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Optical property of nanofluids with particle agglomeration

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Abstract

Nanofluids have been used to improve the efficiency of direct absorption solar thermal collectors (DASC) as working fluids because of their excellent heat transfer and optical absorption properties. However, aggregates could be generated in nanofluids especially in the two-step preparation. A theoretical approach for calculating the extinction coefficients of nanofluids with particle agglomeration is proposed based on diffusion limited cluster aggregation (DLCA) simulation and generalized multi-particle Mie solution (GMM) method, in which the dependent scattering effect between particles is considered. The influences of particle agglomeration, particle diameter and particle volume fraction on the extinction coefficient of nanofluids with particle agglomeration are investigated. Moreover, the harvested solar energy under the real solar irradiation at sea level for the nanofluids with particle agglomeration is also studied. The results show that the particle agglomeration reduces the absorption peak in the short-wavelength as well as enhances the long-wavelength scattering. The nanofluids with particle agglomeration have a higher performance in solar energy harvest.

Keywords: Nanofluids; Solar energy; Optical properties; Particle agglomeration; DLCA simulation; GMM method

1. Introduction

Thermal characteristics of nanofluids have been studied intensively in the past decades (Prasher et al., 2005, 2006; Zeinali et al., 2006; Kim et al., 2007; Müller et al., 2008; Merabia et al., 2009). By adding nanoparticles into the base liquids, terming into nanofluids, the thermal properties will be changed, which has broad applications such as cooling electronic components. Optical properties of nanofluids have also attracted significant interests in recent years for their potential applications in solar energy harvesting (Kameya and Hanamura, 2011; Lenert and Wang, 2012; Mahian et al., 2013; Zhu et al., 2013; Zhang et al., 2014). It was observed that with a low aluminum particle loading, the absorption of incident solar radiation can be increased by 9 times compared to the pure water. Using nanofluids can both absorb and transport solar energy in a volumetric absorption collector. Then the energy loss is reduced and the energy efficiency is improved over conventional flat-plate collectors (Tyagi et al., 2009). Ladjevardi et al. (2013) discussed the improvement of absorption efficiency for solar energy by using nanofluids as a direct absorber. They used numerical codes to solve the radiative transport equation, momentum, mass and energy conversation equations to investigate the performance of graphite–water based nanofluids. The optical property of nanofluids can be tuned by adding plasmonic nanoparticles into fluids. Jeon et al. (2014) measured extinction coefficient of gold nanorod with different aspect ratios. The results showed that the spectral property can be tuned by changing aspect ratio, which can be employed in direct absorption solar

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systems. Lee et al. (2012) developed a Monte Carlo algorithm combined with the Mie scattering theory to determine the optical property of nanofluids. Using plasmonic nanoparticles can broaden the sharp absorption peak which is determined by the surface plasmon. As a result, the absorption efficiency of DASC will be improved. By employing core/shell nanoparticles, Taylor et al. (2012) designed nanofluid-based optical filters for PV/T systems. Compared with conventional optical filters and pure fluids, the nanofluid-based filters show a higher solar-weighted efficiency.

Since pure water can only absorb up to 13% of incident solar radiation (Otanicar et al., 2009), most of the energy is absorbed by the added nanoparticles. It requires full study for the absorption coefficient and scattering coefficient of nanoparticles. Saidur et al. (2012) employed Rayleigh scattering theory to obtain the optical properties of nanofluids. They found that the particle size has little effect on extinction coefficient. And extinction coefficient increases linearly with the particle volume fraction. Taylor et al. (2011) investigated the extinction coefficient of different nanofluids by experiments and numerical simulations. They found that the results calculated by the Maxwell–Garnett effective medium approach and the Mie scattering theory show a very good agreement with experimental results for graphite nanofluids. However, their results could not match well for metal nanofluids.

The above investigations focused on the optical property of a single particle and ignored the multiple scattering effects between particles. However, many experimental results show that most of the particles in nanofluids are agglomerated. It was observed that the particle aggregates had effect on the thermal conductivity of nanofluids (Hong et al., 2006). Yang et al. (2012) examined the effect of particle aggregates on fluid viscosity. They found that the nanofluids with agglomerated particles demonstrated shear thinning effect even at a low concentration. Gharagozloo and Goodson (2010) found that greater aggregation could be generated at higher temperature or higher concentration. In the study of (Taylor et al., 2011), instead of the manufacturer-quoted 20–40 nm, the real average particle diameter in nanofluid is found to be 50–120 nm from the dynamic light scattering (DLS) results. The two-step preparation of nanofluids could bring in particle agglomeration in the preparation process. And agglomeration of small particles into large particles could occur with the time passing by.

Due to the presence of particle agglomeration, the effects of dependent scattering and multiple scattering between agglomerated particles cannot be ignored. The independent scattering model is no longer suitable and new theoretical approaches are required. This paper aims at developing a theoretical method for computing the optical properties of nanofluids with particle agglomeration. The microstructure of agglomerated particle groups can be generated with diffusion limited cluster aggregation (DLCA) simulation. Then, we employ the methods which can take the scattering effects between the particles into account to calculate the optical properties of nanofluids with particle agglomeration, such as the generalized multi-particle Mie solution (GMM) and the T-matrix method. By applying these methods, the effects of particle agglomeration, particle size, and particle volume fraction on the optical properties of nanofluids with particle agglomeration are investigated.

2. Modeling approach

2.1. Generation of microstructure of aggregates

The microstructure of particle agglomeration is generated firstly to investigate the optical properties of nanofluids with particle agglomeration. There are three basic methods to generate random nanoparticle aggregate structures including diffusion limited aggregation (DLA) (Witten and Sander, 1981), reaction-limited cluster–cluster aggregation (RLCA) (Meakin and Jullien, 1988), and diffusion limited cluster aggregation (DLCA) (Gimel et al., 1999). To study the effect of particle agglomeration, we need to generate a structure containing particle groups. Previous studies have indicated that the shape of particle agglomeration is mainly elongated and dendritic. So, we use the DLCA algorithm to generate the structures of particle aggregates in nanofluids with different average particle numbers of aggregates, particle diameters and particle volume fractions.

Firstly, a fixed number of particles are distributed randomly in a three-dimensional space. The number of particles is determined by the particle size, the particle volume fraction and the simulation domain. All the particles are initially in the state of random motion. When the collision occurs between particles, a particle group forms immediately, then the particle group continues to move randomly as a cluster. In the computing domain, many clusters grow independently. When two clusters collide, they merge into one bigger cluster. The three-dimensional structure simulation terminates when the total number of clusters reduces to a fixed value, which is determined by the average particle number of the aggregates. By changing the number of final clusters, the average particle number of the aggregates can be controlled.

The main input parameters in the structure generation code are the total number of particles in the calculation area, the particle diameter d and the number of final clusters. For most nanofluids, the diameters of a single particle are $d = 5$–50 nm. However, because of the existence of particle agglomerates, the diameters of agglomerated particles measured by the DLS are mostly among 70–200 nm (Taylor et al., 2011). It can be deduced that an agglomerate may be made up of dozens or even hundreds of basic particles. Fig. 1 (left) shows the microstructure generated by the DLCA method, consisting of 105 particles of $d = 20$ nm and the volume fraction is $f_v = 2.0\%$. The transmission electron micrograph (TEM) of an aggregate of Cu-nanoparticles suspended in nanofluids is presented in Fig. 1