hot water or space conditioning equipment or to a thermal energy storage tank, from which it can be drawn for use at night or on cloudy days [26]. Solar water heaters are the most popular devices in the field of solar energy. As mentioned in the introduction, the nanofluid-based solar collectors are investigated in two aspects. In the first, these devices are studied from the efficiency viewpoint, and in the second, from economic and environmental viewpoints.

2.1.1. Efficiency of nanofluid-based solar collectors

Tyagi et al. [27] investigated theoretically the effects of different parameters on the efficiency of a low-temperature nanofluid-based direct absorption solar collector (DAC) where the working fluid is a mixture of water and aluminum nanoparticles. A schematic of the direct absorption collector is shown in Fig. 1. The upper side of this collector is covered by a glass while the lower side is well insulated, so it is adiabatic. The efficiency of the collector is obtained by the following equation:

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

where $\dot{m}$ is the mass flow rate of the fluid flowing through the collector; c_p is the specific heat; and $\bar{T}_{in}$ and $\bar{T}_{out}$ are the mean fluid inlet and outlet temperatures, respectively. A is the cover area of the collector, and G_T is the solar flux incident on the solar collector. In the analysis, they assumed that the values of $\bar{T}_{in}$, G_T, and $\dot{m}$ to be 35 °C, 1000 W/m^2, and 1.2 kg/s, respectively.

Tyagi et al. [27] plotted the variation of collector efficiency as a function of the particle volume fraction (%), where the volume fraction varies from 0.1% to 5% (see Fig. 2). Their results showed that by adding nanoparticles to the working fluid, the efficiency increases remarkably for low values of volume fraction of nanoparticles. They attributed the increase of collector efficiency to the increase in attenuation of sunlight passing through the collector due to the nanoparticles addition that leads to the increase of collector efficiency. However, for a volume fraction higher than 2%, the efficiency remains nearly constant, so adding more nanoparticles is not beneficial. Tyagi et al. [27] also investigated the effects of nanoparticles size on the collector efficiency where the volume fraction is equal to 0.8%. The results revealed that the efficiency increases slightly with an increase in the size of nanoparticles (see Fig. 3).

Otanicar et al. [28] investigated both experimentally and numerically the effects of different nanofluids (carbon nanotubes, graphite, and silver) on the performance of a micro scale direct absorption solar collector (DASC). The schematic of the experimental set up showing also the dimensions of the collector is presented in Fig. 4. Fig. 5 shows the variation of collector efficiency with volume fraction for different materials, estimated using Eq. (1). The DASC data are compared to a conventional collector configuration where the solar energy is absorbed on a black plate surface. As

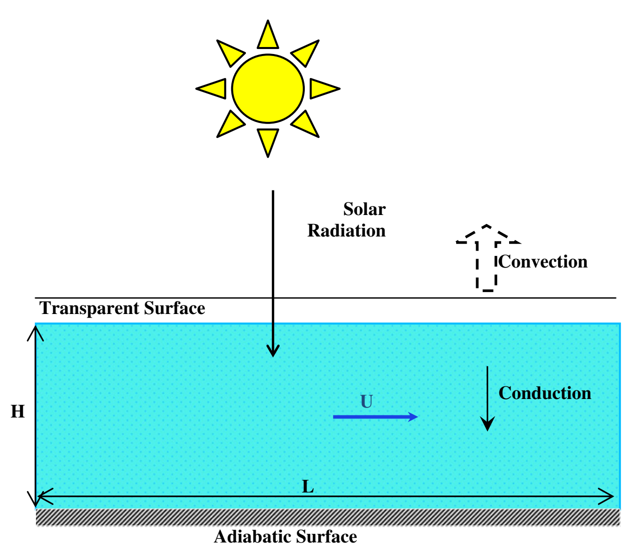

Fig. 1. Schematic of the nanofluid-based direct absorption solar collector (Reprinted from Tyagi et al. [27], with permission from ASME).

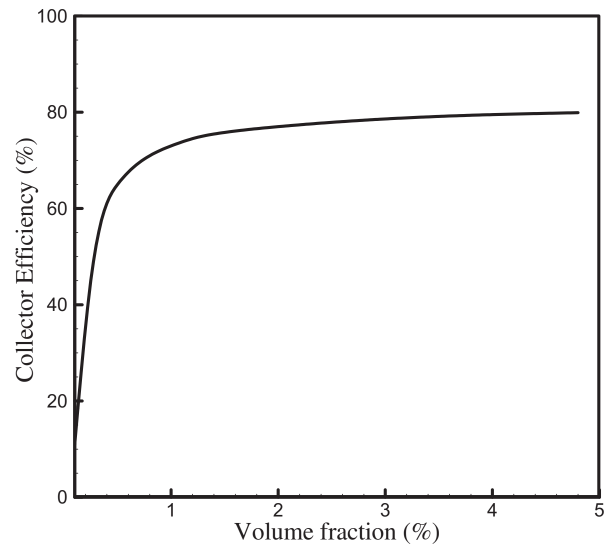

Fig. 2. Effect of particle volume fraction on collector efficiency (Reprinted from Tyagi et al. [27], with permission from ASME).

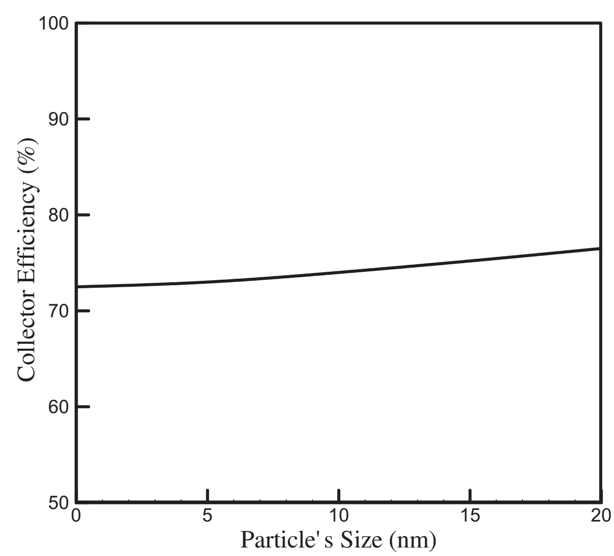

Fig. 3. Effect of nanoparticles size on collector efficiency (Reprinted from Tyagi et al. [27], with permission from ASME).

