TRANSIENT RADIATIVE ENERGY TRANSFER IN INCOMPRESSIBLE LAMINAR FLOWS

By
S. N. Tiwari, Principal Investigator
and
D. J. Singh, Graduate Research Assistant

Progress Report
For the period ended June 30, 1987

Prepared for the
National Aeronautics and Space Administration
Langley Research Center
Hampton, Virginia 23665

Under
Research Grant NAG-1-423
Drs. A. Kumar and J. P. Drummond, Technical Monitors
HSAD- Computational Methods Branch

June 1987
DEPARTMENT OF MECHANICAL ENGINEERING AND MECHANICS
COLLEGE OF ENGINEERING & TECHNOLOGY
OLD DOMINION UNIVERSITY
NORFOLK, VIRGINIA 23508

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P.O. Box 6369
Norfolk, Virginia 23508

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FOREWORD

This is a progress report on the research project entitled "Analysis and Computation of Internal Flow Field in a Scramjet Engine," for the period ended June 30, 1987. Specific attention has been directed to investigate "Transient Radiative Energy Transfer in Incompressible Laminar Flows." This work was supported by the NASA Langley Research Center (Computational Methods Branch of the High-Speed Aerodynamics Division) under research grant NAG-1-423. The grant was monitored by Drs. A. Kumar and J. P. Drummond of the High-Speed Aerodynamics Division.
TRANSPORT RADIATIVE ENERGY TRANSFER
IN INCOMPRESSIBLE LAMINAR FLOWS

S. N. Tiwari¹ and D. J. Singh²
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ABSTRACT

Analysis and numerical procedures are presented to investigate the transient radiative interactions of nongray absorbing-emitting species in laminar fully-developed flows between two parallel plates. The particular species considered are OH, CO, CO₂, and H₂O and different mixtures of these species. Transient and steady-state results are obtained for the temperature distribution and bulk temperature for different plate spacings, wall temperatures, and pressures. Results, in general, indicate that the rate of radiative heating can be quite high during earlier times. This information is useful in designing thermal protection systems for transient operations.

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<td>band absorptance $= A(u,\beta)$, cm$^{-1}$</td>
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<td>$A_o$</td>
<td>band width parameter, cm$^{-1}$</td>
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<td>$C_o$</td>
<td>correlation parameter, atm$^{-1}$ cm$^{-1}$</td>
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<td>$C_p$</td>
<td>specific heat at constant pressure, kJ/kg-k = erg/gm-k</td>
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<td>$e_\omega$</td>
<td>Planck's function, (W-cm$^{-2}$)/cm$^{-1}$</td>
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<td>$e_{\omega_0}$</td>
<td>Planck's function evaluated at wave number $\omega_0$</td>
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<td>$e_{1,e_2}$</td>
<td>emissive power of surfaces with temperatures $T_1$ and $T_2$, W-cm$^{-2}$</td>
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<td>$H_{1,H_1}$</td>
<td>gas property for the large path length limit</td>
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<tr>
<td>$k$</td>
<td>thermal conductivity, erg/cm-sec-K</td>
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<tr>
<td>$K_1$</td>
<td>gas property for the optically thin limit distance between plates</td>
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<td>$M$</td>
<td>large path length parameter, nondimensional</td>
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<td>$N$</td>
<td>optically thin parameter, nondimensional</td>
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<td>$P$</td>
<td>pressure, atm</td>
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<td>$q_R$</td>
<td>total radiative heat flux, W/cm$^2$</td>
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<td>$q_{R,\omega}$</td>
<td>spectral radiation heat flux, (W-cm$^{-2}$)/cm$^{-1}$</td>
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<td>$q_\omega$</td>
<td>wall heat flux, W/cm$^2$</td>
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<td>nondimensional path length $= S P L/A_o$</td>
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<td>$\beta$</td>
<td>line structures parameter</td>
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<td>$\theta$</td>
<td>nondimensional temperature</td>
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\( \theta_b \)  
*dimensionless bulk temperature*

\( \kappa_\omega \)  
spectral absorptin coefficient, cm\(^{-1}\)

\( \xi \)  
nondimensional coordinate = \( y/L = u/u_0 \)

\( \rho \)  
density, kg/m\(^3\)

\( \tau \)  
nondimensional time

\( \omega \)  
wave number, cm\(^{-1}\)

\( \omega_0 \)  
wave number at the band center, cm\(^{-1}\)
INTRODUCTION

The radiative energy transfer in participating medium has received special attention in recent years because of its applications in the areas of the remote sensing, earth's radiation budget studies and climate modeling, fire and combustion research, entry and reentry phenomena, hypersonic propulsion and defense-oriented research. In most studies involving combined mass, momentum, and energy transfer, however, the radiative transfer formulation has been coupled mainly with the steady processes [1-20] and the interaction of radiation in transient processes has received very little attention. However, the transient approach appears to be the logical way of formulating a problem in general sense for elegant numerical and computational solutions. The steady-state solutions can be obtained as limiting solutions for large times.

The limited number of studies available on the transient radiative transfer in gaseous systems [21-31] are reviewed critically in [32-34]. The literature survey reveals that the transient behavior of a physical system can be influenced significantly in the presence of radiation.

The goal of this research is to include the nongray radiative formulation in the general governing equations and provide the step-by-step analysis and solution procedure for several realistic problems. The basic formulations are presented in [32] and the specific case of transient radiative exchange in nongray gases between two parallel plates is investigated in [33, 34]. The objective of this study is to investigate the interaction of transient radiation in fully-developed laminar flows between two parallel plates. Thus, special attention is directed to include the nonsteady phenomenon only in the energy equation. Homogeneous as well as nonhomogeneous mixtures of absorbing-
emitting species are considered. In subsequent studies, the present analysis and numerical techniques will be used to investigate the unsteady flow of compressible and chemically reacting species in one- and multi-dimensional systems.
BASIC FORMULATION

The physical system considered is the energy transfer in laminar, incompressible, constant properties, fully-developed flow of absorbing-emitting gases between parallel plates (Fig. 1). The condition of uniform surface heat flux for each plate is assumed such that the temperature of the plates varies in the axial direction. Extensive treatment of this problem is available in the literature under steady state conditions [8, 11]. The primary motivation of this study is to investigate the extent of transient radiative interaction for high temperature flow conditions.

For the physical problem considered, the energy equation can be expressed as [1]

\[ \rho C_p \left( \frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} \right) = k \frac{\partial^2 T}{\partial y^2} + \beta T \frac{dp}{dx} + \mu \left( \frac{\partial u}{\partial y} \right)^2 - \text{div} q_R \]  

(1)

where \( u \) and \( v \) denote \( x \) and \( y \) components of velocity, respectively. In deriving Eq. (1) it has been assumed that the net conduction heat transfer in the \( x \) direction is negligible compared with the net conduction in the \( y \) direction. This represents the physical condition of a large value of the Peclet number. By an analogous reasoning, the radiative heat transfer in the \( x \) direction can be neglected in comparison to that transferred in the \( y \) direction. If, in addition, it is assumed that the Eckert number of the flow is small, then Eq. (1) reduces to

\[ \frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = \alpha \frac{\partial^2 T}{\partial y^2} - \frac{1}{\rho C_p} \frac{\partial q_R}{\partial y} \]  

(2)

where \( \alpha = (k/\rho C_p) \) represents the thermal diffusivity of the fluid.

For a steady fully-developed flow, \( v = 0 \), and \( u \) is given by the well-known parabolic profile as
Figure 1. Physical model and coordinate systems for flow of radiating gases between parallel plates.
\[ u = 6 \, u_m \, (\xi - \xi^2); \, \xi = y/L \]  

where \( u_m \) represents the mean fluid velocity. Also, for the flow of a perfect gas with uniform heat flux, \( \partial T/\partial x \) is constant and is given by

\[ \frac{\partial T}{\partial x} = \frac{2q_w}{(u_m L/k)} \]  

Now, by combining Eqs. (2) - (4), the energy equation is expressed in nondimensional form as

\[ \frac{\partial \theta}{\partial \tau} + 12 (\xi - \xi^2) = \frac{\partial^2 \theta}{\partial \xi^2} - \frac{1}{q_w} \frac{\partial q_R}{\partial \xi} \]  

where

\[ \tau = at/L^2; \, \theta = (T - T_i)/(q_w L/k) \]

By assuming that the initial temperature distribution in the gas is some uniform value \( T_0 = T_i \), the initial and boundary conditions for this problem can be expressed as

\[ \theta(\xi, 0) = 0 \]  
\[ \theta(0, \tau) = \theta(1, \tau) = 0 \]  
\[ \theta_\xi(\xi = 1/2) = 0; \, \theta_\xi(\xi = 0) = - \theta_\xi(\xi = 1) \]

It should be noted that all the boundary conditions given in Eqs. (6) are not independent and any two convenient conditions can be used to obtain solutions. Also, the initial temperature distribution can be any specified or calculated value of \( \theta(\xi, 0) = f(\xi) \).

As discussed in Refs. 32-34, the radiative transfer equations are formulated for one-dimensional planar systems for many engineering and astrophysical applications. For diffuse nonreflecting boundaries and in the
absence of scattering, the expression for the total radiative flux is given, for an n-band gaseous system, by [1, 8, 32]

\[ q_R(y) = e_1 - e_2 \]

\[ + \frac{3}{2} \sum_{i=1}^{n} \int_{\Delta \omega_i}^{y} F_{1\omega_i}(z) \kappa_{\omega_i} \exp\left[-\frac{3}{2} \kappa_{\omega_i} (y-z)\right] dz \]

\[ - \int_{y}^{L} F_{2\omega_i}(z) \kappa_{\omega_i} \exp\left[-\frac{3}{2} \kappa_{\omega_i} (z-y)\right] dz d\omega_i \tag{7} \]

where

\[ F_{1\omega_i}(z) = e_{\omega_i}(z) - e_{1\omega_i}; F_{2\omega_i}(z) = e_{\omega_i}(z) - e_{2\omega_i} \]

Equation (7) is in proper form for obtaining the nongray solutions of molecular species. In fact, this is an ideal equation for the line-by-line and narrow-band model formulations. However, in order to be able to use the wide band models and correlations, Eq. (7) is transformed in terms of the correlation quantities as [1, 7-13, 32]

\[ q_R(\xi) = e_1 - e_2 \]

\[ + \frac{3}{2} \sum_{i=1}^{n} A_{0i} u_{0i} \int_{\xi}^{\xi'} F_{1\omega_i}(\xi') A_i' \left[\frac{3}{2} u_{0i} (\xi'-\xi)\right] d\xi' \]

\[ - \int_{\xi}^{1} F_{2\omega_i}(\xi') A_i' \left[\frac{3}{2} u_{0i} (\xi'-\xi)\right] d\xi' \tag{8} \]

where

\[ \xi = u/u_0 = y/L; \xi' = u'/u_0 = z/L; \bar{A} = A/A_0; \]

\[ u = (S/A_0) p y; u_0 = (S/A_0) p L; PS = \int_{\Delta \omega} \kappa_\omega d\omega \]
It should be noted that $F_{1\omega_i}$ and $F_{2\omega_i}$ in Eq. (8) represent the values at the center of the $i$th band and $\bar{A}'(u)$ denotes the derivative of $\bar{A}(u)$ with respect to $u$. Upon performing the integration by parts, Eq. (8) can be expressed in an alternate form as \[32\]

$$q_R(\xi) = e_1 - e_2 + \sum_{i=1}^{n} A_{oi} \left( \int_{0}^{\xi} \frac{\delta}{\omega_i} \left[ \delta \left( \frac{\omega_i}{\xi} \right) / \delta \xi' \right] \frac{3}{2} u_{oi} (\xi - \xi') \right) d\xi'$$

$$+ \int_{\xi}^{1} \frac{\delta}{\omega_i} \left( \frac{\delta}{\xi} \right) \frac{3}{2} u_{oi} (\xi' - \xi') d\xi'$$

(9)

A direct differentiation of Eq. (9) provides the expression for the divergence of radiative flux as

$$\frac{d q_R(\xi)}{d \xi} = \frac{3}{2} \sum_{i=1}^{n} A_{oi} u_{oi} \left( \int_{0}^{\xi} \frac{\delta}{\omega_i} \left( \frac{\delta}{\xi} \right) \frac{3}{2} u_{oi} (\xi - \xi') \right) x$$

$$- \left[ \frac{\delta}{\omega_i} \left( \frac{\delta}{\xi} \right) \frac{3}{2} u_{oi} (\xi' - \xi') \right] d\xi'$$

(10)

Equations (8) through (10) are the most convenient equations to use when employing the band-model correlations in radiative transfer analyses.

