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Thermal performance enhancement of flat-plate and evacuated tube solar collectors using nanofluid: A review☆

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ABSTRACT

During the past decades, the technology to make particles in nanometer dimensions has been improved and a new kind of solid–liquid mixture, which is called a nanofluid, has appeared. Nanofluids are an advanced kind of fluid containing a small quantity of nanoparticles (usually less than 100 nm) that are uniformly and stably suspended in the liquid. The dispersion of a small amount of solid nanoparticles in conventional fluids such as water or ethylene glycol changes their thermal conductivity remarkably. Since then, nanofluids have been applied to enhance the thermal performance of many engineering systems. Recently, nanofluids have been used as heat transfer fluids to enhance the performance of solar collector devices. This paper reviews the recent progress and applications of nanofluids in flat-plate and evacuated tube solar collectors. Other than to review the efficiency of solar collectors with nanofluids, the paper also discusses the impact of nanofluids in solar collectors on economic and environmental viewpoints. Finally, the challenges and future trends in the application of nanofluids in thermal solar collectors are discussed.

Contents

1. Introduction

Currently, power generation from fossil fuels such as oil or coal is damaging our environment. For example, nuclear power stations to generate electricity are an unacceptable risk in most locations [1]. Therefore, we need to diversify away from these non-renewable energy sources and look for alternatives. Many developing countries cannot fully rely on these conventional methods as they are aware of the damaging effects of CO_2 emission and try to search for other types of green and renewable energy source. The need for a green and environmentally friendly power generation method is thus obvious and will be further expanded in the near future.

One of the most promising renewable energies available is solar energy since it is freely available, abundant and has minimum ecological impact. It is estimated that one hour of solar energy received by the earth is equal to the total amount of energy consumed by humans in one year [2]. Plants use chlorophyll to photosynthesize the sun's irradiation and provide energy for their growth. Only 14.4% of sunshine survives filtering from the earth's atmosphere and falls on land where it can be harvested. This is, however, 2800 times more than our energy needs [2].

Many research works have been reported in the literature on harvesting energy from solar. In addition, many countries have made immense researches on solar energy utilization [3–15]. Generally, there are two ways of harvesting solar energy depending on the needs: (i) solar–electric conversion (converting solar energy into electrical energy using photovoltaic solar cell or concentrated solar power) and (ii) solar–thermal conversion (converting solar energy into thermal

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energy using solar collectors) [16]. Since the first work on solar cells by Charles Fritts in the 1880s [17], with efficiencies of only 4.5%–6%, many efforts have been done to tap this priceless resource of energy [18–20].

Fig. 1 shows a schematic of a photovoltaic (PV) power system. A photovoltaic system produces direct current (DC) power which fluctuates with the sunlight's intensity. For practical use, this usually requires conversion to certain desired voltages or alternating current (AC), through the use of inverters [21].

Extensive research on PV system has been done by many researchers [22–25]. Blankenship et al. [26] gave an excellent review on the current challenges and future trends on the subject. Michael [27] made a breakthrough research by introducing dye-sensitized nanocrystalline electrochemical photovoltaic systems to replace solid-state junction devices for the conversion of solar energy into electricity. Bernard and Jean-Luc [28] reviewed on the application of low-cost, highly flexible form factors, and the light weight of organic photovoltaics to convert sunlight into electricity by employing thin films of organic semiconductors. Garg and Adhikari [29,30,31] dedicated their researches on the performance analysis of hybrid photovoltaic/thermal air heating collector. Sopian et al. [32] developed a double pass photovoltaic thermal solar collector for solar drying applications.

On the other hand, research on solar–thermal systems has attracted many investigators from all around the globe. Soteris [33] provided an extensive review on the historical development and current progress of solar collectors. Mills [34], in his review article, discussed the current technologies that are being applied in the development of single and two-axis tracking solar collectors, several kinds of low-temperature technologies such as evacuated tube collector, organic Rankine cycle turbine and solar updraft power plants. Several other important reviews relating to solar–thermal conversion are listed in Table 1 (adapted from Table 1 [35]).

A major shortcoming of the solar collectors, however, is their low thermal conversion efficiency. Traditional working fluids (water- or oil-based fluids) have low heat absorption and heat transfer capacity. Cheng et al. [47] also urged the need to improve the thermophysical properties of working fluids used in solar energy for medium and high temperatures.

