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Interaction of short pulse collimated irradiation with inhomogeneity: An accurate model☆

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ABSTRACT

The accurate formulation of radiative source is established with the transient effect of radiation transport for evaluating the correct thermal damage in the proximity of laser source. The accurate formulation of radiative source consists of two parts: the conventional absorption term and the propagation term. The inclusion of the propagation term significantly deviates the energy distribution from earlier steady state radiative source especially in the ultrashort time scale where this term has significance. In the present work, this effect has been investigated in the presence of absorbing, emitting, and anisotropically scattering medium within a two-dimensional rectangular domain subjected to collimated irradiation at one of its boundaries. A small inhomogeneity is taken at the center of the top wall which is irradiated with a laser source. The effects of optical parameters such as absorption coefficient, scattering coefficient, and scattering albedo on the temperature distribution in the medium are analyzed. It is found that the modified radiation energy flux gives an early signal of crossing the thermal damage threshold temperature surrounding the inhomogeneity. Inclusion of propagation term in radiation energy source helps to precisely access the extent of thermal damage surrounding the inhomogeneity which is not traceable as per the existing models.

1. Introduction

The study of short-pulsed collimated radiation transport and ultrafast matter–radiation interaction is of great scientific and technological significance and has received considerable attention over the past few years. In collimated irradiation, radiation energy propagation is strongly directional in nature with all light waves approximately parallel to one another. Potential application of collimated irradiation can be found in laser applications. Many laser applications involve interaction of light with biological tissue during laser microsurgery [1,2], laser-induced hyperthermia [3], optical tomography [4], and other laser therapeutic applications [5]. Most of these laser medical treatments are concerned with the thermal effect where transient radiation transport in participating medium plays a key role [6,7] in understanding the transport mechanism involved in all these abovementioned applications.

Analysis of all these above applications involves transient radiation transport in absorbing, emitting, and scattering media. There exist various analytical and numerical models of transient radiative transfer which are thoroughly reviewed by Mitra and Kumar [8]. Commonly used methods to solve the transient radiative transfer equation are the Monte Carlo method (MC) [9], the discrete ordinate method (DOM) [10], the discrete transfer method (DTM) [11], P1 approximation method [12], the integral equation solution [13,14], the finite volume method (FVM) [15,16], the radiation element method (REM) [17], and the lattice boltzmann method (LBM) [18].

Over the years, several models are developed to predict medium temperature while solving the transient radiative transfer equation (TRTE) coupled with energy equation in submicron time scale [19–21]. In all these models, the conventional steady divergence of flux is used to calculate the radiation source term in the energy equation. However, in a time scale less than the characteristic time scale of photon, where transient radiation effect cannot be neglected, the divergence of radiative heat flux needs to be modified in order to take into account the transient effect of photon transport.

Rath and Mahapatra [22] have modified the radiative source taking into account the transient effect of radiation transport and studied its effect on the temperature distribution inside the participating medium. They found that the steady radiative source underpredicts the temperature. Later, Hunter and Guo [23] re-derived the modified radiative source and called the additional transient term as propagation term. However, they argued that the propagation term does not contribute to the energy deposition in the medium and hence will not affect the temperature inside the medium. Effect of transient radiative source on energy deposition has not yet been addressed properly. Still, more investigation is necessary to understand the effect of transient radiative source on the temperature history in the medium particularly in the ultrashort time scale where propagation term has significance.

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Nomenclature

a	Linear anisotropy factor
c	Speed of photon
C	Specific heat
CN_R	Collimation number
D_{cz}	Direction cosine
G	Incident radiation energy
H	Heavy step function
I	Intensity
I_o	Peak intensity
$\hat{n}$	The unit outward normal vector
q	Heat flux
s	Distance
t	Time
T	Temperature
V	Volume
x	Dimensionless length in x-direction
y	Dimensionless length in y-direction

Greek symbols

β	Extinction coefficient
θ	Polar angle
ϕ	Azimuthal angle
δ	Dirac delta function
∇	Divergence operator
Ω	Solid angle
τ	Optical thickness
Φ	Scattering phase function
σ_s	Scattering coefficient
Γ	Zone
ω	Scattering albedo
ρ	Sensity