For the present physical problem, $e_1 = e_2$ and $F_{1\omega_i} = F_{2\omega_i}$. Thus, for the case of linearized radiation, a combination of Eqs. (5) and (8) results in \[8, 32\]

$$\theta_{\xi \xi} - \theta_{\tau} - 3N \theta - 12 (\xi - \xi^2) = \frac{9}{4} (L/k) \sum_{i=1}^{n} H_{ii} u_{oi}^2 \left\{ \int_{0}^{\xi} \frac{\theta}{\xi} (\xi', \tau) x \right.$$  

$$\left. A_{ii} \left[ \frac{3}{2} u_{oi} (\xi - \xi') \right] d\xi' + \int_{\xi}^{1} A_{ii} \left[ \frac{3}{2} u_{oi} (\xi' - \xi') \right] d\xi' \right\}$$

(11a)
where

\[ N = \frac{(PL^2/k)}{K_1} = \frac{(PL^2/k)}{\sum_{i=1}^{n} S_i(T)} \left( \frac{d\omega_i}{dT} \right) T_1 \]

\[ H_{1i} = A_{o_i}(T) \left( \frac{d\omega_i}{dT} \right) T_1, \quad H_1 = \sum_{i=1}^{n} H_{1i} \]

The dimensionless gas property \( N \) characterizes the relative importance of radiation versus conduction within the gas under optically thin conditions. Also, by combining Eqs. (5) and (10) another form of the transient energy equation is obtained as

\[ \theta_{\xi \xi} - \theta_x - 12 (\xi - \xi') = \frac{3}{2} (L/k) \sum_{i=1}^{n} H_{1i} u_{o_i} \left\{ \int_{0}^{\xi} \left( \frac{\partial \theta}{\partial \xi'} \right) d\xi' \right\} \]

\[ \bar{A}_i \left[ \frac{3}{2} u_{o_i}(\xi - \xi') \right] d\xi' - \int_{\xi}^{1} \left( \frac{\partial \theta}{\partial \xi'} \right) d\xi' \]

\[ \bar{\bar{A}}_i \left[ \frac{3}{2} u_{o_i}(\xi' - \xi) \right] d\xi' \]  \hspace{1cm} (11b)

Note again that Eq. (11b) can be obtained directly by integrating the right-hand side of Eq. (11a) by parts. Quite often, Eq. (11b) is the convenient form to use in radiative transfer analyses.

For flow problems, the quantity of primary interest is the bulk temperature of the gas, which may be expressed as [11]

\[ \theta_b = \frac{(T_b - T_1)}{(q_w L/k)} = 6 \int_{0}^{1} \theta(\xi, \tau)(\xi - \xi^2) d\xi \]  \hspace{1cm} (12)

The heat transfer \( q_w \) is given by the expression, \( q_w = h_c (T_1 - T_b) \), where \( h_c \) is the convective heat transfer coefficient (W/cm²-K). In general, the heat transfer results are expressed in terms of the Nusselt number \( Nu = h_c D_h/k \). Here, \( D_h \) represents the hydraulic diameter, and for the parallel plate geometry it equals twice the plate separation, i.e., \( D_h = 2L \). Upon
eliminating the convective heat transfer coefficient $h_c$ from the expressions for $q_w$ and $\text{Nu}$, a relation between the Nusselt number and the bulk temperature is obtained as

$$\text{Nu} = 2 \frac{q_w}{k(T_1 - T_b)} = -2/\theta_b$$

(13)

The heat transfer results, therefore, can be expressed either in terms of $\text{Nu}$ or $\theta_b$.

LIMITING CASES AND SOLUTIONS

Before discussing the method of solution for the general case, it is advisable to explore the various limiting cases. Quite often, closed form solutions can be obtained for some of these cases. Specifically four limiting cases are considered here and these are the steady laminar flows, the case of negligible radiation, the optically thin limit, and the large path length limit.

Steady Laminar Flow

For steady-state conditions $\partial \theta / \partial \tau = 0$ and Eqs. (11) provide two forms of the energy equation for this case. Another convenient form is obtained by letting $\partial \theta / \partial \tau = 0$ in Eq. (5) such that

$$\theta'' - 12 (\xi - \xi^2) = \left(1/q_w\right) \frac{d q_R}{d\xi}$$

(14)

By integrating Eq. (14) once and using the conditions that at $\xi = 1/2$, $q_R(\xi)$ and $(d\theta/d\xi)$ are equal to zero, one obtains

$$\theta' - 2(3\xi^2 - 2\xi^3) + 1 = q_R(\xi)/q_w$$

(15)

A combination of Eqs. (8) and (15) results in

$$\theta' - 2(3\xi^2 - 2\xi^3) + 1 = \frac{3}{2} \frac{(L/k)}{i=1} \sum_{H_i} u_{oi} \int_0^\xi \theta(\xi') x$$
It should be pointed out that by combining Eqs. (9) and (15) another useful form of the energy equation can be obtained for the steady case.

For the case of negligible radiation, Eq. (16) reduces to a very simple form and utilizing the boundary condition \( \theta(0) = 0 \), the solution of the resulting equation is found to be

\[
\theta(\xi) = \xi(2\xi^2 - \xi^3 - 1) 
\]  

The result for the bulk temperature is found by combining Eqs. (12) and (17a) as

\[
-\theta_b = 17/70 
\]

The results provided by Eqs. (17) are useful in determining the extent of radiative contributions.

Negligible Radiation

For the case of negligible radiation, \( N = 0 \) and both forms of Eq. (11) reduce to

\[
\theta_{\xi\xi} - \theta_\tau = 12(\xi - \xi^2) 
\]

By employing the product solution procedure, the solution of Eq. (18) can be obtained and the result can be expressed in terms of the bulk temperature through use of Eq. (12). Alternately, the solution of Eq. (18) is assumed to be of the form

\[
\theta(\xi,\tau) = g(\xi) + h(\xi,\tau) 
\]
From Eqs. (18) and (19), there is obtained two separate equations as

\[ g'' = 12(\xi - \xi^2) \quad (20) \]

\[ h_{\xi \xi} - h_{\tau} = 0 \quad (21) \]

Solutions of Eqs. (20) and (21) are found separately from which the complete solution for the temperature distribution is obtained as [32]

\[ \theta(\xi, \tau) = \xi(2 \xi^2 - \xi^3 - 1) + \sum_{n=1}^{\infty} C_n \sin(n \xi) \exp(-n \tau); a^2 = n \pi \quad (22a) \]

where

\[ C_n = (4/\pi^5) [(12 - 12a^2 + a^4) \cos(n \pi) - 24], \quad n = 1, 2, \ldots \]

Finally, the expression for the bulk temperature is found by using Eq. (12) as

\[ \theta_b = -17/70 + 6 \sum_{n=1}^{\infty} C_n [(1/a) + (4/a^3)] \exp(-a^2 \tau) \quad (22b) \]

Equations (22) are useful in determining the extent of radiative contributions for the transient case.

Optically Thin Limit

In the optically thin limit, the expression for the bulk temperature for the steady case is found to be [11, 32]

\[ \theta_b = [1/(3N)^3] \{576(3N)^{-1/2} \text{NEXP} - 21.6N^2 + 72N - 288\} \quad (23) \]

where

\[ \text{NEXP} = [1 - \exp \left(-3N^{1/2}\right)]/[1 + \exp \left(-3N^{1/2}\right)] \]

Both forms of the transient energy equation, Eqs. (11a) and (11b), reduce to a simplified form in the optically thin limit as [32]
\[\theta_{\xi \xi} - \theta_{\tau} - 3N\theta = 12(\xi - \xi^2) \quad (24)\]

Assuming a solution of the form given by Eq. (19), Eq. (24) is written as

\[h_{\xi \xi} - h_{\tau} - 3Nh = -g_{\xi \xi} + 3Ng + 12(\xi - \xi^2) \quad (25)\]

Consequently,

\[g'' - 3Ng = 12(\xi - \xi^2) \quad (26)\]

and

\[h_{\xi \xi} - h_{\tau} - 3Nh = 0 \quad (27)\]

From the solution of Eqs. (26) and (27), the solution for Eq. (24) is obtained as

\[
\theta(\xi, \tau) = \left(\frac{16}{3N^2}\right) \left[\frac{\sinh(-\sqrt{3N}/2)}{\sinh(\sqrt{3N})}\right] \\
\cosh \left[\sqrt{3N} (\xi - 1/2)\right] + \left(\frac{4}{N}\right)(\xi^2 - \xi + 2/3N) \\
+ \sum_{n=1}^{\infty} C_n \sin (a\xi) \exp \left[-(3N + a^2) \tau\right]; \quad a = n\pi \quad (28a)
\]

where

\[C_n = 0 \quad \text{for } n \text{ even} \quad (28b)\]

\[= \frac{32 (3N + a^2)/(3N^2 a^3)}{+ 2a/[3N^2(3N + a^2)]} \quad \text{for } n \text{ odd} \quad (28c)\]

By combining Eqs. (12) and (28), the expression for the bulk temperature is obtained as

\[
\theta_b = 6 \left((16/3N^2)[\sinh(-\sqrt{3N}/2)/\sinh(\sqrt{3N})]\right) \times \\
[(1/3N) \cosh(\sqrt{3N}/2) - (4 + \sqrt{3N}) (3N)^{-3/2}] \times
\]
\[\sinh(\sqrt{3N/2}) + (4/N) \left[-1/30 + 1/(9N)\right]\]
\[+ \sum_{n=1}^\infty C_n (1/a + 4/a^3 \exp[-(3N + a^2)\tau])\]  
(29)

**Large Path Length Limit**

In this limit, the steady-state energy equation, Eq. (16), reduces to [8, 11, 32]

\[\theta' - 2(3\xi^2 - 2\xi^3) + 1 = M \int_0^1 \theta(\xi') \frac{d\xi'}{(\xi - \xi')}\]  
(30)

where

\[M = H_1 L/k = (L/k) \sum_{i=1}^n A_{o_i} (de_{o_i}/dT)_T \]

The nondimensional parameter \(M\) constitutes the radiation-conduction interaction parameter for the large path length limit. Equation (30) does not appear to possess a closed form solution; a numerical solution, however, can be obtained easily.

In the large path length limit, the transient energy equations, Eqs. (11a) and (11b), reduce to

\[\theta_{\xi\xi} - \theta_{\tau} - 3N\theta - 12(\xi - \xi^2) = -M \int_0^\xi \theta(\xi',\tau) \frac{d\xi'}{(\xi - \xi')}^2\]
\[+ \int_0^1 \theta(\xi',\tau) \frac{d\xi'}{(\xi' - \xi)^2}\]  
(31a)

\[\theta_{\xi\xi} - \theta_{\tau} - 12(\xi - \xi^2) = M \int_0^1 (\partial\theta/\partial\xi') d\xi'/((\xi - \xi'))\]  
(31b)

Since \(|(\xi - \xi')^2| = |(\xi' - \xi)^2|\), Eq. (31a) can be written as

\[\theta_{\xi\xi} - \theta_{\tau} - 3N\theta - 12(\xi - \xi^2) = -M \int_0^1 \theta(\xi',\tau) \frac{d\xi'}{(\xi - \xi')}^2\]  
(31c)
Through integration by parts, Eq. (31c) can be expressed as

\[ \theta_{\xi \xi} - \theta_{\xi} = -3N\theta - 12(\xi - \xi^2) = M \int_0^1 (\partial \theta / \partial \xi') d\xi' / (\xi - \xi') \]  

Equations (31a) - (31d) represent different forms of the governing equations in the large path length limit. With the exception of the term \(-3N\theta\) on the left-hand side, Eq. (31d) is identical to Eq. (31b). Since \(N\) represents the radiation-conduction interaction parameter only in the optically thin limit [8], it should not appear in the governing equation for the large path length limit. Thus, Eq. (31b) is the correct equation to use for solution in the large path length limit; the solution of this equation is obtained by numerical techniques.

METHOD OF SOLUTION

The solution procedures for both steady and unsteady cases are presented in this section. In principle, the same numerical procedure applies to both the general and large path length limit cases.

