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Nanofluids Applications in Solar Energy Systems: A Review

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A B S T R A C T

Solar energy systems have attracted a lot of attention in the last few decades. Heat transfer enhancement (performance) of the solar thermal systems is one of the significant issues in energy usage, energy saving and compact designs. Since the nanofluids are used to improve the heat transfer characteristics and thermal properties compared with conventional fluids, replacing the working fluid with nanofluids is effective method to enhance the efficiency and performance of the solar thermal systems. This new and novel strategy is a subject of interest of researchers and literatures in recent years. The present review paper investigates applications of the nanofluids in solar thermal engineering systems include collectors and thermal energy storage systems. In addition effects of nanofluids on the performance, efficiency, economic and environmental considerations of mentioned systems are reviewed.

1. Introduction

Energy as one of the essential requirement of human and industries, play an important role in the economic development of any country. The limitation of fossil fuels and the negative impacts of their usage on the environment and climate changes have caused a considerable attention to use renewable energy sources as an appropriate and attractive alternative energy for fossil energy sources. Solar energy is considered as one of the best nature sources of renewable energy in the resent years.

One of the significant issues is heat transfer enhancement and performance of the solar thermal systems. Most of solar systems like solar collectors deal with fluids like water and use it for heat exchanger, i.e. solar water heating. Whatever thermal conductivity of applied fluid in mentioned systems be higher, heat exchange rates will be increased. In addition to, for theremal storage systems using fluids with higher specific heat capacity increases the performance of the storage system. Using ultra fine solid particles suspended in conventional fluids is a effective and novel strategy to improve their thermal conductivity and heat capacity. The mixture of liquid (base fluid) and nano-sized particles (1–100 nm) is called a nanofluid. Choi [1] was the first one who used nanofluid term and developed heat transfer of nanofluids in 1995 [2]. Nanofluids have intensified thermo-physical properties, such as thermal conductivity, specific heat capacity, viscosity, density and convective heat transfer coefficients, compared with conventional fluids [3]. In recent years , many experimental studies [4-10] have shown that nanofluids have the significantly better heat transfer characteristics than the conventional fluids. Several reviews have summarized the thermo physical properties of nanofluids [11-14] and the effects of nanofluids on the enhancement of heat transfer .[15, 16].

Using of solar energy has attracted a lot of attention in recent years. But most of solar energy converting systems suffer from low efficiency; hence transfer enhancement and performance of the solar thermal systems is a significant issue. Nanotechnology and Nanofluids can have a remarkable role in enhancing of the efficiency in solar systems. The present study provides a comperehensive review of recent researches on the application of nanofluids in solar thermal engineering systems such as collectors, water heaters and thermal storage systems. In addition, an investigation on economical and environmental aspects of solar energy has been peresented. This review can be a useful comperehensive refrence to find and determine the effectiveness of nanofluids in solar applications and conduct readers to future work and novel ideas in mentioned field.

2. Applications of nanofluids in solar thermal engineering systems

2.1. Solar Thermal Collectors and Solar water heating

In this section, application of nanofluids in solar thermal collectors (STC) and solar water heating (SWH), are investigated from the application, efficiency, and performance viewpoint.

Solar thermal collectors and solar water heaters are the most popular solar thermal devices. A SWH is a case of kind of heat exchangers that convert incoming solar radiation energy into heat through transforming absorbed solar radiation to fluid like air, water, or oil, in order to warming fluid (specially water) or space conditioning equipment or to a thermal energy storage tank. SWHs can be considered in general group based on type of used fluid and their construction (water, non-freezing liquid, air) and whether they are covered or uncovered [17]. A general division categorizes solar collectors in tow types, non-concentrating and concentrating collectors [18]. The first group is usually used to achieve low and medium temperature such as space heating and cooling, water heating, and desalination. While concentrating solar collectors are designed for high temperature applications such as electricity generation.

