International Journal of Heat and Mass Transfer 102 (2016) 669–678

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Study of radiative transfer in 1D densely packed bed layer containing absorbing–scattering spherical particles

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ARTICLE INFO

Article history:
Received 1 February 2016
Received in revised form 24 March 2016
Accepted 20 June 2016
Available online 5 July 2016

Keywords:
Radiative properties
Absorbing–scattering spheres
Packed bed
Monte Carlo method

ABSTRACT

In this study, transmission process of diffused and collimated beam in a 1D densely packed bed is investigated. Absorbing–scattering spherical particles with the same radius are distributed randomly in transparent and absorbing host media. The refractive indexes of the spheres are different from that of the host medium. The size parameter χ of these spheres is sufficiently large to simulate their interaction with radiation through a Monte Carlo ray-tracing technique based on the geometrical optics approximation. Using the validation of the code for radiative transfer in a single absorbing–scattering sphere and in a packed bed filled with opaque or absorbing spheres, the effects of albedo, optical thickness, refractive index, and incident angle on the transmission process are examined in detail. The information of transmittance, reflectance, bidirectional reflectance distribution function (BRDF) and bidirectional transmittance distribution function (BTDF) are employed to describe the role of absorbing–scattering spheres in transparent and absorbing host media.

1. Introduction

Radiation transfer process in a packed bed of spheres plays a very important role in several engineering applications, which have been reviewed in the works of Viskanta and Mengüç [1], and Baillis and Sacadura [2], such as high-performance cryogenic thermal insulation [3], photocatalytic reactions in the treatment of polluted air and water [4], selective laser sintering technology [5], effective monitoring of PM pollution [6], etc. Therefore, the exact modeling of radiative transfer in a packed bed of spheres can be used not only for prediction, but also for optimization of radiative properties of such types of media. According to the clearance ratios of particles c to wavelength λ, and particles c to the particle size $d = 2R_{\text{sphere}}$, the research on this subject can be divided into two categories: independent and dependent scattering, respectively. For densely packed beds, the independent scattering theory is no longer valid. The interference and multi-scattering effects, which are known as the dependent scattering effect or non-point scattering effect, should be taken into account [7,8].

Because of the complexity of radiative transfer in densely packed beds, approximations are generally employed:

A very common treatment, called the "homogeneous phase approach", is to assume the densely packed bed as a statistically continuous and homogeneous medium [9]. In general, the effective radiative properties should be obtained in advance, including the absorption coefficient, scattering albedo, and phase function. Some researchers employ the correlated theory to scale the radiative properties obtained from the independent theory [14,15]. However, this simple scaling method is only suitable for opaque particles [15]. It is far more complex to model the radiative transfer for semitransparent particles because the rays will travel a given distance through them; in other words, with the exception of the dependent scattering, the ray-transportation effect should also be considered [16]. The geometrical optics approximation for a single semi-transparent sphere has already been studied in detail in [17–21]. A complete solution, such as the internal energy density distribution or spectral emissivity inside the sphere, was obtained and it exhibited major features of the Mie solution. Subsequently, Coquard and Baillis [22] employed the Monte Carlo ray tracing method on a large spherical virtual medium to compute the radiative properties of a packed bed of opaque spheres, which showed very good agreement with the results obtained from the correlation method. This work was then extended for packed beds of absorbing–scattering particles [23,24] in a non-absorbing host media. Randrianalisoa and Baillis further developed a new ray tracing approach based on the theory of mean free path [16] and on an

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.06.065
0017-9310/

Nomenclature

BRDF	bidirectional reflectance distribution function, defined in Eq.(16); sr^{-1}
BTDF	bidirectional transmittance distribution function, defined in Eq.(17); sr^{-1}
d	diameter of sphere, $d = 2R_{sphere}$; m
f_v	volume fraction
i, **j**, **k**	unit vectors
L	thickness of packed bed; m
$\hat{n}$	normal vector of sphere, $\hat{n} = (n_x, n_y, n_z)$
n_i, n_t, n_{host}, n_{ins}	refractive index
N_abso_{sphere}	number of rays absorbed by a sphere
N_tran_{sphere}	number of rays without being scattered or absorbed
$N\_reflect_{bed}(\theta_{r\_bed}, \varphi_{r\_bed})$	number of rays reflected by packed bed in reflected direction $(\theta_{r\_bed}, \varphi_{r\_bed})$
$N\_tran_{bed}(\theta_{t\_bed}, \varphi_{t\_bed})$	number of rays transmitted through the packed bed in refracted direction $(\theta_{t\_bed}, \varphi_{t\_bed})$
N_{ray}	number of rays used in the simulation
Q_{sphere}	extinction efficiency factor of sphere, $Q_{sphere} = 1 - \frac{N\_tran_{sphere}}{N_{ray}}$
R_{sphere}	radius of sphere; m
RND_ρ, RND_s, $RND_{\omega_{ins}}$, RND_θ, RND_φ	random number
R	reflectance of bed, $R = \frac{\sum N\_reflect_{bed}(\theta_{r\_bed}, \varphi_{r\_bed})}{N_{ray}}$
T	transmittance of bed, $T = \frac{\sum N\_tran_{bed}(\theta_{t\_bed}, \varphi_{t\_bed})}{N_{ray}}$
$\hat{\upsilon}_i$	incident direction vector, $\hat{\upsilon}_i = (\upsilon_{ix}, \upsilon_{iy}, \upsilon_{iz})$
$\hat{\upsilon}_t$	refracted direction vector, $\hat{\upsilon}_t = (\upsilon_{tx}, \upsilon_{ty}, \upsilon_{tz})$
x, y, z	Cartesian coordinates; m

