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REVIEW **Open Access**

Performance evaluation of nanofluids in solar energy: a review of the recent literature

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Abstract

Utilizing nanofluid as an absorber fluid is an effective approach to enhance heat transfer in solar devices. The purpose of this review is to summarize the research done on the nanofluids' applications in solar thermal engineering systems in recent years. This review article provides comprehensive information for the design of a solar thermal system working at the optimum conditions. This paper identifies the opportunities for future research as well.

Keywords: Nanofluids; Solar energy; Solar systems; Heat transfer enhancement

Introduction

Energy is an important entity for the economic development of any country. On the other hand, fossil fuels meeting a great portion of the energy demand are scarce and their availability is decreasing continously. Nowadays, solar systems play an important role in the production of energy from renewable sources by converting solar radiation into useful heat or electricity. Considering the environmental protection and great uncertainty over future energy supplies, solar energy is a better alternative energy form in spite of its its slightly higher operation costs. Heat transfer enhancement in solar devices is one of the significant issues in energy saving and compact designs. One of the effictive methods is to replace the working fluid with nanofluids as a novel strategy to improve heat transfer characteristics of the fluid. More recently reserachers have become interested in the use of nanofluids in collectors, water heaters, solar cooling systems, solar cells, solar stills, solar absorption refrigeration systems, and a combination of different solar devices due to higher thermal conductivity of nanofluids and the radiative properties of nanoparticle. How to select suitable nanofluids in solar applications is a key issue. The effectiveness of nanofluids as absorber fluids in a solar device strongly depends on the type of nanoparticles and base fluid, volume fraction of nanoparticles, radiative properties of nanofluids, temperature of the liquid, size and shape of the nanoparticles, pH values, and stability of the nanofluids [1]. It was found that only a few review papers have discussed the capability of nanofluids to enhance the performance of solar systems [2-5].This paper compiles recent research in this field and identifies many issues that are open or even not commenced to investigate. It is authors' hope that this review will be useful to determine the effectiveness of nanofluids in solar applications.

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Literature review of recent years

Using nanofluids in solar collectors

Role of nanoparticles

Gan et al. [6] experimently showed that the radiation absorption of Al_2O_3 nanofluids is less than Aluminuim nanofluids. For nanofluids with Al_2O_3 particles, the situation is different because of the different optical properties of Al_2O_3. The weak radiation absorption of Al_2O_3 nanoparticles will not result in significant localized convective heat transfer from the particles to the base fluids. The use of Al_2O_3/water nanofluid as coolant was simulated for a silicon solar cell using the finite element method by Elmir et al. [7]. They considered the solar panel as an inclined cavity with a slope of 30°. Application of nanofluids increased the average Nusselt number and rate of cooling. They reported 27% enhancement in the heat transfer rate for 10% alumina nanofluid at Re = 5.

Luo et al. [8] simulated the performance of a DAC solar collector with nanofluids using a 2D model by solving the radiative transport equations of particulate

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media and combining conduction and convection heat transfer equations. The nanofluid flows horizontally from right to left in a steady-state solar collector covered with a glass plate. A solar radiation simulator is used to validate their model. They prepared nanofluids by dispersing and oscillating TiO_2, Al_2O_3, Ag, Cu, SiO_2, graphite nanoparticles, and carbon nanotubes into Texatherm oil. Their results show that the use of nanofluid in solar collector can improve the outlet temperature and efficiency. They also found that the efficiency of most nanofluids are similar and larger than that of oil, except for TiO_2.

Rahman et al. [9] performed a numerical study for a triangular shape solar collector with nanofluids by Galerkin weighted residual finite element method for a wide range of Grashof numbers (Gr). The corrugated bottom is kept at a constant high temperature and the side walls of the triangular enclosure are kept at a low temperature as seen in Figure 1. It is assumed that both fluid phase and nanoparticles are in thermal equilibrium and there is no slip between them. Nanofluid is Newtonian and incompressible, and flow is laminar and unsteady. Constant thermophysical properties are considered for the nanofluid except for the density variation in the buoyancy forces determined by using the Boussinesq approximation. Nevertheless, they have not mentioned the particle's diameters. The authors concluded that high value of both Gr and solid volume fraction confirms better heat transfer through convection and conduction. Results showed 24.28% improvement for $Gr = 10^6$ at 10% volume fraction of copper particles. For lower values of Gr number, conduction is the primary mode of heat transfer for any value of solid volume fractions. The results showed that the convective heat transfer performance is better when the solid volume fraction is kept at 0.05 or 0.08. This study also showed that cu-water nanofluid is the best nanofluid for the augmentation of heat transfer.

Faizal et al. [10] investigated the thermal performance of nanofluid solar collector and its contribution size reduction to estimate the cost saving. Their findings indicated that efficiency of solar collector with nanofluids is calculated by the function of working fluid density, specific heat and mass flow rates. The results confirmed that higher density and lower specific heat of nanofluids offers higher thermal efficiency than water and can reduce the solar collector area about 25.6%, 21.6%, 22.1% and 21.5% for CuO, SiO_2, TiO_2 and Al_2O_3 nanofluids as seen in Figure 2. Hence, it will reduce the weight, energy and cost to manufacture the collector. The average value of 220 MJ embodied energy can be saved for each

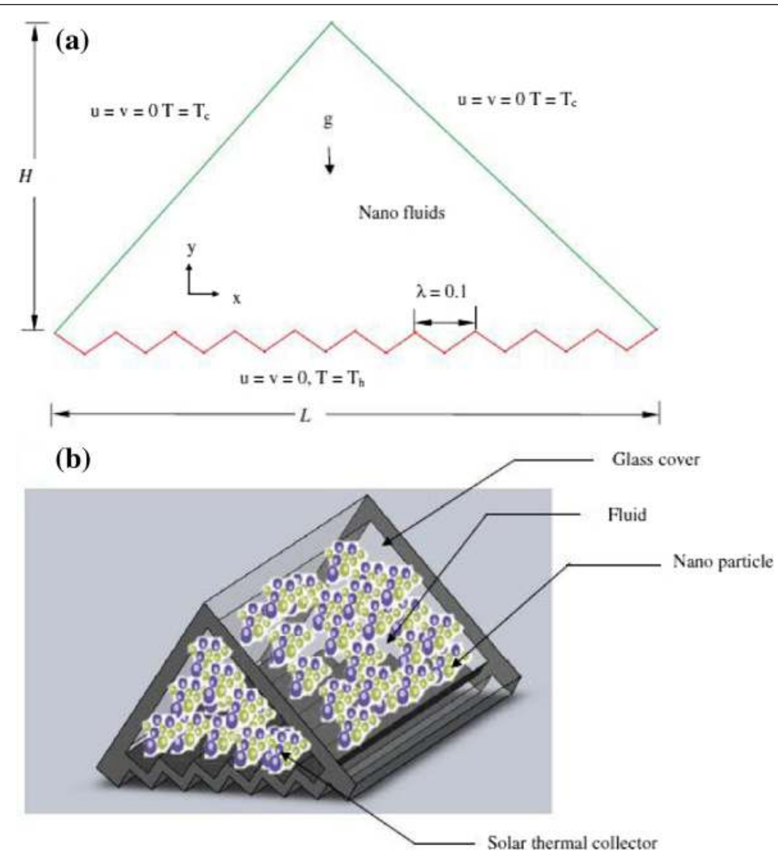

Figure 1 (a) Schematic of the triangular shape collector **(b)** 3D view of a solar thermal collector filled with nanofluid [9].

