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The lattice Boltzmann method for one-dimensional transient radiative transfer in graded index gray medium

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ABSTRACT

The lattice Boltzmann method (LBM) is extended to solve transient radiative transfer in one-dimensional slab containing absorbing and scattering media with graded index subjected to a short square laser irradiation. By using a fully implicit backward differencing scheme to discretize the transient term in the radiative transfer equation, a new type of lattice structure is devised. Firstly, for the case of the refractive index matched boundary, LBM solutions to transient radiative transfer in graded index medium are validated by comparison with results reported in the literature. Afterward, LBM is employed to investigate transient radiative transfer in graded index medium with a refractive index discontinuity at the boundaries. Effects of the graded index distributions, the optical thickness, and scattering phase function on transmittance and reflectance signals are investigated, and several interesting trends on the time-resolved signals are observed and analyzed.

1. Introduction

In the past decade, due to the availability of short-pulse lasers, transient radiative transfer (TRT) in participating media has received considerable attention in many emerging applications. The recent developments in micro/nano-scale systems [1], short-pulsed laser in materials [2], optical tomography [3], laser therapy [4] and other applications have indicated that TRT is an important process which requires rigorous investigation. A detailed review on various aspects of the transient radiative behavior induced by a short-pulsed laser can be found in Kumar and Mitra [5].

In the simulation of radiative transfer in semitransparent medium subjected to an ultra-short pulse laser or a high-energy laser, the transient term must be considered in the radiative transfer equation, and the transfer behavior of the pulse laser is dominated by the transient radiative transfer equation. A lot of numerical methods have been developed to solve transient radiative heat transfer problems, including the Monte Carlo method (MCM) [6,7], discrete ordinate method (DOM) [8,9], integral equation (IE) models [10], finite volume method FVM [11,12], the discontinuous finite element method (DFEM) [13], and the DRESOR method [14].

It needs to be noted that, the methods listed above are mainly for TRT in uniform refractive index media. However, in graded index media, the ray goes along a curved path determined by the Fermat principle. As a result, the solution to transient radiative transfer in graded index media is more difficult than that in uniform index media. In addition, due to the continuous variation of the refractive index, the speed of light does not remain unchanged and is a function of the position in the graded index media, which could bring more interesting time-resolved characteristics of radiation signals than those for the case of uniform refractive index media. The quasi-steady radiative transfer in graded index media has been investigated widely. Ferwerda [15] firstly derived the transient radiative transfer equation for scattering media with a variable refractive index. Abdallah and Dez [16] developed a curved

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Nomenclature

a	anisotropy factor
c	speed of light, m/s
$\vec{e}$	velocity of propagation of the particle distribution function along a lattice link, m/s
H	Heaviside function
I	intensity of radiation, particle distribution function in LBM for radiation, W m^{-2} sr^{-1}
I^{eq}	equilibrium particle distribution function in LBM for radiation, W m^{-2} sr^{-1}
L	geometrical thickness of the scattering slab, m
M	total number of discrete directions
n	refractive index
q	time-resolved reflectance or transmittance signal
S	source term for radiation, W m^{-2}
t	time, s
t_p	pulse-width, s

Greek symbols

β	extinction coefficient, $\kappa_a+\sigma_s$, m^{-1}
Φ	scattering phase function
κ_a, σ_s	absorption coefficient, scattering coefficient, m^{-1}
μ	direction cosine of the polar angle
σ	Stefan–Boltzmann constant, 5.67×10^{-8}, W m^{-2} K^{-4}
$\tilde{\tau}_m$	the relaxation time in LBM, s
ω	scattering albedo, σ_s/β

Subscripts

R	reflectance
T	transmittance

Superscripts

m, m'	index for direction
*	non-dimensional quantity

ray-tracing method to solve the quasi-steady radiative transfer in an absorbing–emitting slab with a spatially varying refractive index. Next, Abdallah and co-workers [17,18] extended the method to solve the quasi-steady radiative transfer in rectangular and spherical media with the graded index. After that Lemonnier and Dez [19] developed the discrete ordinates method (DOM) for the radiative transfer in a slab with a variable refractive index. Tualle et al. [20] and Khan et al. [21] separately derived two different kinds of diffusion approximations based on Ferwerda's RTE. Premaratne et al. [22] pointed out that Ferwerda's equation did not satisfy energy conservation, and so they derived a modified transient radiative transfer equation. Fumeron and Asllanaj [23] derived radiative transfer theory as a kinetic theory for photons in the Gordon spacetime. However, studies devoted to the TRT for graded index media are still relatively few. Wu [24] extended the DOM to solve the TRT in refractive planar media with pulse irradiation. Liu and Hsu [25] applied the discontinuous finite element method to the analysis of the TRT in a participating graded index medium. Wu [26] then reported the use of MCM to simulate the TRT in graded index medium. Recently Wu et al. [27] adopted the discrete ordinates method (DOM) with a first-order spatial scheme and developed a modified DOM (MDOM) to solve transient radiative transfer in a scattering slab with a variable refractive index and diffuse substrate exposed to a diffuse strong irradiation at one of its boundaries. Most recently, Wang et al. [28] extended the DRESOR method to calculate the time-resolved reflectance and transmittance of a one-dimensional anisotropically scattering medium with a linear increasing graded index subjected to a collimated truncated Gaussian pulse.

The lattice Boltzmann method (LBM) is a relatively new computational tool for simulating transport of energy and mass. In the recent decades, it has emerged as an efficient method to analyze a vast range of problems in fluid flow and heat transfer [29,30]. This surge in applications of the LBM is owing to its attractive properties of simple implementation on the computer, mesoscopic nature, ability to handle complex geometry and boundary conditions, capability of stable and accurate simulation, and the inherent parallel nature.

Over the years, the LBM has been applied to solve the energy equation of combined conduction or convection and volumetric radiation in which the radiative information has been computed using the conventional numerical methods like the DTM [31], FVM [32,33] and DOM [34]. Recently, the LBM itself has been adopted for solving radiation transport problems [35–38] where one-dimensional (1D) and two-dimensional (2D) examples were investigated. Asinari and co-workers [35] described the advantage of having common data structures for radiation intensity and fluid flow in radiative transfer and fluid mechanics problems. They extended the LBM to solve a benchmark radiative equilibrium problem for a 2-D rectangular enclosure, and the LBM was found to have an edge over the FVM. Based on the Chapman–Enskog method, Ma et al. [36] proposed the lattice Boltzmann model for 1-D radiative transfer from the Boltzmann equation. Bindra et al. [37] extended the LBM to solving 2-D radiative or neutron transport equation with considering the scattering term. Mishra and co-workers [38] applied the LBM to analysis of transport of collimated radiation in a participating media.

However, to the best of our knowledge, as a promising numerical scheme, the LBM has not been used to solve transient radiative transfer in graded index medium irradiated by the short pulse laser. In this article we present a LBM for solving the transient radiative transfer in a graded index slab containing scattering media subjected to the short laser irradiation. Up to now no works have been reported to investigate the transient radiative transfer in graded index medium with a refractive index discontinuity at the semitransparent boundary. Thus, we further extend the application of LBM to the investigation of this problem.

The outline of this paper is as below. In Section 2, the framework of lattice Boltzmann method for solving the transient radiative transfer for a graded index slab is