Two-Flux Green’s Function Analysis for Transient Spectral Radiation in a Composite
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An analysis is developed for obtaining transient temperatures in a two-layer semitransparent composite with spectrally dependent properties. Each external boundary of the composite is subjected to radiation and convection. The two-flux radiative transfer equations are solved by deriving a Green’s function. This yields the local radiative heat source needed to numerically solve the transient energy equation. An advantage of the two-flux method is that isotropic scattering is included without added complexity. Spectral results using the Green’s function method are verified by comparing with numerical solutions using the exact radiative transfer equations. Transient temperature distributions are given to illustrate the effect of radiative heating on one side of a composite with external convective cooling. The protection of a material from incident radiation is illustrated by adding scattering to the layer adjacent to the radiative source.

Nomenclature

- $a_{ij}$ = spectral absorption coefficient of each layer, m$^{-1}$
- $c_{ij} = C_{1j} - C_{2j}$ = coefficients in Green’s functions
- $c_i$ = specific heat of each layer in the composite, J/kg·K
- $c_0$ = speed of electromagnetic propagation in vacuum, m/s
- $c_{2j}$ = heat capacity ratio of layers, $p_j c_j / p_i c_i$
- $D$ = total thickness of composite, D1 + D2, m
- $D_i$, $E_{i0}$, $E_{20}$ = thickness of each layer in composite, m
- $E_j$ = coefficients in homogeneous solution for each layer
- $e_{ij}(v)$ = blackbody spectral energy in vacuum divided by $a T_i^4$
- $e_i = e_i(v)$ = quantity in each layer, $\kappa_j(D/D_j)(3(1 - \Omega_j))^{1/2}$
- $G$ = flux quantity $2(\dot{q}_1 + \dot{q}_2)$, W/m$^2$
- $g_i$ = Green’s function for $G_j$ in each layer
- $H_{i1}$, $H_{i2}$ = dimensionless parameters, $h_i/\sigma T_i^4$ and $h_i/\sigma T_i^2$
- $h_{i1}$, $h_{i2}$ = convective heat transfer coefficients at $x = 0$ and $D$, W/m$^2$·K
- $K_{ij}$ = extinction coefficient of each layer, $a_i + \sigma_{ij}$, m$^{-1}$
- $k_i$ = thermal conductivity of each layer, W/m·K
- $N_f$ = conductance–radiation parameter of each layer based on $D$, $k_i/4\sigma T_i^4 D$
- $n_i$ = refractive index of each layer
- $P_{2i}$, $P_{4i}$, $P_{6i}$ = quantities $P_{2i} = 2R_i/3K_i v_i$, $P_{4i} = 2R_i/3K_i v_i^2$, $P_{6i} = 2R_i/3K_i v_i^3$
- $q_i$ = radiative flux in the $x$ direction, W/m$^2$
- $q_{i1}$, $q_{i2}$ = external radiation fluxes $\sigma T_i^4$ and $\sigma T_i^4$ incident at $x = 0$ and $D$, W/m$^2$
- $q_{10}$, $q_{20}$ = dimensionless radiation fluxes, $q_{10}/\sigma T_1^4$ and $q_{20}/\sigma T_2^4$
- $q_{1+}$, $q_{2+}$ = radiative fluxes in positive and negative $x$ directions, W/m$^2$
- $R_i$ = reflection coefficients, $R_i = (1 - \rho_i)/(1 - \rho_i) - 1$, $R_1 = (1 - \rho_1)/(1 - \rho_1) - 1$, $R_2 = (1 - \rho_2)/(1 - \rho_2) - 1$
- $R_1 - R_6$ = absolute temperature, K; $t = T/T_i$
- $T_{t1}$, $T_{t2}$ = gas temperatures for convection at $x = 0$ and $D$, K
- $T_i$ = reference temperature, or uniform initial temperature, K
- $T_{t1}$, $T_{t2}$ = temperatures of blackbody radiative surroundings at $x = 0$ and $D$, K
- $T_i = (q_i/\sigma)^{1/4}$, $T_{t1} = (q_{t1}/\sigma)^{1/4}$
- $t_{11}$, $t_{22}$ = dimensionless gas temperatures, $T_1/T_i$, $T_2/T_i$
- $x$ = coordinate in direction across layer, m; $X = x/D$
- $\delta$ = dimensionless thickness of first layer, $D_1/D$
- $\theta$ = time, s
- $\kappa_{ij}$ = optical thickness of each layer, $(a_i + \sigma_{ij})D_i$
- $\nu$ = frequency of spectral radiation, s$^{-1}$
- $\nu_{c}$ = cutoff frequency in each layer, s$^{-1}$
- $\xi$ = location within composite divided by $D$
- $\rho_{ij}$ = density of each layer, kg/m$^3$
- $\sigma_{ij}$ = Stefan–Boltzmann constant, W/m$^2$·K$^4$
- $\sigma$ = spectral scattering coefficient of each layer, m$^{-1}$
- $\tau$ = dimensionless time, $(4\sigma T_i^4/\rho_i c_i D)\theta$
- $\Omega_{ij} = \text{spectral scattering albedo of each layer, } (\sigma_{ij}/(a_i + \sigma_{ij}))$

