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Solar radiation absorption of nanofluids containing metallic nanoellipsoids

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Abstract

Metallic nanoparticles (NP) are promising materials for solar radiation absorption due to the plasmon resonance absorption band in the visible and near IR spectrum that can be tuned modifying the NP shape. Linear optical absorption in the visible and near IR spectral region of aqueous nanofluids containing gold and silver nanoellipsoids (NEs) were studied using the Maxwell–Garnett model, and the solar weighted absorption coefficient was calculated for different concentrations, aspect ratios and NE sizes. The results show an enhance of the solar weighted absorption coefficient in almost 54% and 86% for gold and silver NEs, respectively, when compared to spherical NP of the same materials. Moreover, for a nanofluid-based direct absorption collector with 1 cm thickness, and a nanofluid of gold NEs with a low volume fraction, small NPs (2.5 nm), a high aspect ratio (AR = 4), it is possible to obtain a solar weighted absorption coefficient closer to the ideal solar radiation absorber condition.
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Keywords: Metallic nanoparticles; Solar radiation absorption

1. Introduction

Solar thermal collectors (STC) are heat exchangers that convert solar radiation energy to internal energy of a fluid (usually water). One of the most common STC is the Flat-plate collector (FPC), which are broadly used for applications where the sunlight is non-concentrated. FPC is usually composed by a blackened absorber surface such that the absorbed energy is transferred to the fluid to be carried away for storage or use. Design improvements of these devices are focused in developing new materials and shapes for the black or spectrally selective surfaces, new structures to reduce losses like honeycomb structures, as well as, new fluids to improve its performance (Amri et al., 2014; Suehrcke et al., 2004; Hollands, 1965; Alvarez et al., 2004; Yousefi et al., 2012).

Another mechanism to transfer solar radiation energy to the fluid is the use of the direct absorption solar collector, where the fluid absorbs directly solar radiation due to the matching between its optical absorption and the solar radiation spectrum. Different fluids such as black liquids, gases filled with particles, and colloidal suspensions with nanoparticles (known as nanofluids) have been proposed for that purpose (Minardi and Chuang, 1975; Abdelrahman et al., 1979; Javadi et al., 2013). Nanofluids have attracted much attention due to their remarkable thermal and optical properties which are dependent of different factors, some of which are: intrinsic properties, shape and concentration of the nanoparticle inclusions (NPs), as well as, the liquid host material (Ashrafmansouri and Esfahany, 2014; Shahrul

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et al., 2014; Otanicar et al., 2009). Different NP inclusions such as spherical metallic particles, Al_2O_3, carbon nanotubes and metal oxides have been explored with excellent potential for STC applications (Patel et al., 2003; Sridhara and Satapathy, 2011; Ding et al., 2006; Li and Peterson, 2006). In particular, metallic NPs are promising materials due to the plasmon resonance absorption band in the visible spectrum that can be tuned altering the NPs shape and the material host (Link et al., 1999; Mock et al., 2002). Furthermore, chemical interface damping and the nanostructure geometry are parameters that can be explored for tuning the plasmon resonance absorption band as in the case of core–shell nanostructures (Hövel et al., 1993; Xu et al., 2007).

In this work, the influence of metallic NPs shape on the solar weighted absorption coefficient is investigated theoretically for an aqueous colloid containing spherical and ellipsoidal nanoparticles of gold and silver materials. The theoretical description of linear optical properties of nanofluids was done using the Maxwell–Garnett model, which considers that the NPs size is smaller than the incident wavelength (Garnett, 1906).

2. Theoretical description

Considering the geometry of an aqueous low-concentrated nanofluid containing metallic NPs, where the wavelength of the incident radiation is larger than the interdistance between NPs and much larger than the NPs size ($\lambda \gg d \gg a$), the Maxwell–Garnett model can be used to describe the linear optical properties of the nanofluid. These geometric aspects are considered in order to guarantee that the incident electric field is constant in the inner NP and to avoid the interaction between them. A schematic representation of a prolate NE ($a > b = c$) and a nanofluid solar collector composed by NEs with a Maxwell–Garnett geometry is shown in Fig. 1. The linear absorption coefficient α_0 and the linear refraction index n_0 are given by:

$$\alpha_0 = \frac{2\pi}{\lambda n_0}\epsilon''_{eff} \quad \text{and} \quad n_0 = \sqrt{\frac{\epsilon'_{eff} + \sqrt{\epsilon'^2_{eff} + \epsilon''^2_{eff}}}{2}} \tag{1}$$