Steady-State Solutions

The general solution of Eq. (16) is obtained numerically by employing the method of variation of parameters. For this, a polynomial form for \(\theta(\xi)\) is assumed in powers of \(\xi\) as

\[ \theta(\xi) = \sum_{m=0}^{n} a_m \xi^m \]  

By considering a five term series solution (a quartic solution in \(\xi\)) and satisfying the boundary conditions \(\theta(0) = \theta'(1/2) = 0\) and \(\theta'(0) = -\theta'(1)\), one obtains

\[ \theta(\xi) = a_1(\xi - 2\xi^3 + \xi^4) + a_2(\xi^2 - 2\xi^3 + \xi^4) \]  

(33)
\[ \theta'(\xi) = a_1(1 - 6\xi^2 + 4\xi^3) + a_2(2\xi - 6\xi^2 + 4\xi^3) \]  \hspace{1cm} (34)

A substitution of Eq. (34) in Eq. (16) results in
\[ a_1(1 - 6\xi^2 + 4\xi^3) + a_2(2\xi - 6\xi^2 + 4\xi^3) \]
\[ - 2(3\xi^2 - 2\xi^3) + 1 = \frac{3}{2} (L/k) \sum_{n=1}^{\infty} H_{1n} u_{0i} x \]
\[ \int_{0}^{\xi} \theta(\xi') A_i^t \left[ \frac{3}{2} u_{0i}(\xi - \xi') \right] d\xi' \]
\[ - \int_{\xi}^{1} \theta(\xi') A_i^t \left[ \frac{3}{2} u_{0i}(\xi' - \xi) \right] d\xi' \]  \hspace{1cm} (35)

where expressions for \( \theta(\xi') \) are obtained from Eq. (33).

The two unknown constants \( a_1 \) and \( a_2 \) in Eq. (35) are evaluated by satisfying the integral equation at two convenient locations (\( \xi=0 \) and \( \xi=1/4 \) in the present case). The entire procedure for obtaining \( a_1 \) and \( a_2 \) is described in [32]. With known values of \( a_1 \) and \( a_2 \), Eq. (33) provides the general solution for \( \theta(\xi) \). The expression for the bulk temperature is obtained by combining Eqs. (12) and (33) as
\[ \theta_b = (1/70) (17a_1 + 3a_2) \]  \hspace{1cm} (36)

It should be noted that for the case of no radiative interaction \( a_2 = 0 \) and \( a_1 = -1 \), and Eq. (36) gives the result of Eq. (17).

The governing equation for the large path length limit is Eq. (30). For this equation also the solution is given by Eqs. (33) and (36) but the values of \( a \)'s are completely different in this case [32].
Transient Solutions

The governing energy equations for the transient case are Eqs. (11a) and (11b). General solutions of these equations are obtained also numerically by employing the method of variation of parameters. For the present problem, a polynomial form for $\theta(\xi, t)$ is assumed as

$$\theta(\xi, t) = \sum_{m=0}^{n} a_m(t) \xi^m \quad (37)$$

For a quadratic temperature distribution in $\xi$ (with time dependent coefficients), Eq. (37) is written as

$$\theta(\xi, t) = a_0(t) + a_1(t) \xi + a_2(t) \xi^2 \quad (38a)$$

By using the boundary conditions $\theta(0, t) = 0$ and $\theta_\xi(\xi=1/2) = 0$, this reduces to

$$\theta(\xi, t) = g(t) (\xi - \xi^2) \quad (38b)$$

where $g(t)$ represents the time dependent coefficient. Consequently,

$$\theta_\xi(\xi, t) = g(t) (1-2\xi); \quad \theta_{\xi\xi}(\xi, t) = -2g(t); \quad \theta_\tau(\xi, t) = (\xi - \xi^2) g'(t) \quad (39)$$

Also, a combination of Eq. (6a) and (38b) yields the initial condition

$$\theta(\xi, 0) = g(0) = 0 \quad (40)$$

Note that essential boundary conditions are used already in obtaining the solution represented by Eq. (38b).

By employing Eqs. (38b) and (39), Eqs. (11a) and (11b) are transformed in alternate forms which are expressed in a compact form as

$$g'(\tau) + \begin{bmatrix} J_1(\xi) \\ J_2(\xi) \end{bmatrix} g(\tau) + 12 = 0 \quad (41)$$
where \( J_1(\xi) \) and \( J_2(\xi) \) are defined in [32]. The function \( J_1(\xi) \) is used for solution of Eq. (11a) and \( J_2(\xi) \) is used for solution of Eq. (11b). The solution of Eq. (41) satisfying the initial conditions of Eq. (40) is given by

\[
g(\tau) = \frac{12}{J(\xi)} \{\exp[-J(\xi)\tau]-1\} \tag{42}
\]

The temperature distribution given by Eq. (38b) can be expressed now as

\[
\theta(\xi,\tau) = \frac{12}{J(\xi)} \{\exp[-J(\xi)\tau]-1\}(\xi-\xi^2) \tag{43}
\]

The expression for the bulk temperature is obtained through use of Eq. (12) as

\[
\theta_b = 72 \int_0^1 \frac{[(\xi-\xi^2)^2/J(\xi)]\{\exp[-J(\xi)\tau]-1\}}{0} \tag{44}
\]

Note that in Eqs. (42)-(44), \( J(\xi) \) becomes \( J_1(\xi) \) for solution of Eq. (11a) and \( J_2(\xi) \) for solution of Eq. (11b).

For a quartic solution in \( \xi \), Eq. (37) gives the result similar to Eq. (33) which for the transient case is expressed as

\[
\theta(\xi,\tau) = g(\tau) (\xi - 2\xi^3 + \xi^4) + h(\tau) (\xi^2 - 2\xi^3 + \xi^4) \tag{45}
\]

By substituting Eq. (45) into Eq. (11a), one obtains

\[
x g'(\tau) + J_3(\xi) g(\tau) + yh'(\tau) + J_4(\xi) h(\tau) = -z \tag{46}
\]

where

\[
x = (\xi - 2\xi^3 + \xi^4); \quad y = (\xi^2 - 2\xi^3 + \xi^4); \quad z = 12(\xi - \xi^2)
\]

and functions \( J_3(\xi) \) and \( J_4(\xi) \) are defined in [32]. Equation (46) constitutes one equation in two unknowns, namely \( g(\tau) \) and \( h(\tau) \). However, since the equation is linear in \( \tau \), the principle of superposition can be used.
to split the solution into two equations as

\[ x g'(\tau) + J_3(\xi) g(\tau) = -\frac{z}{2} \]  \hspace{1em} (47)

\[ y h'(\tau) + J_4(\xi) h(\tau) = -\frac{z}{2} \]  \hspace{1em} (48)

The initial condition for this case can be written as

\[ \theta(\xi, 0) = g(0) \left( \xi - 2\xi + \xi^3 \right) \]

\[ + h(0) \left( \xi^2 - 2\xi^3 + \xi^4 \right) = 0 \]  \hspace{1em} (49a)

Consequently,

\[ g(0) = 0; \quad h(0) = 0 \]  \hspace{1em} (49b)

The solution of Eqs. (47) and (48) satisfying the appropriate initial condition of Eq. (49b) is given respectively as

\[ g(\tau) = \left[ z(\xi)/2J_3(\xi) \right] \left\{ \exp\left[ -J_3(\xi)\tau/x(\xi) \right] - 1 \right\} \]  \hspace{1em} (50)

\[ h(\tau) = \left[ z(\xi)/2J_4(\xi) \right] \left\{ \exp\left[ -J_4(\xi)\tau/y(\xi) \right] - 1 \right\} \]  \hspace{1em} (51)

By substituting Eqs. (50) and (51) into Eq. (45), the expression for the temperature distribution is obtained as

\[ \theta(\xi, \tau) = \left[ 6(\xi - \xi^2)(\xi - 2\xi^3 + \xi^4)/J_3(\xi) \right] \times \]

\[ \left\{ \exp\left[ -J_3(\xi)\tau/x(\xi) \right] - 1 \right\} + \left[ 6(\xi - \xi^2) \times \right. \]

\[ \left. (\xi^2 - 2\xi^3 + \xi^4)/J_4(\xi) \right\} \left\{ \exp\left[ -J_4(\xi)\tau/y(\xi) \right] - 1 \right\} \]  \hspace{1em} (52)

The bulk temperature in this case is given by

\[ \theta_b = 36 \int_0^1 \left[ (\xi - \xi^2)(\xi - 2\xi^3 + \xi^4)/J_3(\xi) \right] \times \]
\[
\exp\left[-J_3(\xi)T/x(\xi)\right] - 1 \, d\xi + 36 \int_0^1 \left(\xi - \xi^2\right) \times \\
(\xi^2 - 2\xi^3 + \xi^4)/J_4(\xi) \exp\left[-J_4(\xi)T/y(\xi)\right] - 1 \, d\xi.
\]

(53)

where \(x\) and \(y\) are defined in Eq. (46).

By substituting Eq. (45) into Eq. (11b), there is obtained

\[
xg' + J_5(\xi) g(\tau) + yh + J_6(\xi) h(\tau) = -z
\]

(54)

where again \(x, y, z\) are defined in Eq. (46) and functions \(J_5(\xi)\) and \(J_6(\xi)\) are defined in [32]. The solution procedure for this equation is identical to that for Eq. (46) and the results for temperature distribution and bulk temperature are given respectively by Eqs. (52) and (53) with \(J_3\) replaced by \(J_5\) and \(J_4\) by \(J_6\).

In the large path length limit, the two applicable governing equations are Eqs. (31b) and (31d). The solutions of these equations can be obtained from the general solutions by evaluating the integrals in \(J\) function in the large path length limit [32].

**PHYSICAL CONDITIONS AND DATA SOURCE**

As discussed in [32-34], four specific absorbing emitting species were selected for an extensive study; these are \(CO, CO_2, OH\) and \(H_2O\). The species \(CO\) was selected because it contains only one fundamental vibration-rotation (VR) band and all spectral information are easily available in the literature. It is a very convenient gas to test the numerical procedure without requiring excessive computational resources. Species \(OH\) and \(H_2O\) are the primary radiation participating species for the pressure and temperature range anticipated in the combustor of the scramjet engine. Species \(CO_2\), and combinations of \(CO_2\) and \(H_2O\) are important absorbing-emitting species in many
other combustion processes. Different mixtures of various species (such as \( \text{CO}_2 + \text{H}_2\text{O} \), \( \text{OH} + \text{H}_2\text{O} \), and \( \text{CO}_2^2 + \text{H}_2\text{O} + \text{OH} \)) were selected for parametric studies. Thermophysical properties of these species are given in [33] for different temperatures.

In radiative transfer analyses, it is essential to employ a suitable model to represent the absorption-emission characteristics of specific species under investigation. Several line-by-line (LBL), narrow-band, and wide-band models are available to model the absorption of a VR band [7-12]. However, it is often desirable to use a simple correlation to represent the total absorption of a wide band. Several such correlations are available in the literature [7-12]. The relative merits of these correlations are discussed in [12]. In this study, the correlation proposed by Tien and Lowder [7] is employed and this is given by

\[
A(u) = \ln \left\{ uf(\beta) \left[ \frac{u + 2}{u + 2f(\beta)} \right] + 1 \right\}
\]

(55)

where

\[
f(\beta) = 2.94[1 - \exp(-2.60\beta)]
\]

and \( \beta \) represents the line structure parameter.

The spectral information and correlation quantities and thermodynamic and transport properties needed for different species were obtained from Refs. 7-9 and 33. Spectral information and correlation quantities for important infrared bands are provided in Appendix A. The specific VR bands considered for each species are: CO (4.7\( \mu \) fundamental), OH (2.8\( \mu \) fundamental), CO\(_2\) (15\( \mu \), 4.3\( \mu \) and 2.7\( \mu \)), and H\(_2\)O (20\( \mu \), 6.3\( \mu \), 2.7\( \mu \), 1.87\( \mu \), and 1.38\( \mu \)).