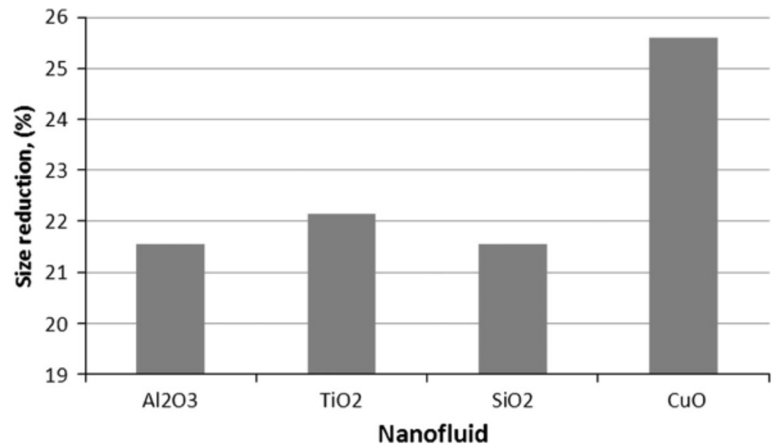

Figure 2 Percentage of size reduction for solar collector by applying different nanofluids.

collector, 2.4 years payback period can be achieved and around 170 kg less CO_2 emissions will be the result of using nanofluid based solar collector compared to a conventional one. Environmental damage cost is also lower with the nanofluid based solar collector.

Parvin et al. [11] numerically investigated the effects of the nanoparticle volume fraction (ϕ = 0%, 1%, 3%, 5% and 7%) and the Reynolds number (Re = 200, 400, 600, 800 and 1000) on the temperature distribution, rate of entropy generation, and collector efficiency. The working fluid was incompressible Cu-water nanofluid under a laminar regime. Their findings were as follows: a) Increasing the particles concentration raises the fluid viscosity and decreases the Reynolds number and consequently decreases heat transfer. b) It is important to find the optimum volume fraction of nanoparticle for each application. c) The collector efficiency can be enhanced nearly 2 times by using Ag-water and Cu-water nanofluids with concentration of 3% as seen in Figure 3 d) The entropy generation is enhanced up to ϕ = 3% as seen in Figure 3. After this level, adding more nanoparticles makes no changes in mean entropy generation.

Ladjevardi et al. [12] numerically studied the effects of using nanofluid on the performance of a solar collector as seen in Figure 4 considering the different diameter and volume fractions of graphite nanoparticles. They observed that in the infrared domain, the water optical characteristics are dominant while in the UV and visible ranges extinction coefficients are dependent on nanoparticle volume fractions. The extinction coefficient is calculated from the absorption and scattering efficiencies in this research. Their numerical results showed that nanofluid collector thermal efficiency increases about 88% compared with the one in pure water collector with the inlet temperature of 313 K. It also can be increased to 227% with the inlet temperature of 333 K.

Filho et al. [13] studied silver nanoparticles as direct sunlight absorbers for solar thermal applications. Their results showed that the maximum stored thermal energy increases by 52%, 93% and 144% for silver particle concentration of 1.62, 3.25 and 6.5 ppm respectively due to the good photothermal conversion properties of silver nanoparticles. They also observed that the

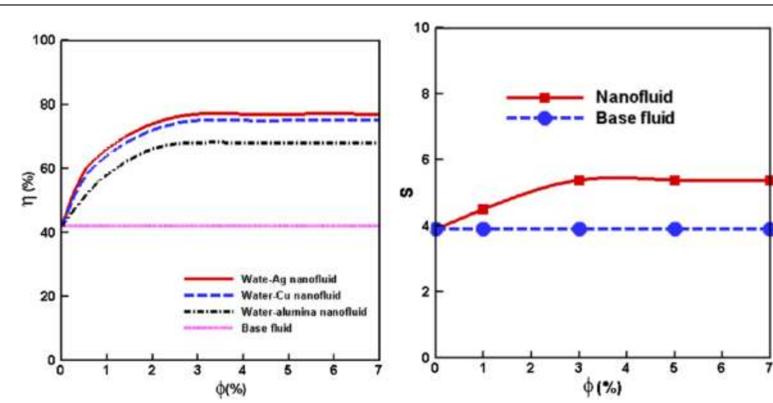

Figure 3 Collector efficiency (η), mean entropy generation (S) and Bejan number (Be) at various concentrations.

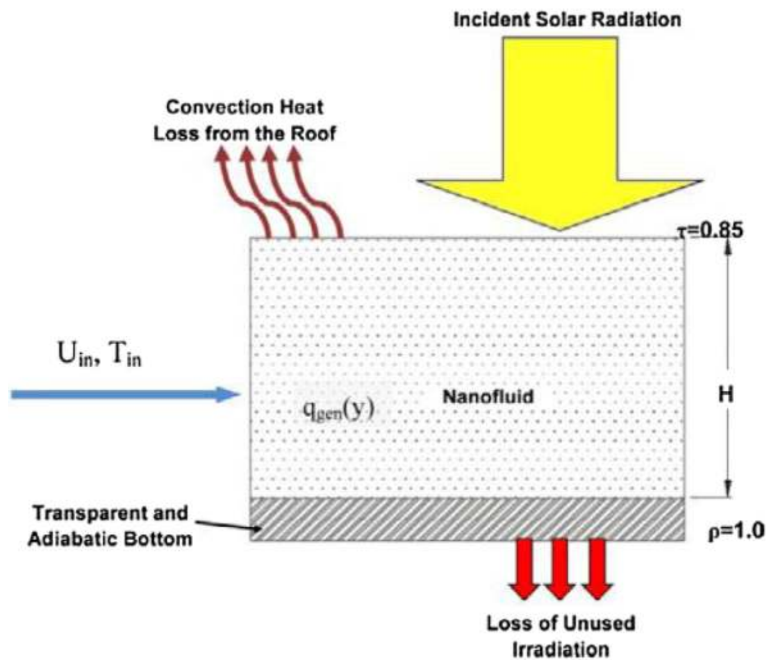

Figure 4 Schematic of volumetric solar collector.

influence of particle concentration on the specific absorption rate (SAR) is only discernable at the initial heating period. It was concluded that reduction in the SAR at higher particle loadings (65 and 650 ppm) might be the result of: (i) The formation of agglomerates and reduction in the intensity of the sunlight into the fluid due to the deposited particles on the surface, (ii) The difference in the absorption efficiency of each particle at different fluid depth, (iii) The heat leak through radiation may become strengthened as the particle concentration exceeds a certain value as seen in Figures 5,6 and 7.

Karami et al. [14] experimentally showed that aqueous suspension based alkaline functionalized carbon nanotubes (f-CNT), 10 nm in diameter and 5-10 μm in length, has good stability as an absorber fluid in low-temperature Direct Absorption Solar Collector (DASC). The reason is associated with the hydrophilic nature of carboxylate groups. f-CNT considerably reduces the transmittance and enhances the thermal conductivity as seen in Figure 8. They recommended the use of this kind of nanofluids to absorb the light directly. In this study, f-CNTs was dispersed into the water by an ultrasonic instrument with the volume fractions less than 150 ppm. Higher concentrations produced a black solution which light was not able to pass through it.

Said et al. [15] found that nanofluids with single wall carbon nanotubes (SWCNTs) in a flat plate solar collector showed the minimum entropy generation compared to the nanofluids prepared by suspending Al_2O_3, TiO_2 and SiO_2 nanoparticles in the same base fluid as seen in Figure 9. They attributed the decrease of the entropy generation to the increase in heat flux on the absorber plate due to the nanoparticles addition. Ultrasonicator and high pressure homogenizer (capacity of up to 2000 bar) is used to disperse the nanoparticles into the water. It was observed the SWCNTs nanofluids could reduce the entropy generation by 4.34% and enhance the heat transfer coefficient by 15.33%. It also had a small penalty in the pumping power by 1.2%.