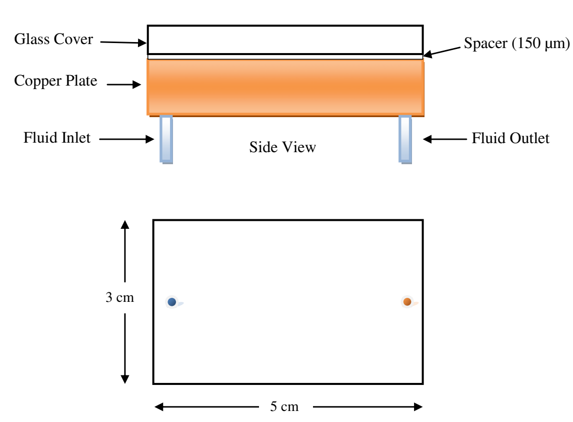

Fig. 4. Experimental schematic of the microsolar thermal collector (Reprinted with permission from Otanicar et al. [28]. Copyright 2010, American Institute of Physics).

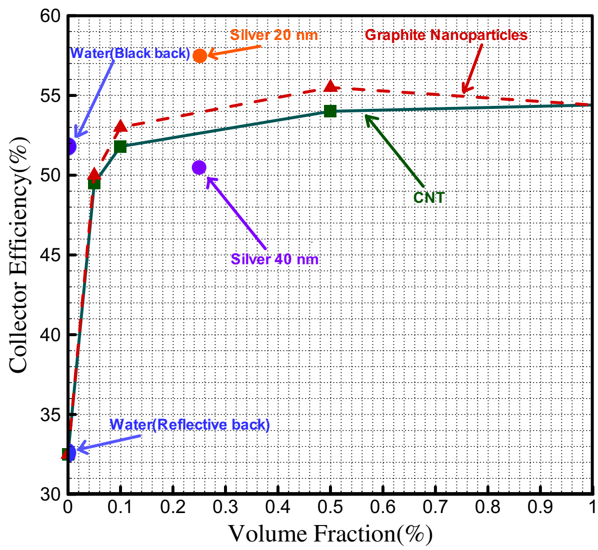

Fig. 5. Experimental microsolar thermal collector: steady-state collector efficiency (Reprinted with permission from Otanicar et al. [28]. Copyright 2010, American Institute of Physics).

shown, adding small quantities of nanoparticles leads to the remarkable enhancement of the efficiency until a volume fraction of approximately 0.5%. After a volume fraction of 0.5%, the efficiency begins to level off and even decrease slightly with increasing volume fraction. The authors attributed this reduction to the high increase of the fluid absorption at high particle loadings. The main difference in the steady-state efficiency between nanofluids occurs in silver particles when the size of the particles is between 20 and 40 nm. When halving the size from 40 to 20 nm, a 6% efficiency increase is found. The effect of particle size on efficiency is shown in Fig. 6 for silver nanoparticles. Unlike the results obtained by Tyagi et al. [27], with increase in size of nanoparticles, the efficiency of the collector decreases.

Taylor et al. [29] compared a nanofluid-based concentrating solar thermal system with a conventional one. Their results show that the use of a nanofluid in the receiver can improve the

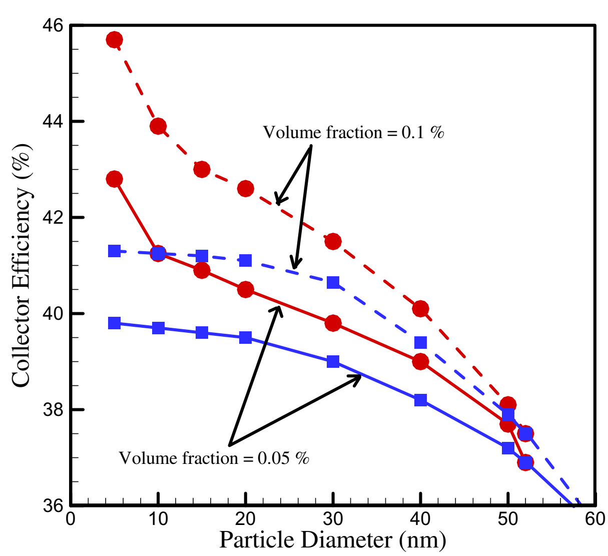

Fig. 6. Collector efficiency as a function of silver nanoparticle diameter (squares: bulk properties; circles: size-dependent properties and volume fraction (Reprinted with permission from Otanicar et al. [28]. Copyright 2010, American Institute of Physics).

efficiency by 10%. They also concluded that for 10–100 MWe power plants, using graphite/therminol VP-1 nanofluid with volume fractions approximately to 0.001% or less could be beneficial. The authors estimated that combining a nanofluid receiver with a solar thermal power tower with the capacity of 100 MWe operating in a solar resource like Tucson, Arizona, could generate $3.5 million more per year. Taylor et al. [29] considered two notional designs of potential nanofluid receivers, designated as A and B, as shown in Fig. 7.

He et al. [30] investigated the light-heat conversion characteristics of two nanofluids, water–TiO_2 and water–carbon nanotube (CNT), in a vacuum tube solar collector under sunny and cloudy weather conditions. The experimental results show a very good light heat conversion characteristic of the CNT–H_2O nanofluid with the weight concentration of 0.5%. Because of the better light-heat conversion characteristics of the CNT–H_2O nanofluid compared to the TiO_2–H_2O nanofluid, the temperature of the CNT–H_2O nanofluid is higher than that of the TiO_2–H_2O one. This means that the CNT–H_2O nanofluid is more suitable than the TiO_2–H_2O to be utilized in a vacuum tube solar collector.

Li et al. [31] studied the effects of three different nanofluids, Al_2O_3/water, ZnO/water, and MgO/water, on the performance of a tubular solar collector. Their results show that ZnO–H_2O nanofluid with 0.2% volume concentration is the best selection for the collector. Taylor et al. [32] investigated the optical property characterization of graphite, silver, copper, gold, and aluminum nanoparticles in water and VP1 as the based fluids to determine their potential to be used in direct absorption solar collectors. They revealed that over 95% of incoming sunlight can be absorbed (in a nanofluid thickness $\geqslant$10 cm) with very low nanoparticle volume fractions (less than 1×10^{-5}, or 10 ppm).