In a mixture of several species, spectral lines and bands overlap in certain spectral regions. The total absorptance in such regions cannot be
calculated simply by adding the contributions of different bands and corrections should be made to account for the partial overlapping. If line-by-line or narrow band models are employed in the general formulation of the physical problem, then there is no need for such corrections [12, 35, 36]. The solution of LBL formulation, however, requires considerably large computational resources. Use of narrow band models offers some computational relief but certain spectral information needed are not available for many species for temperatures higher than about 600 K. A relatively easier procedure (called the block method) is suggested by Edwards [13] and is useful in calculating the total emissivity of a mixture of several species. Another method suggested by Penner and Varanasi [37] is probably the most convenient method to use in the frame work of the radiative flux formulation expressed in terms of the wide-band model absorptance and correlations.

For a homogeneous path, the total absorptance of a band is given by

\[ A(y) = \int_0^\infty [1 - \exp(-\kappa_\omega y)] d\omega \]  \hspace{1cm} (56)

where both \( \kappa_\omega \) and \( \omega \) have units of \( \text{cm}^{-1} \). If in a spectral range \( \Delta \omega_i \), there are contributions from bands of different species, then for a homogeneous path the transmittance is given by

\[ \tau_{\Delta \omega_i} = \exp\left(-\sum_{j=1}^N \kappa_{\omega_{ij}} y\right) \]  \hspace{1cm} (57)

where \( N \) represents the number of participating species in the gaseous mixture. Consequently, Eq. (56) can be expressed as

\[ A_i = \int_{\Delta \omega_i} \left[1 - \exp\left(-\sum_{j=1}^N \kappa_{\omega_{ij}} y\right)\right] d\omega \]  \hspace{1cm} (58)
If two bands of different (or same) species are occupying approximately the same spectral range $\Delta \omega_i$, then Eq. (58) reduces to

$$A_i = \int_{\Delta \omega_i} \left[ 1 - \exp\left(\kappa_{\omega_{i1}} + \kappa_{\omega_{i2}} y \right) \right] d\omega$$

(59)

By employing the relations for the exponentials, Eqs. (59) can be expressed as

$$A_i = \int_{\Delta \omega_i} \left[ 1 - \exp\left( - \kappa_{\omega_{i1}} y \right) \right] d\omega + \int_{\Delta \omega_i} \left[ 1 - \exp\left( - \kappa_{\omega_{i2}} y \right) \right] d\omega - \Delta A$$

(60a)

or

$$A = A_1 + A_2 - \Delta A$$

(60b)

where

$$\Delta A = \int_{\Delta \omega_i} \left[ \left[ 1 - \exp\left( - \kappa_{\omega_{i1}} y \right) \right] \times \right.$$

$$\left. \left[ 1 - \exp\left( - \kappa_{\omega_{i2}} y \right) \right] \right] d\omega$$

(60c)

Use of Eqs. (60) has been made by Felske and Tien [38] and Tien and Lee [39] to calculate absorptances of homogeneous and nonhomogeneous mixtures of CO$_2$ and H$_2$O in the 2.7 $\mu$ region for different pressure and temperature conditions. A similar procedure is used in this study to account for the overlapping effects of different species.

For the physical problem considered, the dependent variables are $\theta$ and $\theta_b$ (or Nu) and independent variables are $\tau$ and $\xi$. The parameters, in general, are $T_w$, $P$, and $L$. The large path length and optically thin limits are characterized respectively by parameters $M$ and $N$. Radiative and thermophysical properties of participating species are evaluated at different specified pressures and temperatures.
RESULTS AND DISCUSSIONS

Extensive results have been obtained for variation of $\theta$ and $\theta_b$ for different conditions and most of these are available in Appendix B. The computer program used for numerical solutions is provided in Appendix C. Selected results are presented here to compare solutions of quadratic and quartic formulations and demonstrate the variation of $\theta$ with $\tau$ and $\xi$ and of $\theta_b$ with $L$ for single component systems and homogeneous mixtures. For all results presented here, a lower value of $\theta$ (or $\theta_b$) in the figures indicates a higher value of temperature in the medium; this, in turn, implies a relatively higher ability of the gas to transfer radiative energy.

Results of quadratic and quartic formulations are compared in Figs. 2-5 for different species. The centerline temperature variations with nondimensional time are compared in Fig. 2 for $P = 1$ atm, $T_w = 500$ K, and $L = 5$ cm. The results show that the steady-state conditions are reached at an earlier time for H$_2$O; and this is followed respectively by CO$_2$, CO, and OH. Significant differences are noted between the quadratic and quartic solutions for larger times. For the conditions of results presented in the figure, the difference are found to be greatest for OH and lowest for H$_2$O. The results for $\theta$ versus $\xi$ are compared for $P = 1$ atm, $L = 10$ cm, and $T_w = 500$ K in Fig. 3 and $T_w = 1,000$ K in Fig. 4. The results demonstrate that considerable differences in solutions can occur at different locations in the channel and that the differences are larger for the lower wall temperature. Results for $\theta_b$ versus $L$ presented in Fig. 5 show that the differences in two solutions are relatively larger at lower plate spacings and that quartic results approach the correct limiting solution for the case of no radiative interaction ($\theta_b = -0.243$). From the results presented in Figs. 2-5 and in Refs. 33 and 34 it is concluded that while quadratic and quartic solutions are...
Figure 2. Comparison of quadratic and quartic results for the centerline
temperature variations with time; $T_w = 500$ K, $P = 1$ atm,
and $L = 5$ cm.
Figure 3. Comparison of quadratic and quartic results for temperature variations across the duct; $P = 1$ atm, $L = 10$ cm, and $T_w = 500$ K.
Figure 4. Comparison of quadratic and quartic results for temperature variations across the duct; $P = 1$ atm, $L = 10$ cm, and $T_w = 1,000$ K.
Figure 5. Comparison of quadratic and quartic results for the bulk temperature; \( P = 1\) atm and \( T_w = 500\) K.
identical for radiative equilibrium and radiation with conduction cases, they differ significantly for the case of combined conduction, convection and radiation. As such, all other results for this study were obtained by using the quartic formulation.

The results for temperature variations with nondimensional time are presented in Figs. 6-9 for various species and for different physical conditions. The centerline temperature distribution for general and limiting cases are illustrated in Fig. 6 for $T_w = 500 \text{ K}$, $P = 1 \text{ atm}$, and $L = 5 \text{ cm}$. The results show that the steady-state conditions are reached at about $\tau = 0.5$ for all species. As noted earlier, these results also demonstrate that $\text{H}_2\text{O}$ is a highly radiation participating gas as compared to $\text{CO}_2$, $\text{CO}$, and $\text{OH}$. In comparison to other species considered, $\text{OH}$ takes relatively longer times to reach the steady state and is least effective in transferring the radiative energy. For the specified physical conditions, the large path length solutions are closer to the general solutions and optically thin solutions provide higher rate of energy transfer. For all species, optically thin solutions reach the steady state faster than other solutions. Also, in the optically thin limit, $\text{CO}_2$ is more effective in the radiative transfer process than other species. The reasons for such trends are given in [8, 33, 34]. The results for $T_w = 500 \text{ K}$ and $1,000 \text{ K}$ are compared in Fig. 7, and they simply indicate that the rate of energy transfer is higher at the higher temperature. The results for $\xi = 0.25$ and $0.5$ are compared in Fig. 8 for $T_w = 1,000 \text{ K}$, $P = 1 \text{ atm}$, and $L = 5 \text{ cm}$. It is noted that the rate of energy transfer is higher at earlier times and at locations closer to the wall. The centerline temperature variations for $L = 5 \text{ cm}$ and $10 \text{ cm}$ are illustrated in Fig. 9 for $T_w = 1,000 \text{ K}$ and $P = 1 \text{ atm}$. As would be expected, the rate of energy transfer is seen to increase with the increasing path length.
Figure 6. Comparison of general and limiting results for the centerline temperature variations with time; $T_w = 500$ K, $P = 1$ atm, and $L = 5$ cm.
Figure 7. Comparison of centerline temperature variations with time for $T_w = 500$ K and $1,000$ K; $P = 1$ atm and $L = 5$ cm.
Figure 8. Comparison of temperature variations with time for $\xi = 0.25$ and $\xi = 0.5$; $T_w = 1,000$ K, $P = 1$ atm, and $L = 5$ cm.
Figure 9. Comparison of centerline temperature variations with time for $L = 5 \text{ cm}$ and $10 \text{ cm}$; $T_w = 1,000 \text{ K}$ and $P = 1 \text{ atm}$.
Figure 10. Comparison of temperature variations across the duct for $T_w = 500$ K, 1,000 K, and 2,000 K, $p = 1$ atm and $L = 10$ cm.
Figure 12. Comparison of temperature variations across the duct for CO; \( T_w = 500 \text{ K}, P = 1 \text{ atm}, \text{ and } L = 10 \text{ cm} \).
Figure 13. Comparison of temperature variations across the duct for CO₂; 
\( T_w = 500 \text{ K}, P = 1 \text{ atm}, \text{ and } L = 10 \text{ cm}. \)
Figure 14a. Comparison of temperature variations across the duct for H$_2$O; $T_w = 500$ K, P = 1 atm.
Figure 14b. Comparison of temperature variations across the duct for H$_2$O; $T_w = 1,000$ K, $P = 1$ atm, and $L = 5$ cm.
The bulk temperature results as a function of the distance between the plates are presented in Figs. 15-19 for different times. General as well as limiting solutions are illustrated in these figures. As mentioned earlier, the limiting value of \( \theta_b = -0.243 \) corresponds to negligible radiation. For all species, the results presented in the figures are for a pressure of one atmosphere. However, for any particular \( L \), the large path length results essentially represent the limiting solutions for high pressures. The results, in general, demonstrate that the rate of energy transfer is higher at earlier times, the effect of radiation increases with increasing plate spacing, and the radiative transfer is more pronounced at the higher wall temperature.

General as well as limiting solutions for the bulk temperature are illustrated in Figs. 15-18 for individual species. It is seen that for all species the general solutions for \( \tau = 0.5 \) and 1.0 are essentially the same for all plate spacings, and the large path length results are valid for spacings greater than \( L = 10 \) cm for all times. The results for \( \text{OH} \) are presented in Figs. 15a and 15b for \( T_w = 500 \) K and 1,000 K, respectively. It is noted that optically thin results provide the correct limiting solutions for plate spacings up to \( L = 3 \) cm for all times. The results for \( T_w = 500 \) K show only slight difference between general and large path length solutions for \( \tau = 0.5 \), and no significant difference was noted at earlier times (Fig. 15a). This, however, is not the case for the results presented in Fig. 15b at \( T_w = 1,000 \) K. This trend in results for \( \text{OH} \) was noted also in \([33, 34]\). The results for \( \text{CO} \) are illustrated in Fig. 16 for \( T_w = 500 \) K and \( P = 1 \) atm. In this case, the optically thin solutions are seen to be valid only up to \( L = 1.5 \) cm. For \( T_w = 1,000 \) K and \( P = 1 \) atm, the results presented in Fig. 17 for \( \text{CO}_2 \) and in Fig. 18 for \( \text{H}_2\text{O} \) show the same general trend but the extent of radiative interaction is entirely different. For \( \text{CO}_2 \), there is a considerable
difference in general and optically thin solutions for all times. For H₂O, however, the optically thin results are closer to the general solutions for spacings up to L = 2.5 cm. The results presented in Figs. 15-18 clearly reveal that for a fixed spacing between the plates the rate of radiative heating will be considerably higher at earlier times than at the steady state. Thus, in a particular physical system, the extent of radiative heating can be very intense during the initial stages of operation. It is also important to note that both the optically thin and large path length results overestimate the influence of radiation. Since these solutions can be obtained with less numerical complications, they can be utilized to assess whether or not, for a given gas, the interaction of radiation is going to be important.

A comparison of the general band absorptance results for the four gases is shown in Figs. 19a and 19b for a pressure of one atmosphere. The results clearly demonstrate the relative ability of the four species for radiative transfer at different path lengths. For a plate spacing of greater than L = 3.0 cm, the results show the same trend as noted in Figs. 2-10. For lower plate spacings and relatively higher temperatures, however, CO₂ shows a significantly higher ability for radiative transfer than other species. This is a typical distinguishing feature of the CO₂ under optically thin conditions [8, 33, 34].

