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Research Paper

Photo-thermal conversion characteristics of MWCNT-H_2O nanofluids for direct solar thermal energy absorption applications

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HIGHLIGHTS

- Heating and light-irradiation cycling tests were performed on MWCNT-H_2O nanofluids.
- Heat treatment improved the photo-absorption capability of MWCNT-H_2O nanofluids.
- The extinction coefficient increased linearly with the MWCNT concentration at a wavelength range of 500–900 nm.
- A temperature increase of 22.7% was achieved for the 0.01 wt% nanofluid as compared with DI water.

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ABSTRACT

Stable water-based multi-walled carbon nanotube (MWCNT) nanofluids with mass fractions ranging from 0.0015% to 0.1% were prepared. To investigate the photo-absorption properties and photo-thermal conversion performance of MWCNT-H_2O nanofluids, heating and light-irradiation cycling tests were experimentally performed at temperatures below 90 °C. Heat treatment is beneficial to improve the optical absorption capability of MWCNT-H_2O nanofluids, and there existed an optimal concentration of about 0.01 wt% with respect to the spectral transmittance and extinction coefficient. Extinction coefficients of MWCNT-H_2O nanofluids increased linearly with the MWCNT concentration in a range of 0–0.01 wt% at wavelengths of 500–900 nm. Compared to DI water, the temperature of MWCNT-H_2O nanofluid at the optimal mass fraction of 0.01% was increased by about 14.8 °C (or 22.7%) after a light irradiation time of 45 min. The photo-thermal conversion performance was enhanced with increasing the light irradiation cycle at appropriate concentrations of nanofluid, and the probable mechanism caused by the CNT-fiber agglomeration was qualitatively analyzed. The receiver efficiency decreased with increasing the light irradiation time, and the highest value was up to 96.4% at 0.01% mass fraction. The prospects for possible applications of MWCNT-H_2O nanofluids in low-temperature direct solar thermal energy absorption were presented.

1. Introduction

Due to the renewable and environment-friendly nature, solar energy is widely applied in diverse areas such as photovoltaic electricity generation, artificial photosynthesis, and solar thermal conversion. The latter is considered as the most efficient form of solar energy harvesting [1], among which the surface-based "flat-plate" solar thermal collector is a typical and cost-effective type, but suffers from relatively low efficiency and outlet temperature [2]. Therefore, a new approach, the so-called direct absorption solar collector (DASC) [3], has been proposed to minimize the heat loss and then enhance the thermal efficiency of flat-plate collectors while simplifying the system via directly absorb solar radiation within fluid volume.

The concept of DASC was first introduced by Minardi and Chaung [4] in 1975. They developed a direct solar collector that absorbed solar radiation by black India inks, however this aqueous suspension has an inherent deficiency of light- and temperature-induced instability or degradation. To replace inks or other organic dyes, nanofluids of nanometer-sized particles or fibers suspended in fluids were selected to function as absorbing mediums. Traditionally, the nanofluid is considered as a route for surpassing the performance of heat transfer liquids currently available [5], especially focused on the anomalous increase of thermal conductivity [6]. Nanofluids are also endowed with the potential to significantly improve photo-absorption and scattering properties of liquids, enabling them a promising alternative for direct solar thermal

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Nomenclature

A_{top}	top surface area (m^2)
c	concentration ($mol\ L^{-1}$)
C	specific heat ($kJ\ kg^{-1}\ K^{-1}$)
G	solar flux incident ($W\ m^{-2}$)
K	extinction coefficient (cm^{-1})
l	optical-path length (cm)
m	mass (kg)
t	time (s)
T	temperature (K)
$T(\lambda)$	spectral transmittance (%)
Greek symbols	
λ	wavelength (nm)
ξ	receiver efficiency
Subscripts	
nf	nanofluid
w	water
Abbreviations	
DASC	direct absorption solar collector
DI	deionized
MWCNT	multi-walled carbon nanotube

energy absorption applications, and thus received a continuing and growing interest recent years [7–9].

