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Performance of copper oxide/water nanofluid in a flat plate solar water heater under natural and forced circulations

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ABSTRACT

Flat plate solar water heater is widely used for heating of water in low-temperature residential applications. In this paper, Copper Oxide/water (CuO/H_2O) nanofluid is prepared from Copper Acetate and its thermal performance was investigated experimentally on a 100 Liters per Day (LPD) thermosyphon based indirect-type flat plate solar water heater. The volumetric fraction of CuO/water nanofluid chosen was 0.05%. Significant improvement in performance was observed in thermosyphon circulation compared to forced circulation, for the low volumetric fraction considered. The CuO/water nanofluid was prepared with the inclusion of surfactant Sodium Dodecyl Benzene Sulfonate (SDBS), as it provided the best CuO nanoparticle dispersion stability compared to pure water suspension and Triton X-100 surfactant suspensions. Also, the thermophysical properties of the synthesized nanoparticle and prepared nanofluid were compared theoretically and experimentally.

1. Introduction

Solar water heater is being used worldwide for low temperature applications mostly in the domestic sector for washing clothes and bathing purposes. Thermosyphon flat plate solar water heater is a solar passive system, which can produce hot water in the temperature range of 60–90 °C. Closed loop or heat-exchanger type or Indirect type solar water heater are used in which a primary fluid namely pure water or glycol–water mixture is added, to prevent the formation of scaling on the inner surface of the copper tubes due to passage of high saline water and to prevent damage to tubes due to water freezing in cold climates. Due to low thermal conductivity of water and the heat exchanger effectiveness, the temperature attained by the secondary fluid is reduced. In order to increase the outlet useful temperature and thermal efficiency, nanoparticles having high thermal properties are mixed with the primary fluid to form nanofluids, thereby increasing the effective thermal conductivity of the primary solution.

The effect of nanofluids in several industrial and residential applications was experimentally and theoretically analyzed by several researchers all over the world. The thermal performance using nanofluids depends on several thermophysical properties of nanoparticle such as particle diameter, shape and the pH, viscosity, thermal conductivity, volume fraction, specific heat of nanofluid. Different theories were established to understand the behavior of nanoparticle under temperature, pH, sonication etc. Theoretical analyses on the heat transfer coefficient based on the effect of particle size, extinction coefficient [1], Brownian motion and Thermophoresis were developed [2]. Consequently, a method to measure the thermal diffusivity and thermal conductivity of nanofluids based on the temperature oscillation technique was also developed [3]. The heat transfer coefficient, outlet temperature and entropy generation among four different nanofluids such as Cu/water, Al_2O_3/water, TiO_2/water and SiO_2/water provided interesting results about the effect of Nusselt number, Bejan number, density, heat capacity and efficiency on the performance of a solar collector [4]. Similarly, a theoretical study on the performance of Al_2O_3/water nanofluid in a flat plate solar water heater was analyzed for different particle sizes and volume fractions [5]; also the effect of Prandtl number on flow and heat transfer was analyzed using FEM method [6]. Experimentally, 15 nm particle size, 0.2% weight fraction Al_2O_3/water nanofluid with Triton X100 surfactant produced a 28.3% [7] and 30% [8] enhancement in thermal efficiency in a flat plate solar water heater. Different thermophysical properties of Al_2O_3 [9] and TiO_2 nanofluid were measured for various temperatures and volume fractions and concluded that low volume fraction nanofluid performed better [10]. The thermal performance of a natural circulation system using Al_2O_3/water nanofluid was tested for 0.5% and 3% volume fractions [11], and a similar enhanced thermal performance up to 22% and 62% were obtained in the evaporator and condenser sections

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respectively [12]. The photoconductive and photothermal CuO nanoparticle [13] of 4% concentration, when mixed with water has impoved the thermal conductivity by 20% [6]. Similarly, a 40 nm particle size, 0.4% volume fraction CuO/water nanofluid found a 21.8% collector efficiency improvement between 1 and 3 kg/min flow rate [14]. Also, a 25.6% improvement was observed for 0.0083 kg/s mass flow rate and 0.1% weight fraction [15]. A compound parabolic evacuated tube air collector using CuO/water nanofluid in thermosyphon mode provided outlet air temperatures above 170 °C [16]. The effect of Cu/glycol nanofluid was tested for various volume fractions and Reynolds number experimentally [17] and analyzed theoretically using FEM analysis [18]. Also, a 23.83% thermal enhancement was observed using Cu/water nanofluid at 0.1% weight fraction and 140 L/h flow rate [19]. Enhanced thermal conductivity up to 32% was obtained in a direct absorber solar collector by adding 150 ppm carbon nanotubes in water [20]. SWCNT/water nanofluid produced a 15.33% increase in heat transfer coefficient with a 4.34% reduction in entropy generation [21]. MWCNT nanofluid of 0.2% weight fraction produced improved performance using Triton X-100 as the surfactant [22]. Another surfactant namely Sodium Dodecyl Sulfate (SDS) also performed as a suitable surfactant for CNT based nanofluids [23]. It was observed that decreasing the pH with respect to isoelectric point helped in producing higher efficiency [24]. An optimum volume fraction and tilt angle for enhanced heat transfer rate using CNT/water nanofluid was analyzed for a solar collector using FEM analysis [25]. Improved electrical and thermal performance of a solar photovoltaic thermal (PV/T) system was observed by the use of silica/water nanofluid [26]. TiO_2/water nanofluid with twisted tape inserts in a solar collector enhanced the thermal performance up to 1.59 times at 0.21% volume fraction [27]. The efficiency, size, cost, savings, payback period and environmental impact of a solar collector were estimated for different nanofluids [28], also it was calculated that nanofluid reduces the embodied energy and carbon emission by approximately 9% and 3% respectively [29]. A review on the performance of solar collector using nanofluids [30], nanofluid applications in different types of solar collectors, photovoltaic systems, solar thermoelectrics, thermal energy storage systems [31], solar water heaters, solar stills, solar PV/T systems, solar ponds [32], industrial and transport applications [33] were presented.

