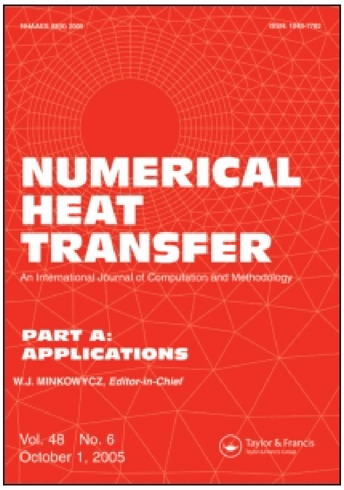

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Ultrafast Radiative Heat Transfer in Three-Dimensional Highly-Scattering Media Subjected to Pulse Train Irradiation

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ULTRAFAST RADIATIVE HEAT TRANSFER IN THREE-DIMENSIONAL HIGHLY-SCATTERING MEDIA SUBJECTED TO PULSE TRAIN IRRADIATION

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Transient radiative transfer in highly-scattering media subjected to time-dependent pulse train heating conditions is scrutinized. A basic problem in which a cube is exposed to a unit step irradiation is first solved via the transient discrete-ordinates method, and the influences of the spatial grid and time step are examined. The temporal solutions for the basic problem are then used for constructing the responses of the same cube subjected to the irradiation of pulse trains via the superposition method. The effects of the pulse width and time interval between the pulses are studied. The characteristics of pulse train irradiation are revealed. The present approach is simple because only one basic solution is needed to construct the solutions for various problems with different pulse widths and/or pulse intervals.

INTRODUCTION

Currently, laser techniques have been applied in various fields such as medical diagnosis and imaging [1, 2], laser ablation and material processing [3–5], tissue treatment and thermal therapy [6–10], and so forth. Since the advent of ultra-short pulsed lasers, the study of ultrafast radiative heat transfer in highly-scattering media, such as biological tissues, has attracted increasing attention [7–16]. The ultrafast radiative heat transfer is defined that the governing equation of radiative transfer (ERT) is time-dependent and radiation propagates with the speed of light [11–15]. It is different from the conventional transient radiative heat transfer in that only the boundary condition is time-dependent, but the ERT is still stationary.

Several numerical methods have been developed for modeling the ultrafast radiative heat transfer problems, including the stochastic Monte Carlo (MC) method [16–18], and deterministic solutions such as the radiation element method [12], the discrete-ordinates method [13–15], the finite-volume method [19], the

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NOMENCLATURE

C_k	expansion coefficient of the Legendre function
c	speed of light in medium
E_b	blackbody radiative emissive power of medium
$f(t)$	boundary condition function
G	incident radiation
I	radiation intensity
I_p	radiation intensity at the node of a control volume
L	length
N	angular discrete order in S_N approximation
n	number of angular discretization
P_k	Legendre function
Q	net radiative heat flux
$\vec{q}$	radiative heat flux
R	reflectance
$\vec{r}$	position vector
S	source term
T	transmittance
t	time
t_d	time interval between two successive pulses
t_p	pulse width
$U(t)$	unit step function
w	angular weight
x, y, z	Cartesian coordinates
Δt	time step
Δx, Δy, Δz	grid size
Φ	scattering phase function
γ	weighting factor
η, μ, ξ	direction cosines
ρ	diffuse reflectivity
σ_a	absorption coefficient
σ_e	extinction coefficient
σ_s	scattering coefficient
ω	scattering albedo

Subscripts

b	blackbody value
d	downstream surface
p	control volume index
u	upstream surface
w	wall

Superscripts

l	discrete direction index
$*$	dimensionless quantity

discrete-ordinates radiation element method [20], and the DRESOR method [21]. Initial work in this field was based on the approach of diffusion approximation [1]. Guo et al. [22] investigated the conditions where and when the diffusion approximation can be adopted and the conditions in which the diffusion approximation may provide misleading results. In 1999, Mitra and Kumar [11] pioneered accurate modeling based on the solution of the transient ERT for one-dimensional (1-D) problems. In 2000, Guo et al. [17] and Wu and Wu [23] considered 2-D problems. In 2002, Guo and co-authors first published simulation work for 3-D problems [14, 16] as well as conducted experimental validation of the models [16]. In recent years, Guo and Mitra have extended the study to incorporate combined heat transfer with conduction and/or blood perfusion [8–10], as well as applications in biomedical imaging [2].

The emphasis of the abovementioned investigations was placed on the transport of a single ultra-short pulse. The source radiation was either collimated or diffuse. The temporal profile was classified by either a step pulse or a Gaussian pulse. In reality, however, continuous pulse trains are usually applied instead. Muthukumaran and Mishra [24, 25] recently analyzed the ultrafast radiative heat transfer in 1-D and 2-D participating media subjected to a pulse train, i.e., a train of periodically-changed pulses. As pointed out by Guo and Kumar [14] as early as 2001, if blackbody emission is neglected in ultrafast radiative heat transfer, the transient ERT is actually a linear equation in terms of the radiative intensity; thus, Duhamel's superposition can be applied to the study of pulsed radiation propagation. Guo and