Subscripts

$h$ = homogeneous solution

$j$ = layer index, $j = 1$ in first layer, $j = 2$ in second layer

Introduction

Detailed transient temperatures are needed to examine heat transfer and thermal stress behavior for materials at high temperature that are partially transparent to thermal radiation. Applications include ceramic components, thermal
protection coatings, tempering of glass windows, high-temperature insulation systems, and porous ceramic burners. For semitransparent materials where thermal radiation affects internal temperatures, transients have been studied much less than steady state.

For transient solutions, numerical procedures such as finite differences and finite elements have been used to solve the transient energy equation coupled with the radiative transfer relations. Some of the literature is reviewed in Refs. 1–7, and so a detailed review of transient solutions is not repeated here. A few investigations of particular interest for the present study provide analyses of composites with two or multiple layers.8–11 In Ref. 8, the radiative transfer equations for absorbing layers with diffuse boundaries are solved numerically in combination with the transient energy equation; scattering is not included. A finite difference method is used in the spatial direction, and a Runge–Kutta method is used to move forward in time. A multilayered region with diffuse boundaries is considered in Ref. 9; scattering is not included. A finite difference method is used with a variable grid size. A two-layer composite is analyzed in Ref. 10 subjected to external radiation at one of its boundaries. Isotropic scattering is included, and the layers are gray. A Galerkin method is used to solve the radiative transfer relations, coupled with a finite difference solution of the transient energy equation.

The present analysis continues the development in Ref. 11 where a two-flux Green’s function method was developed for a two-layer gray composite; spectral properties are now included. The two-flux approximation12 is used for the spectral radiative transfer equations. An advantage of the two-flux method is that isotropic scattering is included without additional effort, as compared with the need to solve the scattering integral equation at each time when using the exact transfer relations. For the global boundary conditions of external convection and radiation for a layer having diffuse interfaces, it was shown in Refs. 13 and 14 that the two-flux method provides accurate temperature distributions and heat fluxes. This was for steady state in single and composite layers with scattering included. For transient behavior, the two-flux method was shown to provide accurate results for a single layer,13 and for a two-layer gray composite.14

In the present analysis, the Green’s function solution11 for the two-flux differential equations is extended for spectral property variations in a composite with general boundary conditions. This solution for the local radiative heat source is combined with an implicit finite difference solution of the transient energy equation using a tridiagonal matrix. Results are obtained to validate the numerical method and to illustrate some aspects of transient behavior. They compare, for example, gray and spectral calculations, and show how additional scattering in one layer of a composite can alter the temperature distribution in an adjacent layer. The solution can be applied to examine many transient effects in a two-layer composite with spectral properties.

Analysis

The analysis is for a plane two-layer composite, Fig. 1, that has different spectral radiative absorption and scattering properties in each layer. The layers are semitransparent absorbing dielectrics with refractive indices larger than one. There is heat conduction and isotropic scattering in each layer. The external boundaries and the interface between the layers are assumed diffuse. The diffuse surface reflectivities are determined from boundaries and the interface between the layers are assumed conduction and isotropic scattering in each layer. The external dielectrics with refractive indices larger than one. There is heat properties in each layer. The layers are semitransparent absorbing spectral properties.

