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Analytical method to study multiple scattering characteristics in participating media

Chuan-Xin Zhang, Yuan Yuan *, Tian-Jiao Li, Shi-Kui Dong, He-Ping Tan *

School of Energy Science and Engineering, Harbin Institute of Technology, 92, West Dazhi Street, Harbin 150001, PR China

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ABSTRACT

The radiative transfer and characteristics of multiple scattering in participating media are critical issues in the fields of atmospheric research and target detection. In this work, the apparent directional radiative intensity distribution influenced by multiple scattering is deduced using angle discretization in a computational domain and path integrals in the direction of transmission. The multiple scattering analytical method (MSAM) is used to determine the apparent directional radiative intensity distribution influenced by multiple scattering in participating media. The apparent directional radiative intensity as a function of the scattering order is calculated. The forward and backward scattering energies, which vary with the optical thickness, are determined using the above-mentioned method and model. The computational accuracy, efficiency, and applied range of the MSAM differ from those of the Monte Carlo method. The forward and backward scattering energy changes with the optical thickness for different scattering orders. Thus, the concept of a "backward optically thick medium" is proposed based on this. The current work perfects the multiple scattering theory. The results obtained are important for quick estimations of the main radiative characteristics of participating media.

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1. Introduction

Light scattering is a reradiation phenomenon that causes atomic or molecular systems to change their propagation direction, phase, and frequency after obtaining energy from an incident wave. In addition, light scattering can be considered as redirection of electromagnetic waves colliding with obstacles or inhomogeneous media. It is essential in crystals, the atmosphere, and biological tissue [1]. Cirrus microphysical and scattering properties have large impacts on how cirrus affects radiation [2]. Scattering of light at tissue, cellular, and subcellular interfaces provides an important source of natural biological contrast that can be harnessed to provide quantitative measurements of cellular and tissue states [3]. The detected foundation and direct climatic effects of aerosols are scattering and absorption of sunlight [4,5]. The direction of light will change due to scattering and absorption during the target detection and identification process. Scattering directly determines the energy in the detection direction and affects the detection and recognition judgment.

Several studies on scattering have been reported owing to its importance. In the study of the atmospheric scattering characteristics of particles, the Lorenz–Mie theory [6], finite-difference time-domain method [7], and *T*-matrix method were developed [8]. In order to consider the planet atmosphere in multiple scattering and absorption problems, a single scattering approximation method and diffusion approximation method were adopted [9]. The past decades have witnessed the development of two kinds of numerical methods to solve scattering of radiative transfer in participating media. One is based on ray tracing, such as the zone method [10], Monte Carlo method [11–13], discrete transfer method [14,15], and ray tracing method [16–19]. The simulation process for these methods is physically based and the ray path is determined analytically using a process that does not explicitly rely on the discretized differential form of the radiative transfer equation. However, these methods have some drawbacks. For instance, a lot of computation time is required to achieve precise numerical results [20]. The other type of numerical method is based on solving a set of discretized partial differential equations, such as heat flux method [21], discrete ordinates method [22–25], finite element method [26,27], spherical harmonics method [28–30], and finite volume method [31,32]. These methods have some obvious advantages, such as high efficiency and excellent flexibility in dealing with multidimensional complex geometries. The radiative transfer characteristics in the internal field of media are analyzed and calculated using these methods. However, the

* Corresponding authors. Tel.: +86 0451 86418194.
E-mail addresses: yuanyuan83@hit.edu.cn (Y. Yuan), tanheping@hit.edu.cn (H.-P. Tan).

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Nomenclature

a	transition variable related to angle, the value is 0 or 1
$I_1, I_2, \ldots, I_n$	radiation intensity of different scattering orders, W/sr
L	distance between two parallel planes, m
$L_0, L_1, \ldots, L_n$	transmission total distance of different scattering orders, m
$x_0, x_1, \ldots, x_n$	transmission path distance of different scattering orders, m
$Z_1, Z_2, \ldots, Z_n$	different fractions divided in the model
E_a	total energy of all direction, W
E_f, E_b	total energy of forward direction and backward direction, respectively, W
E_i	energy in each angle, W
E_{MS}, E_{MC}	total energy calculated by the two methods, W
ε_{rel}	relative error of the two methods

Greek symbols

$\alpha_1, \alpha_2, \ldots, \alpha_n$	zenith angle of different scattering orders, rad
$\kappa_{e\lambda}$	spectral extinction coefficient, m^{-1}
ω	scattering albedo
Φ	scattering phase function
Ω_0	initial solid angle, sr
Ω_s, Ω_i	scattering direction and incidence direction, respectively, rad
$\Delta\Omega_1$	outgoing solid angle of the first scattering, rad
θ	incident, scattering included angle, rad
τ	optical thickness, 1

Subscripts

i	angle label
$1, 2, \ldots, n$	refer to the index of different scattering orders
λ	wave length, μm
s	scattering direction

Superscripts

0	radiation intensity index in radiation transfer
m_1	the outgoing direction

apparent directional radiative intensity distribution affected by scattering is not fully concerned and there is a lack of integrated information on radiative intensity.