Tyagi et al. [19] theoretically investigated the feasibility of using a non concentrating direct absorption solar collector (DAC) and compared its performance with that of a typical flat-plate collector. They used nanofluid of mixture of water and aluminum nanoparticles as the absorbing medium. A schematic of the direct absorption collector, under studied by them is shown in Fig. 1

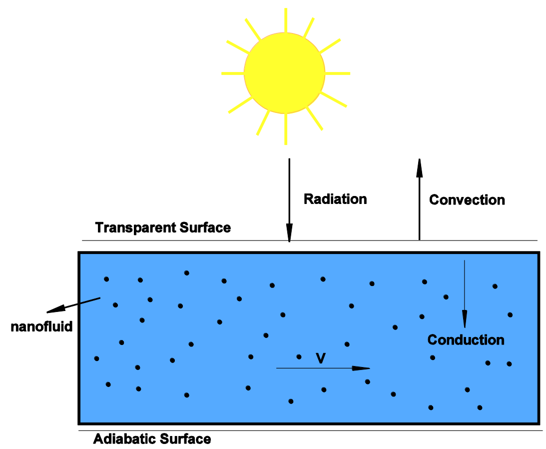

Figure 1. Schematic of the nanofluid-based direct absorption solar collector.

The efficiency of the collector is evaluated by the following equation:

$$\eta = \frac{\text{useful gain}}{\text{available energy}} = \frac{\dot{m} c_p (\bar{T}_{out} - \bar{T}_{in})}{A G_T} \qquad (1)$$

Where $\dot{m}$ is the mass flow rate of the fluid flowing through the solar collector, $\bar{T}_{in}$ and $\bar{T}_{out}$ are the mean fluid inlet and outlet temperatures, respectively, A is the top cover area of the solar collector, and G_T is the solar flux incident on the solar collector. In performed analysis by [19] , used values for $\bar{T}_{in}$, G_T and $\dot{m}$ were 35 °C, 1000 W/m^2 and 1.2 kg/s, respectively. They illustrated the variation of collector efficiency as a function of the particle volume fraction (%). Their results showed that the presence of nanoparticles increases the absorption of incident radiation by more than nine times over that of pure water, hence efficiency increases (significantly for low values of volume fraction of nanoparticles).

Lenert [20] and Lenert and Wang [21] presented a combined modeling and experimental study to optimize the efficiency of liquid-based solar receivers seeded with carbon-coated absorbing nanoparticles. Also they experimentally investigated a cylindrical nanofluid volumetric receiver, and showed good agreement with the model for varying optical thicknesses of the nanofluid. Based on their model, the efficiency of nanofluid volumetric receivers increases with increasing solar concentration and nanofluid height.

Otanicar et al. [22] investigated solar collectors based on nanofluids made from a variety of nanoparticles (carbon nanotubes, graphite, and silver), experimentally and numerically. They demonstrated efficiency improvements of up to 5% in solar thermal collectors by utilizing nanofluids as the absorption mechanism. In addition their experimental data were compared with a numerical model of a solar collector with direct absorption nanofluids. The comparative results showed an initial rapid increase in efficiency with volume fraction, followed by a leveling off in efficiency as volume fraction continues to increase.

The radiation absorption characteristics of a Ni nanoparticle suspension were investigated by spectroscopic transmission measurement by Kameya and Hanamura [23]. They demonstrated that the absorption coefficient of the nanoparticle suspension is much higher than that of the base liquid for visible to near-infrared wavelengths. The results of their investigations on the prediction process of the thermal radiation properties of nanoparticle suspensions could be used in developing direct absorption solar collectors.

Taylor et al. [24] studied a nanofluid-based concentrating solar thermal system (dish collector system). Theirs results showed a enhancement in efficiency of up to 10%. Furthermore, their analysis showed that graphite nanofluids with volume fractions on the order of 0.001% or less are suitable for 10–100 MWe power plants.