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The last term on the right in each equation is the local heat source, including all frequencies, produced by radiative absorption, emission, and scattering. Properties are assumed independent of temperature. The \( \frac{\partial \tilde{q}_1}{\partial t} \) is obtained in terms of the instantaneous temperature distribution by using the two-flux relations; these have provided accurate results in previous steady-state13,14 and transient11 analyses. With \( n_1 \) and \( n_2 \) assumed independent of frequency, the spectral two-flux equations using the Milne–Eddington approximation are:

\[
\frac{\partial \tilde{q}_1}{\partial X} = \frac{K_{1\nu}}{\delta} (1 - \Omega_{1\nu}) [4n_1^2 \tilde{E}_6(X, \tau, \nu)] \quad 0 \leq X < \delta \quad (2a)
\]

\[
\frac{\partial \tilde{q}_2}{\partial X} = \frac{K_{2\nu}}{\delta} (1 - \Omega_{2\nu}) [4n_2^2 \tilde{E}_6(X, \tau, \nu)] 
- \tilde{G}_1(X, \tau, \nu) \quad \delta < X \leq 1 \quad (2b)
\]

where \( \tilde{G}_1(X, \tau, \nu) \) and \( \tilde{G}_2(X, \tau, \nu) \) are related to \( \tilde{q}_1(X, \tau, \nu) \) by

\[
\frac{\partial \tilde{G}_1}{\partial X} = -3 \frac{K_{1\nu}}{\delta} \tilde{q}_1(X, \tau, \nu) \quad 0 \leq X < \delta \quad (3a)
\]

\[
\frac{\partial \tilde{G}_2}{\partial X} = -3 \frac{K_{2\nu}}{\delta} \tilde{q}_2(X, \tau, \nu) \quad \delta < X \leq 1 \quad (3b)
\]

The \( \tilde{q}_1 \) and \( \tilde{G}_1 \) are related to the positive and negative radiative fluxes in Fig. 1 by \( \tilde{q}_1 = \tilde{q}_1^+ - \tilde{q}_1^- \) and \( \tilde{G}_1 = 2(\tilde{q}_1^- + \tilde{q}_1^+) \).

Boundary, Interface, and Initial Conditions

For a semitransparent material, radiation is absorbed within the material interior and not at a surface, since the surface has no thickness. Hence, the relations between convection and convection at the boundaries do not include radiative terms.

\[
\frac{\partial q(x, \tau)}{\partial X} = \frac{H_f}{4N_1} [t_{11} - t(0, \tau)] \quad (4a)
\]
At the internal interface, \( \delta \) is the discontinuity in at an interface, so that \( \delta^2(\delta, \tau) \) are the reflected and transmitted fluxes at a boundary. The boundary conditions for radiation must include the effects of external and internal reflections at the outer surfaces that are exposed to spectral fluxes \( q_1(\nu) \) and \( q_2(\nu) \). The conditions have been developed by considering the incident, reflected, and transmitted fluxes at a boundary.

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\[
\frac{\partial G_i(0, \tau, \nu)}{\partial X} = \frac{2 \delta}{3 \kappa_1 V} R_2 \frac{\partial \delta G_i(\delta, \tau, \nu)}{\partial X} \bigg|_{x=0} \tag{5a}
\]

\[
\frac{\partial G_i(1, \tau, \nu)}{\partial X} = \frac{2 (1 - \delta)}{3 \kappa_1 V} R_4 \frac{\partial \delta G_i(\delta, \tau, \nu)}{\partial X} \bigg|_{x=1} \tag{5b}
\]

At the interface between the two layers the relation between reflected and transmitted fluxes gives

\[
\frac{\partial G_i(\delta, \tau, \nu)}{\partial X} = R_i \frac{\partial G_i(\delta, \tau, \nu)}{\partial X} \bigg|_{x=0} \tag{6a}
\]

There is a discontinuity in \( G_i \) at an interface, so that \( \frac{\partial G_i(\delta, \tau, \nu)}{\partial X} = \frac{\partial G_i(\delta, \tau, \nu)}{\partial X} \bigg|_{x=0} \).