Tang et al. [16] prepared the carbon nanotube/PEG/ SiO_2 composites with high thermal conductivity from multiwall carbon nanotubes (MWCNTs), poly (ethylene glycol) (PEG) and inorganic SiO_2. These composites had higher thermal conductivity than traditional phase-change materials (PCMs) because of the high thermal conductivity of MWCNTs. Their results clearly showed that PEG/ SiO_2/MWCNT composites can effectively improve the efficiency of solar energy applications.

Saidur et al. [17] investigated the effects of different parameters on the efficiency of a low-temperature nanofluid-based direct absorption solar collector (DAC) with water and aluminum nanoparticles. One big advantage of using low-temperature systems is that solar collectors can be relatively simple and inexpensive. Additionally, there are a number of working fluids suitable to low-temperature operation. Commonly used base liquids are

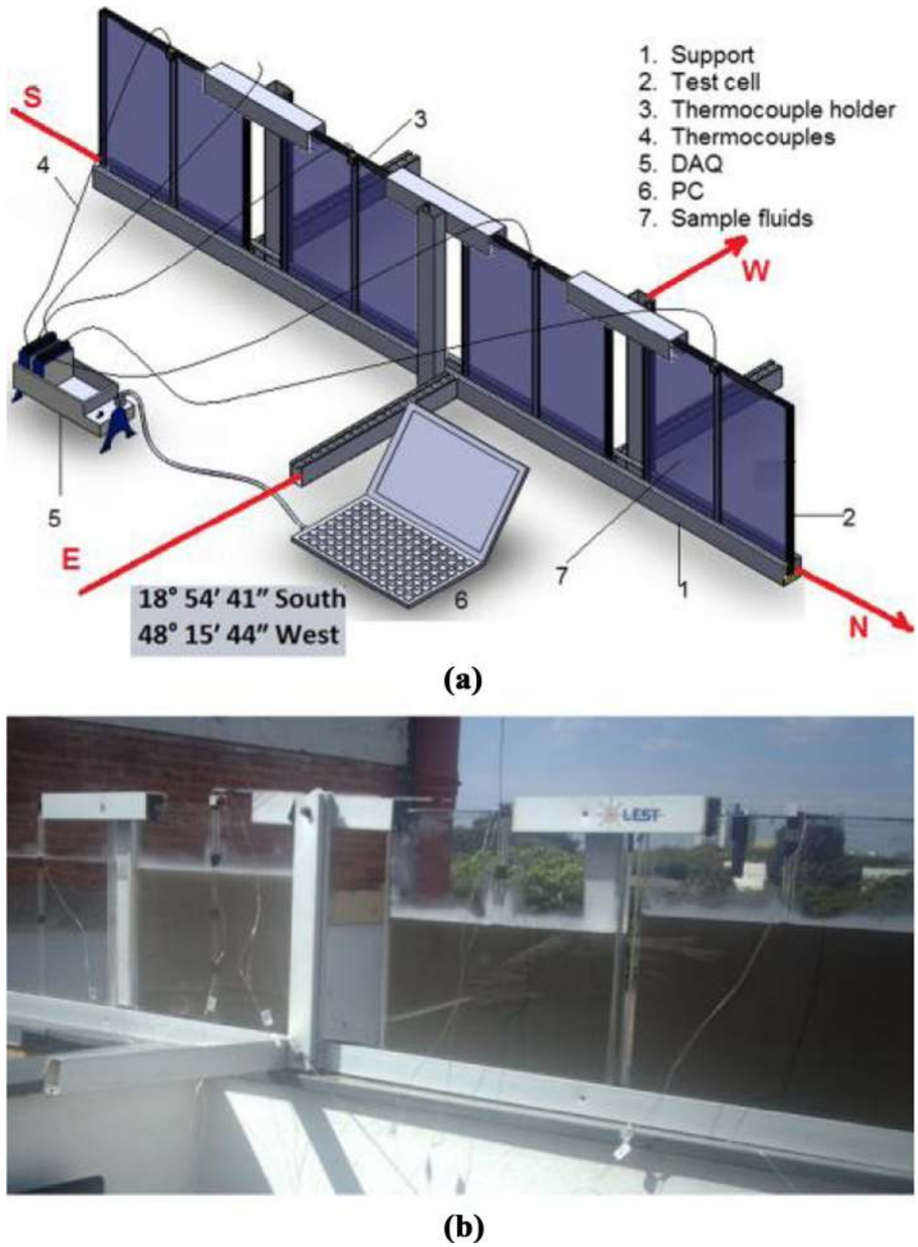

Figure 5 Experimental system: (a) a schematic illustration and (b) a snapshot of the system under direct sunlight on top of a roof.

water, oil, and ethylene glycol. They accounted for the effects of absorption and scattering within the nanofluid to evaluate the intensity distribution within the nanofluid by the radiative transfer equation (RTE). In order to calculate the spectral extinction coefficient of the nanofluid that is sum of scattering coefficient and absorption coefficient, they investigated the optical properties of the based fluid and nanoparticles separately. Their results revealed that Aluminum/water nanofluid with 1% volume fraction improves the solar absorption considerably. They found that the effect of particle size on the optical properties of nanofluid is minimal, but in order to have Rayleigh scattering the size of nanoparticles should be less than 20 nm. They also found that the extinction coefficient is linearly proportionate to volume fraction.

Sokhansefat et al. [18] numerically investigated the heat transfer enhancement for Al_2O_3/synthetic oil nanofluid with concentrations up to 5% in a parabolic trough collector tube at different operational temperatures as seen in Figure 10. Nanofluid enhanced convective heat transfer coefficient as seen in Figure 11.

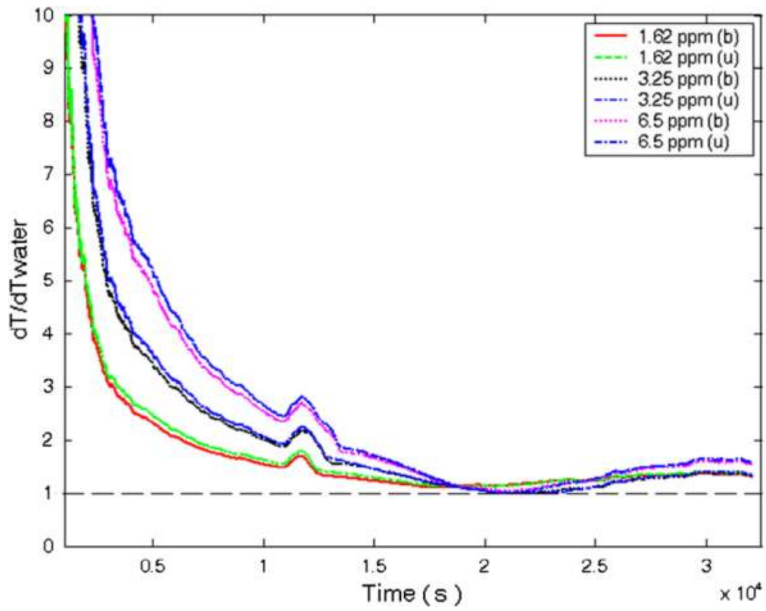

Figure 6 Comparison of the ratio of stored thermal energy at different concentrations (where b and u refer to thermocouples located at the bottom and upper positions respectively).

Nasrin et al. [19] performed a numerical study to investigate the influence of Prandtl number on the flow, temperature fields, convective and radiated heat transfer rates, mean bulk temperature of the fluids and average velocity field in a solar with water- Al_2O_3 nanofluid collector as seen in Figure 12. The results showed that with increasing Pr from 1.73 to 6.62, the convective heat transfer enhances about 26% and 18% for nanofluid and base fluid respectively whereas the radiation enhances by 8%.

Role of base fluid

Colangelo et al. [20] experimently showed that the thermal conductivity improvement of the nanofluids with diathermic oil is greater than that with water in high temperature applications such as solar collectores. They observed that the thermal conductivity reduced with increasing the size of nanoparticles.