As per the literature survey, a fascinating amount of research papers are available regarding solar water heaters. Most of the research papers are devoted to thermosyphon or forced circulations. However, as per the authors knowledge, no journal paper was available focusing on the performance comparison of thermosyphon and forced circulation modes in a single system. In this paper, a flat-plate solar water heating system was tested in natural and forced circulations. However, the quantity of research involved in the application of nanofluids in solar water heaters is still in the nascent stage. Many researchers have experimented solar water heater using nanofluids based on Al_2O_3 and CNT nanoparticles for their high thermal conductivity and low density. In this paper, the performance of solar water heater using the common heat transfer fluid, water was compared to a 0.05% volume fraction CuO/water nanofluid. The CuO/water nanofluid was prepared inhouse from commercially available raw materials and their nanocharacterization tests were also presented.

2. Methodology

The experiment was conducted by synthesizing the CuO nanoparticle, preparing the CuO/water nanofluid and comparing the performance of the prepared CuO/water nanofluid with water in a commercially available 100 LPD thermosyphon indirect type flat plate solar water heater.

2.1. Synthesis of CuO nanoparticles

The volume of the primary working fluid in the 100 LPD indirect type flat plate solar water heater was measured as 8 L. The quantity of nanoparticles required to prepare a 0.05% volume concentration of CuO–water nanofluid was calculated to be 25.3 g. Due to the high cost of commercially available nanoparticles, it was synthesised locally from Copper Acetate by a simple method called Aqueous Precipitation method. Analytical grade Copper Acetate Monohydrate ($Cu(CH_3COO)_2H_2O$) as the precursor and glacial Acetic acid (CH_3COOH) to prevent hydrolysis, are taken in a flat-bottomed glass beaker, and heated with constant stirring in a magnetic stirrer. Sodium Hydroxide (NaOH) pellets as stabilizing agents were added slowly till the pH of the solution reaches between 6 and 7, and the color of the solution slowly turns from blue to black as shown in Fig. 1. The solution is removed from the magnetic stirrer and cooled to room temperature. The black precipitate formed is centrifuged, and then washed with distilled water three times to remove the impure ions. It is then covered with aluminum foil and placed in a hot air oven to completely dry the contents. The dried precipitate is finely powdered, using Agate mortar to produce CuO solid particles in nano dimensions.

2.2. Preparing the nanofluid

The high density (6310 kg/m^3) of the CuO nanoparticles compared to the basefluid, water (1000 kg/m^3), causes the immediate settlement of the CuO nanoparticles at the bottom of the beaker. Hence, a compatible amphiphilic surfactant, namely, Sodium Dodecyl Benzene Sulfonate (SDBS) of 10% weight of the amount of nanoparticles to be added, was first dispersed completely in double distilled water using a magnetic stirrer, and then CuO nanoparticles of the required quantity are slowly added with constant stirring for 30 min. The solution is further sonicated using an ultrasonicator for 60 min to break the agglomerated particles and facilitate a homogeneous mixture of the CuO nanoparticles and water, called CuO/water nanofluid.

The CuO nanoparticles' stability was checked with SDBS surfactant, with Triton X-100 surfactant and without any surfactant. In Fig. 2, the dispersibility of nanoparticles with the SDBS surfactant in water, compared to without-surfactant water after 24 h, clearly shows the stability of the nanoparticles using the surfactant. Similarly, the CuO/water nanofluid showed better stability with the SDBS surfactant, compared to the Triton X-100 surfactant after 3 days. Therefore, it was concluded that the SDBS surfactant performed better compared to the Triton X-100 surfactant for CuO/water nanofluid.

2.3. Description of the system

A 100 LPD thermosyphon based ladder type heat exchanger type solar water heater was used in the study. The detailed specification of the solar water heater is listed in Table 1.

The flat plate collector was tilted at an angle of 13° corresponding to the latitude of the location and facing south, since Chennai is located in the Northern hemisphere. The temperature of the different locations was measured, using PT-100 RTD sensors. The solar radiation was measured on the plane of the solar collector using a pyranometer (Hukseflux LP02); the ambient temperature and the wind speed were measured using a weather station (WatchDog 2000). All the sensors were connected to a data acquisition system (Agilent 34970A), and recorded every 5 min continuously and plotted in graphs. A booster pump and a rotameter were used during forced circulation testing. The complete experimental setup and the schematic diagram of the solar water heating system are shown in Fig. 3.