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Near-field radiative heat transfer between clusters of dielectric nanoparticles

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ABSTRACT

In this work, we explore the near-field radiative heat transfer between two clusters of silicon carbide (SiC) nanoparticles using the many-body radiative heat transfer theory. The effects of fractal dimension of clusters, many-body interaction between nanoparticles and relative orientation of clusters on the thermal conductance are studied. Meanwhile, the applicability of the equivalent volume spheres (EVS) approximation for near-field radiative heat transfer between clusters is examined. It is observed that the thermal conductance is larger for clusters with larger fractal dimension, which is more significant in the near-field. The thermal conductance of EVS resembles that of the clusters, but EVS overestimates the conductance of clusters, especially in the near-field. Compared to the case of two nanoparticles, the conductance of nanoparticle clusters decays much slower with increasing distance in the near-field, but shares similar dependence on the distance in the far-field. The thermal conductance of SiC nanoparticle clusters is inhibited by the many-body interaction when surface phonon polariton is supported but enhanced at frequencies close to the resonance frequency. The total thermal conductance is decreased due to many-body interaction among particles in the cluster. The relative orientation between the clusters is also an important factor in the near-field, especially for clusters with lower fractal dimension.

1. Introduction

Near-field radiative heat transfer (NFRHT) has attracted great attention during the past decades. The most remarkable characteristic of NFRHT, which has been proven both theoretically [1–6] and experimentally [7–13], is that it can exceed the far-field limit set by Planck's black-body law by several orders of magnitude. The dramatic increase of near-field radiative heat flux is attributed to the tunneling of evanescent waves when the separation gap of two bodies is comparable to or smaller than the characteristic radiation wavelength. Moreover, NFRHT can be quasi-monochromatic if the materials support surface resonances [5]. These features make NFRHT very appealing to applications including thermophotovoltaics[14–19], coherent thermal sources [20] and thermal rectification [21,22].

In terms of theoretical study, NFRHT problems are frequently solved in the framework of fluctuation electrodynamics (FE) which combines the Maxwell's electromagnetic wave theory with the fluctuation-dissipation theorem [1,23,24]. The fluctuation-dissipation theorem [1], under the assumption of local equilibrium, links the fluctuating current to the local temperature, the accuracy of which was recently validated for a gap size as small as 2 nm [11,25]. In addition to the widely used dyadic Green's functions method, a great amount of numerical approaches have been put forward to deal with FE problems of various geometries, for example, the finite difference time domain method [26,27], the boundary element method [28], the fluctuating volume-current method [29], the thermal discrete dipole approximation method [30–32], to name a few. Most recent reviews of theoretical and experimental studies of NFRHT refer to Refs. [33,34].

In the context of radiative heat transfer through particulate systems, the classical theory of radiative transfer equation (RTE) [35,36] applies to dilute particle system (Fig. 1(a)), where particles are randomly distributed and separated with distances much larger than the dominant wavelength of thermal emission (far-field condition) [23,37]. However, for non-dilute particle system where the separation distances of particles are comparable to or smaller than the dominant thermal wavelength (Fig. 1(b)), near-field effects like wave interference and evanescent wave tunneling can be significant and RTE ceases to be valid. NFRHT between two neighboring particles have been studied in several researches [38–42]. It was found that the power of radiative heat transfer between two bodies in the dipolar approximation decays as $1/d^6$ in the near-field and as $1/d^2$ in the far-field. Both electric and magnetic dipole-dipole interaction can dominate the radiative heat transfer depending on the materials of the bodies. And for a separating

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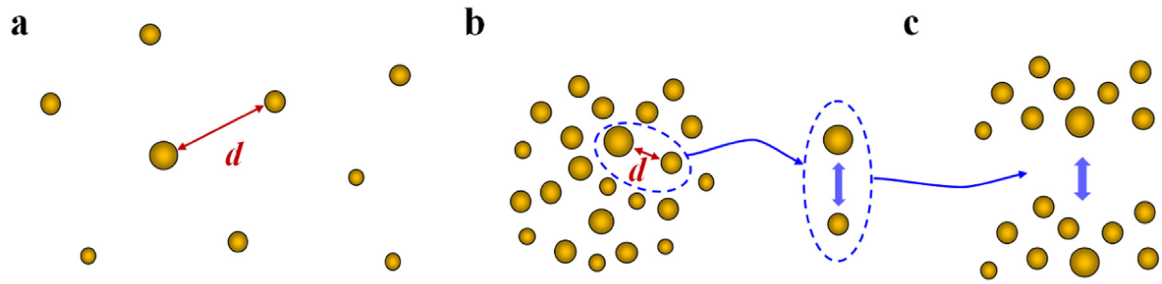

Fig. 1. Particle systems, (a) dilute particle system where the separation distances *d* between particles are much larger than the dominant thermal wavelength, (b) non-dilute particle system where the separation distances *d* are comparable to or smaller than the dominant thermal wavelength, and two particles in the near-field, (c) two clusters of particles in the near-field.

gap smaller than the diameter, higher multipoles can be important.