Hordy et al. [21] made four different nanofluids by dispersing plasma functionalized multi-walled carbon

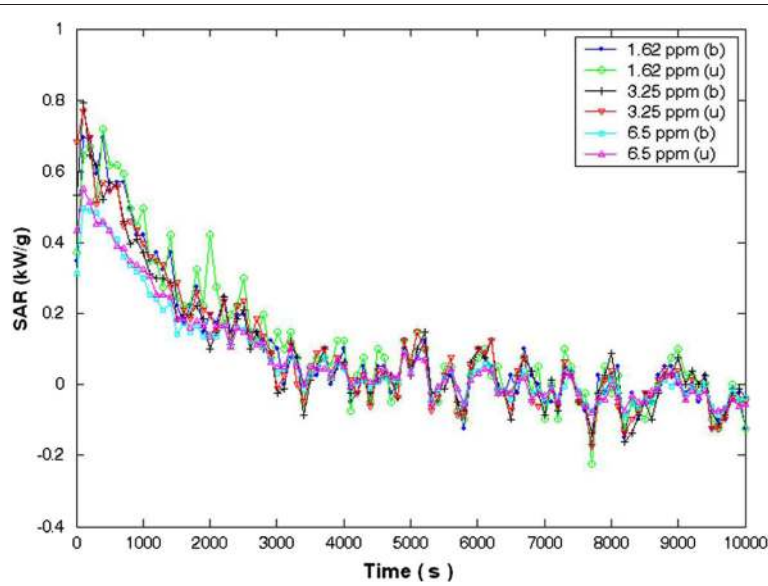

Figure 7 Specific absorption rate of silver nanoparticles (where b and u refer to thermocouples located at the bottom and upper positions respectively).

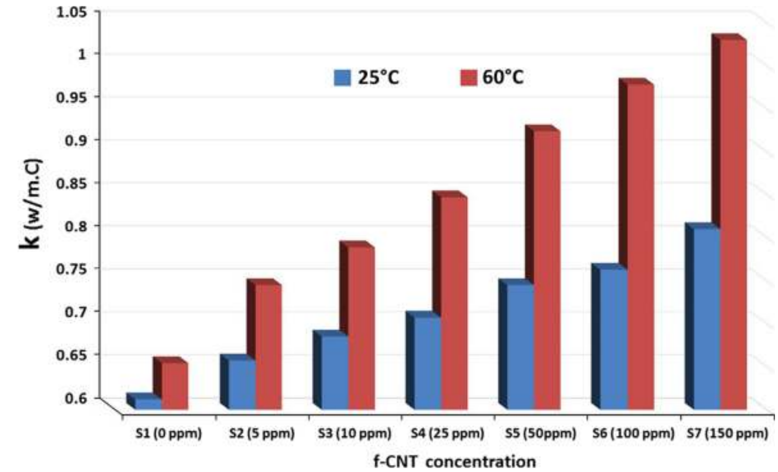

Figure 8 Thermal conductivity of f-CNT/water NFs in ambient temperature and 60°C.

nanotubes (MWCNTs) in water, ethylene glycol, propylene glycol and Therminol VP-1 heat transfer fluids with the aid of an ultrasonic bath. They examined both the long-term and high-temperature stability of CNT nanofluids for use in direct solar absorption. In this work plasma treatment applied to modify the surface of the MWCNTs to improve their dispersion property within the base fluid. This study reported a quantitative demonstration of the high temperature and long-term stability of ethylene glycol and propylene glycol-based MWCNT nanofluids for solar thermal collectors.

Said et al. [22] experimentlly investigated the thermal conductivity, viscosity and pressure drop of water, ethylene glycol (EG) and EG + H2O (60:40)-based Al2O3 (13 nm) nanofluids prepared by using ultrasonic dispersion method in the operating temperature range of 25°C to 80°C at low range concentrations of 0.05% to 0.1% for. They observed that deviation of experimental values from estimated values of thermal conductivity of Al_2O_3/water nanofluids is considerably high but the experimental values of Al_2O_3/EG nanofluids are nearly similar to those of the model calculation as seen in Figure 13. Their results showd that nanofluids pressure drop at a low concentration flowing in a solar collector is slightly higher than the base fluid.

Liu et al. [23] experimentally investigated the feasibility of using the graphene (GE)-dispersed nanofluids based on the ionic liquid 1-hexyl-3-methylimidazolium tetrafluoroborate ([HMIM] BF_4) in high-temperature heat transfer systems (such as solar collectors). Ionic liquids (ILs) are a group of molten salts with a melting below 100°C as well as a wide liquid temperature range from room temperature to a maximum temperature of 459°C. ILs have excellent thermophysical properties such as good thermal and chemical stability, high density and heat capacity and negligible vapor pressure. In

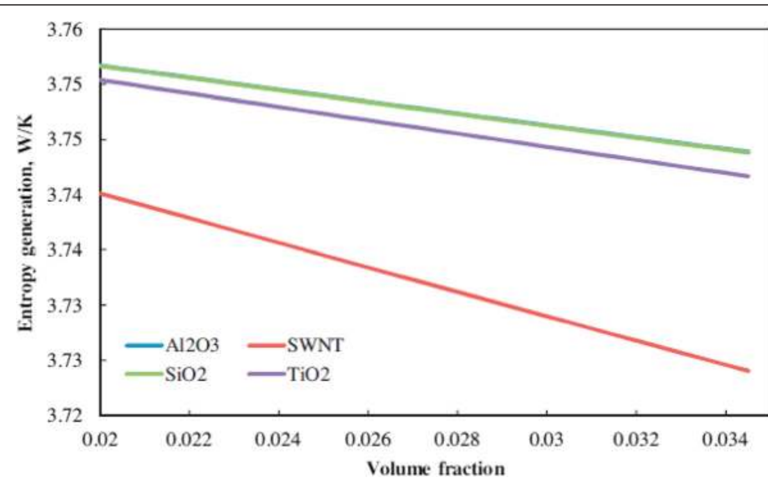

Figure 9 Change of entropy generation with volume fraction.

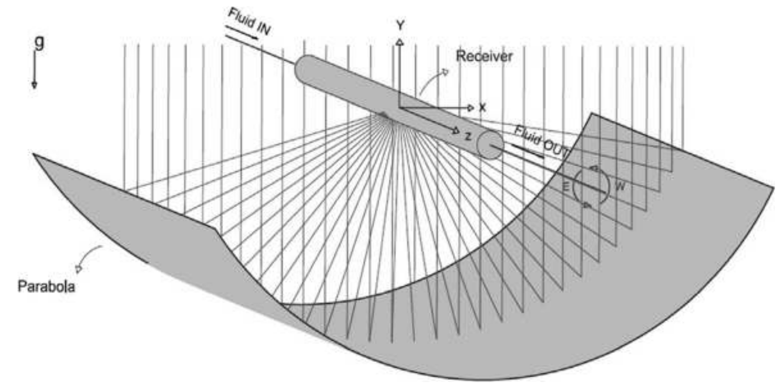

Figure 10 Schematic diagram of the parabolic trough collector and absorber tube.

this work, authors showed how to improve the performance of ILs for solar thermal systems. They observed 15.2%-22.9% enhancement in thermal conductivity using 0.06% graphene in the temperature range from 25 to 200°C as seen in Figure 14. Their results showed that GE is a better nanoadditive for nanofluids than other carbon materials and metal nanoparticles.

The authors attributed this reduction to the self-lubrication characteristic of GE. In addition, the results obtained from the thermogravimetric analysis showed the high thermal stability of GE/BF_4 nanofluids. Their measurements showed that this novel class of nanofluids is very suitable for high temperature applications such as solar collectors.

