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A new application of carbon nanotubes nanofluid as working fluid of low-temperature direct absorption solar collector

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ABSTRACT

Nanofluids are found to have good stability and useful optical and thermal properties as direct sunlight absorbers in solar collectors. The inherent hydrophobic nature of carbon nanotubes was overcome using a new dispersion procedure (treating carbon nanotubes with base media) to prepare nanofluids. To the authors' knowledge, this is the first application of aqueous suspension based on alkaline functionalized carbon nanotubes as an absorber fluid in a sunlight harvesting device. Dispersion stability and optical properties of the nanofluid were estimated. Spectral absorbance analysis confirms the relative stability of prepared nanofluids versus sediment time. The extinction coefficient of aqueous suspensions of functionalized carbon nanotubes shows remarkable improvement compared to the base fluid even at low particle loadings. We also demonstrate thermal conductivity improvements of up to 32% by adding only 150 ppm functionalized carbon nanotubes to water as the absorbing medium. Their promising optical and thermal properties, together with the appropriate stability of nanofluids, make them very interesting for increasing the overall efficiency of low-temperature direct absorption solar collectors.

1. Introduction

Solar collector is one of the most important renewable energy technologies for converting sunlight into useful energy. During the last two decades, the worldwide research in the field of solar energy has focused on the methods to efficiency enhancement of the solar collection and conversion systems.

Direct Absorption Solar Collectors (DASC) is one of the noteworthy outcomes of these researches which have been initially proposed by Minardi and Chaung [1]. They developed a direct collector that absorbed solar radiation by the black fluid (water with 3.0 g/l, India ink).

Abdelrahman et al. studied direct absorption of concentrated solar radiation by suspension of solid micro-particles in gas [2]. Results show that the absorbed fraction of solar radiation is significantly dependent on the particle size and concentration in suspension. Another configuration for DASC as a “volume heat-trap” solar collector is a “fine-particle semitransparent liquid suspension” (FPSS) which was used as a heat storage fluid [3].

For the first time, the effect of using nanofluids (aluminum/water) was investigated as the working fluid to increase the efficiency of low-temperature DASC [4]. The efficiency enhancement of 10% was obtained using nanofluid-based DASC in comparison with a conventional flat-plate collector. By introducing nanofluids as direct absorber of sunlight in solar collectors, their stability and optical properties as well as their thermal properties are of great concern.

One of the most important issues for a two-phase system such as nanofluid is the stability. The agglomeration of nanoparticles results in not only the settlement and clogging of channels and pump failure which reduces system lifetime but also the decreasing of thermal conductivity of nanofluids. On the other hand, sedimentation of nanoparticles in suspension leads to transparency of the working fluid particularly at the top layers of DASC (near transparent surface) in which the maximum attenuation in the solar spectral intensity occurs [4]. This results in sunlight absorption reduction within the nanofluid which causes the decrease in collector efficiency. Therefore, the investigation on stability is also a key issue that influences the properties of nanofluids for DASCs [5]. Stability of nanofluids was studied with the UV–vis spectrophotometer [6–8]. The results demonstrated that the stability of nanofluids was strongly affected by the characteristics of the suspended particles such as particle morphology and the base fluid [6].

Another important parameter which affects the performance of solar heating systems is the thermal conductivity of working fluid. Recent literature suggests that the significant improvement in the thermal properties of a bulk fluid can be achieved by NPs [9–12]. The thermal conductivity enhancement of base fluids was investigated using carbon nanotube (CNT) [13].

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CNTs which behave most similarly to a black body are the best NPs for DASC due to higher absorption coefficient [14]. But the main problem is that CNTs are hydrophobic and unstable in the polar fluids under normal conditions [15,16]. Adding surfactant to the suspension as a dispersion method may enlarge the thermal resistance and limits the enhancement of the effective thermal conductivity [17–19]. For this reason, it should be noted that the surfactant method cannot be a suitable choice for preparing working fluid of DASC. Therefore, chemical functionalization of CNTs is the best method for dispersion [15,20,21].

The objective of this study is to characterize the dispersion stability, optical properties and thermal conductivity of CNT suspension in water for application in low-temperature DASC. Due to the inherent hydrophobic nature of CNTs, a new dispersion procedure (treating CNTs at alkaline media) has been used to prepare nanofluids. To the author's knowledge, aqueous suspension based on alkaline functionalized CNT (f-CNT) have not been applied to date as an absorber fluid in a sunlight harvesting device.

2. Experimental procedures and apparatus

2.1. Material and nanofluid preparation

Distilled water and CNT (MWNT-10 nm in diameter and 5–10 μm in length) were used to produce nanofluids and provided by Research Institute of Petroleum Industry of Iran (RIPI) [22]. CNTs were polarized by chemical base treatment with carboxylate functional groups [23]. Because of hydrophilic nature of carboxylate groups, a better dispersion of CNTs in water can be obtained, without using any surfactants. H_2O_2, Potassium persulfate ($K_2S_2O_8$) and Potassium hydroxide (KOH) granules were from Merck KGaA (Darmstadt, Germany).

