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Photothermal conversion characteristics of gold nanoparticle dispersions

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Abstract

This work proposes and validates a novel idea of using plasmonic nanoparticles (PNP) to improve the solar thermal conversion efficiency. Gold nanoparticle (GNP) is synthesized from an improved citrate-reduction method, and used as an example to illustrate the photothermal conversion characteristics of PNPs under a solar simulator. The experimental results show that GNP has the best photo-thermal conversion capability comparing to other reported materials. At the lowest particle concentration examined (i.e., 0.15 ppm), GNP increases the photo-thermal conversion efficiency of the base fluid by 20% and reaches a specific absorption rate (SAR) of ~10 kW/g. The photo-thermal conversion efficiency increases with increasing particle concentrations, but the SAR shows a reverse trend, which is unexpected as all GNPs should be still in the independent scattering regime.

Keywords: Plasmonic nanoparticle; Gold nanoparticle; Nanofluids; Solar energy; Photo-thermal conversion; Solar collector

1. Introduction

Developing sustainable energy technologies, especially solar energy related, becomes extremely important in securing our energy future. Nanoparticle-based direct absorbing solar energy collector (DASC) is a recent development, which employs nanoparticles to convert light energy into thermal energy directly. Comparing to conventional solar thermal collectors that rely on the transfer of heat through the wall, nanoparticles absorb solar energy directly within the fluid volume. Such an idea transfers the surface heat transfer limitation associated with conventional solar collectors into a volumetric absorption phenomenon. An optimized DASC system could not only simplify the conventional system, i.e. replacing metal pipes with transparent glass tubes, but also increase the absorption efficiency by properly engineering the absorption spectrum at the nanoscale.

Significant advance has been achieved in this field since the concept was first proposed. The photothermal conversion efficiency of a range of nanomaterials were experimentally investigated (Sani et al., 2010; Otanicar et al., 2010; Taylor et al., 2011; Sani et al., 2011; Han et al., 2011; Lenert and Wang, 2012) and a few theories were proposed to maximize the conversion efficiency under optimized particle concentrations (Otanicar et al., 2010; Tyagi et al., 2007; Otanicar et al., 2009). These studies show that certain nanoparticles can absorb sun light directly, which may pave the way for a new generation of solar thermal energy system. However there are still a number of issues that requires special attention: (i) only limited nonmaterials

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Nomenclature

A	area (m^2)	t	time (s)
c	specific heat (J/kg K)		
d	particle diameter (m)	*Greek*	
I	solar intensity (W/m^2)	ε	extinction coefficient
L	distance of light travelled (m)	$\varnothing$	volume fraction (%)
l	particle–particle distance (m)	η	photothermal conversion efficiency (%)
m	mass (kg)	Δ	difference
P	Radiation transmitted through a sample (W/m^2)		
$P0$	Incident radiation (W/m^2)	*Subscript*	
SAR	specific absorption rate (W/g)	w	water
T	Temperature (K)	n	nanoparticle

have been investigated and it is still unclear about the optimized material and particle concentration; (ii) it is unclear about the photothermal conversion mechanisms, especially regarding the interaction between nanoparticles, the solar light and the base fluid, and (iii) a lot of studies were based on the optical properties and characterized by the extinction coefficient (Otanicar et al., 2010; Taylor et al., 2011; Sani et al., 2011; Otanicar et al., 2009; Mercatelli et al., 2011), with limited direct photothermal conversion experiments. The extinction coefficient is a key factor to illustrate the wavelength-selective absorbing feature of nanoparticles; however it may not represent the real photo-thermal energy conversion process. For any application in solar thermal systems, it is the temperature rise that decides the overall efficiency. In addition, the lack of proper control in nanomaterials (i.e., size, shape and concentration) makes it is difficult to study the particle morphology effect and to compare the results among different research groups. Most of the nanoparticles were purchased commercially with a wide size distribution in the form of agglomerations. The presence of surfactant/dispersant in the dispersion may also influence the absorption process significantly.

It is known that commonly-used fluids for solar thermal applications such as water and ethane glycol have good absorption efficiency in the infrared regime. Consequently particles that have strong absorption in the visible light, not much in completion with the base fluid, should be considered more favourably. Plasmonic particles have been widely used in the medical and life science fields, ranging from gene therapy, controlled drug delivery, enhanced imaging and diagnosis, to non-invasive thermal therapies (Hu et al., 2006; Panyala et al., 2009; Becker et al., 2010; Liu et al., 2012). Significant heat can be induced through the surface plasmon resonance process (SPR), where the absorption from the nanoparticles could be greatly enhanced via the coupling of the incident radiation with the collective motion of electrons in metal. As the plasmon resonance frequency is typically comparable with the visible light spectrum, it appears that plasmonic particles could be good candidates for direct photothermal conversion to enhance the solar thermal efficiency especially in the visible light spectrum. Using gold nanoparticle as an example, this paper will investigate the direct photo-thermal conversion characteristics of plasmonic particles. To elucidate clearly the effect of particles, GNPs will be synthesized based on an improved citrate-reduction method followed by a rigorous purification procedure. The photothermal conversion study of various GNP concentrations will be performed under a solar simulator. The specific absorption rate of GNPs will be calculated and compared with other published studies.

2. Experimental approach

2.1. Gold nanoparticle synthesis and characterization

In this work, gold nanoparticle dispersions are formulated through simultaneous production and dispersion of nanoparticles in situ. GNPs were synthesized by the citrate reduction method with the aid of ultrasonication for particle morphology control (Chen and Wen, 2011). In brief, a mixture of 190 ml deionised water (DI) and 5.0×10^{-6} mol of $HAuCl_4$ was heated until boiling, and stirred by a magnetic blender. After 10 ml of 0.5% sodium citrate was added and the solution's color changed to wine-red, the solution was placed in the ultrasonic bath at 80 °C for 30 min. Gold nanoparticle dispersions were purified by the membrane dialysis method. In this process, 100 ml of GNP dispersion was put in a membrane tube with pore size of 2–3 nm in diameter, which allows the smooth diffusion of ions but keeps GNPs inside. The membrane was located in a flask of DI water ~2000 ml, stirred by a magnetic stirrer. The DI water was changed twice per day and the purification process lasted for 5 days. During this process, the concentrations of various impurities diminished exponentially with the times of DI water change, which resulted in a negligible impurities presence in the dispersion as confirmed by the UV–Vis spectrum measurement. This ensures that the photothermal conversion effect in this work is solely due to the effect of gold nanoparticles.