For steady-state conditions, bulk temperature results were obtained for mixtures of different absorbing-emitting species under various conditions and some of these are presented in Figs. 20-27. The relative amount of each species in the mixture and the relative ability of the species for radiative transfer in a given physical condition determine the extent of radiative interaction.
Figure 15a. Variation of bulk temperature with plate spacing for OH; 
$T_w = 500 \text{ K} \text{ and } P = 1 \text{ atm.}$
Figure 15b. Variation of bulk temperature with plate spacing for OH; $T_w = 1,000$ K and $P = 1$ atm.
Figure 16. Variation of bulk temperature with plate spacing for CO; $T_W = 500$ K and $P = 1$ atm.
Figure 17. Variation of bulk temperature with plate spacing for CO$_2$; $T_w = 1,000$ K and $P = 1$ atm.
Figure 18. Variation of bulk temperature with plate spacing for H_2O;
T_w = 1,000 K and p = 1 atm.
Figure 19a. Comparison of bulk temperature results for $T_w = 1,000$ K and $P = 1$ atm.
Figure 19b. Comparison of bulk temperature results for P = 1 atm.
As mentioned before, in many combustion processes involving fossil fuels, the predominant products of combustion are carbon dioxide and water vapor. Extensive studies have been conducted in the literature to determine the total emissivity of CO\textsubscript{2} and H\textsubscript{2}O for homogeneous and nonhomogeneous conditions. However, only limited studies are available involving mixtures of CO\textsubscript{2} and H\textsubscript{2}O for realistic and important physical conditions. The bulk temperature results for three different mixtures of CO\textsubscript{2} + H\textsubscript{2}O are presented in Figs. 20-23 for different temperatures and pressures. As would be expected, the results, in general, show that the extent of radiative interaction increases with increasing temperature, pressure, and path length. It is seen that the radiative interaction is stronger for higher amount of H\textsubscript{2}O in the mixture. However, for the optically thin conditions, the radiative contribution is seen to increase with increasing amount of CO\textsubscript{2} at relatively higher temperatures.

The bulk temperatures results for mixtures of OH and H\textsubscript{2}O are illustrated in Figs. 24-26 and for mixtures of CO\textsubscript{2}, H\textsubscript{2}O, and OH in Fig. 27 for different pressures and temperatures. All these results clearly demonstrate that the radiative ability of a gaseous mixture essentially depends on the amount of highly radiation participating species in the mixture. For example, a comparison of results presented in Figs. 24 and 27 for P = 1 atm indicates that the rate of radiative transfer is significantly higher with the inclusion of 20% CO\textsubscript{2} in the mixture of OH and H\textsubscript{2}O. It is further noted that OH becomes a highly radiation participating species at higher temperatures and pressures.
Figure 20. Bulk temperature results for CO$_2$ + H$_2$O for P = 0.1 atm.
Figure 21. Bulk temperature results for CO\textsubscript{2} + H\textsubscript{2}O for P = 1 atm.
Figure 23. Bulk temperature results for CO\textsubscript{2} + H\textsubscript{2}O for $T_w = 2,000$ K.
Figure 24. Bulk temperature results for OH and H₂O for P = 1 atm.
Figure 25. Bulk temperature results for OH and H$_2$O for P = 10 atm.
Figure 26. Bulk temperature results for OH and H₂O for T_w = 2,000 K.
Figure 27. Bulk temperature results for \( \text{CO}_2 + \text{H}_2\text{O} + \text{OH} \) for \( P = 1 \) atm.
CONCLUDING REMARKS

Analytical formulations and numerical procedures have been developed to investigate the transient radiative interaction of absorbing-emitting species in laminar fully-developed flows. Extensive results have been obtained for OH, CO, CO₂ and H₂O for different physical conditions. Illustrative results for the temperature distribution and bulk temperature are presented for different pressures and wall temperatures. In these results, a lower value of temperature implies a relatively higher ability of the gas to transfer radiative energy.

Comparative results of quadratic and quartic formulations confirm the need to use the quartic formulation in the numerical procedures for the case of combined conduction, convection, and radiation. The results, in general, demonstrate that the steady-state conditions are reached at about \( \tau = 0.5 \) for all species, H₂O is a highly radiation participating species (as compared to CO₂, CO, and OH), the rate of energy transfer is higher at earlier times and at locations closer to the wall, differences between the limiting and general solutions are small at earlier times, the effect of radiation increases with increasing plate spacing, and the radiative transfer is more pronounced at higher wall temperature and pressure. Similar conclusions can be drawn from the results presented for various mixtures. The results clearly show that for a given physical condition the radiative ability of a gaseous mixture depends essentially on the amount of highly radiating species in the mixture. From the results presented in this study, the extent of total heating can be determined for different times. This information is essential in designing thermal protection systems for operations during the initial stages of intense heating.
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SPECTRAL INFORMATION AND CORRELATION QUANTITIES
FOR IMPORTANT INFRARED BANDS

Spectral information and correlation quantities for important infrared bands are available in [7-9]. The exponential band model correlation quantities for important bands of CO, CO$_2$, H$_2$O, and CH$_4$ are given in Table A.1. For some species, revised data are now available in [13].

In developing correlation quantities for different bands, it is important to have information on the integrated band intensity $S(T_o)$ and the band width parameter $A_0(T)$. The band intensities of many molecular bands are available in the literature [7-9, 13, 33] but this is not the case with the band width parameter. Different relations for $A_0(T)$ are proposed by Edwards et al. in references cited in [9]. From a critical evaluation of different relations available in the literature for $A_0(T)$ and after personal communications with Dr. D.K. Edwards, it was decided to adopt the following two relations:

$$A_0(T) = \frac{1}{2} r^2 \left( \frac{3}{4} \right) \left( \frac{4kTB}{hc} \right)^{1/2}$$  \hspace{1cm} (A.1)

$$A_0(T) = 0.9 \ r^2 \left( \frac{3}{4} \right) \left( \frac{2kTB}{hc} \right)^{1/2}$$  \hspace{1cm} (A.2)

where B is the rotational constant of lower level, c is the speed of light, h is the Planck's constant and k is the Boltzmann's constant. The value of B is different for different molecules. Equations (A.1) and (A.2) are
essentially the same except Eq. (A.1) will result in a coefficient of 0.707 instead of 0.9. It is suggested to use Eq. (A.2) in determining approximate relations for $A_0(T)$ for all molecules whose values are not available in the literature. Information on the rotational constants for different molecules is available in the literature (for example, see Ref. 33). It is suggested to use the equivalent value for the rotational constant of polyatomic molecules.

It should be noted that in Eqs. (A.1) and (A.2), $B$, $c$, $h$, and $k$ are constants and do not depend on the temperature. Thus, Eq. (A.2) may be expressed as:

$$A_0(T) = \text{CONST} \left(\frac{T}{T_{ref}}\right)^{1/2} \quad (A.3a)$$

where

$$\text{CONST} = 0.9 \sqrt{\frac{3}{4}} \left(\frac{2k\beta e}{hc}\right)^{1/2} \quad (A.3b)$$

and $\beta e$ represents the equivalent rotational constant. By evaluating Eq. (A.3a) at a reference temperature $T_{ref}$, the value of $A_0(T_{ref})$ can be determined and, therefore, Eq. (A.3a) may be expressed alternately as:

$$A_0(T) = A_0(T_{ref}) \left(\frac{T}{T_{ref}}\right)^{1/2} \quad (A.4)$$

Equation (A.4) is a convenient form to compare its results with experimental values.

By noting that $\sqrt{\frac{3}{4}} = [\sqrt{(3/4)}]^2$ and substituting values for $c$, $h$, and $k$, Eq. (A.3) can be expressed as:

$$A_0(T) = 1.59313 (\beta e T)^{1/2} \quad (A.5)$$
where \( A_0 \) and \( B_e \) have units of \( \text{cm}^{-1} \) and \( T \) is in degrees Kelvin. For a particular gas, \( A_0(T_{\text{ref}}) \) can be obtained from Eq. (A.5) and then Eq. (A.4) can be used to determine \( A_0(T) \) at other temperatures. For example, for CO the rotational constant is 1.931 \( \text{cm}^{-1} \) and at a reference temperature of 300 K, \( A_0(T_{\text{ref}} = 300 \text{K}) = 38.344 \text{ cm}^{-1} \). This compares very well with the experimental value of 38.1 given if Refs. 7 and 9 and presented in Table A.1. Similarly, for the 4.3 \( \mu \) band of \( \text{CO}_2 \), the equivalent rotational constant is 0.3906 \( \text{cm}^{-1} \) and, therefore, \( A_0(T_{\text{ref}} = 300 \text{K}) = 17.246 \text{ cm}^{-1} \); the experimental value of 19.9 \( \text{cm}^{-1} \) given in Table A.1 for this band is slightly higher.

**Spectral Information for OH**

For the fundamental band of OH, the following information is obtained from Ref. 33:

- Band center, \( \omega_c = 3570 \text{ cm}^{-1} \),
- Band strength at STP, \( S(T_0) = 110 \text{ cm}^{-2} \text{ atm}^{-1} \)

Also, from Ref. 33 the information on equilibrium rotational constant for OH is obtained as:

\[
A^2\Sigma^+ \rightarrow 17.355 \text{ cm}^{-1}
\]

\[
X^2\Pi_i \rightarrow 18.871 \text{ cm}^{-1}
\]
Thus, it is suggested to use a value for the equilibrium rotational constant for OH as $B_0 = 18 \text{ cm}^{-1}$.

Using this, a value of $A_0 (T_{\text{ref}} = 300 \text{ K})$ is found as

$$A_0 (T_{\text{ref}} = 300) = 1.59313 (B_e T_{\text{ref}})^{1/2} = 117.0707.$$  \hfill (A.6)

Considering the value of $A_0 (T_{\text{ref}}) = 117 \text{ cm}^{-1}$, the relation for $A_0 (T)$ for OH is given as:

$$A_0 (T) = 117 (T/300)^{1/2}.$$  \hfill (A.7)

By knowing $\omega_c$, $S (T_0)$, and $A_0 (T)$, other required spectral information for OH can be evaluated.
### Table A.1 Exponential Band Model Correlation Quantities**

<table>
<thead>
<tr>
<th>Molecule</th>
<th>Band ( \nu )</th>
<th>Band Center ( \text{cm}^{-1} )</th>
<th>Pressure Parameters</th>
<th>( A_0(T) ) ( \text{cm}^{-1} )</th>
<th>( C_0^2(T) ) atm(^{-1}) ( \text{cm}^{-1} )</th>
<th>( B^2(T) ) dimensionless</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>4.7</td>
<td>2143</td>
<td>1.1</td>
<td>0.8</td>
<td>38.1 ( K_1(T) )</td>
<td>6.24 ( K_2(T) )</td>
</tr>
<tr>
<td></td>
<td>2.35</td>
<td>4260</td>
<td>1.0</td>
<td>0.8</td>
<td>38.1 ( K_1(T) )</td>
<td>0.042 ( K_2(T) )</td>
</tr>
<tr>
<td>CO(_2)</td>
<td>15</td>
<td>667</td>
<td>1.3</td>
<td>0.7</td>
<td>22.3 ( K_1(T) )</td>
<td>15.2 ( K_2(T) )</td>
</tr>
<tr>
<td></td>
<td>4.3*</td>
<td>2350</td>
<td>1.3</td>
<td>0.8</td>
<td>19.9 ( K_1(T) )</td>
<td>98.7 ( K_2(T) )</td>
</tr>
<tr>
<td></td>
<td>2.7</td>
<td>3715</td>
<td>1.3</td>
<td>0.65</td>
<td>41.6 ( K_1(T) )</td>
<td>1.72 ( K_2(T) ) ( \phi_2(T) )</td>
</tr>
<tr>
<td>H(_2)(_O)</td>
<td>1.8</td>
<td>500</td>
<td>5.0</td>
<td>1.0</td>
<td>49.4 ( K_1(T) )</td>
<td>771 ( K_2(T) ) ( \phi_7(T) )</td>
</tr>
<tr>
<td></td>
<td>6.3</td>
<td>1600</td>
<td>5.0</td>
<td>1.0</td>
<td>90.1 ( K_1(T) )</td>
<td>3.35 ( K_2(T) )</td>
</tr>
<tr>
<td></td>
<td>2.7</td>
<td>3750</td>
<td>5.0</td>
<td>1.0</td>
<td>112.6 ( K_1(T) )</td>
<td>1.52 ( K_2(T) )</td>
</tr>
<tr>
<td></td>
<td>1.87</td>
<td>5350</td>
<td>5.0</td>
<td>1.0</td>
<td>79.7 ( K_1(T) )</td>
<td>0.276 ( K_2(T) ) ( \phi_{101}(T) )</td>
</tr>
<tr>
<td></td>
<td>1.38</td>
<td>7250</td>
<td>5.0</td>
<td>1.0</td>
<td>79.7 ( K_1(T) )</td>
<td>0.230 ( K_2(T) ) ( \phi_{101}(T) )</td>
</tr>
<tr>
<td>CH(_4)</td>
<td>7.6</td>
<td>1310</td>
<td>1.3</td>
<td>0.8</td>
<td>39.8 ( K_1(T) )</td>
<td>4.58 ( K_2(T) )</td>
</tr>
<tr>
<td></td>
<td>3.3</td>
<td>3020</td>
<td>1.3</td>
<td>0.8</td>
<td>95.3 ( K_1(T) )</td>
<td>3.15 ( K_2(T) )</td>
</tr>
</tbody>
</table>

**Notes on Table A.1. (See next page)**
1. Correlation quantities are based on the results of reference [9]. The intensity of the band marked with * was taken from the reference [7].