In addition to NFRHT between two bodies, Ben-Abdallah et al. [43] introduced the many-body theory to deal with the radiative heat transfer with the existence of a group of particles. In their work, the nanoparticles were treated as electric dipoles, supposing that the sizes of the nanoparticles were sufficiently smaller than the dominant thermal wavelength. To further make the dipolar approximation valid, a minimal separation distance of 2 R was kept between two adjacent nanoparticles, thus higher electric multipoles can be neglected. Meanwhile, they considered near-field radiative transfer among SiC nanoparticles, for which the magnetic moment contribution was neglected. Based on the many-body radiative heat transfer theory, they discovered a superdiffusion phenomenon of thermal radiation in a randomly distributed nanoparticles system [44]. Phan et al. [45] studied the NFRHT between two gold nanoparticle arrays. Nikbakht [46] extended the many-body theory to anisotropic cases considering the radiative heating by a thermal bath. Moreover, the dynamics of heat transfer in the near-field of a many-body system were also investigated [47–49]. Many-body interactions can make NFRHT very different from that of two bodies, where the relative positions and relative orientations serve as important factors.

It is well known that particles usually get close to each other and even form aggregates, for example, nanoparticles in a fluid and materials like aerogels. Far-field radiative properties of aggregated nanoparticles have been studied extensively [50–54]. However, to the best of our knowledge, NFRHT between clusters of nanoparticles (Fig. 1(c)) have not been studied, which involves many-body interactions in the near-field. Also, studying the NFRHT between two nanoparticle clusters is important for us to understand the near-field effects of the radiative heat transfer though non-dilute particle systems.

In this work, we explore the NFRHT between two clusters of silicon carbide (SiC) nanoparticles using the many-body radiative heat transfer theory proposed by Ben-Abdallah et al. [43]. The effects of the fractal dimension of clusters, the many-body interaction among nanoparticles and the relative orientation of clusters on the thermal conductance are studied. In Section 2, we establish models of nanoparticle clusters with different compactness and define the distance between two clusters. Section 3 provides the theoretical aspects of our study. In Section 4, results are analyzed and discussed.

2. Model establishment of nanoparticle clusters

Clusters of different morphology are considered in this work. The morphology of the fractal aggregate of nanoparticles is usually described by the famous statistical rule [50]:

$$N_s = k_0\left(\frac{R_g}{a}\right)^{D_f} \tag{1}$$

where N_s is the number of monomers in the aggregate, D_f is the fractal dimension, k_0 is the prefactor, a is the radius of the monomers and R_g the radius of gyration which is a measure of the overall cluster radius. The fractal dimension D_f is the main factor that describes the compactness of the aggregate. In this work, we consider SiC nanoparticle clusters where the radius of nanoparticles is $R = 20$ nm. Such a radius is much smaller than the dominant thermal wavelength at 300 K. Moreover, we keep a minimal distance of 2 R edge to edge between nanoparticles in the cluster to further make the dipolar approximation valid [38,43]. For connected nanoparticles, higher multipoles should be included.

First, fractal aggregates are generated using the particle-cluster aggregation algorithm in the open source program provided by Skorupski et al. [55]. Three fractal dimensions of D_f =1.8, 2.3 and 2.8 are chosen to consider aggregates with different compactness. With increasing fractal dimension, the aggregate becomes more compact and spherical-like. The radius of each monomer in the aggregate is set to be $a = 2R = 40$ nm, the prefactor k_0 is 1.0 and the number N of the nanoparticles is assumed to be 100 for all the aggregates. The generated fractal aggregates are shown in Fig. 2(a). Then the radius of each of the 100 monomers in the aggregates is reduced by half while the centers of the monomers remain the same. Thus we get nanoparticle clusters where the radii of the nanoparticles are $R = 20$ nm and the minimal distance between

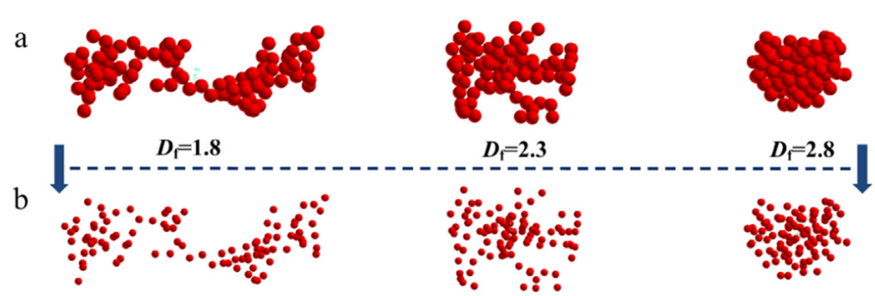

Fig. 2. Generation of nanoparticle clusters with different fractal dimension, the number of nanoparticles is 100, (a) nanoparticle aggregates with monomer radius of 40 nm, (b) the radius of each monomer is reduced by half while their centers remain the same.