Khullar et al. [33] investigated theoretically a nanofluid-based concentrating parabolic solar collector (NCPSC) and compared the results obtained with the experimental results of conventional concentrating parabolic solar collectors operating under similar conditions. They used Aluminum nanoparticles with 0.05 vol.% suspended in Therminol VP-1 as the base fluid for the analysis. Fig. 8 shows the schematic of the nanofluid-based concentrating parabolic solar collector (NCPSC) that they considered in their work. They found that the thermal efficiency of NCPSC compared to a conventional parabolic solar collector is about 5–10% higher under the same weather conditions (see Fig. 9).

Yousefi et al. [34] experimentally investigated the effects of Al_2O_3/water nanofluid on the efficiency of a flat-plate solar collector. They examined the effects of two different weight fractions of the nanofluid, including 0.2% and 0.4%, where the diameter of particles was 15 nm. In addition, they studied the effects on efficiency of Triton X-100 used as a surfactant. The photograph and specifications of the flat-plate collector tested are presented in Fig. 10 and Table 1, respectively.

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. 12).
2. For a wide range of the reduced temperature parameter $(T_i - T_a)/G_T$, 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], using the same experimental setup as in their previous work [34], examined the effects of water–Multi wall carbon nanotubes (MWCNT) – Water nanofluid on the efficiency of the flat plate collector. They observed that:

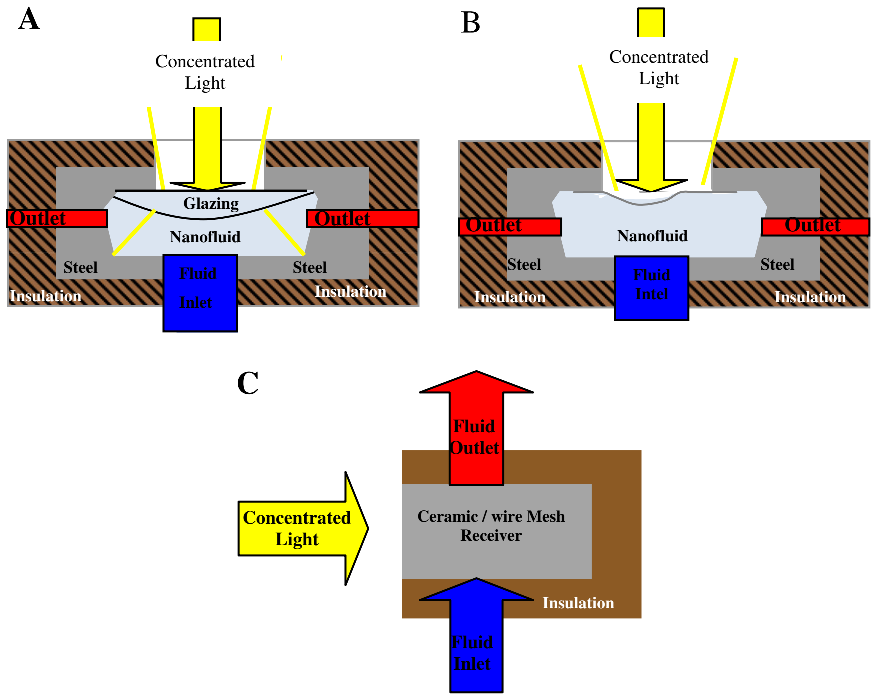

Fig. 7. (a) Conceptual design of a nanofluid concentrating collector with glazing. (b) Conceptual design of a nanofluid concentrating collector without glazing. (c) Conceptual drawing of a conventional power tower solid surface absorber (Reprinted with permission from Taylor et al. [29]. Copyright 2011, American Institute of Physics).

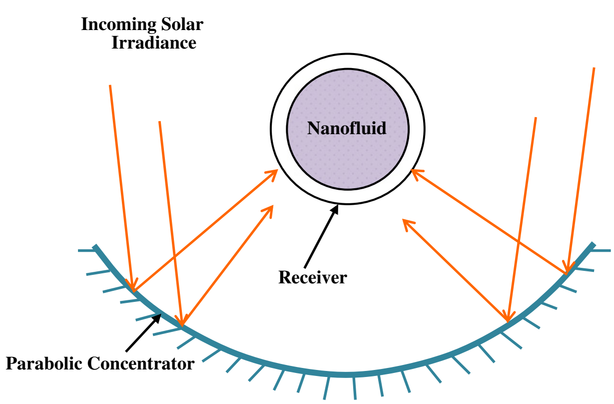

Fig. 8. Schematic of nanofluid-based concentrated parabolic solar collector (NCPSC) (Reprinted from Khullar et al. [33], with permission from ASME).

1. The efficiency of the collector by using of MWCNT–water nanofluid 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.

In another study, Yousefi et al. [36], investigated the effects of pH variation of the MWCNT–water nanofluid on the efficiency of the flat plate collector. They used 0.2 wt.% MWCNT with various pH values −3.5, 6.5, and 9.5 – and Triton X-100 as an additive. They found that a bigger difference between the pH of nanofluid and pH of isoelectric point leads to higher efficiency. The isoelectric point is the point at which the molecules carry no electrical charge. For MWCNT, the pH of the isoelectric point is 7.4. The effects of pH variation of H_2O–MWCNT nanofluid on the efficiency of the flat plate collector are presented in Fig. 13.

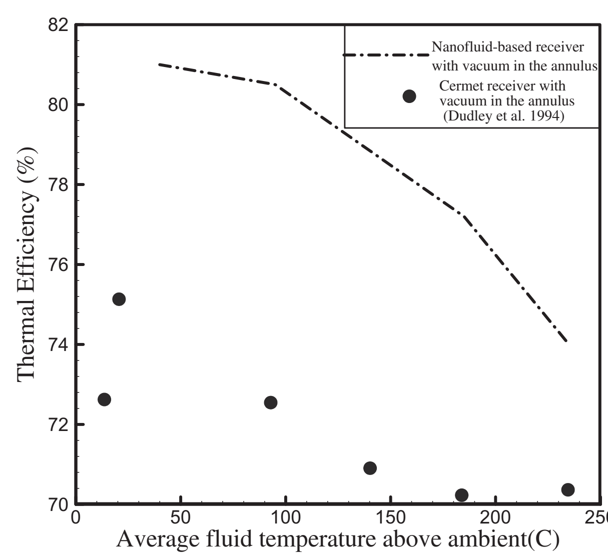

Fig. 9. Comparison of thermal efficiency as a function of average fluid temperature above ambient for NCPSC with conventional linear parabolic solar collector (Reprinted from Khullar et al. [33], with permission from ASME).