2. Notations: \( K_1(T) = (T/300)^{1/2} \), \( K_2(T) = (300/T)^{3/2} \),
\[
\delta_1 = [\phi_1^2(T)/K_1(T)] \times 10^{-3}, \quad \delta_2 = \phi_2^2(T)/[\phi_2(T)K_1(T)]
\]
\[
h = 6.625 \times 10^{-27} \text{ erg-sec}, \quad C = 2.998 \times 10^{10} \text{ cm/sec},
\]
\[
k = 1.380 \times 10^{-16} \text{ erg/K }, \quad hC/k = 1.44 \text{ cm - K}
\]

3. Temperature range: \( 300 \text{ K} < T < T_{\text{max}} \). For CO, \( T_{\text{max}} = 1800 \text{ K} \).

For CO, \( T_{\text{max}} = 1400 \text{ K} \). For \( \text{H}_2\text{O}, \ T_{\text{max}} = 1100 \text{ K} \). For \( \text{CH}_4 \),
\[ T_{\text{max}} = 830 \text{ K} \]

4. For CO, \( \omega = 2143 \text{ cm}^{-1} \) and
\[
\phi_1(T) = [15.15 + 0.22 (T/T_0)^{3/2}] [1 - \exp (-hC\omega/kT)], \quad T_0 = 100 \text{ K}
\]

5. For CO, \( \omega_1 = 1351 \text{ cm}^{-1}, \omega_2 = 667 \text{ cm}^{-1}, \omega_3 = 2396 \text{ cm}^{-1} \)
\[
\phi_2(T) = \{1 - \exp \left[ (-hC/\omega_1) (\omega_1 + \omega_3) \right] \} \times
\]
\[
\{[1 - \exp (-hC\omega_1/kT)] [1 - \exp (-hC\omega_3/kT)]\}^{-1}, \quad \phi_3(T) = 1 + 0.053 (T/100)^{3/2}
\]

6. For H$_2$O, $\omega_1 = 3652$ cm$^{-1}$, $\omega_2 = 1595$ cm$^{-1}$, $\omega_3 = 3756$ cm$^{-1}$

$$\phi_{\nu_1 \nu_2 \nu_3} (T) = \{1 - \exp [-hC(\nu_1 \omega_1 + \nu_2 \omega_2 + \nu_3 \omega_3)/kT]\} \times$$

$$\left\{\left[1-\exp \left(-\frac{h\omega_1}{kT}\right)\right]\left[1-\exp\left(-\frac{h\omega_2}{kT}\right)\right]\left[1-\exp\left(-\frac{h\omega_3}{kT}\right)\right]\right\}^{-1}$$

$$\phi_7 (T) = \exp \left[-17.6 \left(\frac{T}{100}\right)^{-1/2}\right]$$
APPENDIX B
RESULTS OF THE QUARTIC FORMULATION

Extensive results of the quartic formulation are presented in this appendix. The order of presentation of results is $\theta$ vs. $\tau$, $\theta$ vs. $\zeta$, and $\theta_b$ vs. $L$. The order of results for the four species considered is OH, CO, CO$_2$, and H$_2$O. Information on other physical conditions is provided on each figure. The notations used in these figures correspond to the notations used in the main text according to the following relations:

- LARGE PATH = LARGE PATH LENGTH
- OPT THIN = OPTICALLY THIN
- $T_{BULK} = \theta_b = (T_w - T_b)/(q_w L/K)$
- $\Theta = \theta = (T_w - T)/(q_w L/K)$
- $T = \tau$
- $T_W = T_w$
- $Z = \zeta$
Figure B.1. Results for temperature variation with time ($\theta$ vs. $\tau$) for OH.
GAS:  DH (GENERAL)

TW=500.0  P=1.0
L=10.

Figure B.1. (continued)
Figure B.2. Results for temperature variation with time (θ vs. τ) for CO.
Figure B.3. Results for temperature variation ($\theta$ vs. $\tau$) for CO$_2$.
GAS: CO2 (OPT THIN)

$T = 0.25$

$T = 0.50$

$T_{w} = 500.0$, $P = 1.0$

$L = 5.0$

Figure B.3 (continued)
The results for temperature variations within the plates are presented in Figs. 10-14 for different conditions. Since the temperature profiles are symmetric, most of these results are illustrated only for \( \xi = 0 \) to \( \xi = 0.5 \). The steady-state solutions for various species are compared in Fig. 10 for \( P = 1 \) atm, \( L = 10 \) cm, and different wall temperatures. Results again demonstrate the relative importance of different species for energy transfer. It is noted that the results for \( \text{CO}_2 \) at \( T_w = 500 \) K are exactly the same as for OH at \( T_w = 1,000 \) K, and the results for CO and H\(_2\)O are about the same at \( T_w = 1,000 \) K and 2,000 K. This obviously is a coincidence for the physical case considered. The general and limiting solutions for OH, CO, \( \text{CO}_2 \), and H\(_2\)O are presented, respectively, in Figs. 11 through 14a for \( T_w = 500 \) K, \( P = 1 \) atm, and \( L = 10 \) cm. These results also show that the steady-state conditions reach earlier for H\(_2\)O and \( \text{CO}_2 \) than for CO and OH. In general, the differences between limiting and general solutions are found to be small at earlier times; the maximum difference occurs at the steady-state conditions. In each case, the large path length solutions are closer to the general solutions, but the optically thin solutions are found to deviate considerably. This is because for \( P = 1 \) atm and \( L = 10 \) cm, the pressure path length is sufficiently high and the optically thin limit is not the correct limit for the physical case considered. It should be noted that for CO, \( \text{CO}_2 \), and H\(_2\)O, the optically thin solutions are identical for \( \tau > 0.05 \). Additional results given in Appendix B reveal that the differences between general and large path length solutions are insignificant at higher temperatures for all species. The general solutions for the temperature variation across the entire duct are illustrated in Fig. 14b for H\(_2\)O for the physical conditions of \( T_w = 1,000 \) K, \( P = 1 \) atm, and \( L = 5 \) cm. The parabolic nature of the transient profiles is clearly evident and, in this case, the steady-state is reached at \( \tau > 0.5 \).
GAS: CO2 (GENERAL)

\[ z = 0.25 \]
\[ z = 0.60 \]

\[ T_w = 500.0 \quad P = 1.0 \]
\[ L = 10 \]

Figure B.3 (continued)
Figure B.3 (continued)

GAS: CO2 (OPT THIN)

TH=500.0  P=1.0

L=10.
Figure B.4. Results for temperature variation with time (θ vs. τ) for H₂O.
Figure B.4 (continued)
GAS: H2O (LARGE PATH)

TH=500.0  P=1.0
L=10.

Figure B.4 (continued)
GAS: H2O (GENERAL)

$z=0.25$

$z=0.50$

$T_H=1000.0$  $P=1.0$

$L=10$

Figure B.4 (continued)
Figure B.5. Results for temperature variation across the duct ($\theta$ vs. $\xi$) for OH.
GAS: DH (OPT THIN)

\[ T=0.05 \quad T=0.1 \quad T=1.0 \]

\[ T=500.0 \quad P=1.0 \]

\[ L=10. \]

Figure B.5 (continued)
Figure B.6. Results for temperature variation across the duct ($\theta$ vs. $\xi$) for CO.
GAS: CO OPT THIN

TNE=500.0  P=1.0
L=10.

Figure B.6 (continued)
GAS: CO (LARGE PATH)

TH=500.0  P=1.0  L=10.

Figure B.6 (continued)
GAS: CO (GENERAL)

\[ T_0 = 0.05 \]
\[ T_0 = 0.1 \]
\[ T_0 = 1.0 \]

\[ T_H = 1000.0 \quad P = 1.0 \]

\[ L = 10. \]

Figure B.6 (continued)
Figure B.7. Results for temperature variation across the duct ($\theta$ vs. $\xi$) for CO$_2$. 

GAS: CO$_2$ (GENERAL)

\begin{align*}
T_w &= 500.0 & P &= 1.0 \\
L &= 10.
\end{align*}
GAS: CO$_2$ (LARGE PATH)

$T=0.05$  $T=0.1$  $T=1.0$

$T_{W}=500.0$  $P=1.0$

$L=10.0$

Figure B.7 (continued)
GAS: CO2 (GENERAL)

T = 0.05

T = 0.1

T = 1.0

TN = 1000.0  P = 1.0
L = 10.

Figure B.7 (continued)
GAS: CO2 | GENERAL

$T_W = 2000.0 \quad P = 1.0$

$L = 10.$

Figure B.7 (continued)
Figure B.8. Results for temperature variation across the duct (θ vs. ξ) for H₂O.
GAS: H2O (OPT THIN)

TH = 500.0

L = 10.
GAS: H2O (LARGE PATH)

TN=500.0  P=1.0
L=10.

Figure B.8 (continued)
GAS: H2O (GENERAL)

\[ \text{T} = 0.05 \]
\[ \text{T} = 0.1 \]
\[ \text{T} = 1.0 \]

\( \text{TH} = 1000.0 \quad \text{P} = 1.0 \)

\( L = 10.0 \)

Figure B.8 (continued)
GAS: H2O (GENERAL)

TH=2000.0  P=1.0
L=10.

Figure B.8 (continued)
Figure B.9. Results for bulk temperature variation with plate spacing ($\theta_b$ vs. $L$) for OH.
Figure B.9 (continued)
Figure B.9 (continued)
Figure B.9 (continued)
GAS: OH (LARGE PATH)

T_w=2000.0  P=1.0

Figure B.9 (continued)
Figure B.10 (continued)
GAS: CO (LARGE PATH)

\[
\begin{array}{c}
T=0.05 \\
T=0.1 \\
T=0.5 \\
T=1.0
\end{array}
\]

TW=500.0  P=1.0

Figure B.10 (continued)
Figure B.11. Results for bulk temperature variation with plate spacing (θb vs. L) for CO2.
GAS: CO2 (OPT THIN)

\[ \text{TW}=500.0 \quad P=1.0 \]

Figure B.11 (continued)
GAS: CO2 (GENERAL)

T=0.06
T=0.1
T=0.5
T=1.0

TW=1000.0  P=1.0

(d)

Figure B.11 (continued)
Figure B.11 (continued)
Figure B.11 (continued)
Figure B.11 (continued)
Figure B.11 (continued)
Figure B.12 Results for bulk temperature variation with plate spacing ($\theta_b$ vs. $L$) for H$_2$O.
Figure B.12 (continued)
GAS: H2O (LARGE PATH)

- T=0.05
- T=0.1
- T=0.5
- T=1.0

TH=1000.0  P=1.0

Figure B.12 (continued)
Figure B.12 (continued)
Figure B.12 (continued)
APPENDIX C

COMPUTER CODE FOR TRANSIENT ENERGY TRANSFER IN INCOMPRESSIBLE LAMINAR FLOWS

Following the numerical procedure discussed under the section "Method of Solution," a general computer program is developed to calculate the temperature variation and bulk temperature for a fully-developed laminar flow between two parallel plates having uniform wall heat flux. The program provides the general solution as well as the limiting (optically thin and large path length) solutions. The program is written for the three-band CO$_2$ gas, but can be used for any gas by employing appropriate thermophysical and radiative properties.
PROGRAM TRAN(OUTPUT=65,TAPE6,TAPE11,TAPE15,TAPE10,TAPE1,TAPE2, &TAPE3)
C******************************************************************************
C
C THIS PROGRAM CALCULATES THE TRANSIENT RADIATIVE INTERACTION IN FULLY DEVELOPED LAMINAR FLOW OF CO2 BETWEEN TWO PARALLEL BLACK WALLS WITH CONSTANT HEAT FLUX.
C IT IS BASED ON REPORT BY DR. S.N. TIWARI(REPORT NO 1-NAG 432)
C******************************************************************************