Ho et al. [24] found the optimal concentration of alumina nanoparticles in doped molten Hitec (a nitrate salt) by maximizing its specific heat capacity. High-temperature molten salt typically has a high heat capacity and is effective as a working fluid for concentrating solar power (CSP) systems. Their findings are as follows: 1- The addition of less than 2% Al_2O_3 nanoparticles

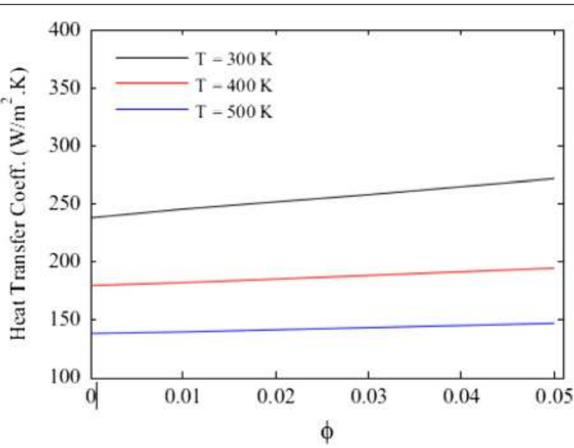

Figure 11 Mean convective heat transfer coefficient vs.particle concentration at the operational temperatures of 300,400 and 500 K.

significantly increases the specific heat of Hitec metal at low temperatures as seen in Figure 15, 2- For the volume fractions less than or equal to 0.5%, adding Al_2O_3 nanoparticles has a negative effect on the specific heat in temperature of 335°C, 3- At all temperatures, a concentration of 0.063 wt.% provides the maximum enhancement of specific heat about 19.9%, 4- The scanning electron microscopic (SEM) images show that, even at a relatively low concentration, nanoparticles aggregate as clusters with the size of 0.2 to 0.6 μm in the grain boundaries of Hitec, 5- The findings of this study suggest that the concentration that yields favorable uniform dispersion and optimal pattern of particles or clusters may maximize the specific heat. The simplified model of the solid-fluid interfacial area demonstrates that interfacial area is maximal at a concentration of 0.023 wt.%. As the nanoparticle concentration increases above 0.023 wt. %, the formed clusters become larger and the interfacial area density between the solid clusters and the base fluid decreases which may reduce the increase in specific heat capacity. According to the results obtained from this study, the maximum enhancement of the specific heat capacity occurs at concentration of 0.063 wt.% instead of 0.023 wt.%. Indeed, some agglomeration of nanoparticles forming submicrometer clusters may be the best for the enhancement of specific heat capacity. However, the total interfacial area at concentration of 0.063 wt. % was slightly less than its value at concentration of 0.023 wt. %.

Role of surfactants

Singh et al. [25] added Cu to commercial solar heat transfer fluids (Therminol 59 (TH59) and Therminol 66 (TH66)) by the combination of temperature and ultrasonic ripening processes. They stated that surfactant selection has an important role in preparing stable nanofluids. Choosing the right surfactant is mainly dependent on the properties of the base fluids and particles. For example, silicon oxide nanoparticles were successfully

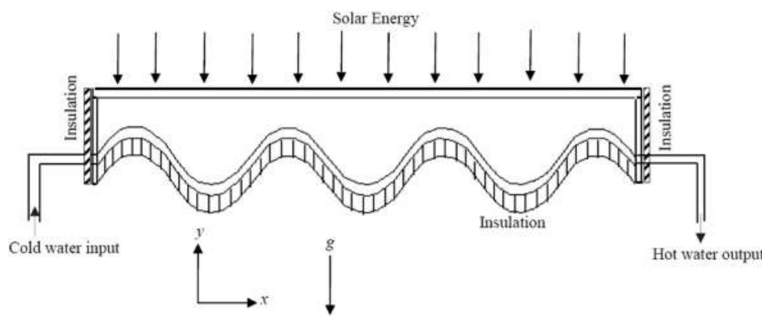

Figure 12 Schematic diagram of the solar collector.

dispersed in TH66 using benzalkonium chloride (BAC, Acros Organics) as a surfactant but the use of BAC surfactant with Cu nanoparticles did not provide sufficient stability of suspension due to the lack of specific interaction between the nanoparticles and the surfactant molecules. The bi-layer arrangement of surfactant molecules should provide good adhesion to the nanoparticle surface and miscibility with the aromatic solvent. In this work, authors used a combination of oleic acid and BAC and a mixture of octadecyl thiol (ODT) and BAC surfactants to disperse Cu nanoparticles in TH66 and TH59, respectively. They observed that 3D Cu nanoparticle agglomerates do not break by conventional sonication with ultrasound gun without temperature ripening. They showed that a sonication time of about 4 h leads to the effective breakup of Cu agglomerates into individual grains at a 120°C. They also concluded that Cu/TH66 nanofluids appear to be more stable than the Cu/TH59 nanofluids because of the higher dynamic viscosity.

Yousefi et al. [26,27] studied the effect of Al_2O_3 (15 nm) and MWCNT (10-30 nm) water nanofluid on the efficiency of a flat plate solar collector experimentally. The weight fractions of the nanoparticles were 0.2% and 0.4%, and the experiments were performed with and without Triton X-100 as surfactant. Their findings showed that the surfactant presence in the nanofluid extremely affects solar collector's efficiency.

Lenert et al. [28] presented a combined modeling and experimental study to optimize the performance of a cylindrical nano-fluid volumetric receiver. They concluded that the efficiency is more than 35% when nanofluid volumetric receivers are coupled to a power cycle and optimized with respect to the optical thickness and solar exposure time. This study provides an important perspective in the use of nanofluids as volumetric receivers in concentrated solar applications. In this work, 28 nm carbon-coated cobalt (C-Co) nanoparticles dispersed and suspended in Therminol VP-1 after 30 min in a sonication bath without any surfactant.

Role of the pH

Yousefi et al. [29] investigated the effect of pH of MWCNT-H2O nanofluid on the efficiency of a flat-plate solar collector as seen in Figure 16. The experiments were carried out using 0.2 wt% MWCNT (10-30 nm) with various pH values (3.5, 6.5 and 9.5) and with Triton X-100 as an additive. They found that increasing or decreasing the pH with respect to the pH of the

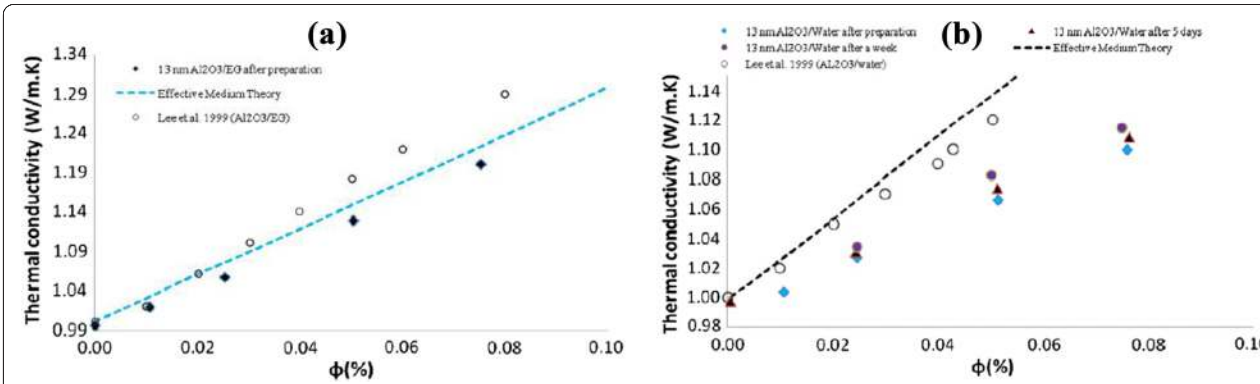

Figure 13 Thermal conductivity of Al2O3/EG (a) and Al2O3/water (b) nanofluids at different volume fractions and at 25°C.