In the following, some previous works are reviewed in which the potential of nanofluids for use in solar energy system is performed through the study of optical properties and thermal conductivity of nanofluids. Link and El-Sayed [37] reviewed the optical properties of gold nanoparticles. Particularly, they studied the shape and size dependence of radiative, and photothermal properties of gold nanocrystals. Khlebtsov et al. [38] investigated the effects of the size, shape, and structure of gold and silver nanoparticles on the optical properties of the nanofluids and perceived that the shape and size of the nanoparticle have great effect on the optical properties of a nanofluid. Sani et al. [39] reported the

Fig. 10. Flat-plate collector used by Yousefi et al. (Reprinted from Yousefi et al. [34], with permission from Elsevier).

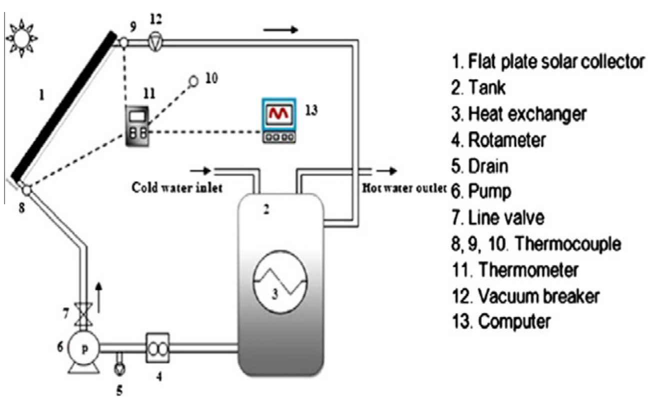

Fig. 11. Schematic of the experiment used by Yousefi et al. (Reprinted from Yousefi et al. [34], with permission from Elsevier).

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	–

optical characterization of a new fluid consisting of single-wall carbon nanohorns and ethylene glycol for solar energy applications. They concluded that carbon nanohorns could enhance remarkably the sunlight absorption with respect to pure base-fluid. The results obtained are compared with those obtained for fluids suspending more conventional carbon forms, i.e., carbon-black particles. They found that nanohorn spectral features are considerably more favorable than those of amorphous carbon for a specific applica-

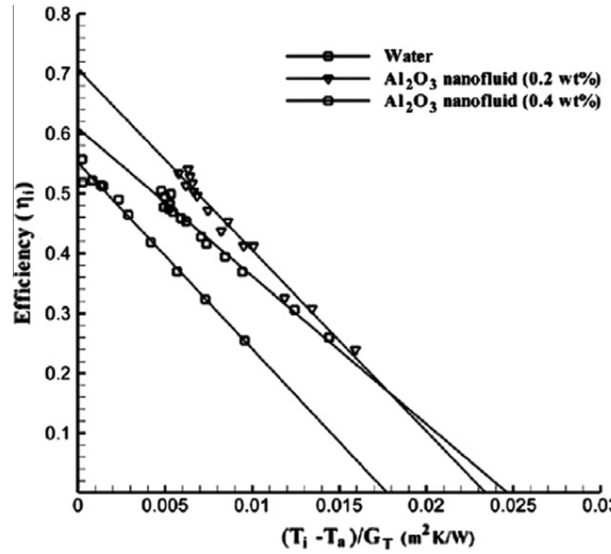

Fig. 12. The efficiencies of solar collectors for Al_2O_3 nanofluid without surfactant and for water (Reprinted from Yousefi et al. [34], with permission from Elsevier).

tion. This result shows that using carbon nanohorn-based nanofluids in thermal solar devices leads to the enhancement of efficiency and compactness in the systems. Mercatelli et al. [40,41] investigated the potential of single-wall carbon nanohorns nanoparticles with two different base fluids including water and glycol. Their measurements showed that these nanofluids are very suitable for direct absorption solar devices because only about 5% of the total extinction is scattered by SWCNH particles. In another work, Mercatelli et al. [42] applied a simple spectrophotometric to estimate the spectral scattering albedo of SWCNHs/water nanofluid. Recently, Saidur et al. [43] investigated the potential of Aluminum/water nanofluid to use in direct absorption solar collectors. They concluded that Aluminum/water nanofluid with 1% volume fraction improves considerably the solar absorption so that it is a fine solution for a direct solar collector. To use of the nanofluid they suggested, although the particle size has no effect on the extinction coefficient of nanofluid, in order to have Rayleigh scattering the size of nanoparticles should be less than 20 nm. They also found that the extinction coefficient varies linearly with volume fraction. Lenert and Wang [44] and Lenert [45] presented a combined theoretical and experimental work to optimize the efficiency of liquid-based solar receivers seeded with carbon-coated absorbing nanoparticles. They concluded that the efficiency of nanofluid volumetric receivers increases with increasing solar concentration and nanofluid height. Colangelo et al. [46] measured the thermal conductivities of CuO, Al_2O_3, ZnO and Cu with different shapes and volume fraction by 3%, where water and diathermic oil are as the base fluids, to evaluate their potential to use for high temperature applications such as in solar collectors. They found that the thermal conductivity enhancement of the nanofluids with diathermic oil is higher than that with water, with the same nanoparticles and at the same conditions. They also concluded that the thermal conductivity is reduced with increasing the size of particles. Kameya and Hanamura [47] found experimentally that the solar radiation absorption for the nanofluid of Ni/alkyl naphthalene with 0.1% volume fraction is much higher than the base fluid. Gan and Qiao [48] investigated the optical properties of ethanol-based nanofluids containing multiwalled carbon nanotubes (MWCNTs), carbon and aluminum nanoparticles. They concluded that MWCNTs leads to more absorption than aluminum and carbon nanoparticles. Finally, Gan and Qiao [49] found that for ethanol-based nanofluids, the radiation absorption for nanofluids

