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Transient coupled heat transfer in an anisotropic scattering composite slab with semitransparent surfaces

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ABSTRACT

Transient heat transfer of coupled radiation and conduction inside a semitransparent composite slab of absorbing–emitting-anisotropic scattering medium is examined. The composite slab includes two layers with different physical properties. Surfaces and interface between two layers are supposed to be semitransparent and total reflection will occur there at the critical angle. Specular reflection is considered and reflectivities are determined by Fresnel's law and Snell's law. A fully implicit control-volume method is used to solve the transient energy equation and a ray-tracing/nodal-analyzing method is used to compute the radiative information. A criterion for total reflection is proposed for solving the problem of integral singularity at the critical angle. Effects of conduction–radiation parameter, scattering albedo and refractive index on coupled heat transfer are investigated. Results show that in a semitransparent medium with natural surfaces, there are two sorts of temperature peaks appearing at transient heat transfer: one is caused by external radiation heating and environmental convection cooling, still existing in steady state; the other is due to maximum of absorption of heat caused by inhomogeneous optical properties, only existing in transients of heat transfer.

1. Introduction

Coupled radiative and conductive heat transfer is the main mode of energy transfer in a semitransparent solid medium at elevated temperatures, in high temperature surroundings, with large incident radiation, or in vacuum circumstances with weak convection of low and moderate temperature. Some errors will be caused if only considering conduction or radiation. For a long time, considerable attention has been given to the problem for its many important applications, such as multilayer spaceborne optical windows, combustion fabrication device, the insulation properties of fibrous and ceramic materials.

A solution to coupled radiation–conduction involves two parts: the solution to the radiative transfer equation, and the solution to the energy equation. An evaluation of the former can adopt such methods as DOM (discrete ordinates method), DTM (discrete transfer method), flux method, RTNAM (ray-tracing/nodal-analyzing method), zone method, FVM (finite-volume method) and so on. The latter can be solved using FDM (finite difference method), FVM, FEM (finite element method), LBM (lattice Boltzmann Method) and meshless method.

Muresan et al. [1] solved the coupled conductive radiative heat transfer in a two-layer non-scattering slab with Fresnel interfaces subject to diffuse and obliquely collimated irradiation using a DOM for the solution to the radiative transfer problem and a FDM for the solution to the energy equation. In Ref. [1], adaptive directional quadratures were developed to overcome the difficulties usually encountered at the interfaces. Mishra et al. [2] examined transient conductive–radiative heat transfer in a 2-D rectangular enclosure filled with an optically absorbing, emitting and scattering medium using LBM for the solution to the energy equation and the collapsed dimension method for the radiative transfer equation, and analyzed the effects of the conduction–radiation parameter, extinction coefficient and scattering albedo. Using DOM/FDM for the solution to the radiative transfer equation and the energy equation, David et al. [3] investigated transient heat transfer involving radiation and conduction in a 2-D non-gray purely absorbing glass. Using FVM/LBM, the transient conduction–radiation heat transfer in 1-D planar and 2-D rectangular geometries was solved, and effects of the scattering albedo, the conduction–radiation parameter and the boundary emissivity were analyzed [4].

Most of the previous work on radiative heat transfer only considered isotropic scattering or non-scattering in the semitransparent material. However, it is well known that scattering of thermal radiation by real particles, fibers, or impurities in a medium is by no means isotropic and that the anisotropic scattering can play a significant role on overall heat transfer. Consequently it is necessary to carry on an investigation in radiative heat transfer within