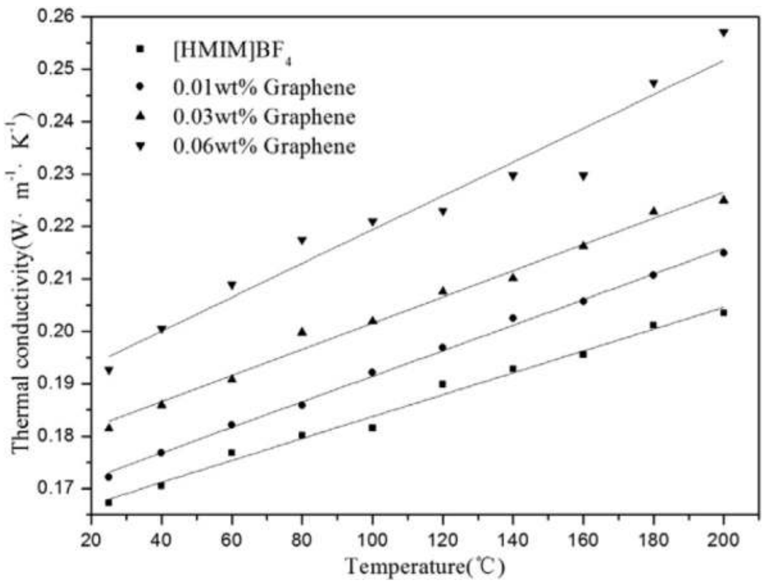

Figure 14 Thermal conductivity of [HMIM]BF4 and the GE-dispersed Ionanofluids as a function of temperature.

isoelectric point (IEP) would enhance the positive effect of nanofluids on the efficiency of the solar collector. The collector efficiency enhanced while the differences between the pH of nanofluids and that of isoelectric increased. As the nanofluids become more acidic (lower pH value), more charges are accumulated on the particle surface, leading to lower agglomeration of nanoparticles in the suspension. Consequently, the effective thermal conductivity of the nanofluid increases. In addition, with the increase in pH of the nanofluid, the surface charge of the CNT increases leading to the increase in thermal conductivity and stability of nanofluid.

Using nanofluids in photovoltaic/thermal (PV/T) system

Sardarabadi et al. [30] performed experiments to study the effects of using SiO2/water nanofluid as a coolant on the thermal and electrical efficiencies of a photovoltaic thermal (PV/T) system. A flat plate solar collector was attached to a PV panel. The tilt angle of the collector was set at a constant value of 32° to maximize the solar collecting area. It was observed that by adding a thermal collector to a PV system, the total exergy for the three cases with pure water, 1% silica/water nanofluid and 3% silica/water nanofluid increased by 19.36%, 22.61% and 24.31%, respectively as seen in Figure 17. Thermal

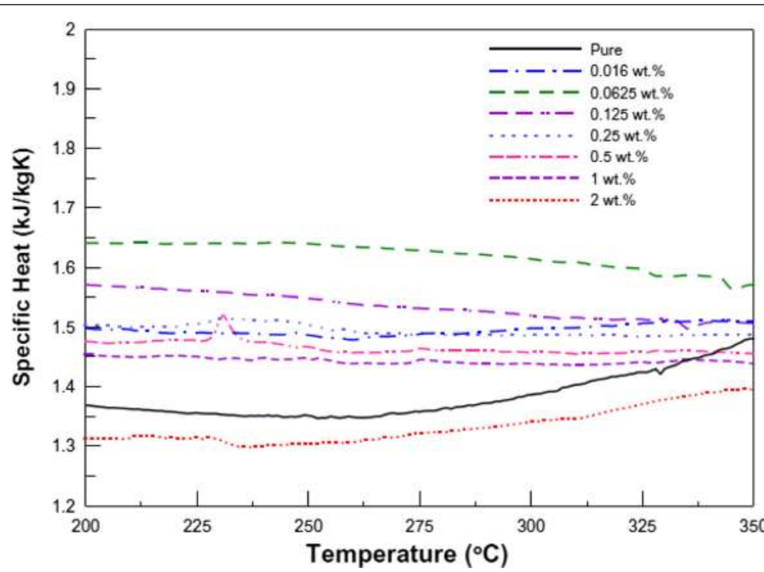

Figure 15 Variation of specific heat capacity with temperature for the pure and the different nanoparticle concentration of Hitec nanofluid.

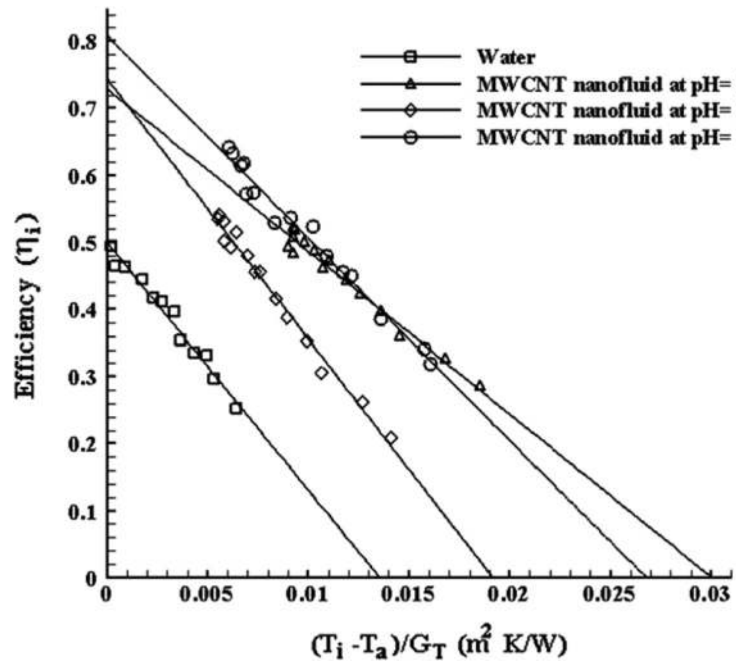

Figure 16 The efficiency of the flat-plate solar collector with MWCNT nanofluid as base fluid at three pH values as compared with water in0.0333 kg/s mass flow rate.