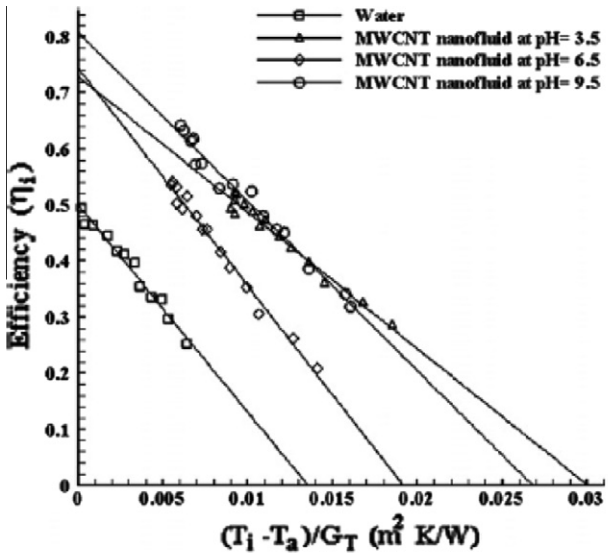

Fig. 13. The efficiency of the flat-plate solar collector with MWCNT nanofluid as a base fluid at three pH values compared water at a 0.0333 kg/s mass flow rate (Reprinted from Yousefi et al. [36], with permission from Elsevier).

containing Al_2O_3 nanoparticles is higher than nanofluids containing aluminum nanoparticles.

2.1.2. Economic and environment considerations

An accepted way to determine the economic and environmental impacts of a product is life cycle assessment [50]. This section presents the economic and environment considerations of nanofluid-based collectors. Otanicar and Golden [50] compared the environmental and economic aspects of using a conventional solar collector against a nanofluid based collector located in Phoenix, Arizona. The economic analysis shows that the capital cost and maintenance costs of the nanofluid-based solar collector compared to the conventional one are \$120 and \$20 higher, respectively (see Table 2). However, because of the higher efficiency and annual solar fraction of the nanofluid-based solar collector, the fuel cost savings per year, for both electricity and natural gas, is greater than that of the conventional solar collector. Moreover, due to the high cost of nanofluids compared the conventional collector, the payback period for a nanofluid-based collector is longer, but at the end of its useful life, it has the same life cycle savings as a conventional collector.

Embodied energy for both solar collectors, including conventional and nanofluid-based collectors, are compared in Table 3. The embodied energy for the nanofluid-based collector is about 9% lower. Additionally, from an environmental point of view, as shown in Table 4, the manufacturing of the nanofluid-based solar collector leads to 34 kg fewer CO_2 emissions while during its operation it saves 50 kg year when compared to the conventional solar collector. The magnitudes of other emissions including SO_x and NO_x are very small, so the differences are not considerable. Over the 15-year expected lifetime of the solar collectors, the nanofluid-based solar collector would offset more than 740 kg of CO_2 in comparison to a conventional collector. The authors concluded that more than one million metric tons of CO_2 could be offset per year if the usage of nanofluid-based solar collector systems for hot water heating increases by 50% in Phoenix, Arizona.

Khullar and Tyagi [51] examined the potential of the nanofluid-based concentrating solar water heating system (NCSWHS) as an alternative for systems based on fossil fuels. Using NCSWHS leads to annual electricity and liquefied petroleum gas (LPG) savings of approximately 1716 kWh/household/year and 206 kg/household /year, respectively, which produces significant economic benefits. In addition, they concluded that based on the annual estimation, CO_2 emissions are reduced by about 2.2×10^3 kg of CO_2/household/year. The use of nanofluid-based collectors is beneficial to reduce the environment problems. Table 5 summarizes the most important results obtained from the former works concerning the application or potential of nanofluids to use in solar collectors.

2.2. Other applications

In this section, other applications of nanofluids in solar energy systems including their applications in thermal energy storage materials, solar cells, and solar stills are reviewed. It should be noted that the reported works in this field are very scarce.

2.2.1. Thermal energy storage

Typical solar thermal-energy storage facilities require the storage medium to have high heat capacity and thermal conductivity. However, few materials are available with these properties and applicable in high temperatures. Recently, Shin and Banerjee [52] reported the anomalous enhancement of specific heat capacity of high-temperature nanofluids. They found that Alkali metal chloride salt eutectics when is doped with silica nanoparticles at 1% mass concentration increases the specific heat capacity of the nanofluid by 14.5%, so that this material can be a suitable one to use in solar thermal-energy storage facilities. One of techniques of storing solar energy is the application of PCMs. Among lots of PCMs available, paraffin is the most suitable due to its desirable characteristics, including large latent heat capacity, negligible super cooling and low cost. However, the inherent low thermal conductivity (0.21–0.24 W/mK) strongly prevents possible applications [53]. Wua et al. [53] numerically investigated the melting processes of Cu/paraffin nanofluids PCMs. Their results revealed that with 1 wt.% Cu/paraffin, the melting time can be saved by 13.1%. Therefore, they concluded that adding nanoparticles is an efficient technique to enhance the heat transfer in latent heat thermal energy storage system.

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

Table 3
Embodied energy comparisons for conventional and nanofluid-based solar collectors (Reprinted with permission from Otanicar and Golden [50]. Copyright (2009) American Chemical Society).

Description	Embodied energy index (MJ/kg)	Conventional solar collector		Nanofluid-based solar collector	
		Mass (kg)	Embodied energy content (MJ)	Mass (kg)	Embodied energy (MJ)
Insulation					
Polyester	53.7	1.74	93.22	1.74	93.22
Fiberglass	30.3	3.26	98.75	3.26	98.75
Glass	15.9	14.20	225.76	28.40	451.52
Copper pipe					
Collector	70.6	4.97	350.72	0.00	0.00
Manifold	70.6	3.48	245.57	3.48	245.57
Aluminum extrusion	201.0	0.56	111.58	0.56	111.58
Aluminum backplate	199.0	2.12	421.75	2.12	421.75
Steel backplate	34.8	0.00	0.00	5.97	207.65
Sealant	87.0	0.70	60.90	0.70	60.90
Black paint	90.4	0.30	27.12	0.30	27.12
Casing paint	90.4	0.90	81.36	0.90	81.36
Screws	34.8	0.00	0.04	0.00	0.04
Copper absorber	70.6	4.05	285.80	0.00	0.00
Nanoparticles	246.8	0.00	0.00	0.06	15.55
Thermal fluid	17.0	5.84	99.28	5.84	99.28
Conversion rate (27%)			567.50		516.86
Total		42.10	2669.34	53.32	2431.14

Table 4
Embodied energy emissions and consumer phase operational energy (Reprinted with permission from Otanicar and Golden [50]. Copyright (2009) American Chemical Society).