L        DISTANCE BETWEEN PLATES (IN CM)
TW        WALL TEMPRATURE ( K)
P        PRESSURE (ATM)
TT        TIME (NON DIMENSIONAL)
Z        NON DIMENSIONAL DISTANCE BETWEEN THE PLATES
Z = 0.0 AT LOWER WALL
Z = 1.0 AT UPPER WALL

REAL L,KFB
DIMENSION U(60),EPS(3),PRES(IO),TEMP(8),ZZ(60),TT(60),TB(65) &TBO(65),TBL(65),DZZ(20)
COMMON F1,F2,F3,B1,B2,B3,Z
DATA U/0.1,0.2,0.4,0.5,1.0,2.,3.,4.,6.,7.,8.,10.,20.,40.,60.,80. &100.,200.,500.,1000./ DATA PRES/0.01,0.1,1.0,10.0/ DATA TEMP/500.0,1000.0,2000.0,3000.0/ DATA TT/0.05,0.1,0.5,1.0/ DATA DZZ/0.2,0.3,0.4,0.5,6.,7.,8./ WRITE(6,110) WRITE(10,120) WRITE(15,130)
NP=20
NT=4

C
C TIME MARCHING
C
DO 22 ITT=1,NT
T=TT(ITT)
IB=1
C SET IB=0 FOR CALCULTING BULK TEMPRATURE,OTHERWISE IB=0
IM=1
C SET IM=1 FOR QUARTIC AND IM=2 FOR QUADRATIC
IF(IB.EQ.1) GOTO 108
WRITE(6,150) WRITE(10,150) WRITE(15,150)
GOTO 109
108 WRITE(6,118) WRITE(10,118)
109 WRITE(15,118)
WRITE(6,140) T
WRITE(15,140) T
WRITE(10,140) T
DO 44 IT=1,3
   TW=TEMP(IT)
DO 55 KK=3,3
   P=PRES(KK)
DO 66 I=1,NP
   L=U(I)
C
   N11=7
   DZ=0.1
   DO 77 IZ=1,N11
      Z=DZZ(IZ)
C
   CALCULATION OF PLANCK FUNCTION AND ITS DERIVATIVE
C
   WNB BAND CENTER (1/CM)
   HCK CONSTANT (K CM)
   CCC C1*C2 (ERG-K-CM**3/SEC)
   PFDBI PLANCK FUNCTION DERIVATIVE FOR I BAND
C
   CESS=TW**2
   STU=TW**0.5
   SNT=TW/273.0
   HCK=1.439257246
   CCC=0.000053847734
C
   SPECTROSCOPIC PROPERTIES OF CO2
   HERE WE HAVE CONSIDERED ONLY THREE BANDS(15,4.3 & 2.7 MICRONS)
   WNB1 BAND CENTER (1/CM)
C
   WNB1=667.0
   WNB2=2347.0
   WNB3=3716.0
   C2B1=HCK*WNB1
   C2B2=HCK*WNB2
   C2B3=HCK*WNB3
   CCC=0.000053847734
   CCB1=CCC*(WNB1**4)
   CCB2=CCC*(WNB2**4)
   CCB3=CCC*(WNB3**4)
   TB1=C2B1/TW
   TB2=C2B2/TW
   TB3=C2B3/TW
   TEB1=EXP(TB1)
   TEB2=EXP(TB2)
   TEB3=EXP(TB3)
   SNTB1=CESS*((TEB1-1.0)**2.0)
   SNTB2=CESS*((TEB2-1.0)**2.0)
   SNTB3=CESS*((TEB3-1.0)**2.0)
   PFDB1=(CCB1*TEB1)/SNTB1
   PFDB2=(CCB2*TEB2)/SNTB2
   PFDB3=(CCB3*TEB3)/SNTB3
C
   BAND MODEL CORRELATIONS (TIEN & LOWDER WIDE BAND MODEL)
AZI AOI (1/CM)
CZSI COI**2 (1/(ATM-CM))
BSI B**2 (NON DIMENSIONAL)
OMGI WAVE NUMBER(1/CM)
SI INTEGRATED BAND INTENSITY (1/(ATM CM**2))

AK1=(TW/300.0)**0.5
AK2=(300.0/TW)**1.5
AZ1=1.29*STU
AZ2=1.15*STU
AZ3=2.4*STU

KFB THERMAL CONDUCTIVITY (ERG/CM-SEC-K)

KFB=(1488.365171)*(SNT**1.23)
OMG1=1351.0
OMG2=667.0
OMG3=2396.0
TX=-(HCK/TW)
TX1=TX*OMG1
TX2=TX*OMG2
TX3=TX*OMG3
ETX1=EXP(TX1)
ETX2=EXP(TX2)
ETX3=EXP(TX3)
C1=1.0-ETX1
C2=1.0-ETX2
C3=1.0-ETX3
BRKT=TX*(OMG1+OMG3)
PHI2=(1.0-EXP(BRKT))/(C1*C3)
TS=300.0/TW
S1=339.685*TS
S2=2702.7*TS
S3=71.497*TS*PHI2
CZS1=S1/AZ1
CZS2=S2/AZ2
CZS3=S3/AZ3

PL PRESSURE PATH LENGTH (ATM-CM)

PL=P*L
UZ1=CZS1*PL
UZ2=CZS2*PL
UZ3=CZS3*PL
BS1=0.0841*AK1
BS2=0.32895*AK1
PHI3=1.0+0.053*((TW/100.0)**1.5)
DEL2=(PHI3**2.0)/(PHI2*AK1)
BS3=0.1112*DEL2

PE1 EFFECTIVE PRESSURE FOR EACH BAND (NON DIMENSIONAL)

PE1=(1.3*P)**0.7
PE2=(1.3*P)**0.8
PE3=(1.3*P)**0.65
BETAI LINE STRUCTURE PARAMETER

\[
\begin{align*}
\text{BETAI} &= \text{BS1} \times \text{PE1} \\
\text{BETAI} &= \text{BS2} \times \text{PE2} \\
\text{BETAI} &= \text{BS3} \times \text{PE3}
\end{align*}
\]

CORRELATION FOR EACH BAND

\[
\begin{align*}
F1 &= 2.94 \times (1.0 - \exp(-2.60 \times \text{BETAI})) \\
F2 &= 2.94 \times (1.0 - \exp(-2.60 \times \text{BETAI2})) \\
F3 &= 2.94 \times (1.0 - \exp(-2.60 \times \text{BETAI3})) \\
B1 &= 1.5 \times \text{UZ1} \\
B2 &= 1.5 \times \text{UZ2} \\
B3 &= 1.5 \times \text{UZ3} \\
H1 &= \text{AZ1} \times \text{PFDB1} \\
H2 &= \text{AZ2} \times \text{PFDB2} \\
H3 &= \text{AZ3} \times \text{PFDB3} \\
Z2 &= \text{Z} \\
CZ &= 1.0 / (\text{Z} - \text{Z2})
\end{align*}
\]

NUMERICAL INTEGRATION

FOR DETAILS OF INTEGRATION REFER MATHEMATICAL LIBRARY
AT NASA LANGLEY (DOCUMENT N-3)

\[
\begin{align*}
\text{EPS(1)} &= 1 \times 10^{-12} \\
\text{EPS(2)} &= 1 \times 10^{-12} \\
X &= 0.0 \\
\text{IF}(\text{IM}. \text{EQ. 1}) \text{ GOTO 678} \\
\text{CALL CADRE}(X,Z,F211,\text{EPS}, \text{ITEXT}, \text{G211}, \text{IERR}) \\
\text{CALL CADRE}(X,Z,F212,\text{EPS}, \text{ITEXT}, \text{G212}, \text{IERR}) \\
\text{CALL CADRE}(X,Z,F213,\text{EPS}, \text{ITEXT}, \text{G213}, \text{IERR}) \\
\text{CALL CADRE}(Z,1.,F221,\text{EPS}, \text{ITEXT}, \text{G221}, \text{IERR}) \\
\text{CALL CADRE}(Z,1.,F222,\text{EPS}, \text{ITEXT}, \text{G222}, \text{IERR}) \\
\text{CALL CADRE}(Z,1.,F223,\text{EPS}, \text{ITEXT}, \text{G223}, \text{IERR}) \\
\text{SUM21} &= (\text{G211} - \text{G221}) \\
\text{SUM22} &= (\text{G212} - \text{G222}) \\
\text{SUM23} &= (\text{G213} - \text{G223}) \\
\text{BR1} &= \text{H1} \times \text{UZ1} \times \text{SUM21} \\
\text{BR2} &= \text{H2} \times \text{UZ2} \times \text{SUM22} \\
\text{BR3} &= \text{H3} \times \text{UZ3} \times \text{SUM23} \\
\text{BR} &= \text{BR1} + \text{BR2} + \text{BR3} \\
\text{AJ2} &= \text{CZ} \times (2 + 1.5 \times \text{L/KFB} \times \text{BR}) \\
\text{GT2} &= 12 \times (\exp(-\text{AJ2} \times T) - 1) / \text{AJ2} \\
\text{THETA} &= \text{GT2} \times (\text{Z} - \text{Z2}) \\
\text{GOTO 679}
\end{align*}
\]

678 CONTINUE

\[
\text{CALL CADRE}(X,Z,F511,\text{EPS}, \text{ITEXT}, \text{G511}, \text{IERR}) \\
\text{CALL CADRE}(X,Z,F512,\text{EPS}, \text{ITEXT}, \text{G512}, \text{IERR}) \\
\text{CALL CADRE}(X,Z,F513,\text{EPS}, \text{ITEXT}, \text{G513}, \text{IERR}) \\
\text{CALL CADRE}(Z,1.,F521,\text{EPS}, \text{ITEXT}, \text{G521}, \text{IERR}) \\
\text{CALL CADRE}(Z,1.,F522,\text{EPS}, \text{ITEXT}, \text{G522}, \text{IERR}) \\
\text{CALL CADRE}(Z,1.,F523,\text{EPS}, \text{ITEXT}, \text{G523}, \text{IERR}) \\
\text{CALL CADRE}(X,Z,F611,\text{EPS}, \text{ITEXT}, \text{G611}, \text{IERR}) \\
\text{CALL CADRE}(X,Z,F612,\text{EPS}, \text{ITEXT}, \text{G612}, \text{IERR})
CALL CADRE(X,Z,F613,EPS,ITEXT,G613,IERR)
CALL CADRE(Z,1.,F621,EPS,ITEXT,G621,IERR)
CALL CADRE(Z,1.,F622,EPS,ITEXT,G622,IERR)
CALL CADRE(Z,1.,F623,EPS,ITEXT,G623,IERR)
SUM51=G511-G521
SUM52=G512-G522
SUM53=G513-G523
SUM61=G611-G621
SUM62=G612-G622
SUM63=G613-G623
BR51=H1*UZ1*SUM51
BR52=H2*UZ2*SUM52
BR53=H3*UZ3*SUM53
BR61=H1*UZ1*SUM61
BR62=H2*UZ2*SUM62
BR63=H3*UZ3*SUM63
YZ=Z**2-Z
ZZ=12*(Z-Z**2)
AJ5=ZZ+1.5*L/KFB*(BR51+BR52+BR53)
AJ6=-2.+.15/L/KFB*(BR61+BR62+BR63)
DAL=AJ5*T/XZ
DAL1=AJ6*T/YZ
DS=EXP(-DAL)
DS1=EXP(-DAL1)
GT=ZZ/(.2*AJ5)*(DS-1)
HT=ZZ/(.2*AJ6)*(DS1-1)
THETA=GT*XZ+HT*YZ
IF(IB.EQ.1) GOTO 207
WRITE(6,160) TW,P,L,THETA,Z
CONTINUE

C

LARGE PATH LENGTH

IF(IM.EQ.1) GOTO 801
DS=ABS(Z/(Z-1))
AJ=ALOG(DS)+ALOG(-2/Z+1/Z**2+1)*Z+2
H=H1+H2+H3
AJL=CZ*(2+H*L*AJ/KFB)
GL=12*(EXP(-AJL*T)-1)/AJL
THEL=GL*(Z-Z2)
GOTO 802

