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Experimental study of photothermal conversion using gold/water and MWCNT/water nanofluids

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ABSTRACT

This work experimentally investigated photothermal conversion behavior of Gold/water and MWCNT/water nanofluids at different volumetric concentrations (0.0001–0.004% and 0.0001–0.03%, respectively) in a direct absorption solar collector (DASC). The experiments were conducted for ~10 h outdoor on each test day, without interruptions. The results show that the tested nanofluids have excellent photothermal conversion capability even under very low concentrations. Specific absorption rate (SAR) presented an exponential decay with increasing volumetric concentration of nanoparticles in the sample while both the total energy stored by the fluid sample during the heating period and the stored energy ratio (SER) increased with the increase in nanoparticles concentration. The results indicate the existence of an "optimal" volumetric concentration, above which further nanoparticle addition becomes indifferent or infeasible. This optimal nanoparticle volumetric concentration was found to be 0.002% for the gold nanofluid and 0.001% for the MWCNT samples for the setup used in this work.

1. Introduction

Solar energy is a renewable source widely used for heating purposes and becomes more and more important for our future energy supply. For solar heating applications, collectors rely on black or selective surfaces for the absorption of incident radiation, and transfer of the absorbed heat to a working fluid flows inside tubes. The solar heating process that occurs on these traditional systems are not as efficient as it should be, since there are at least three different thermal resistances between the solar radiation incidence and the working fluid heating: radiation absorption by the solar absorber, conduction heat transfer from the absorber to the tubes, and convection from the tubes to the working fluid.

The first practical idea of a system projected to overcome the limitations of the traditional collectors was originated in the 1970's. It was based on the concept of direct absorption of solar radiation by a fluid, promising to increase the absorbed energy and reduce heat losses to the ambient. The propose was to replace the absorber surface and metal pipes by a transparent cover or pipes with running fluids inside, which absorbs solar energy directly in the liquid phase, transforming the heat transfer process into a volumetric phenomenon. One of the pioneer reports of such work is from Minardi and Chuang [1], who used a so-called "highly absorbent black liquid" to capture solar energy in transparent channels. Years later, with the advances in measurements technology, it was possible to discover that the type of fluid used by Minardi and Chuang [1], an India Ink, very like China Ink properties, was a type of nanoscale particle dispersion [2]. Later, Arai et al. [3] experimentally tested a "volume heat-trap type solar collector" using a fine-particle semitransparent liquid suspension to enhance the efficiency. These prior works using very small particles (nanometer scale) dispersed on different liquids opened many possibilities, which has challenged researchers on obtaining stable "nanofluids", a term first used by Choi and Eastman [4]. Intensive interest in nanofluids has been received in past years and many progresses have been made. The

Abbreviations: bf, base fluid; CNT, Carbon Nanotubes; CPC, Compound Parabolic Concentrator; DASC, Direct Absorption Solar Collector; Dir, Direction; ETSC, Evacuated Tube Solar Collector; f, fluid; FPSC, Flat Plate Solar Collector; Inst, Instantaneous; LSPR, Localized Surface Plasmon Resonance; MWCNT, Multi-Walled Carbon Nanotubes; nf, nanofluid; np, nanoparticle; PSC, Parabolic Solar Collector; SAR, Specific Absorption Rate; SER, Stored Energy Ratio; SWCNT, Single-Walled Carbon Nanotubes; Vel, Velocity; VSAR, Volumetric Specific Absorption Rate

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Table 1
Nanoparticles and base fluids used in recent experimental studies.