Emissions	Pollution from collector embodied energy		Saving of solar energy	
	Conventional (kg)	Nanofluid-based (kg)	Conventional (kg/year)	Nanofluid-based (kg/year)
Carbon dioxide (CO_2)	599.77	564.94	1500.89	1550.33
Sulfur oxides (SO_x)	0.51	0.48	0.83	0.85
Nitrogen oxides (NO_x)	0.84	0.79	1.53	1.58

2.2.2. Solar cells

Cooling of solar cells can improve the efficiency of such solar devices. Nanofluids can be used as a solution to cool the solar cells. Elmir et al. [54] simulated the cooling of a silicon solar cell using the finite element method. They considered the solar panel as an inclined cavity (with a slope of 30°) and solved the equations in Cartesian coordinate system. They used Al_2O_3/water nanofluid for their analysis, where the thermal conductivity and viscosity of the nanofluid are estimated using the models of Wasp [55] and Brinkman [56], respectively. As seen in Fig. 14, they concluded that using nanofluids leads to the increase of the average Nusselt number, and, hence, the rate of cooling increases with increases in volume fraction. Of course, it should be noted that the thermophysical properties, which are used in this study, are old and they do not predict the thermal conductivity and viscosity of nanofluids correctly. Therefore, it is suggested that in the future works, temperature-dependent models, or at least newer temperature-independent models are used to calculate the thermophysical properties of nanofluids. For example, to calculate the viscosity of nanofluids, the models and relation presented by Maiga et al. [57], Buongiorno [58], Nguyen et al. [59], Koo and Kleinstreuer [60], and Duangthongsuk and Wongwises [61] can be used. To estimate the thermal conductivity of nanofluids, the relations presented 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] can be applied.

2.2.3. Solar stills

Potable water demand is increasing due to rapid population increase and due to uncontrolled pollution of freshwater resources. According to the World Health Organization, nearly 2.8 billion people (approximately 40% of the world population) currently have no access to safe drinking water, and water-borne diseases account for 90% of all infectious diseases in the developing world [67]. In arid remote regions in the world, the provision of fresh water is more critical. In these regions, solar desalination systems can solve part of the problem where solar energy is available. Solar stills can be used to avoid the greenhouse gas emissions from the production of fresh water [68]. Many researches have carried out research on solar stills, and different methods are applied to improve their productivity. Recently, Gnanadason et al. [69] reported that using nanofluids in a solar still can increase its productivity. The schematic of their experimental set-up is shown in Fig. 15. They investigated the effects of adding carbon nanotubes (CNTs) to the water inside a single basin solar still. Their results revealed that adding nanofluids increases the efficiency by 50%. Nevertheless, they have not mentioned the amount of nanofluid added to the water inside the solar still. Regarding the addition of nanofluids to the solar still, the economic viability should be considered. In literature, some works reported that adding dyes to solar stills could improve the efficiency. For instance, Nijmeh et al. [70] concluded that adding violet dye to the water inside the solar still increases the efficiency by 29%, which is considerable. On the other hand, it is evident that nanofluids (especially CNTs) compared to dyes are more expensive, hence this may be a challenge on using nanofluids in solar stills, because in this type of use of nanofluids in solar stills the nanofluids have no flow in a closed loop so that they could be recovered.

3. Future work

The above review shows that the application of nanofluids in solar energy applications is still in its infancy. Nanofluids can be used in many fields of solar energy. Here, some suggestions are presented for future work in the area. The authors hope that these

Table 5
Summary of former works on the application or potential of nanofluids to use in solar collectors.

Author(s) and type of study	Collector type	Nanofluid type and nanoparticle size	Results
Tyagi et al. [27] (Theoretically)	Non-concentrating direct absorption	Aluminum/water (0–20 nm)	–Efficiency remarkably increases for volume fraction less than 2% –Efficiency remains nearly constant for volume fraction higher than 2% –Efficiency increases slightly with an increase in the size of nanoparticles
Otanicar et al. [28] (Theoretically and experimentally)	Non-concentrating micro scale direct absorption	Graphite/water (30 nm) silver/water (20 and 40 nm) carbon nanotube/water (6–20 nm diameter, 1000–5000 nm length)	–Efficiency considerably increases for volume fractions less than 0.5% –Efficiency for volume fractions higher than 0.5% may even decrease –Efficiency increases by 6%, with decreasing the nanoparticle size in Silver/Water nanofluid
Taylor et al. [29] (Theoretically and experimentally)	Concentrating direct absorption	Graphite/therminol VP-1 aluminum/therminol VP-1 silver/therminol VP-1 copper/therminol VP-1 (10–100 nm)	–Efficiency increases up to 10% by using a nanofluid in the receiver –Using graphite/therminol VP-1 nanofluid with volume fractions less than 0.001% is beneficial for 10–100 MWe power plants
He et al. [30] (Experimentally)	Vacuum tube	TiO_2/water (5–10 nm) CNT/water (10–50 nm diameter, 100–1000 nm length)	–CNT/water nanofluid is more suitable than the TiO_2/water to be used in a vacuum tube solar collector
Li et al. [31] (Experimentally)	Tubular	Al_2O_3/water ZnO/water MgO/water(size < 20 nm)	–ZnO/water nanofluid with 0.2% volume concentration is the best selection for the collector
Taylor et al. [32] (Theoretically and experimentally)	Direct absorption	Graphite/water and graphite/VP1 aluminum/water and aluminum/VP1 copper/water and copper/VP1 silver/water and silver/VP1 gold/water and silver/VP1	–Over 95% of incoming sunlight can be absorbed for nanofluid thickness $\geqslant$ 10 and nanoparticle volume fractions less than 1×10^{-5}
Khullar et al. [33] (Theoretically)	Concentrating Parabolic	Aluminum/therminol VP-1 (5 nm)	–Thermal efficiency of nanofluid concentrating parabolic collectors compared to a conventional parabolic solar collector is about 5–10% higher
Yousefi et al. [34] (Experimental)	Flat plate	Al_2O_3/water (15 nm) Triton X-100 is used as a surfactant	–Efficiency of the solar collector with 0.2% weight fraction (wt) nanofluid is higher than that with water by 28.3%. –Efficiency increases by15.63% using the surfactant
Yousefi et al. [35] (Experimental)	Flat plate	Water-Multi wall carbon nanotubes (MWCNT)/water (10–30 nm) Triton X-100 is used as a surfactant	–Efficiency of the collector increases remarkably for 0.4 wt.% nanofluid, whereas with 0.2 wt.% the efficiency reduces compared to water –For 0.2 wt.% nanofluid, using surfactant increases the efficiency of the collector compared to water
Yousefi et al. [36] (Experimental)	Flat plate	Water-Multi wall carbon nanotubes (MWCNT)/water with various pH values: 3.5, 6.5, and 9.5 Triton X-100 is used as a surfactant	–A bigger difference between the pH of nanofluid and pH of isoelectric point leads to higher efficiency
Otanicar and Golden [50] (Theoretical)	Direct absorption	Graphite/water and propylene glycol	–Using a nanofluid-based solar collector leads to fewer CO_2 emissions compared to the conventional solar collector
Khullar and Tyagi [51] (Theoretical)	Concentrating direct absorption	Aluminum/water	–Using this type of collector leads to fewer CO_2 emissions by 2.2×10^3 kg in 1 year