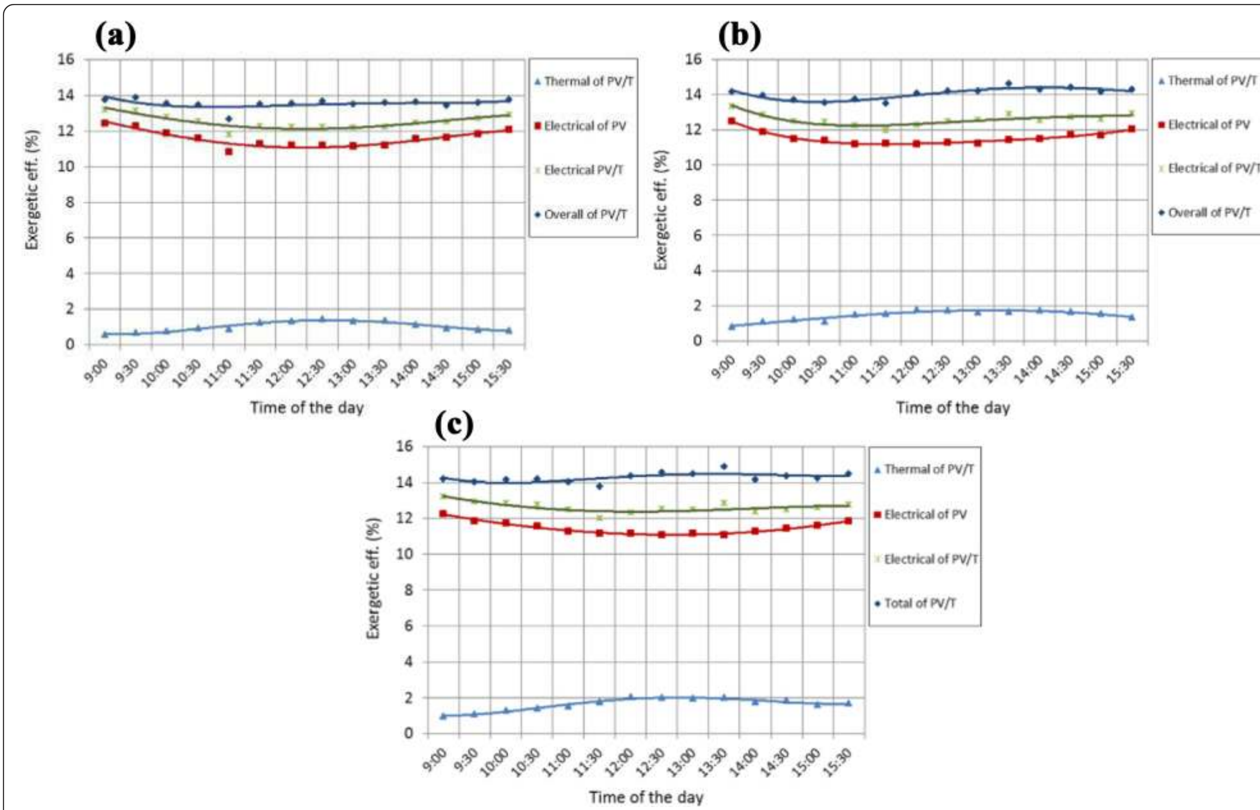

Figure 17 Exergetic efficiency of the system for the three cases with pure water (a), 1% silica/water nanofluid (b) and 3% silica/water nanofluid (c) during the daily experiment.

efficiency of the PV/T collector for the two cases of 1 and 3 wt% of silica/water nanofluid increased 7.6% and 12.8%, respectively.

Karami et al. [31] experimentlly investigated the cooling performance of water based Boehmite (AlOOH. xH_2O) nanofluid in a hybrid photovoltaic (PV) cell. The PV cell is mono-crystalline silicon. Results showed that the nanofluid performed better than water and the average PV surface temperature decreased from 62.29°C to 32.5°C as seen in Figure 18. They reported that the electrical efficiency falls as the concentration of the nanofluid rises beyond a certain level. The authors attributed this reduction to the high surface activity of nanoparticles and their tendency to agglomeration/clustering at high particle loadings. Table 1 summarizes the results of nanofluids influence on different solar thermal applications.

Using nanofluids in solar stills

Kabeel et al. [32] investigated a small unit for water desalination coupled with nano-fluid-based (Cu/water) solar collector as a heat source as seen in Figure 19. The system consists of a solar water heater (flat plate solar collector), a mixing tank and a flashing chamber plus a helical heat exchanger and a condenser. The desalination process is based on the evaporation of sea water under a very low pressure (vacuum). The evaporated water is then condensed to obtain fresh water. The simulation results showed that the nanoparticle concentration is an important factor on increasing the fresh water production and decreasing cost. Authors reported that the water cost can be decreased from 16.43 to 11.68 $/m^3 at $\phi = 5\%$ as seen in Figure 20.

Kabeel et al. [33] used Al_2O_3 nanoparticles with water inside a single basin solar still. Their results showed that using nanofluids improves the solar still water productivity by about 116% and 76% with and without operating the vacuum fan. The authors attributed this increment to the increase of evaporation rate inside the still. Utilizing nanofluid increases the rate of evaporation. In addition, due to this vacuum inside the still the evaporation rate increases further and the productivity increases compared with the still working at atmospheric conditions.

Using nanofluids in solar pond

Al-Nimr et al. [34] presented a mathematical model to describe the effects of using silver-water nanofluid on the thermal performance of a shallow solar pond (SSP) and showed that the energy stored in the nanofluid pond is about 216% more than the energy stored in the brine pond. The upper layer of the pond is made of mineral oil and the lower layer is made of silver (Ag) water-based nanofluid. Their results showed that for solar radiation of 1000 W/m^2, the nanofluid pond required a depth less than 25 cm in order to absorb the light, while the brine pond depth must be more than 25 m to absorb the same amount of light. They attributed the increase of stored energy to the increase in thermal conductivity of the base fluid due to the nanoparticles addition that leads to uniform

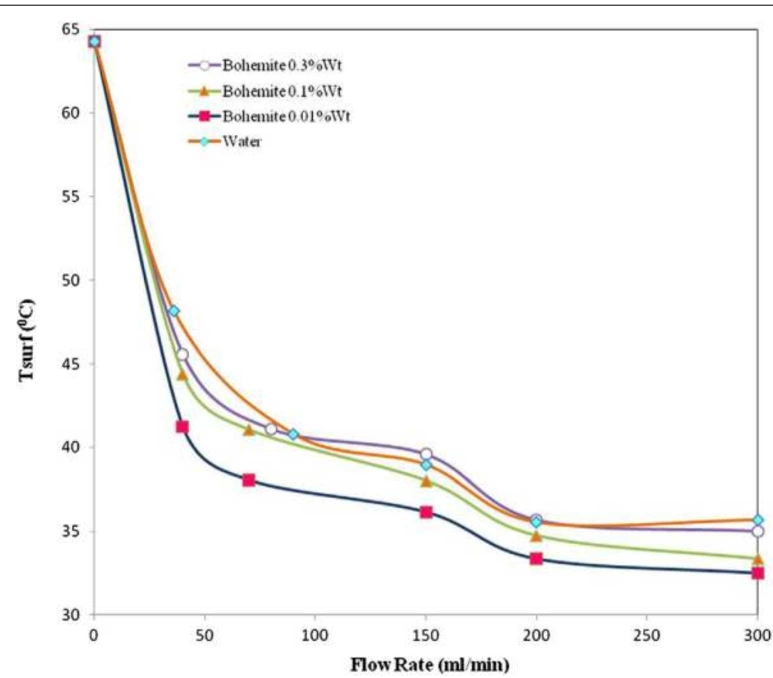

Figure 18 Variation of the average temperatures of the PV surface at various flow rates for water and three different concentrations of nanofluid.