As compared to conventional applications in the heat transfer community, the concentration of nano-materials required for solar collectors is only about one or two orders of magnitude lower and quantities on the scale of mg/L or tens of ppm, however the tiny amount of nano-additives can improve the optical absorption properties profoundly over the solar spectrum at relatively short penetration distances. Taylor et al. [10] obtained extinction coefficients of nanofluids and found that over 95% of incoming sunlight could be absorbed with extremely low nanoparticle volume fractions (less than 10 ppm). Theoretically, the nanofluid-based low-temperature DASC exhibited an enhancement of about 10% in efficiency compared with surface-based collectors [3,11]. Furthermore, the concentration of nanoparticles can be easily controlled and thus enable the incident radiation being well-absorbed over the entire volume of nanofluids instead of over a thin surface layer (about 1 cm), limiting heat losses to the ambiance. Lee and Jang [12] showed that the solar irradiation energy can be completely absorbed in a penetration depth of 10 cm using water-based multi-wall carbon nanotube (MWCNT) nanofluids with a volume fraction of 0.0005%. Hence, the desirable optical and thermal properties of nanofluids render them highly appealing for use in solar thermal collectors.

To data various nano-materials, including metal, oxide, carbon materials, etc., were utilized for DASCs, and conventional host fluids mainly include water, ethylene glycol (EG), and heat transfer oil [13]. As a unique one-dimensional nano-material, MWCNTs have recently attracted considerable attention for DASCs because of their extremely high capability of absorbing solar spectrum and acceptable stability [14–16]. The light absorption properties of Cu-H_2O, Co-H_2O, and MWCNT-H_2O nanofluids were experimentally tested and compared by He [17], and demonstrated that the MWCNT-H_2O nanofluid, work as an absorbing medium, has the lowest spectral transmittance. Similar results were obtained by Gan and Qiao [18] according to the comparison of optical absorption capability among ethanol-based MWCNTs, aluminum- and carbon-nanoparticles at a small mass fraction of 0.1%. They found that the ethanol-based MWCNT nanofluid provided high scattering coefficient and hence more solar energy was absorbed by it. Meng et al. [15] have investigated photo-thermal properties using MWCNT-EG nanofluid as a medium with oxidation treatment by HNO_3. Strong optical absorption of MWCNT glycol nanofluids was detected in a wavelength range of 200–2500 nm. An enhancement of 18% in the photo-thermal conversion efficiency at 0.5% mass fraction was achieved with respect to pure EG. Delfani et al. [19] investigated the performance characteristics of MWCNTs, both numerically and experimentally, in a binary mixture of water and EG (70%: 30% in volume), and confirmed that the addition of MWCNTs improved the collector efficiency by 10–29% than the base fluid. Besides, the collector efficiency increased with the increase of nanofluid volume fraction and flow rate. Recently, aqueous suspension of MWCNTs after the alkaline functionalization treatment was utilized for a DASC [14]. The addition of 150 ppm f-CNTs contributed to a significant increase of extinction coefficient of pure water by about 4.1 cm^{-1}. Consequently, MWCNT nanofluids are considered likely to play a central role in developing nanofluid-based solar thermal collectors.

The introduction of MWCNT nanofluids into DASCs is now still mainly focused on the low-temperature range (below 100 °C). One of the major problems for MWCNT applications in low-temperature DASCs is the suspension instability and performance degradation at elevated temperature. Therefore, a number of physical and chemical methods have been developed to overcome the inherent hydrophobic nature of MWCNTs to achieve stable dispersion as summarized by Yazid et al. [20]. Among all these methods, the addition of surfactants remains an important solution and is considered as a common but easy-handling, time-saving and cost-effective choice for mass production. Such systems require understanding more than optical properties merely at room temperature, but also the underlying impact of repeated-heating induced possible agglomeration and sedimentation due to solar radiation, as well as the resultant changes of optical and photo-thermal properties.

In this study, water-based MWCNT nanofluids were prepared using the two-step method. Transmittances of MWCNT-H_2O nanofluids in the solar energy wavelength range of 200–2000 nm were experimentally tested after the treatment via heating cycling, and consequently extinction coefficients of nanofluids were obtained. In addition, effects of concentration and light-irradiation cycling on the photo-thermal conversion performance of nanofluids were tested and discussed, and the receiver efficiency was presented. This study largely proves the performance stability of water-based MWCNT nanofluids after repeated utilization, making them a viable solution as the absorber in low-temperature DASCs.

2. Experimental

For the present study, stable water-based MWCNT nanofluids at different concentrations were prepared for the photo-thermal conversion experiment. To characterize the MWCNT-H_2O nanofluids, the transmission spectrum was provided to indicate the optical properties.