Particle scattering needs to be studied to determine the apparent directional radiative intensity distribution in participating media. The single scattering method, in which each photon experiences scattering only once, has been developed to study the process of particle scattering. The single scattering approximation is applied to thin optical media. However, multiple scattering needs to be considered in thick optical media. A lot of work has been done on multiple scattering of particles. Twersky [33] analyzed the interface effects on multiple scattering using large, low-refracting, and absorbing particles. He obtained complete results for flux in a detecting cone at an arbitrary angle of observation, in terms of one-particle scattering functions, scatterer concentration, and distribution thickness, for a plane wave normally incident on a slab-region distribution. Kocifaj and Lukac [34] used the multiple scattering theory to calculate of the radiative fluxes from experimental aerosol data. Elias and Elias [35] studied new and fast calculations for incoherent multiple scattering. Hong [36] determined the parameterization of the scattering and absorption properties of nonspherical ice crystals at microwave frequencies. Based on the calculated mean optical properties, the mean scattering efficiency, absorption efficiency, and asymmetry factor as functions of the ice cloud effective particle size were parameterized. Zhai et al. [37] studied a vector radiative transfer model for coupled atmosphere and ocean systems based on the successive order of scattering method. Cheng and Wang [38] performed a numerical study of the characterization of forward scattering Mueller matrix patterns of turbid media with triple forward scattering assumptions. The results showed that the forward scattering Mueller matrix is characterized by special symmetric structure unlike the backscattering Mueller matrix patterns. Ge et al. [39] researched the dust aerosol forward scattering effects on ground-based aerosol optical depth retrievals. Hovenier and Guirado [40] studied zero slopes of the scattering function and scattering matrix for strict forward and backward scattering with mirror symmetric collections of randomly oriented particles. These studies enriched the single and multiple scattering theories in media.

To the best of our knowledge, an analytical method for determining the apparent directional radiative intensity distribution in participating media has never been reported, which motivated us to study this further. Hence, we established a one-dimensional radiative model in participating media based on an analysis of radiative transfer characteristics. The apparent directional radiative intensity in participating media was determined and a multiple scattering analytical method (MSAM) for calculating the apparent directional radiative intensity was established. Based on this model and method, the apparent directional radiative intensity distribution for different scattering orders was calculated. In addition, the apparent directional radiative intensity for forward and backward changing with optical thickness were determined. The present work is expected to be useful for atmospheric radiation and space object detection.

2. Method and model

The transmission direction and energy of light change when light passes through media, resulting in different apparent directional radiative intensity distributions [41]. Assuming that the media are participating media (i.e., absorption and scattering media), the radiative energy transfer is concerned with space coordinates, direction, and wavelength of light [42–44]. Clouds are selected as the media for this research. Clouds occupy more than 60% of the sky at any given time and are the main regulators of weather and climate [45]. The area of a cloud is infinite compared with its thickness. It can be assumed that a cloud is a one-dimensional infinite plate. A one-dimensional infinite plate model is adopted in the following analysis and calculation. The radiative intensity I in the field of optics is used as the emergent energy,

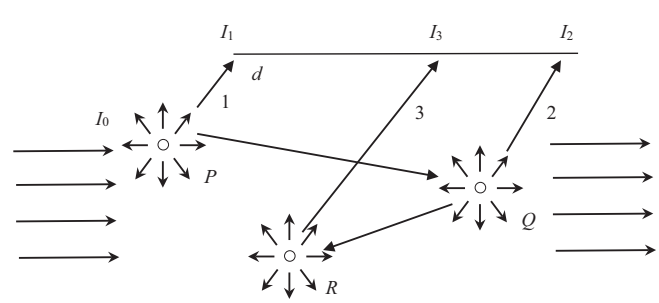

Fig. 1. Process of first-, second-, and third-order scattering in direction d.

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