Solar Energy 137 (2016) 393–400

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

Plasmonic nanofluids based on gold nanorods/nanoellipsoids/nanosheets for solar energy harvesting

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ARTICLE INFO

Article history:
Received 24 March 2016
Received in revised form 1 August 2016
Accepted 19 August 2016

Keywords:
Nanofluids
Solar energy
DDA
LSPR

ABSTRACT

Due to the localized surface plasmon resonance (LSPR) effect excited on the surface of metallic nanoparticles, plasmonic nanofluids have been used to improve the efficiency of direct absorption solar thermal collectors (DASC) as working fluids. In this study, optical properties of plasmonic nanofluids containing gold nanoparticles with different shapes, sizes, aspect ratios and concentrations are studied numerically. The results show that the LSPR of gold nanorods and nanoellipsoids can be improved by tuning the aspect ratio. Particle size has little effect on extinction coefficient. Nanosheets show a great potential in solar thermal conversion. To achieve a broad-band absorption in both visible and near-infrared spectral region at a low particle concentration, the gold blended nanofluids made up of 20% nanoellipsoids of AR = 2, 60% nanorods of AR = 5, and 20% nanosheets of $l/h = 7$ are proposed according to the plasmon resonance absorption band. An enhancement in solar energy harvesting of 104% for the gold blended nanofluids is achieved compared to the gold sphere nanoparticles even at an extremely low concentration and small particle size, which overcomes the instability of nanofluids under high concentration.

1. Introduction

Solar energy is the cleanest and most abundant energy in the world. A lot of studies have been carried out on solar thermal collectors for solar thermal utilizations (Suehrcke et al., 2004; Kalogirou, 2004; Valipour and Rashidi, 2015). Solar thermal collectors are heat exchangers that can convert solar radiation into internal energy of working fluids. Most of traditional solar thermal collectors are surface-based absorbers which lead to a high temperature of the absorbing surface and thus result in significant radiative heat loss. Direct absorption solar thermal collector (DASC) is a type of volumetric absorber which have been used to minimize the surface temperature of receivers (Hogan et al., 2014; Lenert and Wang, 2012). By adding plasmonic nanoparticles into the base liquids, terming into nanofluids, the optical properties will be significantly changed. Nanofluids have attracted significant interests in recent years for their potential applications in solar energy harvesting (Ni et al., 2015; Du and Tang, 2015; Pustovalov et al., 2015; Khullar et al., 2014; Otanicar et al., 2010). By applying plasmonic nanofluids in the DASC, solar radiation energy can be converted into thermal energy of base fluids more efficiently (Chen et al., 2015; Xuan et al., 2014; Duan and Xuan, 2014; Lee et al., 2012). Compared with pure water, it was proved that under a low aluminum particle loading, the absorption of incident solar energy can be increased by 9 times. Using nanofluids can both absorb and transport solar energy in the DASC and the energy loss can be reduced as well. The total solar thermal conversion efficiency can be improved compared to the traditional flat-plate collectors (Tyagi et al., 2009).

The localized surface plasmon (LSP) is the oscillation of free electrons on the surface of nano-sized metallic particles, which is a resonance phenomenon activated by proper incident light (Raether, 1988). The resonance phenomenon can be tuned by changing the geometry and permittivity of nanoparticles (Zayats et al., 2005). When the LSP occurs, the incident photon energy can be resonantly transferred into surface plasmon. As a result, a great amount of heat is generated in the particle and transferred to the surrounding medium.

The total conversion efficiency of nanofluids based on the DASC mainly depends on the match between its optical properties and the solar radiation spectrum. Higher particle concentration is required due to their comparatively small extinction coefficient if using metal-oxide nanoparticles-based nanofluids (Yousefi et al., 2012; Said et al., 2014) and graphite nanofluids (Ladjevardi et al., 2013). However, the high particle concentration brings about particle deposition and agglomeration which causes the fluids unstable. Some researchers added metal nanoparticles to enhance

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http://dx.doi.org/10.1016/j.solener.2016.08.029
0038-092X/

the absorption of solar radiation (Saidur et al., 2012; He et al., 2013). Due to the broad spectrum range of solar radiation and a narrow absorption peak in the visible light of metal sphere particles, nanofluids containing metal sphere particles have a poor performance in the near-infrared range. Broad-band absorption can be achieved by using blended core-shell particles or blended noble metal nanoparticles. To excite the LSP on silica-gold core-shell particles in near-infrared region, the shell thickness is required to be less than 5 nm, causing serious difficulty in fabrication (Taylor et al., 2013). In addition, the scattering effect of core-shell structure is significantly high (Jain et al., 2006), which is unfavorable in photon-thermal applications.