proposals will be helpful for the development on the use of nanofluids in the solar thermal devices.

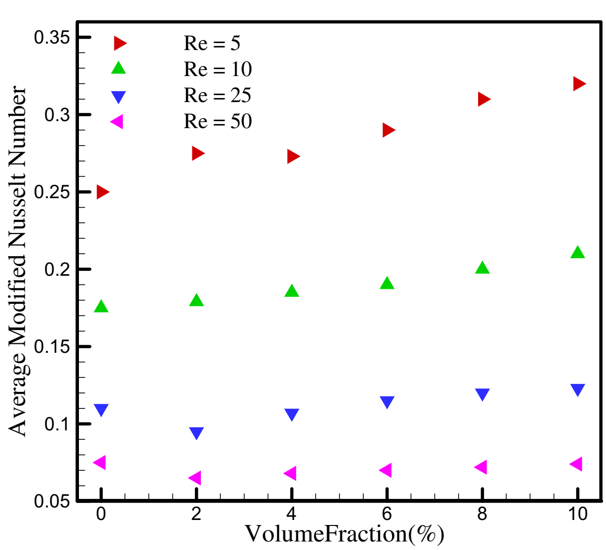

Fig. 14. Effects of volume fraction on Nusselt number for cooling a solar cell (Reprinted from Elmir et al. [54], with permission from Elsevier).

3.1. Parabolic trough systems

As mentioned, only a theoretical work has been done on parabolic trough collectors, therefore some experimental studies can be performed on the effects of nanofluids on the efficiency of parabolic trough systems.

3.2. Photovoltaic/thermal systems

A photovoltaic/thermal (PV/T) system is a hybrid structure that converts part of the sun's radiation to electricity and part to thermal energy [71]. One can investigate experimentally the effects of using different nanofluids on the cooling rate, and, hence, the efficiency of the PV/T systems. In this area, the effects of different volume fractions, nanoparticle size on the efficiency of the system can be studied. A review of the literature shows that many researches have been carried out on the potential of nanofluids for cooling of different thermal systems such as electronic devices [72–74], automobile radiator [75], and micro channel heat sinks [76]. Therefore, using nanofluids to cool the PV/T system may be reasonable.

3.3. Solar thermoelectric cells

In recent years, interest in the development of solar thermoelectric systems has been considerably increased [77]. The

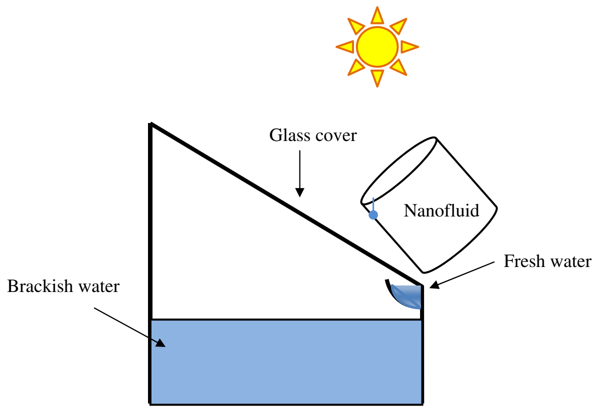

Fig. 15. Schematic of the experimental set up used by Gnanadason et al. [69].

thermoelectric cells can be used to convert the solar energy to electricity due to the temperature difference between two hot and cold surfaces. A greater temperature difference between the hot and cold surfaces of the thermoelectric cell leads to a bigger electricity production. The authors would like to suggest an experimental set-up to investigate the effects of nanofluids on the performance of such systems. Fig. 16 shows the schematic of the set-up, which is a development of the work done by Fan et al. [77]. In this work, a dish concentrates the solar radiation on the thermoelectric cells installed on the focal point of the dish. In this way the effects of different nanofluids with various mass flow rates on the efficiency of the solar thermoelectric cell can be studied.

3.4. Solar ponds

Salinity gradient solar ponds are great bodies of water between 2–5 m deep, which could collect solar radiation and store it in the form of heat [78,79].

Heat can be extracted from the solar ponds and has been used for industrial process heating, space heating, and power generation. In all these applications heat is extracted from the bottom of the solar pond which is at a temperature of about 50–60 °C higher than the top surface of the solar pond [80,81]. Concerning the application of nanofluids in solar ponds an experimental set up is proposed in Fig. 17. As seen, a nanofluid flows through a heat exchanger mounted at the bottom of the solar pond to absorb the heat. It expects that nanofluids could enhance the rate of heat removal from the bottom of the solar pond.

3.5. Other possibilities

The above suggestions are only a few of the possible applications relating to the use of nanofluids in solar energy. Besides the above ideas, nanofluids also can be used in solar cooling systems, solar absorption refrigeration systems, and a combination of different solar devices. Here, for instance, the authors would like to suggest some Refs. [82–86], in which there is a potential to use a nanofluid as the working fluid. In addition, in numerical studies such as the simulation of solar cell cooling, which it is mentioned in Section 2.2.2, new models can be used to calculate the thermophysical properties. Additionally, the nanofluid can be considered as a two-phase mixture [87].

4. Challenges

The possible challenges for the application of nanofluids in solar thermal devices are mentioned briefly in the following sections.

4.1. High cost

The first possible challenge in the use of nanofluids in solar thermal devices is the high cost of nanofluids because of difficulties in production. The high cost of nanofluids to use in thermal engineering systems such as heat exchangers is emphasized as a disadvantage in some works [88,89].