In this study, f-CNT was added to water to fabricate nanofluids based on a two-step method. Then the mixture stirred well and placed in the ultrasonic bath for 30 min at ambient temperature. An Ultrasonic instrument (Branson Ultrasonics Corporation) was used as a high power sonication to disperse the f-CNTs into water. Since in the volume fractions more than 150 ppm of f-CNT in water, color of the solution becomes completely black and light is not able to pass through it, so the samples have synthesized at the volume fractions less than 150 ppm. Therefore, seven ranges volume fractions (S1: 0 (distilled water), S2: 5, S3: 10, S4: 25, S5: 50, S6: 100 and S7: 150 ppm) were selected.

2.2. Characterization method

The morphological characterization of f-CNTs was obtained using scanning electron microscopy (SEM) at 20 kV. The morphological characterization of the synthesized f-CNT was obtained using SEM which is shown in Fig. 1. SEM observations (Fig. 1) reveal that the CNTs with basic treatment are not aggregated. Since CNTs are functionalized and according to Fig. 1, f-CNTs have been separately with respect to each other, then these can cause formation of hydrogen bonds between f-CNTs and water; so a stable suspension can be form.

In this paper, the stability of the nanofluids was characterized by using UV–vis–NIR spectrophotometer (Perkin-Elmer Lambda 1050). It works on the principle of Beer–Lamberts law (i.e., absorption of the solution is directly proportional to the solution volume fraction).

Optical transmittance spectra have been measured using a double-beam spectrophotometer (Perkin-Elmer Lambda 1050). The effect of multiple reflections at the interfaces between air, glass and fluid is assumed to be negligible. Effective medium theory shows that this assumption is valid for small volume fractions [25], as was the case in this paper. A 10 mm quartz cuvette was filled with the f-CNT nanofluid. In filling the cuvettes, care was taken to avoid bubbles. Each measurement was repeated for three times to achieve the best precision [24]. The thermal conductivity was measured using a KD2 Pro thermal properties analyzer (Decagon devices, Inc., USA) based on transient hot-wire technique [26] widely employed to measure thermal conductivity of nanofluids [27,28].

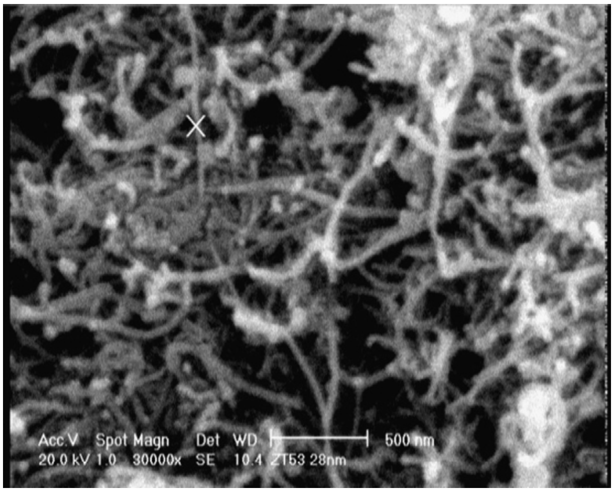

Fig. 1. SEM image of f-CNT.

A number of studies have reported the positive effect of temperature on the thermal conductivity of nanofluids [26]. In order to study the effect of temperature, a thermostat bath was used, which meets the standards of ASTM D5334 [29] at temperature range of 10–60 °C. The enhancement in thermal conductivity of the samples was calculated the variation of nanofluids effective thermal conductivity (K_{eff}), using the relation $K_{eff}=K_n/K_f$ where K_f and K_n are the sample and base fluid thermal conductivity, respectively.

3. Results and discussion

3.1. Stability of the nanofluids

The stability of the samples was studied first because of its importance. The procedure of nanofluid preparation assured stability of dispersion at least after a month of preparation. Fig. 2 shows the peak absorbance of the samples around the range of 283 nm.

According to Fig. 3, a linear relation is obtained between the volume fraction of the samples and the absorbance of suspended particles. From this relation, the relative stability of nanofluids can be estimated with sediment time. Absorption variations of the samples (S2 to S5) versus time were measured for more precise consideration and the results were shown in Table 1. It should be mentioned that the samples S6 and S7 are completely opaque in the UV region and their spectra do not show any peaks in this region.

Based on Table 1, it can be concluded that the absorption of f-CNTs changes slightly with increasing sediment time. The maximum difference between values is about 0.038 which could be due to the instrument error. With these results, long term stability of dispersions is assured at least after a month of the preparation.

3.2. Optical properties variations vs. volume fraction

The overall transmittance spectra of the samples with respect to the air were shown in Fig. 4. They represent the spectral transmittance of the whole system built by NPs and base fluid.