Nanofluid, an advanced kind of fluid containing small quantity of nanoparticles (usually less than 100 nm), was introduced by Choi [48] and it has been proven to provide efficient heat transfer compared to conventional fluids. The dispersion of a small amount of solid nanoparticles in conventional fluids such as water or ethylene glycol changes their thermal conductivity remarkably.

Table 1
Reviews on solar–thermal conversion.

Authors	System
Soteris [33]	Solar thermal collector
Shukla et al. [36]	Solar water heaters
Ogueke et al. [37]	Solar water heating system
Jaisankar et al. [38]	Solar water heaters
Barlev et al. [39]	Concentrated collectors
Kumar and Rosen [40]	Photovoltaic–thermal collectors
Ibrahim et al. [41]	Photovoltaic–thermal collectors
Hossain et al. [42]	Solar water heaters
Chamoli et al. [43]	Double-pass solar water heaters
Tyagi et al. [44]	Solar air heating system
Shukla et al. [45]	Solar water heating system
Ho and Iverson [46]	Solar concentrating system

Thermal conductivity of nanofluids has been measured by several authors with different nanoparticle volume fractions, materials and dimensions in several base fluids. Most of the findings show that thermal conductivity of nanofluid is higher than the base fluids. Among them, Lee et al. [49] demonstrated that oxide ceramic nanofluids consisting of CuO or Al_2O_3 nanoparticles in water or ethylene-glycol exhibit enhanced thermal conductivity. For example, using Al_2O_3 nanoparticles having a mean diameter of 13 nm at 4.3% volume fraction increased the thermal conductivity of water under stationary conditions by 30% [50]. On the other hand, larger particles with an average diameter of 40 nm led an increase of less than 10% [50]. Vajjha et al. [51] investigated the thermal conductivity enhancement of three different nanofluids CuO, ZnO_2 and Al_2O_3. Also, thermal conductivity increases with increasing temperature and volume concentration. A model was proposed by Murshed et al. [52] to predict the thermal conductivity theoretically under dynamic and static processes, taking into account the effect of Brownian motion, particle size, nanolayer and particle surface. They concluded that thermal conductivity is due to both static and dynamic mechanisms. In a different study, Hong et al. [53] reported a nonlinear model of thermal conductivity enhancement of 18% at a volume fraction of 0.05 vol.% using Fe-ethylene glycol nanofluid. Eastman et al. [54] compared the thermal conductivity between Cu-ethylene glycol nanofluid and pure ethylene glycol. The result indicated 40% increase in thermal conductivity of Cu-ethylene nanofluid at a volume fraction of 0.3 vol.%. Liu et al. [55] recorded 23.8% thermal conductivity enhancement of Cu/water nanofluid using a chemical reduction method. The enhancement of thermal conductivity as reported by various researchers is presented in Table 2 (adapted from Table 1 [56]).

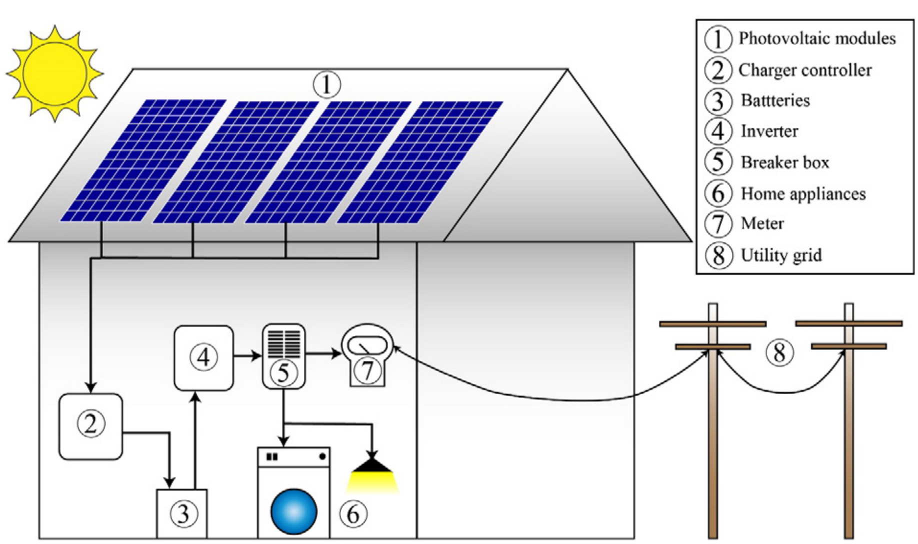

Fig. 1. Schematic of photovoltaic (PV) power system.