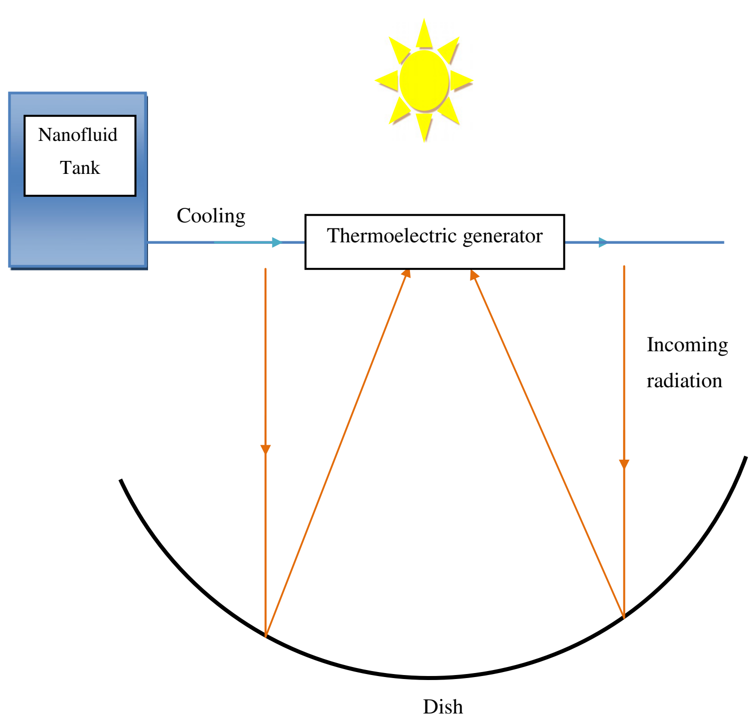

Fig. 16. The experimental set-up proposed for using nanofluids in thermoelectric cells.

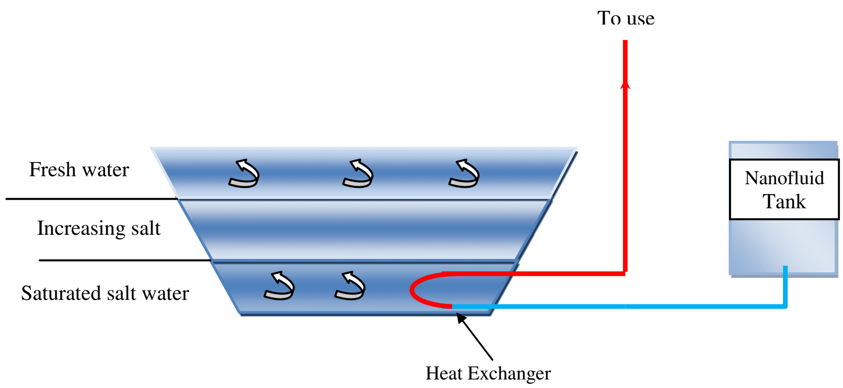

Fig. 17. The experimental set-up proposed for using nanofluids in solar ponds.

4.2. Instability and agglomerating

Instability and agglomerating of the nanoparticles is another problem. Therefore, using nanofluids in solar systems with natural circulation (such as thermosiphons) where there is no pump to circulate the fluid, is not reasonable. It should be also noted that for high temperature gradients the agglomeration of nanoparticles seems to be more serious [90]. Therefore, exact investigations are needed for an appropriate selection of a nanofluid for applications in high temperatures.

4.3. Pumping power and pressure drop

Using a nanofluid with higher viscosity compared to the base fluid leads to the increase of pressure drop and consequently the increases in the required power for pumping. For example, Duangthongsuk and Wongwises [91] found during their experiments that the pressure drop under a turbulent regime increases with an increase in volume fraction of TiO_2/water nanofluid. In another experimental research, Razi et al. [92] also concluded that using CuO/oil nanofluid increases the pressure drop under a laminar regime.

4.4. Erosion and corrosion of components

Existing of nanoparticles in nanofluid may lead to corrosion and erosion of thermal devices in a long time. Celata et al. [93] recently investigated the effects of nanofluid flow effects on erosion and corrosion of metal surfaces. They conducted their experiments for TiO_2, Al_2O_3, SiC, ZrO_2 nanoparticles with water as the base fluid where the nanofluids flow in pipes with three different materials, i.e., aluminum, copper and stainless. They concluded that the nanofluids have no effect on the erosion of the stainless pipe, while the aluminum pipe has highest erosion. They also found that ZrO_2 and TiO_2 nanoparticles lead to highest erosion while SiC nanoparticles results in lowest erosion.

5. Conclusion

Nanofluids are advanced fluids containing nano-sized particles that have emerged during the last two decades. Nanofluids are used to improve system performance in many thermal engineering systems. This paper presented a review of the applications of nanofluids in solar thermal engineering. The experimental and numerical studies for solar collectors showed that in some cases, the efficiency could increase remarkably by using nanofluids. Of course, it is found that using a nanofluid with higher volume fraction always is not the best option (Yousefi et al. [34]). Therefore, it is suggested that the nanofluids in different volume fractions should be tested to find the optimum volume fraction. It is also seen that the available theoretical works give different results on the effects of particle size on the efficiency of the collectors (see Refs. [27,28]). It is worth to carry out an experimental work on the effect of particle size on the collector efficiency. It is also concluded that some factors such as adding surfactant to nanofluid and a suitable selection of the pH of nanofluid are effective in the collector efficiency. From the economic and environmental point of view, the previous studies showed that using nanofluids in collectors leads to a reduction in CO_2 emissions and annual electricity and fuel savings. Some other reported works of applications of nanofluids in solar cells, solar thermal energy storage, and solar stills are also reviewed. It is also stressed that for the numerical study of solar systems (for example cooling of solar cells), it is better to use the new thermophysical (temperature-dependent) models and two phase mixture models for the nanofluid to have a more exact prediction of the system performance. This review reveals that the application of nanofluids in solar energy is yet in its infancy. Therefore, some proposals are presented to develop the use of nanofluids in different solar systems such as solar ponds, solar thermoelectric cells, and so on. Finally, the most important challenges on the use of nanofluids in solar systems including high costs of production, instability and agglomeration problems, increased pumping power and erosion are mentioned. These challenges may be reduced with the development of nanotechnology in the future.

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