One promising method to achieve a broad-band solar absorption is to employ noble nanoparticles in nanofluids. Jeon et al. (2014) experimentally studied the optical property of nanofluids based on gold nanorods with different aspect ratios. The results show that gold nanorods have great absorption in both visible and near-infrared spectral region. And by enlarging the aspect ratio of gold nanorods, the peak position of LSPR shows a red-shift. Rativa and Gómez-Malagón (2015) investigated the optical property of nanoellipsoids with different aspect ratios by the Maxwell-Garnett model. They found that the LSPR of nanoellipsoids can be tuned by adjusting aspect ratio. And gold nanoellipsoids with small particle size (2.5 nm) and high aspect ratio (AR = 4) can obtain a solar weighted absorption coefficient close to the ideal condition. However, a comparative investigation on optimal parameters of nanoparticle shapes for solar energy harvesting is still missing. In this study, we focus on the effects of gold nanoparticle shape, size and concentration on the optical properties of plasmonic nanofluids. By applying the discrete dipole approximation method, the extinction coefficients of gold nanorods, nanoellipsoids and nanosheets are studied numerically. Then, an optimal design for blended nanofluids containing three different gold nanoparticles is proposed, which can make full use of LSPR in the solar spectrum. The main purpose of current work is aiming at designing nanofluids with excellent photothermal performance under a low particle concentration which can achieve higher stability.

2. Modeling approach

Optical properties of nanofluids are determined by both base fluid and nanoparticles. Therefore, the optical properties for base fluid and nanoparticles are studied separately.

2.1. Optical property of base fluid

Water is chosen as base fluid in this study because of its easy availability and good absorptivity in near-infrared range. For pure water, the scattering effect of the medium can be neglected, and only the absorption effect needs to be considered in the calculation. The spectral absorption coefficient of base fluid can be calculated with

$$K_{af} = \frac{4\pi k}{\lambda} \tag{1}$$

where k is the absorption index of base fluid and λ is the wavelength of incident light. The optical constant of water is taken from (Hale and Querry, 1973).

Fig. 1 shows absorption coefficient of pure water calculated by Eq. (1). It can be seen that pure water is a very poor absorbing medium in the spectrum of ultraviolet and visible light. In the wavelength range of 250–1300 nm, water can be regarded as a transparent medium. However, when the wavelength shifts to near-infrared region, water becomes a very efficient absorber.

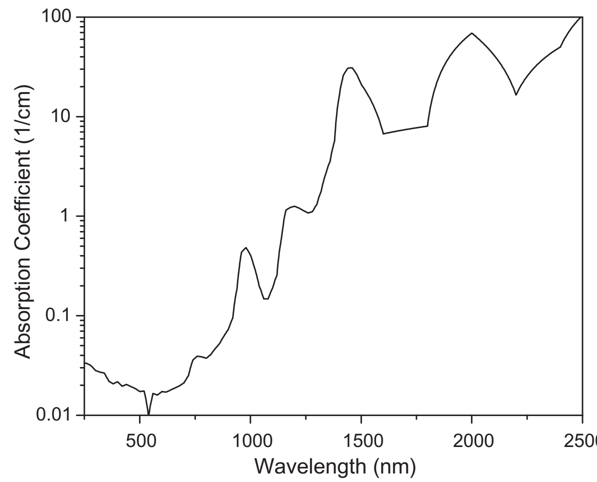

Fig. 1. Absorption coefficient of pure water.

Therefore, the added nanoparticles should have the ability to enhance the absorption in the wavelength range of 250–1300 nm. The present work focuses on developing plasmonic nanofluids to meet the need of broad-band solar radiation absorption.

2.2. Optical property of nanoparticles

As discussed above, most of the solar radiation is absorbed by the added nanoparticles, so the optical properties of nanoparticles need to be well studied.

Compared with the characteristic incident wavelength, the size of suspended plasmonic nanoparticles is quite small and the volume fraction can be very low in a real DASC based on nanofluids with a sizable absorption path length. Thus, the scattering effect of plasmonic nanoparticles in base fluids can be regarded as independent scattering. We can treat the optical properties of nanoparticles as a simple proportionality to the total number of suspended particles so as to simplify the calculation greatly.

The optical properties of sphere particles can be calculated through the Mie theory, which is a theoretical analysis based on Maxwell equations. The Mie theory has a good agreement with experimental results for sphere particles (Amendola and Meneghetti, 2009; Amendola et al., 2006). However, when the particle shape is irregular, it is difficult to get an exact solution of electromagnetic problems. To consider the complex geometry of metallic nanoparticles, the discrete dipole approximation (DDA) scheme (Draine and Flatau, 1994) is employed to calculate the optical properties of nanoparticles. DDA is one of the mostly used numerical approaches in the calculation of optical properties for nanoparticles. In the DDA method the structures of nanoparticles are replaced by a series of discrete dipoles. There is no restriction to particle shape. And each dipole j has a specific polarization $\mathbf{P}_j$ given by

$$\mathbf{P}_j = \alpha_j \mathbf{E}_j(\mathbf{r}_j) \tag{2}$$

where α_j is the polarizability of the dipole, and $\mathbf{E}_j$ is the electric field at position $\mathbf{r}_j$ consisting of two parts: one is the incident electromagnetic field that activates the dipoles, and the other is the interaction from all other dipoles in the simulation zone.

$$\mathbf{E}_j(\mathbf{r}_j) = \mathbf{E}_{\mathrm{Inc},j}(\mathbf{r}_j) - \sum_{n \neq j} \mathbf{A}_{nj}\mathbf{P}_n \tag{3}$$

where $\mathbf{A}_{nj}$ is a 3×3 interaction matrix given by