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Thermal performance of a thermosyphon heat pipe evacuated tube solar collector using silver-water nanofluid for commercial applications

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ABSTRACT

An experimental study was performed to determine the thermal efficiency of thermosyphon heat pipe (THP) evacuated tube solar collector using silver-water nanofluid for commercial applications. Firstly, the synthesis of silver-water nanofluid was carried out which can maintain its long-term stability. The identification of nanofluid was determined by X-ray diffraction, scanning electron microscopy, UV–visible spectroscopy and thermophysical analysis. Secondly, the heat transfer properties of cylindrical copper THPs charged with silver-water nanofluid and pure water was investigated experimentally. Experiments of THP charged with silver-water nanofluid were repeated four times at intervals of two weeks in order to observe changes in the performance of THP. It was observed that the THP charged with silver-water nanofluid maintained its improved heat transfer characteristic in the THP experiments. Nanofluid working fluid increased the efficiency of solar collector between 20.7% and 40% compared with the pure water. In conclusion, the experimental results show the use of silver-water nanofluid provides a significant improvement in the THP evacuated tube solar collector.

1. Introduction

Demands of energy increase day by day all over the world. Clean, sustainable and renewable alternative energy sources are needed to provide this increasing demand due to the harmful effects of fossil fuels. Undoubtedly the solar energy is one of the most important alternative energy sources. Solar energy is converted into heat and electricity by using various technologies. Among these technologies, an evacuated tube solar collector (ETSC) converts solar energy to heat energy. There are two types of ETSC. These are flat-plate solar collector and thermosyphon heat pipe evacuated tube solar collectors (THP-ETSC) [1–5]. THP-ETSC consists of the THP and vacuum tube. Vacuum tube is made of two concentric glass tubes. Due to the vacuum between two tubes, the thermal losses on conduction and convection are reduced to the minimum level [6–9]. This situation raises considerably the efficiency of ETSC systems during the winter months [9–12]. The outer surface of inner tube is coated with a selective material to convert absorbing solar radiation into heat energy. The selective material also reduces the radiation heat loss. Moreover, the roundness of vacuum tubes ensures that solar radiations are always taken vertically during the day, which contributes to the yield of solar collector. The absorbed heat energy on the selective surface is transferred to the evaporator section of THP in the vacuum tube.

The THP is a closed passive heat transfer device that vacuumed and charged with working fluid. The condenser, adiabatic and evaporator are three basic sections of THP. The working fluid receives the heat from evaporator section then evaporates and then reaches to the condenser section. The evaporated working fluid condenses by releasing the heat to the condenser section. The condensed fluid returns to the evaporator section, and also the cycle is completed and repeated. Generally, the gravity and capillary forces are used to transport the condensed fluid to the evaporator section. In this way a few working fluids can transfer large amount of heat by the phase change characteristic of working fluid.

The conventional fluids used in HP-ETSC have poor heat transfer coefficients, thermal conductivity and critical heat fluxes [13–15]. The thermal properties of conventional working fluids were developed by dispersing metal and metal oxide nanoparticles into these fluids [16–18]. Moreover, nanofluids increase the heat

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transfer because nanofluids have the turbulence effect of Brownian motion of nanoparticles and modify the solid-liquid contact angle, the surface roughness of heater [19–21]. Thus, nanofluids, new type of a fluid, replaced with traditional fluids in solar collectors [5,22]. Experimental investigations on the use of nanofluids in solar collectors carried out by many researchers [5,22–26].

Liu et al. investigated the thermal performance of open thermosyphon using nanofluid for evacuated tubular high temperature air solar collector [27]. CuO-water nanofluid with an average particle size of 50 nm was prepared by the two-step method. It was observed that the efficiency of the system using the nanofluid and the air outlet temperature were higher than the system using pure water. The air outlet temperature in the system using the nanofluid exceeded 170 °C at the volumetric flow rate of 7.6 m^3/h in winter.

Iranmanesh et al. performed the thermal performance experiments of ETSC using graphene nanoplatelets (GNP)-water nanofluids [28]. GNP-water nanofluids were synthesized with two step method at the mass concentrations of 0.025%, 0.05%, 0.075% and 0.1% without surfactant. All of the produced nanofluids remained stable for three months. ETSC consisted of 12 vacuum tubes with a length of 1.8 m. The THPs were attached to the absorber plate placed in the glass tube. The solar collector thermal efficiencies were examined at the volumetric flow rates of 0.5, 1, 1.5 L/min. It was recorded the inlet-outlet temperature difference of collector increased by the increasing nanofluids concentration. Also, the researchers emphasized that collector efficiency was directly related to the concentration of nanofluids and increased with the increasing concentration. The highest thermal efficiency was found as 90.7% in the ETSC using nanofluid with mass concentration of 0.1% at a volumetric flow rate of 1.5 L/min. It was recorded that the increase in the thermal efficiency was 35.8% at the same volumetric flow rate compared to ETSC using pure water.

