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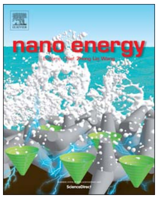

Full paper

Nanofluids effects on the evaporation rate in a solar still equipped with a heat exchanger

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ABSTRACT

In this paper, the performance of a solar still equipped with a heat exchanger using nanofluids has been studied both experimentally and theoretically through three key parameters, i.e., freshwater yield, energy efficiency and exergy efficiency. First, experiments are performed on a set-up, which is mainly composed of two flat plate solar collectors connected in series, and a solar still equipped with a heat exchanger. After heated in the collectors, the nanofluid enters the heat exchanger installed in the solar still basin to exchange heat with brackish water. The research question is to know how much the effect of nanofluids on the evaporation rate inside the solar desalination system is. The experiments are conducted for different nanoparticle volume fractions, two sizes of nanoparticles (7 and 40 nm), two depths of water in the solar still basin (4 and 8 cm), and three mass flow rates of nanofluids during various weather conditions. It is found that the weather conditions (mainly the sun radiation intensity) have a dominant influence on the solar still performance. To discover the effects of nanofluids, a mathematical model is developed and validated by experimental data at given weather conditions. The results reveal that using the heat exchanger at temperatures lower than 60 °C is not advantageous and the corresponding yield is smaller than that of solar still without the heat exchanger; although in such a case, using nanofluids as the working fluid in the heat exchanger can enhance the performance indices about 10%. At higher temperatures (e.g. 70 °C), the use of heat exchanger is beneficial; however, using nanofluids instead of water can augment the performance indices marginally i.e. just around 1%. In addition, it is found that in high temperatures using SiO_2/water nanofluids, which have a lower effective thermal conductivity than that of Cu/water nanofluids, provides higher performance indices.

1. Introduction

Nowadays, “Nano” and “Energy” have been two hot keywords, not only in the scientific community but also in our daily life. During recent decades, researchers have attempted to apply nanotechnology to various energy and power systems such as electric generators, fuel cells, batteries, and solar cells [1–5]. Nanotechnology has also been implemented to enhance the heat transfer potential of common liquids like water and oil to ameliorate the efficiency of thermal systems; this can be done through adding solid nanoparticles (particles with a size of 1–100 nm) to the liquids. The mixture of nanoparticles and conventional liquids is named “nanofluid” [6]. Despite some limitations such as relatively high preparation cost and stability issues, extensive attempts have been made to develop the applications of nanofluids in energy systems such as solar energy based devices [7–13], cooling and thermal management of electronic equipment [14,15], grinding and drilling, absorption systems, medicine, heating and cooling of buildings, domestic refrigerators, and so on [16,17].

In recent years, the problems of global warming and increase of the world population have highlighted the drinking water crisis. Although water covers more than 70% of the earth, most of this is not drinkable. Therefore, providing potable water has always been a major problem

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for governments and researchers. One of the solutions to overcome the deficiency of freshwater, especially in arid areas, is the usage of solar stills. The main advantage of solar stills is the use of solar energy, a free and clean source, as the driving force for desalination; albeit, on the other hand, their overall efficiency is relatively small. In 2012, Gnanadason et al. [18] investigated experimentally the effect of using carbon nanotubes (CNTs)-based nanofluids on the performance of a single slope solar still equipped with a vacuum pump. They concluded that adding nanofluids to the basin of solar still can enhance the efficiency up to 50%.

Kabeel et al. [19] experimentally investigated the effects of using a fan as well as adding copper oxide and aluminum oxide based nanofluids into the basin on the productivity of a conventional solar still. For a mass concentration of 0.2% and the use of a fan, it was found that using copper oxide, and aluminum oxide nanofluids increased the productivity by 134% and 125%, respectively. In an economic analysis, they concluded that the use of nanoparticles and the fan lowered the final price of one-liter drinking water compared to conventional solar stills. Kabeel et al. [20] evaluated the effect of using aluminum oxide based nanofluids and a fan with variable speeds and reported a maximum enhancement of 116% for a nanofluid volume concentration of 0.2% under the highest speed of the fan. In another work, Omara et al. [21] experimentally compared the productivity of two solar stills with different configurations. The first was a conventional single slope solar still without any modification while the structure of the second one was modified by corrugated and wick absorbers, an internal reflector, and an external condenser. In addition, copper oxide, and aluminum oxide were added into the basin of the second solar still. The authors concluded that productivity of modified solar still using copper oxide nanoparticles was nearly 285% higher than that of conventional solar still while in the case of aluminum oxide the productivity enhancement was about 255%. Elango et al. [22] prepared four different water-based nanofluids with a concentration of 0.1%, which included aluminum oxide, zinc oxide, iron oxide, and tin oxide for adding to the basin of a single slope solar still with a water depth of 1 cm. They found that nanofluids containing iron oxide had no sufficient stability to be used in the tests, so they performed experiments with the other three nanofluids. Their results indicated that the amount of productivity of solar still was directly proportional to the effective thermal conductivity of the nanofluid that was added to the basin. The maximum enhancement in solar still productivity was nearly 30%, which was obtained by aluminum oxide nanoparticles. The productivity improvement values caused by zinc oxide and tin oxide based nanofluids were 19% and 13%, respectively.

