Journal of Quantitative Spectroscopy & Radiative Transfer 111 (2010) 1372–1388

Contents lists available at ScienceDirect

Journal of Quantitative Spectroscopy & Radiative Transfer

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

Radiative properties of densely packed spheres in semitransparent media: A new geometric optics approach

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ARTICLE INFO

Article history:
Received 2 September 2009
Received in revised form
26 November 2009
Accepted 19 January 2010

Keywords:
Radiative properties
Radiative transfer
Dispersed media
Packed beds
Opaque
Semitransparent
Particle
Geometric optics
Ray tracing
Monte Carlo
Non-point scattering
Ray transportation

ABSTRACT

This contribution presents a new Ray-tracing method for calculating effective radiative properties of densely packed spheres in non-absorbing or semitransparent host medium. The method is restricted to the geometric optic objects and neglects the wave effects. The effective radiative properties such as the absorption and scattering coefficients, and phase function are retrieved from the calculation of mean-free paths of scattering and absorption, and the angular scattering probability of radiation propagating in the dispersed medium. The model accounts for the two geometric effects called here as non-point scattering and ray transportation effects. The successful comparison of the current model with data of radiative properties and transmittances of particle beds in a non-absorbing medium reported in the literature confirm its suitability. It is shown that: (i) for opaque or absorbing particles (not systematically opaque), the non-point scattering is the dominant geometric effects whereas both non-point scattering and ray transportation effects occur for weakly absorbing and transparent particles. In the later cases, these two geometric effects oppose and may cancel out. This may explain why the Independent scattering theory works well for packed of quasi-transparent particles; (ii) the non-point scattering and ray transportation effects can be captured through the scattering and absorption coefficients while using the classical form of phase function. This enables using the standard radiative transfer equation (RTE); (iii) the surrounding medium absorption can be accounted for without any homogenization rule. It contributes to increasing the effective absorption coefficient of the composite medium as expected but, at the same time, it reduces the particle extinction; and (iv) the current transfer calculation predicts remarkably the results of direct Monte Carlo (MC) simulation. This study tends therefore to confirm that the RTE can be applied to densely packed media by using effective radiative properties.

1. Introduction

Radiative transfer in dispersed media is of crucial importance in various fields of sciences such as thermal engineering, [1] atmospheric science, [2] remote sensing, [3] oceanography, [4] and morphological diagnostic. [5] In the current study, attention is paid to the modeling of radiative transfer in densely packed media constituting of optically large spherical particles and semitransparent host medium. Examples of these media, usually encountered in thermal engineering problems, are packed beds, fluidized beds, composite coating, and paint layers. [6,7]

The exact solution of the radiation propagation in a dispersed medium should be determined from the first principles consisting of solving the Maxwell equations for the electromagnetic field. A review of the existing solution methods was carried out by Kahnert. [8] However, this

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doi:10.1016/j.jqsrt.2010.01.014

Nomenclature

a	particle radius, m
c	surface-to-surface particle distance, m
CP	cumulative probability distribution function
d	particle diameter, m
$\mathrm{d}_{\mathrm{abs}i}$	traveled distance by a radiation bundle before undergoing absorption in the substance i, m
d_{ij}	straight distance traveled by the ray bundle between the jth and ith extinction locations, m
d_{int}	traveled distance by a radiation bundle between two successive interactions with the internal particle surface, m
dist	sum of traveled paths by N_{ext} ray bundles undergoing extinction, m
ds_i	direction vector of the ray bundle at the ith extinction location
$\mathrm{d}_{\mathrm{sca}}$	traveled distance by a radiation bundle before undergoing scattering, m
d_{tr}	transportation distance within the particles, m
$E(R,\theta)$	proportion of rays leaving the large sphere of radius R in a direction of angle
f_v	volume fraction of dispersed phase
$I(z,\mu)$	radiation intensity at the position z propagating along the direction of cosine μ with respect to z axis, $\mathrm{W\,m^{-2}\,sr^{-1}}$
L	thickness of a plane packed bed sample, m
mfp	mean-free path, m
n	real part of the complex refractive index
N	number
P	probability function
Q	efficiency factor of a particle
q_0	incident radiation flux, $\mathrm{W\,m^{-2}}$
R	radius of a spherical packed bed, m
r	projected radius of a sphere on a vertical plane, m
r_i	ith discrete position of rays measured from the initial position $r_0=0$ from which the track of their paths starts, m
s_i	position vector of the ray bundle at the ith extinction location, m
S_{np}	scaling (or correction) factor of non-point scattering
t	outward normal vector on the particle surface
T	hemispherical transmittance defined in Eq. (13)
$W(\Theta)$	number of radiation bundles scattered in the angular interval $[\Theta, \Theta+d\Theta]$,
x	particle size parameter
y	abscise of the intensity I propagating in the medium surrounding a particle, m
z	abscise of the intensity I along the sample thickness direction, m

Greek symbols

α	absorption coefficient, $\mathrm{m^{-1}}$
β	extinction coefficient, $\mathrm{m^{-1}}$
χ	absorptivity parameter
δ	constant in Eq. (11)
Δ	direction vector of radiation
ε	error function defined in Eq. (8)
Φ	scattering phase function
γ	constant in Eq. (11)
η	refractive index ratio
φ	azimuth angle associated with the solid angle Ω, rad
ϑ	characteristic polar angle of a ray bundle, referred to the outward normal to a particle surface, rad
κ	imaginary part of complex refractive (or absorption) index
λ	radiation wavelength, m
μ	direction of cosine of the radiation intensity I
θ	angle between the initial direction of a ray within the dispersed medium and its exit direction, rad
Θ	scattering angle, rad
ρ_i	reflectivity at the ith interaction point at the continuum–particle interface
σ	scattering coefficient, $\mathrm{m^{-1}}$
ω	scattering albedo
Ω	solid angle, sr
$\xi,\xi',\xi_0,\xi_1,\xi_2,\xi_n$	random numbers uniformly distributed between 0 and 1
ψ	characteristic azimuth angle of a ray bundle, referred to the outward normal to a particle surface, rad

Subscripts

abs	refers to absorption parameters or number of rays undergoing absorption
abs0, abs1	refer to absorption in the continuous phase, and absorption in the dispersed phase, respectively
ext	refers to extinctions or number of rays undergoing extinction
dir	refers to the number of discrete directions in the angular interval [0,π]
inc	refers to the direction of the incident ray
ind	refers to independent scattering radiative properties
np	refers to radiative properties accounting for non-point scattering effects
pos	refers to the number of discrete positions.
ray	refers to the number of rays to be tracked in the ray-tracing algorithm
sca	refers to scattering parameters or number of rays undergoing scattering
0	refers to the continuous substance surrounding particles
1	refers to the dispersed phase or particles