Sabiha et al. experimentally investigated the thermal performance of ETSC using the single walled carbon nanotubes (CNT) nanofluids [9]. CNT-water nanofluid was produced with a two-step method by using Sodium Dodecyl Sulfate (SDS) surfactant at the volumetric concentration of 0.05%, 0.1% and 0.2%. As the mass flow rate of cooling water increased, the thermal efficiency increased in all the ETSC using both pure water and nanofluids. The highest thermal efficiency was observed in the ETSC using the nanofluid with volumetric concentration of 0.2%. Additionally, the efficiencies of ETSCs using nanofluid with volumetric concentration of 0.05%, 0.1% were higher than of ETSC using water.

Ghaderian and Sidik examined experimentally effect of Al_2O_3-water nanofluid on the efficiency of ETSC [4]. Al_2O_3-water nanofluids were synthesized at the volumetric concentration of 0.03% and 0.06% by dispersing Al_2O_3 nanoparticles having an average particle size of 40 nm in distilled water by two step method. Triton X-100 was used as surfactant. All-glass passive circulation ETSC was used in the experiments and ETSC occurred from 18 vacuum tubes. Efficiencies of ETSCs using nanofluid were found higher than ETSC using water. Efficiencies at the mass flow rates of 20, 40, and 60 L/h were respectively 13.95%, 17.51%, and 22.85% for ETSC using water; 24.64%, 32.72%, and 39.52% for ETSC using 0.03 vol% Al_2O_3 nanofluid; 30.07%, 45.13%, and 58.65% for ETSC using 0.06 vol% Al_2O_3 nanofluid.

Mahendran et al. carried out the thermal performance experiments of ETSC using water-based titanium oxide nanofluid [29]. Titanium oxide nanopowder dispersion with an average particle size of 30–50 nm was used for nanofluid synthesis. 0.3 vol% TiO_2-water nanofluid produced by diluting TiO_2 nanopowder dispersion. The inlet/outlet temperature difference of ETSC using TiO_2-water nanofluid was more than ETSC using water. It was reported that the maximum outlet temperature of ETSC using TiO_2-water nanofluid is 19% higher than ETSC using water and ETSC using TiO_2-water nanofluid was 8% more efficient than ETSC using water.

Moghadam et al. studied experimentally effects of CuO-water nanofluid on the efficiency of flat-plate solar collectors [30]. Black CuO nanoparticles used in nanofluid synthesis were approximately 40 nm in diameter and spherical shape. CuO-water nanofluid was synthesized at the volume concentration of 0.4% to avoid sedimentation and instability of the nanofluid. Thermal efficiency tests of flat plate solar collector were performed at the mass flow rates of 1, 2 and 3 kg/min. At all mass flow rates, the thermal efficiency of flat-plate solar collector using nanofluid was found to be higher than that of the flat-plate solar collector using water. The flat-plate solar collector using nanofluid exhibited a thermal efficiency enhancement of 16.7% compared to the flat-plate solar collector using water.

Said et al. used two methods to synthesize a more stable TiO_2-water nanofluid [31]. They used polyethylene glycol 400 as a dispersant at the first method. High pressure homogenizer was used to disperse the nanoparticles in the base fluid at the second method. The fabricated TiO_2-water nanofluids were utilized in the flat-plate solar collector. It was noted that the energy and exergy efficiency of the flat-plate solar collector using nanofluid was higher than that of the flat-plate solar collector using water. In their other research they carried out energy and exergy analysis of a flat plate solar collector using pH treated Al_2O_3-water nanofluid [32]. It was emphasized that the most stable Al_2O_3-water nanofluid has pH value of 9. Moreover it was noted that the thermal efficiency of the solar collector was 50% higher than the similar collectors in the literature.

Chougule et al. experimentally investigated effects of the collector tilt angle and the nanofluid concentration on the thermal performance of two phase thermosyphon flat-plate solar collectors using CNT-water nanofluid [33]. CNT were possessed of the particle size of 10–12 nm and the length of 0.1–10 μm. It was emphasized that the collector thermal efficiency increased with the increasing nanofluid concentration, decreased when the CNT concentration exceeds 0.6% and increased up to a certain value with increasing tilt angle.

Kim et al. studied the effects of particle size and Al_2O_3-water nanofluid concentration on the thermal performance of U-tube solar collector [34]. It was emphasized that the thermal performance of solar collectors increased with decreasing particle size and the highest thermal efficiency among nanofluids with the volume concentrations of 0.5%, 1% and 1.5% belonged to the U-tube solar collector using 1 vol% Al_2O_3-water nanofluid.

When studies in the literature are examined, studies on the THP using nanofluid are a short time [35–43]. In other words, it is not specified how long after the nanofluid synthesis were the THP tests performed. At the same time, the THP tests do not depend on time. In this present study, the characterization of nanofluid was performed after one year from the nanofluid synthesis and it was examined the change in the structural and thermophysical properties of nanofluid. In addition, the time dependence of heat transfer enhancement mechanism of THP was investigated by repeated THP tests at intervals of two weeks.

2. Experimental setup and procedure

2.1. Preparation of nanofluid

In the experiments, an optimum concentration was determined to maintain long-term stability of the synthesized nanofluid, without sedimentation and agglomeration. Only silver-water nanofluid was prepared at the concentration of 20 ppm. The silver-water nanofluid was synthesized by a two-step electrochemical method. In the first stage, silver ions were dispersed in