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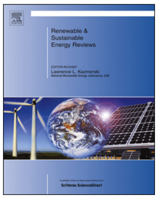

A review on the applications of nanofluids in solar energy systems

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ABSTRACT

The negative impact of human activities on the environment receives tremendous attention, especially on the increased global temperature. To combat climate change, clean and sustainable energy sources need to be rapidly developed. Solar energy technology is considered as one of the ideal candidates, which directly converts solar energy into electricity and heat without any greenhouse gas emissions. In both areas, high-performance cooling, heating and electricity generation is one of the vital needs. Modern nanotechnology can produce metallic or nonmetallic particles of nanometer dimensions which have unique mechanical, optical, electrical, magnetic, and thermal properties. Studies in this field indicate that exploiting nanofluid in solar systems, offers unique advantages over conventional fluids. In this paper, the applications of nanofluids on different types of solar collectors, photovoltaic systems and solar thermoelectrics are reviewed. Beside the wide range of energy conversion, the efforts done on the energy storage system (ESS) have been reviewed. In the field of economics, nanotech reduces manufacturing costs as a result of using a low temperature process.

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1. Introduction

Heat transfer has many applications in industries with the aim of both increasing and decreasing temperature. The imperfection of thermal engineering devices is the low thermal conductivity of conventional fluids such as water, ethylene glycol, or oil. Nanofluids have solved this constraint because of their remarkable heat transfer abilities. A fluid which contains nanometer-sized particles (1–100 nm in one dimension) is called nanofluid. Comparing to base fluids, nanofluids enhance the rate of heat transfer. Hence, they have a wide range of utility in industry, thermal generation, transportation and microelectronics. Adding nanometer-sized particles to a fluid was initially investigated by Choi in 1995 [1], in which the results revealed better thermal conductivity.

In the past two decades, researchers have theoretically and experimentally surveyed the thermophysical characteristics of nanofluids. In many research, the intensification of heat transfer for nanofluids compared to conventional fluids has been proven [2–8]. The study of Lee et al. [9] showed that Cu-water, Al_2O_3-water and CuO-ethylene glycol nanofluids cause augmentation of thermal

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conductivity. In another study on engine oil containing 1.0% volume carbon nanotube, 160% enhancement in thermal conductivity was observed by Choi et al. [10]. Nanofluid minimum quantity lubrication (MQL), which has been recently mentioned, was investigated by Nam et al. [11]. They found that using nanofluid MQL in micro drilling process decreases the drilling torques and thrust forces. Many studies have been carried out about the effect of nanofluids on convective heat transfer coefficient and friction factor [12–15]. Sundar et al. [16] reported the enhancement of convective heat transfer coefficient and friction factor by adding Fe_3O_4 nanoparticles to water. Duangthongsuk and Wongwises [17] stated that water nanofluid consisting of 0.2% volume TiO_2 nanoparticles caused 6–11% enhancement in the heat transfer coefficient.

A group of literatures investigated the effects of nanoparticle size and volume fraction on the heat transfer [18–25]. Wongcharee and Eiamsa-ard [26] studied CuO-water nanofluid in three different volume fractions of 0.3%, 0.5%, 0.7% for a laminar regime. The reults exhibited an improvement of Nusselt number as nanofluid concentration rose. Santra et al. [27] in their assessment of copper-water nanofluid for a range of Reynolds numbers ($Re=5$ to 1500) and solid volume fraction between 0.00 and 0.05 assuming the fluid in two phases (Newtonian and non-Newtonian), observed the enhancement of heat transfer with enrichment in solid volume fraction. Fotukian and Nasr-Esfahany [28] investigated the heat transfer features of γ-Al_2O_3/water nanofluid in a circular tube with a solid volume fraction less than 0.2%. By adding nanoparticles to water, thermal conductivity augmented. Meanwhile, increasing solid volume fraction beyond 0.2% caused no change in the heat transfer rate. Arani and Amani [29] in an experimental research examined TiO_2-water nanofluid with Reynolds numbers between 8000 and 51000 and volume fraction in the range of 0.002–0.02. Heat transfer was improved with increasing of nanoparticles volume fraction. They also observed that at high Reynolds numbers, more power is needed to overcome the pressure drop of nanofluid, so it is not beneficial to use nanofluid at high Reynolds numbers compared to low Reynolds numbers. Sebdani et al. [30] investigated Al_2O_3-water in mixed convection in a square cavity at constant Rayleigh numbers, the results demonstrated the heat transfer reduction for low Reynolds number ($Re=1$) while volume fraction was more than 0.05, but in high Reynolds number (10–100), increasing of nanoparticles percentage, enhanced heat transfer. Also, for a constant Reynolds number, the effect of adding nanoparticles on heat transfer was correlated to Rayleigh number, so that augmentation of heat transfer continued until $Ra=10^3$ while for $Ra=10^4$ and $Ra=10^5$ heat transfer decreased with adding more nanoparticles [30].