Sani et al. [25] reported the optical characterization of a new fluid consisting of single-wall carbon nanohorns and ethylene glycol for solar energy applications. They found that nanohorn spectral features are far more favorable than those of amorphous carbon for the specific application. Their result showed that carbon nanohorn-based nanofluids can be useful for increasing the efficiency and compactness of thermal solar devices, reducing both environmental impact and costs.

The extinction coefficient of water based aluminum nanofluid was investigated and evaluated by varying nanoparticle size and volume fraction by Saidur et a. [26] . They showed that the particle size has minimal influence on the optical properties of nanofluid. On the other hand, the extinction coefficient was linearly proportionate to volume fraction.

Mercatelli and coworkers [27, 28] investigated the scattering and spectrally resolved absorption properties of nanofluids consisting in aqueous and glycol suspensions of single-wall carbon nanohorns in view of their use as sunlight absorber fluids in a solar device. They observed nanoparticle-induced differences in optical properties appeared promising, leading to a considerably higher sunlight absorption with respect to the pure base fluids. Scattered light was found to be not more than about 5% with respect to the total attenuation of light. Both these effects, together with the possible chemical functionalization of carbon nanohorns, made this new kind of nanofluids very interesting for increasing the overall efficiency of the sunlight exploiting device.

Said et al. [29], carried out experimental investigations for obtaining the thermophysical properties of 60:40 (by mass) ethylene glycol/water mixture and water based alumina nanofluids and effect of density and viscosity on the pumping power for flat plate solar collector. Nanofluids of 0.05–0.1%v/v concentrations were prepared and characterized. They found that water based alumina nanofluids (AL_2O_3) were more preferable against sedimentation and aggregation than ethylene glycol/water (EG/water) mixture based nanofluids. The measured thermal conductivities of both types of the nanofluids increased almost linearly with concentration. In contrast to thermal conductivity, viscosity measurements showed that the viscosity of the Al_2O_3–water nanofluids exponentially decreases with increasing temperature.

The effect of pH variation of MWCNT–H_2O nanofluid on the efficiency of a flat-plate solar collector was investigated experimentally by Yousefi et al. [30]. Their results showed that by increasing or decreasing the pH values with respect to the pH of isoelectric point, the positive effect of nanofluid on the efficiency of solar collector is increased. In another study by Yousefi et al. [31], the effect of Al_2O_3–water nanofluid, as working fluid, on the efficiency of a flat-plate solar collector was investigated experimentally. In contrast with previous study in this filed, their results showed that, in comparison with water as absorption medium using the nanofluids as working fluid increase the efficiency. For 0.2 wt% the increased efficiency was 28.3%. From the results it was concluded that the surfactant causes an enhancement in heat transfer.

Colangelo et al. [32] presented the experimental results and the potential performance of the investigation on flat solar thermal collectors using nanofluids as innovative heat transfer fluids for solar energy applications. After different nanofluids were tested on the panel prototype, water–Al_2O_3 was chosen as heat transfer fluid. A thermal conductivity enhancement up to 6.7% at a concentration of 3 vol% was observed, while the convective heat transfer coefficient increased up to 25%.

Paul et al. [33] performed an experimental assessment on Nanoparticle Enhanced Ionic Liquids (NEILs), by measuring thermophysical property and evaluating forced convection performance. Their experimental results showed clear advantages of the NEILs over the base Ionic liquids (ILs) both in heat storage capacity and heat transfer performance. Up to 6% enhancement in thermal conductivity, 23% enhancement in heat capacity, and 20% enhancement in convective heat transfer performance has been observed for the 1% (Weight%) aluminium oxide (Al2O3) enhanced ILs compared to the base ILs.

The effect of CuO–water nanofluid, as the working fluid, on the performance and the efficiency of a flat-plate solar collector was investigated experimentally by Moghadam et al. [34]. The volume fraction of nanoparticles was set to 0.4% and the mean particle dimension is kept constant at 40 nm. The working fluid mass flow rate was varied from 1 to 3 kg/min. Their experimental results revealed that utilizing the nanofluid increases the collector efficiency in comparison to water as an absorbing medium as the flow rate of 1 kg/min increases the collector efficiency about 21.8%.

