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Three-Dimensional Transient Radiative Transfer Modeling Using Discontinuous Spectral Element Method

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Nomenclature

A	=	area, m^2
a	=	anisotropy parameter of linear anisotropic-scattering phase function
c	=	speed of light, m/s
G	=	integrated intensity, as defined by Eq. (8a), W/m^2
$\mathbf{H}$	=	matrix, as defined in Eq. (7)
h	=	one-dimensional standard nodal basis function
$\hbar$	=	three-dimensional standard nodal basis function
I	=	radiative intensity, $W/(m^2 \cdot sr)$
I_b	=	blackbody radiative intensity, $W/(m^2 \cdot sr)$
I_p	=	transient intensity on the boundary, $W/(m^2 \cdot sr)$
I_0	=	amplitude of transient intensity, $W/(m^2 \cdot sr)$
K	=	general hexahedral element
K_{st}	=	standard hexahedral element
$\mathbf{k}$	=	unit direction vector of z direction
L_R	=	reference length scale, m
$\mathbf{M}$	=	matrix, as defined in Eq. (7)
M	=	number of discrete-ordinate directions
N_{sk}	=	number of solution nodes on each element
N_t	=	number of discretized time steps
N_θ	=	number of subdivisions for a zenith angle
N_φ	=	number of subdivisions for an azimuthal angle
$\mathbf{n}_w$	=	unit normal vector of the wall
$\mathbf{n}_{\partial K}$	=	unit normal vector at the boundary of element K
p	=	order of polynomial expansion
q_z	=	heat flux of z direction, as defined by Eq. (8b), W/m^2
$\mathbf{r}$	=	vector of spatial coordinates (x, y, z)
$\tilde{S}$	=	function, as defined in Eq. (7d), W/m^3
T	=	temperature, K
t	=	time, s
t^*	=	dimensionless time ct/L_R, dimensionless time step
u	=	unit step function
V	=	volume, m^3
w	=	weight of discrete-ordinates approximation, sr
x, y, z	=	global coordinate system variables
$\mathbf{x}_{st}$	=	local coordinate vector (x_{st}, y_{st}, z_{st})
x_{st}, y_{st}, z_{st}	=	reference coordinate system variables
β	=	extinction coefficient $(\kappa_a + \kappa_s)$, m^{-1}
$\tilde{\beta}$	=	function, as defined in Eq. (7c), m^{-1}
Δt^*	=	dimensionless time step
θ	=	zenith angle
κ_a	=	absorption coefficient, scattering coefficient, m^{-1}
κ_s	=	scattering coefficient, m^{-1}
ρ	=	bidirectional reflection function
σ	=	Stefan–Boltzmann constant, $W/(m^2 \cdot K^4)$
τ_L	=	optical thickness, βL
τ_p	=	transmissivity
Φ	=	scattering phase function
ϕ	=	global nodal basis function
φ	=	azimuthal angle
ψ	=	map function, as defined by Eq. (5)
Ω	=	solid angle, sr
$\mathbf{\Omega}$	=	unit vector of the radiation direction
ω	=	single scattering albedo

Subscripts

i	=	mapped one-dimensional index
i', j', k'	=	elemental spatial node index
l	=	node index of the standard hexahedral element
n	=	time step index
w	=	value at wall

Superscripts

m, m'	=	index of discrete-ordinate direction

I. Introduction

TRANSIENT radiative transfer within a participating medium has attracted the interest of many researchers due to the availability of short-pulse lasers and their application to many emerging new technologies [1–3]. A number of methods have been developed to solve the transient radiative transfer equation (TRTE); such as the Monte Carlo method [4], the integral equation method [5], the discrete-ordinates method (DOM) [6,7], and the finite volume method (FVM) [8]. Among them, the methods based on the differential form of the TRTE, such as the DOM and the FVM, are efficient and easy to apply to problems with complex media and boundary conditions. However, the DOM and the FVM suffer from large false scattering, and the transient wave front cannot be captured efficiently and accurately.