The homogeneous forms of Eqs. (5a) and (5b) are differentiated in \( X \), and \( \frac{\partial G_i(\delta, \tau, \nu)}{\partial X} = 0 \) through a discontinuity of \( \nu \) at each \( X = \delta \). This yields the relations for \( C_{2i}(\xi, \nu) \) and \( C_{4i}(\xi, \nu) \):

\[
C_{2i}(\xi, \nu) + C_{4i}(\xi, \nu) = 0 \quad \xi < \delta \quad \delta \leq X < \xi \tag{10a}
\]

and for \( C_{2i}(\xi, \nu) \) and \( C_{4i}(\xi, \nu) \):

\[
C_{2i}(\xi, \nu) + C_{4i}(\xi, \nu) = 0 \quad \xi < \delta \quad \delta \leq X < \xi \tag{10b}
\]

Equations (11a) and (11b) are solved for \( C_{2i}(\xi, \nu) \) and \( C_{4i}(\xi, \nu) \), and Eqs. (12a) and (12b) for \( C_{2i}(\xi, \nu) \) and \( C_{4i}(\xi, \nu) \). After substituting into Eqs. (10a) and (10b), the final Green's functions are

\[
g_i(X, \xi, \nu) = \left\{ \begin{array}{ll}
C_{2i}(\xi, \nu) \cos \epsilon_i X + C_{4i}(\xi, \nu) \sin \epsilon_i X & 0 \leq X < \xi \\
C_{2i}(\xi, \nu) \cos \epsilon_i X + C_{4i}(\xi, \nu) \sin \epsilon_i X & \xi < X \leq \delta
\end{array} \right. \tag{8a}
\]

\[
g_i(X, \xi, \nu) = \left\{ \begin{array}{ll}
C_{2i}(\xi, \nu) \cos \epsilon_i X + C_{4i}(\xi, \nu) \sin \epsilon_i X & 0 \leq X < \xi \\
C_{2i}(\xi, \nu) \cos \epsilon_i X + C_{4i}(\xi, \nu) \sin \epsilon_i X & \xi < X \leq \delta
\end{array} \right. \tag{8a}
\]

\[
g_i(X, \xi, \nu) = \left\{ \begin{array}{ll}
\left[\frac{\tan \epsilon_i (\xi - \delta)}{\Delta} + P_\Delta \epsilon_i \right] \cos \epsilon_i \xi & 0 \leq X < \xi \\
\left[\frac{\tan \epsilon_i (\xi - \delta)}{\Delta} + P_\Delta \epsilon_i \right] \cos \epsilon_i \xi & \xi < X \leq \delta
\end{array} \right. \tag{13a}
\]
Eqs. (5) and (6) are applied and the result is four simultaneous
equations to obtain the complete solution for the homogeneous
term containing the mode.

\[
\begin{align*}
\text{Denom}_{1v} &= e_{1v} [(R_3 + P_6 e_{1v}) \tanh e_{1v} \delta + e_{1v} (P_{1v} + P_3 R_3) \cosh e_{1v} \delta] \\
\text{Denom}_{2v} &= e_{2v} [1 + e_{2v} P_{6v} \tanh e_{2v} (1 - \delta)] \\
&\times \cosh e_{2v} (1 - \delta)
\end{align*}
\]

The \(g_i(X, \xi, \nu)\) in Eq. (13) are used to account for the nonhomogeneous term containing \(e_i(X, \tau, \nu)\) in Eq. (7) when computing \(G_i(X, \tau, \nu)\) at each time during the transient. To obtain the complete solution for \(G_i(X, \tau, \nu)\), the homogeneous solution is needed for Eq. (7). This has the form \(G_i(X, \nu) = E_{1v} \sinh e_{1v} X + E_{2v} \cosh e_{2v} X\). The boundary conditions in Eqs. (5) and (6) are applied and the result is four simultaneous equations for the \(E_{1v}\) and \(E_{2v}\), coefficients:

\[
\begin{align*}
P_{2v} e_{1v} E_{11v} &= -E_{21v} = -4R_6 \tilde{G}_{21}(\nu) \\
\left(\frac{e_{1v} \delta}{K_{1v}} \cosh e_{1v} \delta\right) E_{11v} &= \left(\frac{e_{1v} \delta}{K_{1v}} \sinh e_{1v} \delta\right) E_{21v} \\
- \left[\frac{e_{2v} (1 - \delta)}{K_{2v}} \cosh e_{2v} \delta\right] E_{12v} &= -\left[\frac{e_{2v} (1 - \delta)}{K_{2v}} \sinh e_{2v} \delta\right] E_{22v} = -C_{1v}
\end{align*}
\]

Using the Green’s functions \(G_{ij}(X, \nu)\), the general spectral solution of Eq. (7) in each layer at each time is

\[
\tilde{G}_i(X, \tau, \nu) = \tilde{G}_{i0}(X, \tau, \nu) + 4e_{2v}^2 n_1^2 \int_0^\delta \tilde{G}_i(X, \tau, \xi, \nu) e_\xi(\xi, \tau, \nu) d\xi
\]

The forms for two spectral bands can be written in the same way as in Ref. 3, where a spectral Green’s function analysis is given for a single layer.