In 2016, Sahota and Tiwari [23] theoretically investigated the effect of adding alumina oxide nanoparticles on the productivity of a passive double slope solar still. The analysis was done for three different mass concentrations (i.e., 0.04%, 0.08%, and 0.12%) and two values of water mass in the basin (35 and 80 kg). They found that the productivity was increased by 12.2% and 8.4% for water masses of 35 and 80 kg, respectively. Later, Sahota and Tiwari [24] modeled a double slope solar still using three different inorganic based nanofluids including alumina oxide, titanium oxide, and copper oxide at a mass concentration of 0.25%. They found that the thermal and exergy efficiencies of the solar still were maximized by using alumina oxide. The thermal and exergy efficiencies alumina-water based solar still were approximately 13% and 9% higher than those of conventional ones, respectively. In another paper, Sharshir et al. [25] experimentally studied the effect of graphite and copper oxide micro-flakes with concentrations between 0.125% and 2% on the productivity of solar stills where the glass cover was chilled by flowing water. The depth of working fluid in the basin was changed from 0.25 to 5 cm, and the mass flow rate of cooling water running on the glass cover varied between 1 and 12 kg/h. The main conclusion of their work was that using graphite particles ameliorated the productivity about 57.6% while copper oxide particles enhanced the yield by 47.8%.

From the review of the abovementioned articles, it can be concluded that in all of them, nanoparticles were in a direct contact with water inside the solar still basin and there is no any research that investigates both experimentally and theoretically the integration of a solar still to solar collectors through a heat exchanger containing a nanofluid. The motivation behind the present research is based on some reports on the extraordinary enhancement of heat transfer rate caused by nanofluids. Here, two of these reports are mentioned briefly.

Ding et al. [26] experimentally investigated the laminar flow of CNTs/water nanofluids at very low concentrations (0.5%) in a horizontal pipe with a short length (less than 1 m). They found that the heat transfer rate was increased by 350%. In another experimental work, Xie et al. [27] studied the heat transfer of MgO based nanofluids in a pipe with constant temperature boundary condition under laminar flow. They reported an enhancement as high as 250% in the heat transfer rate for a nanoparticle volume fraction of 1% at Reynolds number of 1000.

Such an extraordinary potential of nanofluids in heat transfer enhancement encouraged us to study the effects of using nanofluids on the evaporation rate of water inside the basin of a solar still equipped with a heat exchanger. The present study aims at giving a comprehensive analysis of the influence of nanofluids on the productivity as well as the energy and exergy efficiencies of a single slope solar still equipped with a heat exchanger through experiments and mathematical modeling. The effects of various parameters including nanofluid type, concentration and size of nanoparticles, mass flow rate of working fluid, water depth in the basin, and inlet temperature to heat exchanger have been carried out in this study. In addition, a discussion has been presented for the physical reasons behind the effective parameters on the evaporation rate in the solar still.

2. Experimental set-up and procedure

2.1. Experimental materials

Fig. 1 illustrates a schematic diagram of the experimental set-up. The main parts of the set-up include two flat plate solar collectors connected in series, a single slope solar still equipped with a heat exchanger, and a tank for nanofluid supply. After being heated in the solar collectors, the nanofluid enters the heat exchanger installed inside the basin of the solar still to exchange heat with the brackish water and then returns to the nanofluid tank. The basin water evaporates due to the direct solar radiation received as well as heat added by the heat exchanger. The vapor thus created rises from the basin water surface and is condensed on the inner surface of the glass cover. Due to the slope of glass, the condensed water droplets flow towards a channel which collects fresh water. The surface area of the solar still is 0.425 m^2 (length of 85 cm and width of 50 cm), and total effective surface area of the two flat plate solar collectors is about 4.6 m^2. To have the maximum solar radiation on the solar still during the year, the glass cover slope is adjusted to be equal to the latitude of test location (King Mongkut's University of Technology Thonburi, Bangkok, Thailand), which is approximately 13°. The solar still body is made of stainless steel while the heat exchanger is fabricated from copper pipes. To minimize heat loss from the solar still body to the environment, the bottom and the side walls of the still were insulated. To measure the temperature at different points of the system (i.e., inlet and outlet of the heat exchanger, inside and outside of the solar still), T-type thermocouples with an accuracy of ± 0.1% have been used. Thermocouples are calibrated using Fluke Calibrator.

The performance of a solar still strongly depends on the temperatures of basin water and the inner surface of the glass cover. The reported value for basin water temperature (T_w) is the average of temperatures given by three thermocouples inserted in different locations of the basin. Additionally, the inner surface temperature of the glass cover is estimated by measurements of the ambient tempera-