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Multidimensional Monte Carlo Simulation of Short-Pulse Laser Transport in Scattering Media

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The Monte Carlo technique is used to simulate the two-dimensional transient radiative heat transfer in scattering and absorbing media. The transient behavior of transmissivity and reflectivity, subject to short-pulse laser radiation incident on highly scattering media, is investigated. The influences of medium dimensions, anisotropic scattering characteristics, incident pulse width and spatial and temporal Gaussian distributions, and the effect of Fresnel reflection resulting from refractive index changes at the boundaries are discussed. It is found that the temporal distribution shape and spread of the predicted transmissivity and reflectivity are significantly influenced by the incident pulse width and the dimensions of the media. Forward scattering increases the magnitude of maximum transmissivity and reduces the transmitted pulse width. Neglecting the boundary reflection results in overestimated transmissivity and reflectivity and shortens the transmitted pulse width.

Nomenclature

A_1	=	linear anisotropic scattering coefficient
c	=	speed of light through medium, mm/ps
c_0	=	speed of light in vacuum, $= 0.3$ mm/ps
D	=	path length, mm
$H(t)$	=	Heaviside function
I_c	=	incident laser intensity, W/m^2
I_1	=	maximum value of Gaussian input pulse intensity
I_2	=	maximum value of step input pulse intensity
L	=	thickness, mm
n_s	=	refractive index
R	=	random number between 0 and 1
r	=	radial coordinate
r_i	=	radius of incident laser beam, mm
$\hat{s}$	=	unit direction vector
t	=	time, ps
t_1	=	start time of input pulse, ps
t_2	=	end time of input pulse, ps
t_p	=	pulse width of incident laser, ps
W	=	width, mm
x, y, z	=	Cartesian coordinates
θ	=	polar angle
θ'	=	polar angle measured from an axis pointing in the incoming light direction
θ_i	=	incident angle
θ_r	=	refractive angle
ρ	=	reflectance
σ_e	=	extinction coefficient, mm^{-1}
Φ	=	scattering phase function
ψ	=	circumferential angle
ψ'	=	circumferential angle measured in a plane normal to the incoming light direction
ω	=	scattering albedo

Introduction

IN the past decade, many researchers have focused on evaluating the propagation and scattering characteristics of short-pulse light transport through highly scattering media. Many applications have burgeoned due to the advent of the short-pulse laser. Examples are optical tomography of tissue, remote sensing of oceans and atmospheres, laser material processing of microstructures, and the possibilities of using short-pulse x rays for noninvasive diagnostics. A review by Kumar and Mitra[1] summarized the microscale aspects of thermal radiation transport and short-pulse laser applications.

Significant progress has been made in the development of solution methods for multidimensional radiative heat transfer in participating media in recent years. However, the analysis of radiative heat transfer in most engineering problems traditionally neglects the effect of speed-of-light propagation, even if the boundary conditions and/or the sources that are responsible for the radiative intensity vary with time. With laser pulse widths as short as picoseconds to femtoseconds,[2] neglecting the time dependence of radiative transport may induce significant errors in the prediction of transient radiation heat transfer.

Very few studies have addressed transient radiative transport. Kumar and Mitra[3] and Kumar et al.[4] are among the first to consider the entire transient radiative equation by using a variety of models for short-pulse applications. Mitra et al.[5] solve the two-dimensional wavelike transient radiative transfer equation using the P_1 approximation for a boundary-driven problem. Mitra and Kumar[6] compare several numerical models for the prediction of light pulse transport through one-dimensional scattering–absorbing media. Previously, the transient radiative transfer equation, with a source of constant strength at the boundaries, had been solved using Laplace transforms and adding-doubling methods.[7,8] Other formulations considering the entire hyperbolic radiative equation for laser pulses have not been covered in the literature, except for a brief discussion by Ishimaru.[9] Most studies consider the parabolic transient P_1 diffusion approximation, obtained by dropping certain time derivatives to parabolize the transfer equation.[10] Some of these studies have also experimentally investigated short-pulse laser transport through tissues, where the scattering albedo is very large, and have indicated that the P_1 diffusion approximation is adequate for optically thick tissue samples. However, these parabolic models have not matched experimental results in other studies.[11]

Although one-dimensional transient radiative heat transfer has been discussed broadly, the study of multidimensional transient radiative transfer is sparse. Moreover, a more realistic simulation of short-pulse laser transport is required, which would include the input of a realistic laser beam, the boundary reflection due to the

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