International Journal of Heat and Mass Transfer 79 (2014) 437–449

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Transient radiative transfer in a complex refracting medium by a modified Monte Carlo simulation

Hong-Liang Yi, Cun-Hai Wang, He-Ping Tan *

School of Energy Science and Engineering, Harbin Institute of Technology, Harbin 150001, PR China

ARTICLE INFO

Article history:
Received 25 January 2014
Received in revised form 20 July 2014
Accepted 12 August 2014

Keywords:
Transient radiative transfer
Multilayer
Graded index
Monte Carlo method
Time shift and superposition
Reflection mode

ABSTRACT

A modified Monte Carlo (MMC) method applied with time shift and superposition principle is developed for solving transient radiative transfer in one-dimensional scattering media with arbitrary distributions of refractive index exposed to a collimated short pulse-laser irradiation at one of its boundaries. We consider a multilayer medium and a graded index medium. The accuracy and computational efficiency of the MMC algorithm are examined firstly. Our results are compared with those obtained by the reverse Monte Carlo method (RMC), the modified discrete ordinates method (MDOM) and the lattice Boltzmann method (LBM), and the excellent agreements are achieved. With the time shift and superposition principle, the MMC method can greatly improve the computational efficiency. We have a parametric investigation on the transient radiative transfer in the three-layer systems and graded-index media, illustrating the effects of refractive index distribution, optical thickness, interface/surface reflection mode, scattering phase function and scattering albedo on the time-resolved signals of reflectance and transmittance. Results show that the reflection mode has an important influence on the transient radiative transfer; the specular reflection at interfaces/boundaries can enhance the effects of forward scattering, while the diffuse reflection can enhance the effects of backward scattering.

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1. Introduction

The interests of transient radiative transfer (TRT) have been extended to many aspects due to the availability of short-pulse lasers, for example, optical imaging [1], remote sensing techniques of air or sea [2,3], nondestructive diagnostic [4], and particle detection and sizing [5]. A detailed review on various aspects of the TRT behavior induced by a short-pulsed laser was presented by Kumar and Mitra [6]. The interaction of short-pulse laser and medium has become the focus of current research. Researchers have developed several methods to investigate the TRT in participating media. Tan et al. [7] developed a time-dependent integer equation (IE) formulation which provides high-order accuracy solutions for the TRT. Wu et al. [8,9] investigated the TRT in multi-dimensional absorbing and anisotropically scattering media by solving the integral equation formulation. Guo et al. [10] and Liu et al. [11] studied the TRT by using the discrete ordinates method (DOM) and discontinuous finite element method (DFEM) separately. Rath et al. [12] applied discrete transfer method (DTM) to the TRT problem and Zhou et al. [13] solved the TRT in an isotropically scattering gray plane-parallel medium using DRESOR method. Recently, the DRESOR method has been used to solve transient radiative transfer in graded index media [14]. Mishra [15] compared the steady/transient radiative transfer results in participating medium obtained by the finite volume method (FVM) and collapsed dimension method (CDM) respectively. Roger et al. [16] developed a new multi-scale model for 1D transient radiative transfer that is based on a new strategy for coupling the radiative transfer equation (RTE) with the diffusion equation (DE), which consists in introducing a buffer zone, in which two equations at two different scales (mesoscopic and macroscopic) are solved.

In the community of radiative transfer, the Monte Carlo (MC) method [17,18] is generally recognized as an accurate solution method. Compared with other numerical methods, conversion between space and time is easy to achieve in the MC simulation, and with this advantage, the MC method is very suitable for solving transient radiative transfer. Besides, as a method based on ray tracing, the MC scheme has a unique advantage for solving radiative transfer in participating media with Fresnel surfaces/interfaces. Hsu et al. [19] developed a time-dependent MC method for modeling the TRT within absorbing and scattering media and studied the multiple scattering and reflective boundary effects. Guo et al. [20] found good agreements between the experimental and the MC simulation results in a three-dimensional scattering and absorbing

* Corresponding author. Tel.: +86 0451 86412674.
E-mail addresses: yihongliang@hit.edu.cn (H.-L. Yi), tanheping@hit.edu.cn (H.-P. Tan).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2014.08.031
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Nomenclature

a	anisotropic factor
c_0	light speed in vacuum, m s^{-1}
$H(t)$	heaviside step function
I	radiation intensity, W m^{-2} sr^{-1}
L	the width of the medium in direction x, m
N	total number of the simulated bundles
n	refractive index
t_p	the incident pulse width, s
t_p^*	The dimensionless incident pulse width, $t_p^* = \beta c_0 t_p$
t^*	dimensionless time, $t^* = \beta c_0 t$
Greek symbols	
Φ	scattering phase function
μ	direction cosine of the polar angle
β	extinction coefficient, m^{-1}
ω	scattering albedo
τ	optical thickness, $\tau = \beta L$

media. A MC method based on the path length and time of flight in close form is developed by Wu et al. [21] to solve the TRT in a medium with a variable refractive index.