Greek letters

β_{host}, β_{ins}	extinction coefficient; m^{-1}
ε	porosity
θ	polar angle of scattering; rad
θ_i, θ_{i_bed}	polar angle of incident radiation relative to the normal of sphere and packed bed; rad
θ_r, θ_{r_bed}	polar angle of reflected radiation relative to the normal of sphere and packed bed; rad
θ_t, θ_{t_bed}	polar angle of refracted radiation relative to the normal of sphere and packed bed; rad
κ_{host}	absorption coefficient; m^{-1}
λ	wavelength; m
ρ, $\rho(\theta_i, \theta_t)$	reflectivity
φ	azimuthal angle of scattering; rad
φ_i	azimuthal angle of incident radiation relative to the normal of sphere; rad
φ_r	azimuthal angle of reflected radiation relative to the normal of sphere; rad
φ_t	azimuthal angle of refracted radiation relative to the normal of sphere; rad
χ	size parameter, $\chi = 2\pi R_{sphere}/\lambda$
Ω_r, Ω_t	solid angle; sr
ω_{ins}	albedo of inside medium
ω_{sphere}	scattering albedo of sphere, $= \frac{N_{ray} - N\_abso_{sphere} - N\_tran_{sphere}}{N_{ray} - N\_tran_{sphere}}$

Subscripts

ins	inside medium
bed	packed bed

analytical approach [8], respectively, to calculate the effective radiative properties of densely packed beds of absorbing spheres in an absorbing host medium. Combining these effective radiative properties, the radiative transfer equation (RTE) could be solved using various techniques [10,11]. Because of the complexity of obtaining a complete and accurate solution of the RTE in dispersed systems, engineering approaches, such as, differential approximations [12], are widely used, and have been summarized in a monograph by Dombrovsky and Baillis [13].

Other researchers focused on the "multiphase approach"[25], in which the radiative transfer in a two-phase arbitrary-type media in the limit of geometric optics could be modeled using two sets of continuum-scale radiative transfer equations and effective radiative properties associated with each phase. In comparison with the homogeneous phase approach, Randrianalisoa pointed out that the multiphase approach is not suitable, especially when considering packed beds of absorbing spheres [9].

In this work, we studied the transmission process of diffused and collimated beam in a densely packed bed of absorbing–scattering spheres in transparent and absorbing host media. Although this kind of sphere has been previously studied by Coquard and Baillis [24], we further considered that the refractive index of the spheres may be different from that of the host medium. In addition, we also considered a non-transparent host medium, where the radiative energy is absorbed. For large spheres with a size parameter of $\chi = 2\pi R_{sphere}/\lambda \gg 1$, the Monte Carlo ray tracing technique based on the geometrical optics approximation was used to treat the interaction of the radiation with the spheres [26]. This method easily captured the dependent scattering between the spheres as well as the transmission process in the absorbing–scattering spheres and host medium. Because the diffraction rays of this kind of sphere contribute mainly in the incident direction [26–29], the diffraction can be treated as transmission [23].

This paper is organized as follows. In Sections 2 and 3, the Monte Carlo ray tracing technique for radiative transfer in a single semitransparent sphere and 1D densely packed bed layer of semitransparent spheres is introduced. After the validation of the code, the reflection and transmission characteristics of radiative transfer, such as the reflectance, transmittance, BRDF and BTDF, are finally discussed in Section 4. The effects of albedo, optical thickness, refractive index, and incident angle on the transmission process are fully studied.

2. Radiative transfer in a single semitransparent sphere

The interaction of radiation with an optically large semitransparent sphere is described in detail in Coquard's work [23]. In this paper, we further consider that the refractive index of the sphere could be different from that of the host medium. In addition, we used an absorbing host medium. The Monte Carlo ray tracing algorithm [10] is employed to determine the ray transmission process in the sphere. A total number of $N_{ray} = 10^6$ rays [8,23] are used in the simulation in order to obtain the statistical results. The interaction process of each ray of the incident beam with the semitransparent sphere is shown in Fig. 1.

2.1. Reflection and refraction at the interface

Reflection and refraction take place at the interface when the refractive index of the sphere is different from that of the environment (air). The reflectivity can be calculated using the Fresnel reflection equation:

$$\rho(\theta_i, \theta_t) = \frac{1}{2}\left\{\left[\frac{\sin(\theta_i - \theta_t)}{\sin(\theta_i + \theta_t)}\right]^2 + \left[\frac{\tan(\theta_i - \theta_t)}{\tan(\theta_i + \theta_t)}\right]^2\right\} \tag{1}$$