Karami et al. [35] investigated application of aqueous suspension based on alkaline functionalized carbon nanotubes as an absorber fluid in a sunlight harvesting device. In their investigations, the extinction coefficient of aqueous suspensions of functionalized carbon nanotubes showed remarkable improvement compared to the base fluid even at low particle loadings. They also demonstrated thermal conductivity improvements of up to 32% by adding only 150 ppm functionalized carbon nanotubes to water as the absorbing medium.

Saeid et al. [36] studied TiO_2–water nanofluid as a working fluid for enhancing the performance of a flat plate solar collector. In their experimental, the volume fraction of the nanoparticles was 0.1% and 0.3% respectively, while the mass flow rates of the nanofluid varied from 0.5 to 1.5 kg/min, respectively. Their results revealed energy efficiency increased by 76.6% for 0.1% volume fraction and 0.5 kg/min flow rate, whereas the highest exergy efficiency achieved was 16.9% for 0.1% volume fraction and 0.5 kg/min flow rate. In addition, their results showed that the pressure drop and pumping power of TiO_2 nanofluid was very close to the base fluid for the studied volume fractions.

Also, the references [37-49] can be introduced as some of useful and the newest studies in field of nanofluids applications in solar collectors. Moreover, the review studies carried out by [17, 50-54] summarized former works in mentioned filed.

2.2. Thermal energy storage

Energy storage is a key issue in renewable energies field. Unlike fossil energies, solar thermal energy storage is very difficult. Because it needs facilities like materials and mediums with high availability storage and few materials are available with these properties especially for high-temperature thermal storage. Since nanotechnology can improve some thermo-physical properties of materials, hence using nanomaterials can play an important role in solar thermal energy storage.

Zhu [55] investigated the heat transfer enhancement in a two-dimensional enclosure containing nanofluids. They simulated phase change behavior of $SiC\text{-}H_2O$ nanofluids considering different volume fractions. Their simulation results showed that the freezing rate of nanofluids is enhanced due to the addition of nanoparticles. Adding 5% SiC nanoparticles into water, the total freezing time can be saved by 17.4%. They showed that adding nanoparticles is an efficient way to enhance the heat transfer in a latent heat thermal energy storage system.

A anomalous enhancement of specific heat capacity of high-temperature nanofluids was reported by [56]. Alkali metal chloride salt eutectics were doped with silica nanoparticles at 1% mass concentration. The specific heat capacity of the nanofluid was enhanced by 14.5%.

Latent heat storage with phase change materials (PCMs) is very attractive, because of its high-energy storage density and its isothermal behavior during the phase change process. Wu et. al [57] numerically investigated the melting processes of Cu/paraffin nanofluids PCMs. Their results demonstrated that the phase change heat transfer of paraffin was enhanced due to the addition of nanoparticles. For 1 wt% Cu/paraffin, the melting time could be saved 13.1%.

Lin et al. [58] studied the copper nanoparticles–Paraffin wax compositions for solar thermal energy storage, experimentally. Their experimental results showed that the thermal conductivity of the Cu–PCM nanocomposites was increased by 14.0%, 23.9%, 42.5% and 46.3% when 0.5%, 1.0%, 1.5%, and 2.0% weight of nano Cu was dispersed in the PCM, respectively. Site test, using integrated solar-TES system, showed efficiency enhancement by 1.7% when 1.0% nano Cu has been added to the paraffin wax.

The performed investigations by [59-65] are among the newest studies in recent year in the field of nanomaterial applications in solar thermal energy storage. They all have shown that adding nanoparticles is an efficient way to increase performance of thermal energy storage system.