Generally speaking, if only the number of the simulation bundles emitting from the volume or surface elements is sufficiently large, the numerical solutions obtained by the MC method for radiative transfer can be accurate enough. While the most obvious disadvantage of the MC method is that it is time consuming for obtaining stable results, especially for the transient radiative transfer problem. If the number of bundles is not big enough, the rapid fluctuations in the results by the MC method will appear for the case of large optical thickness [19,21,22]. Lu and Hsu [23,24] developed a reverse Monte Carlo (RMC) method which shortened the computation time and improved the computational efficiency in the investigation of transient radiative transfer.

Liu et al. [25] extended the application of DFEM to solving transient radiative transfer in participating media, with the use of a time shift and superposition (TSS) principle for improving the computational efficiency. Guo et al. [26] applied the DOM coupled with superposition method to the solution to transient radiative transfer in 3-D highly-scattering media subjected to a time-dependent pulse train. In this paper, a modified Monte Carlo (MMC) method in which the TSS principle is first introduced is developed to overcome the time-consuming problem and improve the computational efficiency.

So far, most of the works reported have not considered the effect of reflection at the surface/interface. Moreover, previous works on transient radiative transfer in multilayer system have only considered the case of non-refracting medium [24,27,28]. In fact, as we know, reflection/refraction at the surface/interface changes the propagation directions and transmission paths of bundles. Transfer behavior caused by specular reflection/refraction at the Fresnel surface/interface can be different from that caused by diffuse reflection/refraction at the Lambertian surface/interface. Therefore, different reflection/refraction properties of the surfaces/interfaces are expected to have a significant influence on the transient radiative transfer. In addition, there are also not many publications on the investigation of transient radiative transfer in graded index media [11,14,21,29,30].

This paper is organized as follows. In Section 2, the MC algorithm coupled with TSS principle is outlined for the solution to transient radiative transfer in participating media with variable refractive index. The reflectivity of the diffuse and specular surface/interface is formulated. In Section 3, the accuracy and efficiency of the MMC are verified. Afterwards, the MMC algorithm is applied to solving the TRT in a three-layer medium with different refractive index in each layer and graded index medium. A parametric study on the transient radiative transfer is carried out, mainly focusing on the effects of refractive index distribution, the optical thickness, scattering albedo, the interface/surface reflection mode et al. on temporal transmittance and reflectance.

2. Theory

2.1. Physical model and photons interaction with media

Consider transient radiative transfer in a one-dimensional slab containing a scattering medium with arbitrary distributions of refractive index, as shown in Fig. 1. The medium consists of M sub-layers, and in the ith sub-layer the refractive index is denoted by n_i. The environment surrounding the medium with refractive index of $n_0 = 1.0$ is nonparticipating. The total thickness of the slab is $L = 1.0$ mm.

We consider a short square pulse irradiation normally incident on the left boundary as shown in Fig. 1. The radiation intensity incident on the boundary at $x = 0$ can then be expressed as

$$I(0,t) = I_0[H(t) - H(t - t_p)] \tag{1}$$

Here, t_p is the pulse width, and $H(t)$ is the Heaviside step function.

In the MC simulation, the photon bundles incident on the left boundary are partly reflected, and partly refracted into the medium, which is decided by comparing pseudo random number with the reflectivity. The bundles refracted into the medium which experience free propagation, scattering, reflection and transmission are traced in the medium until they are absorbed by the medium or transmitted through the boundaries into the environment. From the starting point, transfer direction and the propagation distance of the bundle, we can decide whether it interacts with the media or the interfaces after a free propagation. If the bundle is inferred to have interaction with the media, a random number between 0 and 1 is available to decide the bundle to be absorbed or scattered. Otherwise, when the bundle interacts with the surface/interface in the multilayer system, the transmission or reflection event will happen. In the multilayer media, refractive index in

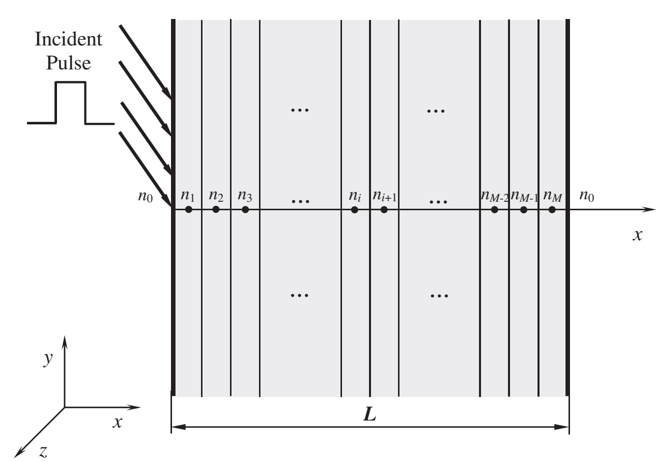

Fig. 1. Sketch of the geometry of the physical model.

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