Superscripts

l	Index for the discrete direction
$*$	Non-dimensional parameter
PI	Previous iteration value
o	Value from previous time step

Subscripts

b	Blackbody
c	Collimation
r	Spatial location
D	Downstream
inh	Inhomogeneity
m	Modified
P	Node
P^*	Value from previous iteration
th	Threshold
U	Upstream

Accurate estimation of temperature history in the laser irradiated zone is essential in laser micro surgery to prevent the thermal damage in the surrounding healthy tissues. Looking at this gap in the above studies, the present paper focuses on the study of the effect of radiative source on the energy dissipation in the medium in the ultrashort time scale. Earlier formulation of Rath and Mahapatra [22] has been extended in the present article to address the effect of collimated irradiation with local inhomogeneity in the present article. The anisotropic scattering medium is also taken into account in the present article.

This article is divided into five sections. In the next section, the physical problem is described. The finite volume discretization of TRTE is presented in the numerical method section followed by overall solution procedure. The results of the chosen problem are discussed in the results and discussion section followed by conclusion.

2. Physical problem description

A two-dimensional anisotropically scattering medium with a small inhomogeneity at the center of the top wall is chosen to study the thermal damage surrounding the inhomogeneity while treating the inhomogeneity with a laser source. The schematic of the present problem and the computational domain are shown in Fig. 1a. The laser beam is irradiated on the top of inhomogeneity of size 0.25 m × 0.25 m. The optical properties of the medium are assumed to be constant with different value in the region of inhomogeneity. The initial temperature (at $t = 0$) within the medium including the inhomogeneity is maintained at 310 K, which closely resembles the healthy living tissue temperature. Suddenly, at $t > 0$, the top wall of the inhomogeneity is subjected to laser irradiation of intensity I_o. Being apart from the laser irradiation zone, the left, right, and bottom boundaries are maintained at the initial temperature, i.e. 310 K. The conduction heat transfer inside the medium is neglected in the ultrashort time scale (time scale less than the thermal relaxation time). Under this assumption, the temperature distribution in the medium is governed by the following energy equation [20].

$$\rho C_p \frac{\partial T}{\partial t} = -\nabla \cdot q_r \tag{1}$$

Based on the new generalized formulation taking into account the transient effect of thermal radiation, the divergence of radiative heat flux [22,23] is given as

$$\nabla \cdot q_r = \kappa[4\pi I_b(r,t) - G(r,t)] - \frac{1}{c}\frac{\partial G(r,t)}{\partial t} \tag{2}$$

The incident radiation, $G(r, t)$ can be obtained by solving the TRTE [24], which is given as

$$\frac{1}{c}\frac{\partial I(r,\hat{s},t)}{\partial t} + \hat{s}\cdot\nabla I(r,\hat{s},t) = -\beta I(r,\hat{s},t) + kI_b(r,t) + \frac{\sigma_s}{4\pi}\int_{4\pi} I(r,\hat{s}',t)\Phi(r,\hat{s}',\hat{s},t)d\Omega' \tag{3}$$

The temperature T inside the medium can be obtained by solving energy equation with the following initial and boundary conditions.

$$T(r,t=0) = 310\ K,\ \text{ in }\ \Omega(\mathrm{r}) \tag{4a}$$

$$T(r,t>0) = 310\ K,\ \text{ at }\ \Gamma_1,\Gamma_2\ \text{ and }\ \Gamma_3 \tag{4b}$$

$$q(r,t>0) = 0,\ \text{ at }\ \Gamma_4,\ \Gamma_5\ \text{ and }\ \Gamma_6 \tag{4c}$$

$$I(r,t) = I_o[H(t) - H(t-t_{th})]\,\delta\left(\theta-\theta_c^l\right)\delta\left(\phi-\phi_c^l\right),\ \text{ at }\ \Gamma_5 \tag{4d}$$

where, t_{th} is the time required to reach to the damage threshold temperature surrounding the inhomogeneity. In Eq. (3), a linear anisotropic phase function (Φ) is taken, which is given as

$$\Phi(\hat{s}',\hat{s}) = 1 + a(\hat{s}',\hat{s}) \tag{5}$$

where a is the linear anisotropy factor.