3. Economical and environmental aspects

Life cycle assessment (LCA) is an accepted methodology that can be used to assess economic and environmental impacts of products [66]. To overcome the environmental negative impacts of fossil fuels like global warming, environmental pollution and also limited energy sources of fossil fuels, renewable energy sources like solar thermal energy are attracted as an alternative and increasing demand of energy. Recently many researchers have used LCA methodologies to evaluate the economic and environmental impact of solar hot water heating systems [67-69]. Solar energy is sustainable, clean and infinite; although the current solar technology is still expensive and low in efficiency.

Otanicar and Golden [66] compared environmental and economic impacts of using nanofluids to enhance solar collector efficiency as compared to conventional solar collectors for domestic hot water systems located in Phoenix, Arizona. They showed that for the current cost of nanoparticles the nanofluid based solar collector has a slightly longer payback period but at the end of its useful life has the same economic savings as a conventional solar collector. Their result demonstrated a nanofluid based collector has a lower embodied energy (~9%) and approximately 3% higher levels of pollution offsets than a conventional collector. In addition if 50% penetration of residential nanofluid based solar collector systems for hot water heating could be achieved in Phoenix, Arizona over 1 million metric tons of CO2 would be offset per year. Their economic analysis showed that the capital cost and maintenance costs of the nanofluid-based solar collector compared to the conventional one are $120 and $20 higher, respectively.

Khullar and Tyagi [70] investigated the potential of the nanofluid-based concentrating solar water heating system (NCSWHS) as an alternative to systems based on fossil fuels. Their analysis revealed that considerable emission reductions (about 2.2 x 10^3 kg of CO_2/household/ year) and fuel savings can be achieved if the NCSWHS are adopted. Tiwari et al. [71] presented a comprehensive overview and environmental impact analysis on solar water heating using nanofluids.

A analysis on the impact on the performance, fluid flow, heat transfer, economic, and environment of a flat-plate solar thermal collector by using silicon dioxide nanofluid as absorbing medium was presented by Faizal [72]. Their analysis is based on different volume flow rates and varying nanoparticles volume fractions. They showed that using SiO_2 nanofluid in solar collector could also save 280 MJ more embodied energy, offsetting 170 kg less CO_2 emissions and having a faster payback period of 0.12 years compared to conventional water-based solar collectors.

4. Concluding remarks and future work

Limited sources and negative impacts of fossil fuels have caused that the governments and scientists look for alternative energy sources that doesn’t have mentioned problem. Solar energy is one of the best options but its technology still suffers from low efficiency and high cost. Nanotechnology can be used in solar systems to their improve performance and efficiency. This paper presents a review of the recent developments and the applications of nanofluids in solar thermal engineering systems. This review reveals some important points. First, importance of type of used nanofluid in solar thermal system considering application of the system. For a solar collector, the target is increasing of thermal conductivity and coefficient of heat transfer convection of nanofluid, while for thermal energy storage the target is enhancement of specific heat capacity. Second, depends on some parameters such as working temperature and mass flow rate, solar thermal system has maximum efficiency or best performance in an optimal volume fraction of used nanofluid. Because it was observed form literature (the experimental and numerical studies) that nanofluid with higher volume fraction always is not the best option. Moreover (the third point), it was found that by increasing a low value of volume fraction of nanoparticels in base fluid, remarkable increasing of efficiency is observed, and by more increasing in valume fraction, no significant effect is observed in efficiency value. Hence, considering relatively high cost of nanoparticles, it is not logical to increase value of valume fraction in viewpoint of economic. Fourth, the effect of particle size on the solar collector efficiency could be significant. Fifth, from the economic and environmental viewpoint, the reviewed studies revealed that using nanofluids in solar collectors leads to a reduction in CO2 production and annual electricity and fuel savings. Sixth, utilizing nanofluid in solar systems is a new strategy and has a shrt history less than two decades. Hence, this field is in firest steps and has enormous potential to work and research in the future. Seventh, It’s recommended to work on other applications of nanofluid and nanotechnology in solar energy system such as solar photovoltaic thermal systems, solar cooling systems, solar stills and also research on development of the nanoparticles production in order to decreasing in production costs which are the subject of interest of author’s future work.

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