Recently, based on a discontinuous Galerkin (DG) approach, Liu and Hsu [9] developed and analyzed transient radiative transfer in two-dimensional graded index media using a discontinuous finite element method (DFEM). In the DG approach, the approximation space is composed of discontinuous functions, which is expected to be ideal in solving transient radiative transfer problems and accurately capturing the sharp wave fronts. The DFEM showed good performance in solving the transient radiative transfer problems. As an advanced version of the DFEM, a discontinuous spectral element

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method (DSEM) [10] that enriches the DFEM due to the high-order accuracy of the spectral method, was developed to solve transient radiative transfer problems. The DSEM was shown to be efficient and accurate in capturing the sharp wave front of the transient radiative transfer process. However, performance of the DSEM has only been examined in one- and two-dimensional cases.

In this note, the DSEM is formulated and applied to solve the three-dimensional transient radiative transfer problems. Its performance in solving three-dimensional transient radiative transfer is studied and verified.

II. Transient Radiative Transfer Equation

The discrete-ordinates form of the TRTE for an absorbing, nonemitting, and scattering medium can be written as [11]

$$\frac{\partial I^m(\mathbf{r},t)}{c\partial t} + \boldsymbol{\Omega}^m \bullet \nabla I^m(\mathbf{r},t) + \beta I^m(\mathbf{r},t) = \frac{\kappa_s}{4\pi}\sum_{m'=1}^{M} I^{m'}(\mathbf{r})\Phi(\boldsymbol{\Omega}^m,\boldsymbol{\Omega}^{m'})w^{m'} \tag{1a}$$

with the boundary condition and initial condition given as [11]

$$I^m(\mathbf{r}_w,t) = I_p(\mathbf{r}_w,\boldsymbol{\Omega}^m,t)\tau_p(\mathbf{r}_w,\boldsymbol{\Omega}^m) + \sum_{\mathbf{n}_w\bullet\boldsymbol{\Omega}^{m'}<0} \rho(\mathbf{r}_w,\boldsymbol{\Omega}^m,\boldsymbol{\Omega}^{m'})I_w^{m'}|\mathbf{n}_w\bullet\boldsymbol{\Omega}^{m'}|w^{m'} \qquad \mathbf{n}_w\bullet\boldsymbol{\Omega}<0 \tag{1b}$$

$$I(\mathbf{r},\boldsymbol{\Omega},t) = 0, \qquad t = 0 \tag{1c}$$

The DSEM is then developed, based on Eqs. (1), to model transient radiative transfer processes.

III. Discontinuous Spectral Element Method Discretization

The radiative intensity field of the nth time step and direction $\boldsymbol{\Omega}^m$ is approximated in a function space spanned by Chebyshev nodal basis functions defined on an element K as [10]

$$I_n^m(\mathbf{r}) \simeq \sum_{i=1}^{N_{sk}} I_{n;i}^m \phi_i(\mathbf{r}) \tag{2}$$

where $I_{n;i}^m$ denotes the radiative intensity of the ith node and ϕ_i is the nodal basis function of node i defined on K. In the present study, the solution domain is subdivided into hexahedral elements. The standard element K_{st}, defined in the reference coordinate system as shown in Fig. 1, is a cube:

$$K_{\mathrm{st}}\colon\ x_{\mathrm{st}}, y_{\mathrm{st}}, z_{\mathrm{st}}[-1,1]$$

The three-dimensional nodal basis function defined on K_{st} is formulated as

$$\hbar_i(x_{\mathrm{st}},y_{\mathrm{st}},z_{\mathrm{st}}) = h_{i'}(x_{\mathrm{st}})h_{j'}(y_{\mathrm{st}})h_{k'}(z_{\mathrm{st}}) \qquad i',j',k' = 1,\ \ldots,\ p+1, \qquad i = 1,\ \ldots,\ (p+1)^3 \tag{3}$$

where $h_{i'}$ is the one-dimensional Chebyshev nodal basis function defined on $[-1,1]$ [12] and i is an index map defined as

$$i = i(i',j',k') = i' + (j'-1)(p+1) + (k'-1)(p+1)$$

and p is the order of the Chebyshev polynomial expansion.