The reports on the effect of nanoparticles size on the thermal conductivity are antagonist. A numerical modeling research by Lelea [31] showed that at constant Reynolds numbers in a microchannel heat sink, the enhancement of heat transfer reduces as Al_2O_3 nanoparticle diameter increased in base fluid. Teng et al. [32] surveyed the changes in heat transfer of Al_2O_3-water nanofluid at different diameter size of nanoparticles and a variety of temperatures; they declared better thermal conductivity in smaller nanoparticle diameter. The interesting aspect of this study was that the heat transfer enhanced considerably at higher temperatures. In contrary, Beck et al. [33] observed reduction of thermal conductivity for water-based and ethylene glycol-based alumina with decreasing in particle size. The same results were obtained for water-gold nanofluid by Shalkevich et al. [34].

Nanofluid may be utilized as a coolant for electronic devices. Recently they are used in heat sinks to improve thermal conductivity [35–41]. Ijam and Saidur [42] investigated the influence of SiC-water and TiO_2-water nanofluids as the coolant in a minichannel heat sink, the results exhibited an improvement in thermal conductivity compared to base fluid. In another study by Selvakumar and Suresh [43] on CuO-water nanofluids in an electronic heat sink, the same results were obtained. Hung and Yan [44] researched on a double-layered microchannel heat sink and demonstrated that adding Al_2O_3 nanoparticles to water raises the thermal performance. Nanofluid is also capable to improve oil recovery, Suleimanov et al. [45] demonstrated that an aqueous solution of anionic surface-active agents with addition of light non-ferrous metal nanoparticles permitted a 70–90% reduction of surface tension on an oil boundary in comparison with surface-active agent aqueous solution and is characterized by a shift in dilution.

By the rapid expansion in global population, demand for more energy sources is not refutable. Since fossil energy sources are being restricted, solar energy is acquiring worldwide attention as a proper alternative which is completely environmentally benign. Solar energy converting systems suffer from low efficiency; hence harvesting solar radiation with a high efficiency technology is the key issue. Nanotechnology has opened a new field to solve this deficiency. Nanofluid plays a key role to enhance the efficiency in solar systems. In this paper, the previous studies on nanofluid applications in solar systems has been reviewed and an analysis are carried out on the achievements.

2. Applications of nanofluids in solar energy

2.1. Solar collector

In solar collectors, the absorbed incident solar radiation is converted to heat. The working fluid conveys the generated heat for different applications. Solar collectors are categorized in tow types, non-concentrating and concentrating collectors [46]. Non-concentrating solar collectors are usually used for low and medium temperature applications such as space heating and cooling, water heating, and desalination. While concentrating solar collectors are exploited in high temperature applications such as electricity generation. However these systems are acquiring more and more attention, prevailing to low efficiency is still a big deal. Nanofluid has shown a good ability in enhancing the efficiency of solar systems. In this part, the research over employing nanofluid in solar collectors are reviewed.

Tyagi et al. [47] theoretically investigated the performance of a direct absorption solar collector (DAC) exploiting aluminum-water nanofluid as the absorbing medium. Fig. 1 shows the schematic of a nanofluid-based DAC of their study with glass surface on the top and completely isolated at the bottom side. They supposed a steady-state two-dimensional model for heat transfer. By using the following equation, the collector efficiency is obtained:

$$\eta=\frac{\text{useful gain}}{\text{available energy}}=\frac{\dot{m}C_p(\overline{T}_{out}-\overline{T}_{in})}{AG_t} \tag{1}$$

where $\dot{m}$ is the mass flow rate flowing through the collector, c_p is the specific heat, $\overline{T}_{in}$ and $\overline{T}_{out}$ are the mean fluid inlet and outlet temperatures respectively, A is the area of the collector and G_t is the solar flux incident on the solar collector. Fig. 2 depicts the collector efficiency versus the variation of particles size in the range of 1–20 nm. The collector efficiency increased gradually with ascendance of nanoparticle size. They attributed this to the enhancement of absorption coefficient which is directly affected by the term D^2. From Fig. 3, the augmentation of collector efficiency is obvious as the volume fraction increases. This is due to the enhanced attenuation of sunlight passes through the collector. Since the attenuation varies exponentially with volume fraction, the efficiency initially increases rapidly at low concentrations and then reaches an asymptotic value in higher concentrations more than 1%. The result revealed that, under similar