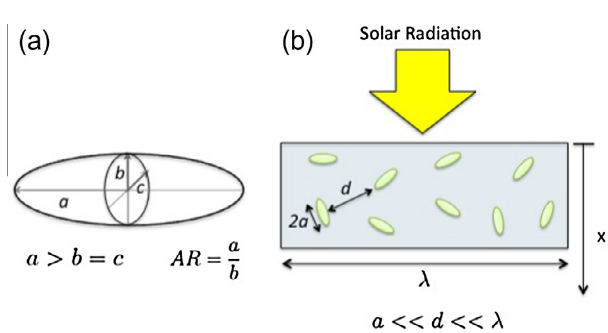

Fig. 1. (a) Schematic representation of a prolate NE ($a > b = c$) and (b) a nanofluid solar collector composed by NEs with a Maxwell–Garnett geometry ($\lambda \gg d \gg a$).

where λ is the wavelength of the incident light, as well as, ϵ'_{eff} and ϵ''_{eff} are the real and imaginary parts of the effective dielectric permittivity, respectively.

The effective dielectric permittivity depends on the dielectric permittivity of the constituents and the NPs shape. In the case of anisotropic inclusions such as ellipsoidal nanoparticles (NEs), the bulk metal dielectric permittivity is corrected such that the orientation dependence is considered. For Prolate NEs ($a > b = c$), with lengths $2a, 2b$ and $2c$ along the z, x and y axes, the dielectric permittivity along the direction $k = x, y, z$, is given by:

$$\epsilon_{k,NE} = \epsilon_\infty - \frac{1}{\lambda_p^2(1/\lambda^2 + i/(\gamma_k\lambda))} + \sum_{j=1,2}\frac{A_j}{\lambda_j}\left[\frac{e^{i\phi_j}}{(1/\lambda_j - 1/\lambda - i\gamma_j)} + \frac{e^{-i\phi_j}}{(1/\lambda_j + 1/\lambda + i\gamma_j)}\right] \tag{2}$$

where ϵ_∞ is the high-frequency limit dielectric permittivity, λ_p is the plasma wavelength, λ_j is the interband transition wavelength, γ_j is the transition broadening, γ_k is the damping in the direction k, A_j is the dimensionless critical point amplitude and ϕ_j is the phase. The first two terms are due to the Drude contribution and the summation includes the interband transitions (j) in the violet/near-UV region using the Critical Point Model. The fitting of Eq. (2). to the experimental values reported in the literature for silver and gold were published previously (Etchegoin et al., 2006; Furtado and Gómez-Malagón, 2014).

The size dependence of the dielectric permittivity is introduced into Eq. (2) through the damping term $\gamma_k = 2\pi c/(\Gamma_0 + \Gamma_s)$, where c is the speed of light, Γ_0 is the bulklike optical scattering rate given by $\Gamma_0 = 2\pi c/\gamma_p$, and Γ_s is the size-dependent damping term. Explicitly, $\Gamma_s = Av_F/L_{k,eff}$, where A is a surface factor that describes the surface scattering process, v_F is the Fermi velocity, and $L_{k,eff}$ is the effective confinement length in direction k.

According with Juve et al. (2013) there are discrepancies between the size dependence of Γ_s obtained experimentally with the frequently used billiard model for electron-surface scattering (Coronado and Schatz, 2003) or with quantum mechanical models based on simple infinite confinement (Kraus and Schatz, 1983). They have introduced a phenomenological approach assuming that the impact of size reduction on the localized surface plasmon resonance width can be described by a relation on the effective confinement length given by $L_{eff} = L^\beta D^\beta$, where $\beta = 0.5$ is related with a symmetrical role for D and L, the size-dependence relation has been validated for aspect ratios varying from one to five (Juve et al., 2013).

Hence, for spherical NPs $L_{eff} = L^{0.5}L^{0.5}$, where $D = L$ is the NPs diameter such that $L_{x,eff} = L_{y,eff} = L_{z,eff} = D$. For ellipsoidal NPs, the dielectric permittivity are equal along the transversal direction, $L_{x,eff} = L_{y,eff} = 2b$, whereas along

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