The elemental nodal basis function $\phi_i(x,y,z)$, defined on a general hexahedron element K, can be obtained from the reference basis function $\hbar_i(x_{\mathrm{st}},y_{\mathrm{st}},z_{\mathrm{st}})$ defined on the standard element K_{st} using a coordinate transformation, as depicted in Fig. 1. The coordinate transformation is defined based on the coordinates of the eight vertices of K_{st} ($\mathbf{x}_{\mathrm{st},l}$, $l = 1,\ \ldots,\ 8$), as shown in Fig. 1, and the corresponding coordinates of the eight vertices of K and $\mathbf{r}_l$ as

$$\mathbf{r}(\mathbf{x}_{\mathrm{st}}) = \sum_{l=1}^{8} \mathbf{r}_l \psi_l(\mathbf{x}_{\mathrm{st}}), \qquad \mathbf{r} = (x,y,z) \in K \qquad \mathbf{x}_{st} = (x_{\mathrm{st}},y_{\mathrm{st}},z_{\mathrm{st}}) \in K_{\mathrm{st}} \tag{4}$$

where ψ_l is a mapping function related to the vertex $\mathbf{x}_{\mathrm{st},l}$ that is defined as

$$\psi_l(\mathbf{x}_{\mathrm{st}}) = \tfrac{1}{8}[1+\mathrm{sign}(x_{\mathrm{st},l})x_{\mathrm{st}}][1+\mathrm{sign}(y_{\mathrm{st},l})y_{\mathrm{st}}][1+\mathrm{sign}(z_{\mathrm{st},l})z_{\mathrm{st}}] \qquad l = 1,\ \ldots,\ 8 \tag{5}$$

Then, $\phi_i(x,y,z)$ is obtained from $\hbar_i(x_{\mathrm{st}},y_{\mathrm{st}},z_{\mathrm{st}})$ as

$$\phi_i(\mathbf{r}) = \phi_i[\mathbf{r}(\mathbf{x}_{\mathrm{st}})] = \hbar_i(\mathbf{x}_{\mathrm{st}}), \qquad \mathbf{r}\in K, \qquad \mathbf{x}_{\mathrm{st}}\in K_{\mathrm{st}} \tag{6}$$

By substituting the three-dimensional spectral approximation of the intensity field [Eq. (2) into the TRTE Eqs. (1)] and following the general discontinuous Galerkin approach outlined in the preceding work [10,13], the final DSEM discretization of Eqs. (1) over element K at the nth time step is obtained as

$$\mathbf{M}_n^m \mathbf{I}_n^m = \mathbf{H}_n^m, \qquad n = 1,\ \ldots,\ N_t \tag{7a}$$

where the matrices $\mathbf{M}_n^m$ and $\mathbf{H}_n^m$ are defined, respectively, as

$$M_{n;ji}^m = -\int_K \phi_i \boldsymbol{\Omega}^m \bullet \nabla\phi_j \,\mathrm{d}V + \frac{1}{2}\int_{\partial K}(\boldsymbol{\Omega}^m\bullet\mathbf{n}_{\partial K} + |\boldsymbol{\Omega}^m|)\phi_i\phi_j\,\mathrm{d}A + \int_K \tilde{\beta}_n\phi_i\phi_j\,\mathrm{d}V \tag{7b}$$

$$H_{n;j}^m = \int_K \tilde{S}_n^m\phi_j\,\mathrm{d}V - \frac{1}{2}\int_{\partial K}(\boldsymbol{\Omega}^m\bullet\mathbf{n}_{\partial K} - |\boldsymbol{\Omega}^m|)I_n^{m,-}\phi_j\,\mathrm{d}A \tag{7c}$$

where the superscript operator $-$ denotes the values at the outside of element K [10], in which $\tilde{\beta}_n$ and $\tilde{S}_n(\mathbf{r},\boldsymbol{\Omega})$ are defined, respectively, as

$$\tilde{\beta}_n = \frac{2}{L_R\Delta t^*} + \beta \tag{7d}$$

$$\tilde{S}_n^m(\mathbf{r}) = \frac{\kappa_s}{4\pi}\sum_{m'=1}^{M}[I_n^{m'}(\mathbf{r}) + I_{n-1}^{m'}(\mathbf{r})]\Phi(\boldsymbol{\Omega}^m,\boldsymbol{\Omega}^{m'})w^{m'} - \boldsymbol{\Omega}^m \bullet \nabla I_{n-1}^m(\mathbf{r}) - \left[\beta - \frac{2}{L_R\Delta t^*}\right]I_{n-1}^m(\mathbf{r}) \tag{7e}$$

where L_R is a reference length and is selected as the characteristic length of the problem, $t^* = ct/L_R$ is dimensionless time and Δt^* is the dimensionless time step. The matrix equations given by Eqs. (7) are solved element by element, at each time step, through Gaussian elimination.