### Numerical Solution

Starting with a specified \(t(X, 0)\), the blackbody function \(\tilde{g}_0(X, 0, \nu)\) is known. The Green’s functions are used in Eqs. (15a) and (15b) to obtain \(\tilde{G}(X, 0, \nu)\) and \(\tilde{G}(X, 0, \nu)\), and the \(\tilde{q}_i(X, 0, \nu)\) is then evaluated from Eq. (2). This spectral quantity is integrated over all \(\nu\), so that it can be used in the energy equation that involves total energy quantities (the results given later are for two spectral bands with the same cutoff frequency in both layers). Using Eq. (1), \(\t(\nu)\) is integrated forward one time increment using the finite difference relations that follow. Then the new temperature distribution is used with the Green’s functions to obtain \(\tilde{G}(X, \Delta \tau, \nu)\) and \(\tilde{q}(\Delta \tau, \nu)\)/\(\Delta X\). The \(\tilde{q}(\Delta \tau, \nu)\)/\(\Delta X\) is integrated over all \(\nu\) and is used in Eq. (1) to continue on to obtain \(t(X, \tau)\) at the next time step.

From Eqs. (1) and (1b), the following implicit finite difference algorithms are used at the interior points of a uniform grid (to advance the temperature distributions each \(\Delta \tau\) in each layer:

\[
\begin{align*}
-\frac{N_0 \Delta \tau}{(\Delta X)^2} t(X - \Delta X, \tau + \Delta \tau) &= \left[1 + \frac{2N_0 \Delta \tau}{(\Delta X)^2}\right] t(X, \tau + \Delta \tau) \\
-\frac{N_0 \Delta \tau}{(\Delta X)^2} t(X, \tau + \Delta \tau) &= t(X, \tau) - \frac{\Delta \tau \tilde{q}_i}{4e_\xi(\xi, \tau, \nu) d\xi}
\end{align*}
\]

For the boundary points \(X = 0\) and \(1\), Eq. (16) is applied, and the \(\tilde{t}(-\Delta X, \tau + \Delta \tau)\) and \(\tilde{t}(1 + \Delta X, \tau + \Delta \tau)\) that appear are eliminated by using the boundary conditions Eqs. (4a) and (4b), expressed as

\[
\begin{align*}
\tilde{t}(\Delta X, \tau + \Delta \tau) - \tilde{t}(-\Delta X, \tau + \Delta \tau) &= \frac{2 \Delta X}{H_0^0} [t(0, \tau + \Delta \tau) - t(0, \tau + \Delta \tau)] \\
\tilde{t}(1 + \Delta X, \tau + \Delta \tau) - \tilde{t}(1, \tau + \Delta \tau) &= \frac{2 \Delta X}{H_0^0} [t(1, \tau + \Delta \tau) - t(1, \tau + \Delta \tau)]
\end{align*}
\]
This yields the finite difference relations at $X = 0$ and 1 as

\[
1 + \frac{2N_1\Delta \tau}{(\Delta X)^2} + \frac{H_1\Delta \tau}{2\Delta X} \right] n(0, \tau + \Delta \tau)
\]

\[
-\frac{2N_1\Delta \tau}{(\Delta X)^2} t(\Delta X, \tau + \Delta \tau) = t(0, \tau) - \frac{\Delta \tau}{4} \partial^2 n \bigg|_{X = 0} + \frac{H_1\Delta \tau}{2\Delta X} t_s
\]

\[
-\frac{2N_2\Delta \tau}{c_2\delta n(\Delta X)^2 / \delta X} t(1 - \Delta X, \tau + \Delta \tau) + \left[ 1 + \frac{2N_2\Delta \tau}{c_2(\Delta X)^2} + \frac{H_2\Delta \tau}{2c_2\Delta X} \right] \times t(1, \tau + \Delta \tau) = t(1, \tau) - \frac{\Delta \tau}{4} \partial^2 n \bigg|_{X = 1} + \frac{H_2\Delta \tau}{2c_2\Delta X} t_s
\]