CONTINUE
Z1=Z-1
AL1=Z1**3./3.-3.*Z1**2./2.+3.*Z1-Z1**3.*ALOG(1-Z)-Z**3.
&*(11./6.-ALOG(Z))
AL2=-(Z1**2./2.-2.*Z1+Z**2*ALOG(1-Z)+Z*(1.5-ALOG(Z))
AL3=-(ALOG(1-Z)-ALOG(Z))
AL=4.*AL1-AL2+AL3
AJ5=Z+L/KFB*AL*(H1+H2+H3)
ALL1=-1.-Z*ALOG(1-Z)+Z*ALOG(Z)
ALL2=AL3
ALL2=-2+ALL1-ALL2
AJ6=-2+L/KFB*ALL*(H1+H2+H3)
DAL = AJ5 * T / XZ
DAL1 = AJ6 * T / YZ
DS = EXP(-DAL)
DS1 = EXP(-DAL1)
GT = ZZ / (2. * AJ5) * (DS - 1)
HT = ZZ / (2. * AJ6) * (DS1 - 1)
THEL = GT * XZ + HT * YZ

802  TBL(IZ) = THEL * (Z - Z2)
IF (IB .EQ. 1) GOTO 208
WRITE (10, 160) TW, P, L, THEL, Z
CONTINUE

C C C

OPTICALLY THIN

C

IF (IM .EQ. 1) GOTO 701
AN1 = H1 * UZ1
AN2 = H2 * UZ2
AN3 = H3 * UZ3
AN = L / KFB * (AN1 + AN2 + AN3)
AJ0 = 2 * CZ + 3 * AN
GO = 12 * (EXP(-AJ0 * T) - 1) / AJ0
THEO = GO * (Z - Z2)
GOTO 702

701  CONTINUE
AN1 = P * L * L / KFB * (S1 * PFDB1 + S2 * PFDB2 + S3 + PFDB3)
EE = Z**4 - 2 * Z**3 + Z
FF = Z**2 - Z
AJ5 = ZZ + 3. * AN1 * EE
AJ6 = -2. + 3. * AN1 * FF
DAL = AJ5 * T / XZ
DAL1 = AJ6 * T / YZ
DS = EXP(-DAL)
DS1 = EXP(-DAL1)
GT = ZZ / (2. * AJ5) * (DS - 1)
HT = ZZ / (2. * AJ6) * (DS1 - 1)
THEO = GT * XZ + HT * YZ

702  TBO(IZ) = THEO * (Z - Z2)
IF (IB .EQ. 1) GOTO 209
TBO(IZ) = THEO * (Z - Z2)
IF (IB .EQ. 1) GOTO 209
WRITE (15, 160) TW, P, L, THEO, Z
CONTINUE

209  CONTINUE

77  CONTINUE

IF (IB .EQ. 0) GOTO 234
TBUL = 0.
TBULL = 0.
TBULO = 0.
DO 10 JB = 1, N11
TBUL = TBUL + TB(JB)
TBULL = TBULL + TBL(JB)
TBULO = TBULO + TBO(JB)
10  BULK = 6. * DZ * TBUL
BULKL = 6. * DZ * TBULL
BULK0 = 6. * DZ * TBULO
WRITE (6, 160) TW, P, L, BULK
WRITE(10,160) TW,P,L,BULKL
WRITE(15,160) TW,P,L,BULK0
234 CONTINUE
66 CONTINUE
55 CONTINUE
44 CONTINUE
33 CONTINUE
22 CONTINUE
110 FORMAT(7X,*GENERAL SOLUTION FOR CO2 (CONSTANT FLUX CASE)*)
118 FORMAT(4X,*TW*,T18,*P*,T28,*L*,T38,*TBULK*)
120 FORMAT(7X,*LARGE PATH LENGTH FOR CO2 (CONSTANT FLUX CASE)*)
130 FORMAT(7X,*OPTICALLY THIN FOR CO2 (CONSTANT FLUX CASE)*)
140 FORMAT(10X,*TIME=*,F8.3)
150 FORMAT(4X,*TW*,T18,*P*,T28,*L*,T38,*THETA*,T48,*Z*)
160 FORMAT(7(IX, F9.4))
STOP
END
FUNCTION F211(ZB)
COMMON FI,F2,F3,B1,B2,B3,Z
XX=B1*(Z-ZB)
DEN1=(FI*((XX**2.0)+(2.0*XX)+2.0)+XX)*(XX+2.0*FI)
AUD1=(FI*((XX**2.0)+(4.0*XX*FI)+(4.0*FI)))/DEN1
F211=(1-2*ZB)*AUD1
RETURN
END
FUNCTION F212(ZB)
COMMON FI,F2,F3,B1,B2,B3,Z
XX=B2*(Z-ZB)
DEN2=(F2*((XX**2.0)+(2.0*XX)+2.0)+XX)*(XX+2.0*F2)
AUD2=(F2*((XX**2.0)+(4.0*XX*F2)+(4.0*F2)))/DEN2
F212=(1-2*ZB)*AUD2
RETURN
END
FUNCTION F213(ZB)
COMMON FI,F2,F3,B1,B2,B3,Z
XX=B3*(Z-ZB)
DEN3=(F3*((XX**2.0)+(2.0*XX)+2.0)+XX)*(XX+2.0*F3)
AUD3=(F3*((XX**2.0)+(4.0*XX*F3)+(4.0*F3)))/DEN3
F213=(1-2*ZB)*AUD3
RETURN
END
FUNCTION F221(ZB)
COMMON F1,F2,F3,B1,B2,B3,Z
XX=B1*(ZB-Z)
DEN1=(F1*((XX**2.0)+(2.0*XX)+2.0)+XX)*(XX+2.0*F1)
AUD1=(F1*((XX**2.0)+(4.0*XX*F1)+(4.0*F1)))/DEN1
F221=(1-2*ZB)*AUD1
RETURN
END
FUNCTION F222(ZB)
COMMON F1,F2,F3,B1,B2,B3,Z
XX=B2*(ZB-Z)
DEN2=(F2*((XX**2.0)+(2.0*XX)+2.0)+XX)*(XX+2.0*F2)
AUD2=(F2*((XX**2.0)+(4.0*XX*F2)+(4.0*F2)))/DEN2
F222=(1-2*ZB)*AUD2
RETURN
END
FUNCTION F223(ZB)
COMMON F1,F2,F3,B1,B2,B3,Z
XX=B3*(ZB-Z)
DEN3=(F3*((XX**2.0)+(2.0*XX)+2.0)+XX)*(XX+2.0*F3)
AUD3=(F3*((XX**2.0)+(4.0*XX*F3)+(4.0*F3)))/DEN3
F223=(1-2*ZB)*AUD3
RETURN
END
FUNCTION F511(ZB)
COMMON F1,F2,F3,B1,B2,B3,Z
XX=B1*(Z-ZB)
DEN1=(F1*((XX**2.0)+(2.0*XX)+2.0)+XX)*(XX+2.0*F1)
AUD1=(F1*((XX**2.0)+(4.0*XX*F1)+(4.0*F1)))/DEN1
F511=(1-6*ZB*ZB+4*ZB**3)*AUD1
RETURN
END
FUNCTION F512(ZB)
COMMON F1,F2,F3,B1,B2,B3,Z
XX=B2*(Z-ZB)
DEN2=(F2*((XX**2.0)+(2.0*XX)+2.0)+XX)*(XX+2.0*F2)
AUD2=(F2*((XX**2.0)+(4.0*XX*F2)+(4.0*F2)))/DEN2
F512=(1-6*ZB*ZB+4*ZB**3)*AUD2
RETURN
END
FUNCTION F513(ZB)
COMMON F1,F2,F3,B1,B2,B3,Z
XX=B3*(ZB-Z)
DEN3=(F3*((XX**2.0)+(2.0*XX)+2.0)+XX)*(XX+2.0*F3)
AUD3=(F3*((XX**2.0)+(4.0*XX*F3)+(4.0*F3)))/DEN3
F513=(1-6*ZB*ZB+4*ZB**3)*AUD3
RETURN
END
FUNCTION F521(ZB)
COMMON F1,F2,F3,B1,B2,B3,Z
XX=B1*(ZB-Z)
DEN1=(F1*((XX**2.0)+(2.0*XX)+2.0)+XX)*(XX+2.0*F1)
AUD1=(F1*((XX**2.0)+(4.0*XX*F1)+(4.0*F1)))/DEN1
F521=(1-6*ZB*ZB+4*ZB**3)*AUD1
RETURN
END
FUNCTION F522(ZB)
COMMON F1,F2,F3,B1,B2,B3,Z
XX=B2*(ZB-Z)
DEN2=(F2*((XX**2.0)+(2.0*XX)+2.0)+XX)*(XX+2.0*F2)
AUD2=(F2*((XX**2.0)+(4.0*XX*F2)+(4.0*F2)))/DEN2
F522=(1-6*ZB*ZB+4*ZB**3)*AUD2
RETURN
END
FUNCTION F523(ZB)
COMMON F1,F2,F3,B1,B2,B3,Z
XX=B3*(ZB-Z)
DEN3=(F3*((XX**2.0)+(2.0*XX)+2.0)+XX)*(XX+2.0*F3)
AUD3=(F3*((XX**2.0)+(4.0*XX*F3)+(4.0*F3)))/DEN3


\[ F523 = (1 - 6ZBZB + 4ZB^3) \times AUD3 \]
RETURN
END

FUNCTION F611(ZB)
COMMON F1, F2, F3, B1, B2, B3, Z
XX = B1 * (Z - ZB)
DEN1 = (F1 * ((XX^2.0) + (2.0 * XX) + 2.0) + XX) * (XX + 2.0 * F1)
AUD1 = (F1 * ((XX^2.0) + (4.0 * XX * F1) + (4.0 * F1)))/DEN1
F611 = (2 * ZB - 1) * AUD1
RETURN
END

FUNCTION F612(ZB)
COMMON F1, F2, F3, B1, B2, B3, Z
XX = B2 * (Z - ZB)
DEN2 = (F2 * ((XX^2.0) + (2.0 * XX) + 2.0) + XX) * (XX + 2.0 * F2)
AUD2 = (F2 * ((XX^2.0) + (4.0 * XX * F2) + (4.0 * F2)))/DEN2
F612 = (2 * ZB - 1) * AUD2
RETURN
END

FUNCTION F613(ZB)
COMMON F1, F2, F3, B1, B2, B3, Z
XX = B3 * (Z - ZB)
DEN3 = (F3 * ((XX^2.0) + (2.0 * XX) + 2.0) + XX) * (XX + 2.0 * F3)
AUD3 = (F3 * ((XX^2.0) + (4.0 * XX * F3) + (4.0 * F3)))/DEN3
F613 = (2 * ZB - 1) * AUD3
RETURN
END

FUNCTION F621(ZB)
COMMON F1, F2, F3, B1, B2, B3, Z
XX = B1 * (ZB - Z)
DEN1 = (F1 * ((XX^2.0) + (2.0 * XX) + 2.0) + XX) * (XX + 2.0 * F1)
AUD1 = (F1 * ((XX^2.0) + (4.0 * XX * F1) + (4.0 * F1)))/DEN1
F621 = (2 * ZB - 1) * AUD1
RETURN
END

FUNCTION F622(ZB)
COMMON F1, F2, F3, B1, B2, B3, Z
XX = B2 * (ZB - Z)
DEN2 = (F2 * ((XX^2.0) + (2.0 * XX) + 2.0) + XX) * (XX + 2.0 * F2)
AUD2 = (F2 * ((XX^2.0) + (4.0 * XX * F2) + (4.0 * F2)))/DEN2
F622 = (2 * ZB - 1) * AUD2
RETURN
END

FUNCTION F623(ZB)
COMMON F1, F2, F3, B1, B2, B3, Z
XX = B3 * (ZB - Z)
DEN3 = (F3 * ((XX^2.0) + (2.0 * XX) + 2.0) + XX) * (XX + 2.0 * F3)
AUD3 = (F3 * ((XX^2.0) + (4.0 * XX * F3) + (4.0 * F3)))/DEN3
F623 = (2 * ZB - 1) * AUD3
RETURN
END