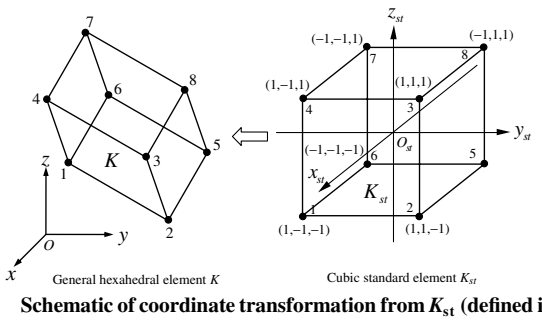

Fig. 1 Schematic of coordinate transformation from K_{st} (defined in the reference coordinate system $x_{\mathrm{st}}, y_{\mathrm{st}}, z_{\mathrm{st}}$) to K (in the global coordinate system x, y, z).

Table 1 Boundary condition and medium property for different cases

Case	Bottom boundary, $z = 0$[a]	Medium property	Other boundaries
1	Diffuse emission, $I_p = I_0 u(t)$, $I_0 = 1$ W/m$^2 \cdot$ sr	Isotropic scattering, $\tau_L = 1$, $\omega = 0.1$	Transparent, nonreflective
2	Diffuse emission, $I_p = I_0 u(t)$, $I_0 = 1$ W/m$^2 \cdot$ sr	Linear anisotropic scattering: $\Phi = 1 + a\boldsymbol{\Omega} \bullet \boldsymbol{\Omega}'$ $\tau_L = 1$, $\omega = 1$, $a = -1, 0, 1$	Transparent, nonreflective
3	Collimated intensity in z direction, $I_p = I_0 u(t)\delta(\boldsymbol{\Omega} - \mathbf{k})$, $I_0 = 1$ W/m$^2 \cdot$ sr	Isotropic scattering, $\tau_L = 0.1, 1, 2$, $\omega = 1$	Transparent, nonreflective

[a]Here, $u(t)$ is the unit step function, which is unity for $t > 0$, and zero otherwise; $\mathbf{k}$ is the unit direction vector of the z direction.

IV. Results and Discussion

The DSEM described previously is applied to solve the transient radiative transfer problem in a cubic medium of side length L for the boundary-driven problems listed in Table 1. As for a numerical solution, the cubic medium is defined in the global coordinate system (Fig. 1) with $x, y, z \in [0, L]$ and will thereafter be subdivided into many small rectangular hexahedral elements, as described in Sec. III, during the DSEM solution. The medium is initially cold. In the first case, diffuse radiation emits from the bottom wall $z = 0$ of the cube at $t = 0$ and then travels in the medium at a finite speed c. At any given time of t, the wave front will travel a distance of $z = ct$ and the dimensionless time of $t^* = ct/L = z/L$ will give the exact fractional position of the wave front.

The transient incident radiation function (or integrated intensity) $G(x, y, z, t)$ and the z-direction transient radiative heat flux $q_z(x, y, z, t)$ distribution along the centerline of the cube ($x = 0$, $y = 0$) obtained by DSEM for case 1 are presented in Figs. 2a and 2b, respectively. The transient incident radiation function and radiative heat flux of the z direction is defined and computed as

$$G(x, y, z, t) = \int_0^{2\pi} \int_0^{\pi} I(x, y, z, t, \theta, \varphi) \sin\theta \, \mathrm{d}\theta \, \mathrm{d}\varphi \qquad (8a)$$