The condition at the internal interface, Eq. (4d), is written by using three-point derivatives, and Eq. (4c) is substituted to give

\[
\frac{N_1}{2\Delta X} [t(\delta - 2\Delta X, \tau) - 4t(\delta - \Delta X, \tau) + 3t(\delta, \tau)]
\]

\[
= \frac{N_2}{2\Delta X} [-4t(\delta + 2\Delta X, \tau) + 4t(\delta + \Delta X, \tau) - 3t(\delta, \tau)]
\]

Equation (16) is written for $t$ at $X = \Delta X$ and $X = -\Delta X$, and these relations are used to eliminate the nontridiagonal elements $i(\delta - 2\Delta X, \tau)$ and $i(\delta + 2\Delta X, \tau)$. The result is a tri-diagonal finite difference expression at the internal interface

\[
\frac{(\Delta X)^2}{\Delta \tau} - \frac{2N_1}{\Delta X} i(\delta - \Delta X, \tau + \Delta \tau) + 2(N_1 + N_2) i(\delta, \tau + \Delta \tau)
\]

\[
+ \left[ \frac{c_2(\Delta X)^2}{\Delta \tau} - 2N_2 \right] i(\delta + \Delta X, \tau + \Delta \tau)
\]

\[
= \frac{(\Delta X)^2}{\Delta \tau} [i(\delta - \Delta X, \tau) + c_2i(\delta + \Delta X, \tau)]
\]

\[
- \frac{(\Delta X)^2}{4} \left( \frac{\partial^2 n}{\partial X^2} \bigg|_{\delta - \Delta X, \tau} - \frac{\partial^2 n}{\partial X^2} \bigg|_{\delta + \Delta X, \tau} \right)
\]

The $t(X, \tau)$ is advanced to the next $\Delta \tau$ using Eqs. (16–18) solved as a tridiagonal matrix using the algorithm in Ref. 16. As described in Ref. 4, overall energy balances were checked at each step by using the calculated temperature distributions to evaluate the amounts contributed by radiation, convection, and internal energy storage. For the grid sizes used, the overall energy balance was satisfied within 0.5% throughout the transient calculations. After checking various grid sizes, it was found that 81 evenly spaced points across each layer gave accurate grid-independent solutions for $\kappa_\nu < 3$ in each layer. For $\kappa_\nu > 3$, 101 points were used, which gave accurate solutions for $\kappa_\nu \sim 10$. A time increment of $\Delta \tau = 0.0025$ provided stable and time-accurate solutions for the results calculated here, as validated by comparisons with some previous numerical solutions using the exact radiative transfer relations.

**Results and Discussion**

The objective of the analysis was to develop a convenient and accurate method for obtaining transient temperature distributions in a two-layer semitransparent composite with spectral radiation properties, isotropic scattering, and differing refractive indices in each layer. The composite is subjected to external convection and radiation on both sides. A Green's function solution was derived for the spectral two-flux radiative transfer equations in two layers, and for the results given here, the solution was applied in two spectral bands with the same cutoff frequency in both layers. By summing over the two bands, the Green's function is used to obtain the radiative energy source term in the transient energy equation at each time step. The energy equation was solved with an implicit finite difference method that includes convective boundary conditions, and the required temperature and heat conduction conditions at the internal interface. Some of the transient results that will be presented are to verify the method for spectral calculations. This is done by comparing transient temperatures with previous spectral steady-state and transient results obtained or verified with the exact radiative transfer equations. The other figures that follow illustrate the variety of transient results with spectral effects that can be obtained with the present combined analytical and computational procedure.