Table 1 The influence of nanofluid on different solar thermal applications

Author(s)	Nanofluid	Type of application	Observation
Luo et al. [8]	TiO2, Al2O3, Ag, Cu, SiO2, graphite, and carbon nanotubes in Texatherm oil	DAC solar collector	use of nanofluid in the solar collector can improve the outlet temperature and the efficiency
Rahman et al. [9]	Cu, Al2O3 and TiO2 in water	triangular shape solar collector	Results showed 24.28% improvement for $Gr=10^6$ at 10% volume fraction of copper particles. the convective heat transfer performance is better when the solid volume fraction is kept at 0.05 or 0.08.
Faizal et al. [10]	CuO, SiO2, TiO2 and Al2O3 in water	solar collector	results confirmed that higher density and lower specific heat of nanofluids offers higher thermal efficiency than water and therefore can reduce the solar collector area about 25.6%, 21.6%, 22.1% and 21.5% for CuO, SiO2, TiO2 and Al2O3 nanofluids. Environmental damage cost is also lower with the nanofluid based solar collector
Parvin et al. [11]	Cu/water	solar collector	Increasing the particles concentration raises the fluid viscosity and decreases the Reynolds number and consequently decreases heat transfer. There is a need to find the optimum volume fraction for each application
Ladjevardi et al. [12]	Graphite/water	solar collector	Their numerical results showed that nanofluid collector thermal efficiency increases about 88% compared with the pure water collector with the inlet temperature of 313 K. It also can be increased to 227% with the inlet temperature of 333 K.
Said et al. [15]	single wall carbon nanotubes, Al_2O_3, TiO_2 and SiO_2	flat plate solar collector	It was observed that SWCNTs nanofluids could reduce the entropy generation by 4.34% and enhance the heat transfer coefficient by 15.33%
Saidur et al. [17]	Aluminum/water	direct absorption solar collector	Their results revealed that Aluminum/water nanofluid with 1% volume fraction improves the solar absorption considerably. They found that the effect of particle size on the optical properties of nanofluid is minimal, but in order to have Rayleigh scattering the size of nanoparticles should be less than 20 nm. They also found that the extinction coefficient is linearly proportionate to volume fraction
Sokhansefat et al. [18]	Al_2O_3/synthetic oil	parabolic trough collector tube	Nanofluid enhanced convective heat transfer coefficient.
Hordy et al. [21]	multi-walled carbon nanotubes/water ethylene glycol, propylene glycol	solar collector	quantitative demonstration of the high temperature and long-term stability of ethylene glycol and propylene glycol-based MWCNT nanofluids for solar thermal collectors
Said et al. [22]	Al2O3, water, ethylene glycol	Solar collector	Their results showed that nanofluids pressure drop at a low concentration flowing in a solar collector is slightly higher than the base fluid.
Liu et al. [23]	Grapheme/ ionic liquid 1-hexyl-3-methylimidazolium tetrafluoroborate	solar collectors	They observed 15.2%-22.9% enhancement in thermal conductivity using 0.06% volume graphene in the temperature range from 25 to 200°C. Their results showed that GE is a better nanoadditive for nanofluids than other carbon materials and metal nanoparticles
Ho et al. [24]	Alumina/ doped molten Hitec	concentrating solar power systems	The addition of less than 2% Al_2O_3 nanoparticles significantly increases the specific heat of Hitec metal at low temperatures
Singh et al. [25]	Cu/Therminol 59 (TH59) and Therminol 66 (TH66)		They stated that surfactant selection has an important role in preparing stable nanofluids. Choosing the right surfactant is mainly dependent on the properties of the base fluids and particles
Yousefi et al. [29]	MWCNT/water	flat plate solar collector	They found that increasing or decreasing the pH with respect to the pH of the isoelectric point (IEP) would enhance the positive effect of nanofluids on the efficiency of the solar collector
Sardarabadi et al. [30]	SiO2/water	PV/T	Thermal efficiency of the PV/T collector for the two cases of 1 and 3 wt% of silica/water nanofluid increased 7.6% and 12.8%, respectively.
Kabeel et al. [32]	Cu/water	water desalination unit	the water cost can be decreased from 16.43 to 11.68 $/m^3 at $\varphi=5\%$
Kabeel et al. [33]	Al2O3/water	solar still	using nanofluids improves the solar still water productivity by about 116% and 76% with and without operating the vacuum fan
Al-Nimr et al. [34]	silver-water	shallow solar pond	energy stored in the nanofluid pond is about 216% more than the energy stored in the brine pond
Liu et al. [35]	CuO/water		maximum and mean values of the collecting efficiency of the collector with open thermosyphon using nanofluids increased 6.6% and 12.4%, respectively.

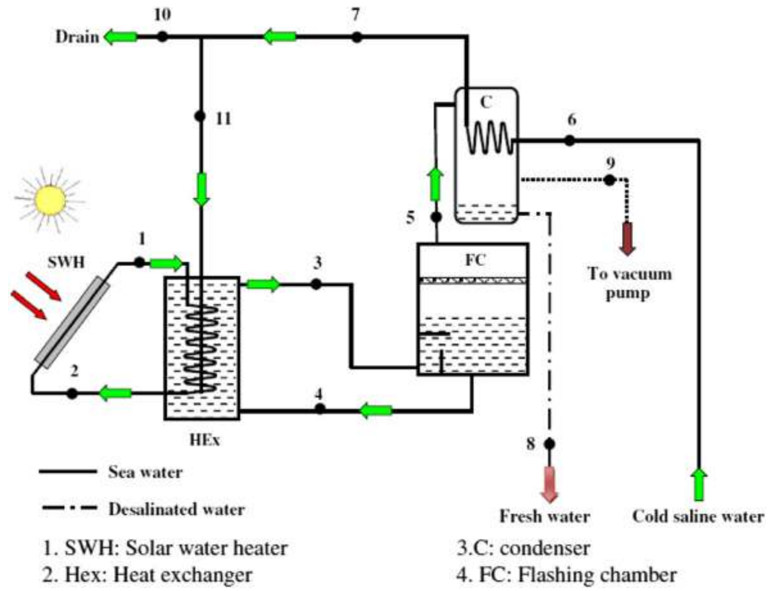

Figure 19 Schematic diagram of single stage flash (SSF) system.

temperature distribution within the layer with reduction in heat losses.

Using nanofluids in the solar collector integrated with open thermosyphon

Liu et al. [35] experimentally showed that the solar collector integrated with open thermosyphon has a much better collecting performance compared to the collector with concentric tube and its efficiency could be improved by using CuO/water nanofluid as the working fluid as well. Their results showed that the maximum and mean values of the collecting efficiency of the collector with open thermosyphon using nanofluids increased 6.6% and 12.4%, respectively.

Conclusions

Nanofluids have been utilized to improve the efficiency of several solar thermal applications. Theoretical and experimental studies on solar systems proved that the system performance enhances noticeably by using nanofluids. A number of investigations presented the existence of an optimum concentration for nanoparticles in the base fluid.

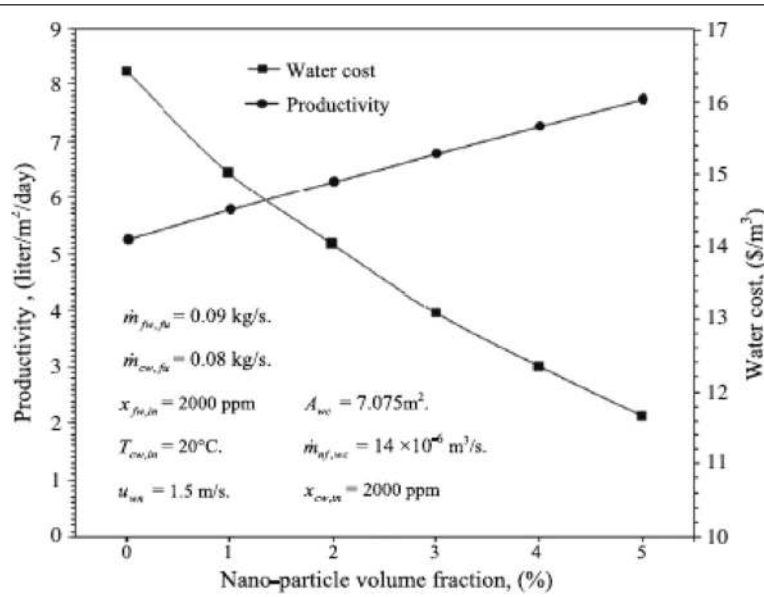

Figure 20 Variations in system productivity and water cost as a function of nano-particle volume fraction.

Adding nanoparticles beyond the optimum level no longer enhances the efficiency of the solar system.

Optimal conditions are a function of nanoparticles size and concentration, base fluid, surfactant and pH as discussed throughout this article. Nanofluid utilization in the solar thermal systems is accompanied by important challenges including high cost of production, instability, agglomeration and erosion. This review article is an attempt to elucidate the advantages and disadvantages of nanofluids application in the solar system.

Competing interests
The authors declare that they have no competing interests.

Authors' contributions
MS conducted the extensive literature review and NB wrote the article. Both authors read and approved the final manuscript.

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