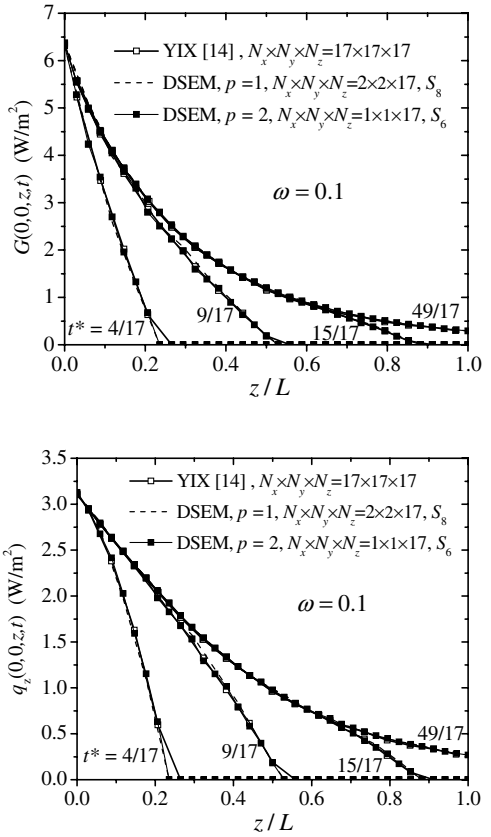

Fig. 2 Transient incident radiation function and heat flux distribution along the centerline of a cube with one diffusive emission boundary: a) incident radiation function and b) heat flux.

$$q_z(x, y, z, t) = \int_0^{2\pi} \int_0^{\pi} I(x, y, z, t, \theta, \varphi) \cos\theta \sin\theta \, \mathrm{d}\theta \, \mathrm{d}\varphi \qquad (8b)$$

The results obtained using the YIX method [14] (named after the shape of the pattern of the integration points for three, two, and four angular directions) are also shown as a comparison. Here, two mesh decomposition schemes are used for the DSEM: namely, $N_x \times N_y \times N_z = 2 \times 2 \times 17$ elements in which $p = 1$ and $N_x \times N_y \times N_z = 1 \times 1 \times 17$ elements in which $p = 2$, where N_x, N_y, and N_z denote the number of elements (subdivisions) for corresponding dimensions. These two spatial decompositions require comparable computational effort. The angular discretization uses the S_N approximation [15]. The direct component of diffuse irradiation is discretized into $N_\theta \times N_\varphi = 60 \times 120$ as equivalent beams by a piecewise constant approximation (PCA) scheme, following the special treatment described in [10]. For the temporal discretization, the dimensionless time step is taken as $\Delta t^* = 1/34$. The typical computation time for this case when using a Pentium 4, 1.8 GHz computer is about 30 min. Generally, for different instants in time, the results of the DSEM agree very well with the results of the YIX method [14]. The maximum relative error based on the results of the YIX method is less than 3%. It is seen that the higher-order approximation ($p = 2$) gives better accuracy. Because the DSEM allows discontinuities at the element boundary, it ensures accurate prediction of the wave front when it is located on the element boundary. This characteristic of the DSEM agrees well with the examination conducted in one and two dimensions [10].

In the second case, the DSEM is applied to model transient radiative transfer in an anisotropically scattering medium. The scattering phase function of the medium is $\Phi(\boldsymbol{\Omega}, \boldsymbol{\Omega}') = 1 + a\boldsymbol{\Omega} \bullet \boldsymbol{\Omega}'$. For $a = -1$, 0, and 1, the phase function is backward, isotropic, and forward scattering, respectively. The transient incident radiation and the radiative heat flux distribution along the centerline of the cube ($x = 0$, $y = 0$), obtained by the DSEM for case 2, are shown in Figs. 3a and 3b, respectively. The cube is decomposed into $N_x \times N_y \times N_z = 2 \times 2 \times 17$ elements in which $p = 2$ for the spectral element approximation. The angular discretization is by the S_6 approximation. The direct component of diffuse irradiation is discretized into $N_\theta \times N_\varphi = 160 \times 80$ equivalent beams by the PCA scheme. The DSEM accurately predicts the wave front at different instants of time. Compared with isotropic scattering, forward scattering significantly enhances heat flux, which is the opposite for backward scattering. This is reasonable because more energy emitted from the bottom wall is scattered upward (in the positive z direction) for forward scattering, and vice versa for backward scattering. The effect of different phase functions on the incident radiation results in more complex behavior. At a given instant in time, both enhancement and weakening happens in the incident radiation curve.

A collimated beam propagating through a purely isotropic scattering medium of three different optical thicknesses (namely, $\tau_L = 0.1$, 1, and 2) is considered in the third case. The beam enters the bottom wall of the cube and transmits in the z direction. The transient incident radiation and the radiative heat flux distribution along the centerline of the cube ($x = 0$, $y = 0$) obtained by the DSEM for case 3 are shown in Figs. 4a and 4b, respectively. In this study, the cube is divided into $N_x \times N_y \times N_z = 4 \times 4 \times 10$ elements in which $p = 2$ for the spectral element approximation. The angular discretization uses the S_8 approximation. The dimensionless time step is taken as $\Delta t^* = 0.02$. Here, the dimensionless time t^* gives the position of the wave front, as was the situation for the former cases.