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Nomenclature

C_n	specific volume heat capacity of the layer n, $=c_n\rho_n$, J m^{-3} K^{-1}
FV_n	a direct exchange area of V_i vs V_i in the nth layer, equal to $FV_n = 4\kappa_n\Delta x_n - 2[1 - E_3(\kappa_n\Delta x_n)]$, n = 1, 2
h_1, h_2	convective heat transfer coefficient at surfaces of S_1 and S_2, respectively, W m^{-2} K^{-1}
H_1, H_2	convection–radiation parameter, $H_1 = h_1/\sigma T_r^3$ and $H_2 = h_2/\sigma T_r^3$
L	thickness of the composite medium, m
k_n	thermal conductivity of the nth layer, W m^{-1} K^{-1}, n = 1, 2
k_{ie}, k_{iw}	harmonic mean thermal conductivity at interface ie and iw of control volume i, respectively
N_n	$k_n/(4\sigma T_r^3 L)$, conduction–radiation parameter of the nth layer, n = 1, 2
N_{cv1}, N_{cv2}	number of control volumes in the first layer and the second layer, respectively
M_t	total number of control volumes of the composite medium
n_i	refractive index of the control volume i; when $i \leqslant N_{cv1}$, n_i is equal to the refractive index of the first layer, and when $i > N_{cv1}$, n_i is equal to the refractive index of the second layer
n_n	refractive index of the nth layer, n = 1, 2
S_u, S_v	black surfaces, $S_{-\infty}$ and $S_{+\infty}$, respectively
S_1, S_2	boundary surfaces
$S_{-\infty}$, $S_{+\infty}$	black surfaces representing the surroundings
(S_uS_v), (S_uV_j), (V_jS_u), (V_iV_j)	absorbing RTCs of surface vs surface, surface vs volume, volume vs surface and volume vs volume
$[S_uS_v]$, $[S_uV_j]$, $[V_jS_u]$, $[V_iV_j]$	scattering RTCs of surface vs surface, surface vs volume, volume vs surface and volume vs volume
T	absolute temperature, K
T_{g1}, T_{g2}	gas temperatures for convection, K
T_r,T_0	reference temperature, initial temperature, K
t	physical time, s
t^*	dimensionless time, $(4\sigma T_r^3/C_nL)t$, only for the case of C_n = constant
x_i^j	normal distance between element i and element j, m
β_n	a common ratio of geometric progression when the radiation transfers in the nth layer, n = 1, 2
β_{ij}	a common ratio of geometric progression when the radiation enters the jth layer from the ith layer and transfers inside the two-layer medium
γ_{ij}	transmissivity at interface when radiation enters the j layer from the i layer, equal to $1 - \rho_{ij}$
Δt	time interval, s
Δx_n	thickness of each control volume of the nth layer, m
δ_{ij}	a Dirac functor; if $i = j$, then δ_{ij} = 1, and if $i \neq j$, then δ_{ij} = 0
$(\delta x)_{ie}$, $(\delta x)_{iw}$	distance between nodes i and i + 1 and between i and $i - 1$, respectively
η_n	$1 - \omega_n$, n = 1, 2
$\Theta_n^q(\theta)$, $\Theta_n^h(\theta)$	radiative energy distribution function of forward scattering and backward scattering respectively, for the nth layer, n = 1,2
θ, θ_s	incident angle, scattering angle, rad
θ_{ij}	refractive angle when radiation enters the j layer from the i layer
κ_n	extinction coefficient of the nth layer, m^{-1}, n = 1, 2
ρ_{ij}	reflectivity at interface when radiation enters the j layer from the i layer
σ	Stefan–Boltzmann constant, =5.6696 × 10^{-8} W m^{-2} K^{-4}
Φ_n	scattering phase function of the nth layer, n = 1, 2
Φ_i^r	radiative heat source of the control volume i
ω_n	scattering albedo of the nth layer, n = 1, 2

Subscripts

$\parallel, \perp$	component for parallel and perpendicular polarization, respectively
ie,iw	right and left interface of control volume i
$-\infty$, $+\infty$	black surfaces $S_{-\infty}$ and $S_{+\infty}$, respectively

Superscripts

b,f,t	incidence radiation from negative, positive and both direction relative to the x axis, respectively
h, q	backward scattering and forward scattering relative to the incident direction, respectively
r	radiation

anisotropic scattering participating medium. Much attention has been focused by many researchers on the problem [5–19].

Using the zone method, Goyheneche and Sacadura [7] established a new explicit matrix relation for the calculation of the total exchange areas (TEA) in emitting, absorbing and linearly anisotropic scattering semitransparent medium with black surfaces. Chai [9] presented a FVM to calculate transient radiative transfer in two-dimensional irregularly shaped enclosures with anisotropic scattering. Elghazaly [16] used the Galerkin-iterative technique to solve the coupled conductive–radiative transfer problem in a slab with two homogeneous layers of linearly anisotropic scattering with specularly reflecting boundaries and analyzed the effects of phase functions and anisotropic scattering coefficient on heat fluxes. Reflectivity was supposed to be zero in Ref. [16]. Zhou et al. [17] adopted the DRESOR method to deal with the radiative transfer in an anisotropic scattering, emitting, absorbing, plane-parallel medium with opaque surfaces, analyzing the effects of anisotropic scattering coefficient, scattering albedo and optical thickness. Asllanaj et al. [19] investigated transient radiative–conductive heat transfer in a fibrous medium with anisotropic optical properties using two-flux method/FEM for the solution to the radiative transfer equation and the energy equation.

The RTNAM was firstly proposed by Tan and Lallemand [20] and its advantage is that when solving radiative transfer equation, the radiative intensity does not need to be dispersed along the space coordinate, and the solid angle is not dispersed but is directly integrated. Thus, false scattering and ray effect will not exist in the method. So, the accuracy of this method is high in theory. Sadooghi et al. [21,22] and Sharbati et al. [23] adopted the method for the solution to the radiative transfer and investigated the coupled heat transfer in a purely absorbing ceramic layer [21,22] and a cellulose acetate layer [23]. Tan et al. [24,25] developed a two-layer [24] and a multilayer [25] radiative transfer model using RTNAM and solved the transient coupled heat transfer. Scattering was not considered in Refs. [21–23] and anisotropic scattering was not considered in Refs. [24,25]. After that, using this method, Tan et al. [26] built a radiative heat transfer model for an anisotropic scattering layer.

Present work develops a radiative transfer model for a two-layer composite with anisotropic scattering using the RTNAM. In this paper, RTCs (radiative transfer coefficients) include all information about the radiative transfer, and they are deduced by the ray-tracing method. Local radiative heat source in the energy equation is expressed in terms of RTCs and is deduced using the nodal-analyzing method. Semitransparent interfaces between two layers