The transient temperatures given here begin from a uniform temperature distribution $t(X, 0) = 1$, although the solution applies for a general distribution $t(X, 0)$. For a partial validation of the present method, the solid lines in Fig. 2 are transient results for a two-band symmetric case using the same parameters as the transient solution in Fig. 6c of Ref. 3. The two-band spectral optical thicknesses of the layers in order of increasing frequency are $\kappa_1 = \kappa_2 = 5$ and 0.05. For $T = 0$, the composite is exposed on both sides to a high-temperature gas at $T_{T_1} = T_{T_2} = 4T_0$, and there is large convective heating on both sides. The surroundings remain at $T_s = T_2 = T_0$, so that as the temperatures rise, radiative cooling occurs from within the composite interior. Radiative cooling has a strong effect, and the transient interior temperatures are always considerably below the surface temperatures. At steady state, the interior temperature in the central region of the composite is close to the uniform temperature for a composite that is opaque. The present results duplicated those in Ref. 3, where a single spectral layer was analyzed, and additional calculations were then made to illustrate the effect of heat capacity in the second layer of a two-layer composite. The dashed lines in Fig. 2 illustrate how increased heat capacity can delay the transient response. Heat capacity, however, does not alter the steady-state temperature distribution.

Figure 3 provides a comparison with a numerical solution of the exact transfer equations for steady state given in Fig. 3 of Ref. 14. The transient results at large time agree very well with this steady-state solution, which is for a two-layer com-
posite with each layer having two spectral bands. For these results, the composite is heated by blackbody radiation at \( X = 0 \) with temperature \( T_0 = 1.2T \). As the surface temperature rises at \( X = 0 \), convective cooling occurs, since the gas temperature remains at the initial temperature \( T_{el} = T \). There is stronger cooling by both radiation and convection at \( X = 1 \), where there are lower blackbody surroundings and gas temperatures, \( T_{el} = T_{el0} = 0.25T \). For comparison, the steady-state solution is shown (dot-dashed line) for a composite that is opaque, and so radiation exchange occurs only at the external surfaces, and there is only heat conduction within the interior. The transient solution has large internal radiation transfer and, at steady state, is considerably different from the opaque result.

After the solution method was verified in Figs. 2 and 3, and by some additional comparisons, it was used to examine a few transient effects to illustrate how the solution can be applied; these results are shown in Figs. 4–7. A few steady-state solutions are also shown for an opaque composite, and it is evident that in these examples, considerable radiation effects are present.

In Fig. 4, the effect of adding scattering to the first layer is illustrated as a possible method to protect the second layer from external radiative heating. For the solid lines, the two-band spectral optical thicknesses of the first layer in order of increasing frequency are \( \kappa_{\nu} = 2 \) and \( 0.1 \). For the dashed lines, a uniform amount of scattering has been added to both bands so \( \kappa_{\nu} = 6.9 \) and 5. The first layer has thus been made more opaque, and it tends to shield the second layer from the radiation incident at \( X = 0 \); this significantly reduces the temperatures in the second layer. During the transient, however, the maximum temperature is increased in the first layer. At steady state, the dashed results approach somewhat more the temperature distribution for an opaque composite.

To illustrate the importance of spectral effects, the results without scattering in Fig. 4 are compared in Fig. 5 with temperatures when each layer is gray. In each layer the larger of the two-band optical thicknesses in Fig. 4 was used, and so, in Fig. 5, \( \kappa_{\nu} = 2 \) and \( \kappa_{\nu} = 5 \) for all \( \nu \). The bands have been eliminated that are more transparent, so that radiation incident at \( X = 0 \) is not transmitted as readily into the composite. Incident radiation is absorbed strongly in the region at small \( X \). The result is increased maximum temperatures that are closer to \( X = 0 \), and reduced temperatures in the second layer. By comparison with the dot-dashed line in Fig. 4 it is evident that the optical thicknesses in Fig. 5 are significantly smaller.
As a final illustrative example, Fig. 7 examines the effect of removing the convective cooling at the \( x = 0 \) boundary. The solid lines are the same as the solid lines in Fig. 6, where \( H_1 = 4 \); for the dashed lines, \( H_1 = 0 \). As expected, removing convective cooling at \( x = 0 \) raises the temperatures near this boundary throughout the transient, and at \( x = 0 \) the temperature distributions have a zero derivative. At steady state, the entire temperature profile is raised because of the reduced convective cooling on one side. The temperature at steady state with a uniform thermal conductivity illustrate, as in Fig. 4, that there are substantial internal radiation effects.

**References**


8. Tsai, C.-F., and Nixon, G., "Transient Temperature Distribution of