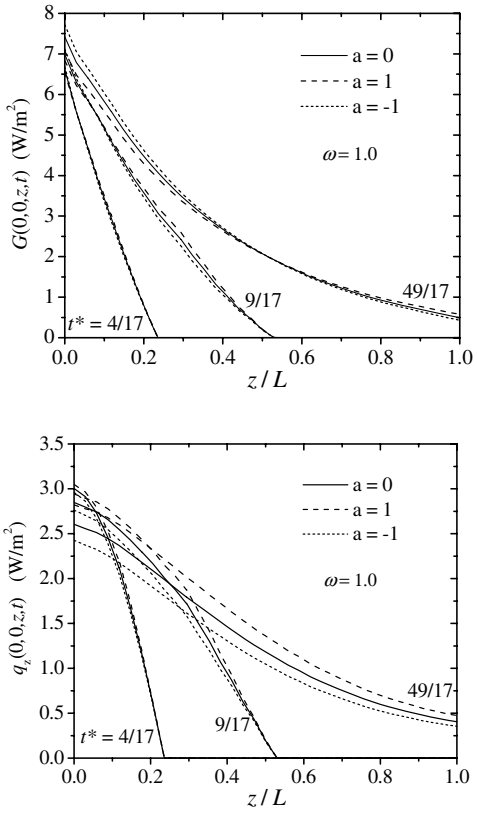

Fig. 3 Transient incident radiation function and heat flux distribution along the centerline of a cube filled with linear anisotropic-scattering medium: a) incident radiation function and b) heat flux.

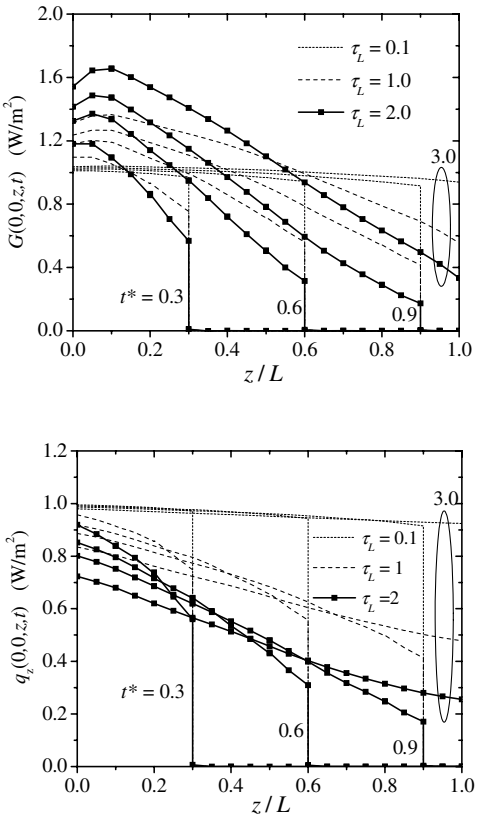

Fig. 4 Transient incident radiation function and heat flux distribution along the centerline of a cube with one collimated intensity emitting boundary: a) incident radiation function and b) heat flux.

The DSEM accurately predicts the transient sharp wave fronts for different instants in time. With increasing optical thickness, the scattering effect is enhanced. A peak appears in the incident radiation curve at each instant in time. The position of maximum incident radiation is not at the bottom wall, due to the scattering contribution. At each instant in time, the heat flux distribution monotonically decreases with increasing optical thickness. The DSEM shows very good performance in solving a transient collimated beam radiative transfer problem and can accurately capture the sharp wave fronts.

V. Conclusions

DSEM is presented to solve transient radiative transfer problems in a three-dimensional semitransparent medium. The performance of the DSEM in modeling three-dimensional transient radiative transfer processes is examined. The predictions of the DSEM agree well with reported solutions in the literature. The DSEM is demonstrated to be efficient and accurate in capturing the sharp wave fronts of a transient radiative transfer process. Because of high accuracy of spatial discretization, accurate results can be obtained by DSEM with relatively few elements.

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