Authors	Nanoparticle	Base Fluid	Subject	Type of study
Otanicar et al. [6]	Graphite, CNT, Ag	Water	Application: micro-solar-thermal-collector	Experimental
Taylor et al. [7]	Al, Ag, Cu, Graphite	Therminol VP1	Optical properties/ Application: PSC	Theoretical -Experimental
Taylor et al. [8]	Al, Au, Ag, Graphite, Cu, TiO_2	Water, Therminol VP1	Optical properties	Theoretical -Experimental
He et al. [9]	TiO_2, MWCNT	Water	Application: ETSC	Experimental
Lenert and Wang [10]	Co-Carbon	Therminol VP1	Optimization: volumetric receiver using concentrated solar radiation	Theoretical -Experimental
Yousefi et al. [11]	Al_2O_3	Water	Application: FPSC	Experimental
Yousefi et al. [12]	MWCNT	Water	Application: FPSC	Experimental
Yousefi et al. [13]	MWCNT	Water	Application: FPSC	Experimental
Khullar et al. [14]	Al	Therminol VP1	Application: PSC	Experimental
He et al. [15]	Cu	Water	Photothermal properties	Experimental
Jamal-Abad et al. [16]	Cu	Water	Application: FPSC	Experimental
Liu et al. [17]	CuO	Water	Application: evacuated tubular solar air collector with CPC	Experimental
He et al. [18]	Cu	Water	Application: FPSC	Experimental
Hordy et al. [19]	MWCNT	Water, ethylene glycol, Therminol VP1, propylene glycol	Application: solar collector	Experimental
Bandarra Filho et al. [20]	Ag	Water	Photothermal conversion efficiency	Experimental
Karami et al. [21]	CNT	Water	Photothermal properties	Experimental
Zhang et al. [22]	Au	Water	Photothermal conversion efficiency	Experimental
Gupta et al. [23]	AL_2O_3	Water	Application: DASC	Experimental
Karami et al. [24]	CuO	Water-ethylene glycol	Application: DASC	Experimental
Sabiha et al. [25]	SWCNT	Water	Application: ETSC	Experimental
Salavati Meibodi et al. [26]	SiO_2	Water-ethylene glycol	Application: FPSC	Experimental
Tong et al. [27]	MWCNT	Water	Application: U tube solar collector	Experimental
Delfani et al. [28]	MWCNT	Water-ethylene glycol	Application: DASC	Experimental
Vakili et al. [29]	Graphene	Water	Application: DASC	Experimental
Verma et al. [30]	MgO	Water	Application: FPSC	Experimental
Vincely e Natarajan [31]	Graphene oxide	Water	Application: FPSC	Experimental
Jeon et al. [32]	Au	Water	Application: FPSC	Theoretical -Experimental
Chen et al. [33]	Au	Water	Application: DASC	Experimental
Amjad et al. [34]	Au	Water	Photothermal conversion efficiency	Experimental
Fu et al. [35]	Graphene oxide-Au	Water	Application: Solar vapor generation	Experimental
Rose et al. [36]	Graphene oxide	Ethylene Glycol	Optical properties	Theoretical -Experimental
Iranmanesh et al. [37]	Graphene	Water	Application: ETSC	Experimental
Chen et al. [38]	Au	Water	Photothermal conversion efficiency	Theoretical -Experimental
Wang et al. [39]	Chinese ink Cu, CuO, Carbon Black	Water	Photothermal conversion efficiency	Experimental
Mahbubul et al. [40]	SWCNT	Water	Application: ETSC	Experimental
Duan et al. [41]	Au, SiO_2 cores coated with Au nanoshell	Water	Photothermal conversion efficiency	Theoretical
Liu et al. [42]	Reduced Graphene Oxide	Water	Application: Solar vapor generation	Experimental
Amjad et al. [43]	Ag, Cu and Zn and Fe, Si and Al2O3-γ	Water	Application: DASC	Experimental

Table 2
Characteristics of the primary nanofluids used in the present work.

Nanoparticle type	Nanoparticle format	ρ_{np} (g/cm^3)	Nanoparticle size	Base fluid	Φ_w (%)	ϕ_v (%)
Gold	Spherical	19.3	Diameter 10–30 nm	Distilled water	0.2896	0.015
MWCNT	Tubular, with multiple walled	2.1	Outside Diameter 50–80 nm Inside Diameter 5–15 nm Length 10–20 µm	Distilled water	9	4.485

advances in production techniques make it easier to produce a wide variety of nanofluids, especially for the two-step production method, in which nanoparticles can be obtained from a wide range of materials at higher quantities and lower cost (step one) and then dispersed in selected liquids (step two) [5].

Among the recent experimental studies in photothermal conversion using nanofluids, a wide range of nanofluids were produced from metal [6–8,14–16,18,20,22,32–34,38,39,43], oxides [8,9,11,17,23,24,26,30,31,36,39,42,43], carbon-based nanoparticles [6–9,12,13,19,21,25,27–29,37,39,40] dispersed in water, ethylene glycol, propylene glycol and Therminol VP1, and also, some studies involving hybrid nanofluids can be found [10,35,41], as shown in Table 1.

The use of plasmonic nanoparticles (nanoparticles produced from noble metal) have been highlighted for photothermal conversion applications due to their improved absorptivity, provided by the Localized Surface Plasmon Resonance (LSPR), a phenomenon of resonant energy transfer from incident light photons to the free electrons present in the metal surface. This resonance, for noble metals, occurs in the frequencies of visible light and enhance the photothermal conversion efficiency of plasmonic nanofluids [20,22,32–34,38,41,43,44].

Carbon-based nanoparticles have also been reported by many authors as potential candidates for use in solar collectors, especially for low to medium temperature applications (< 400 °C) due to their high spectral absorptivity over the entire solar range, low cost compared with other nanoparticle's material and good photothermal conversion efficiency even at low concentrations [7–9,19,25,28,29,37,39,40,45].

Recent results show that, despite of great nanoparticle optical characteristics and proven enhancement on photothermal conversion