Nongray Radiative Heat Transfer in High-Temperature Nonisothermal CO_2–N_2 Mixtures

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An analysis of nongray equilibrium radiative heat transfer in the stagnation region of a blunt, axisymmetric body entering a CO_2–N_2 atmosphere is presented. The analysis considers only the radiative transport problem, but is coupled to an existing flowfield solution so that the radiative flux predictions reflect the influence of viscosity, conductivity, dissociation and ionization. The nongray nature of the gas is accounted for by a spectral evaluation of the radiative energy transfer, employing simple spectral absorption coefficients for the transport processes due to photoionization, free-free electron interactions, and molecular band transitions. For molecular band systems, a simplified absorption model which smooths out the detailed vibrational-rotational structure, but retains the general band shape, is developed, and its accuracy and range of applicability are established. The simplified absorption models are utilized in the study to assess the contribution of the CN and CO(4+) band systems to the total radiative emission and to evaluate the effect of self-absorption by the CO(4+) system on the radiative flux to the surface. Stagnation-point spectral and integrated radiative heat transfer results are presented for several flight conditions, body sizes, and CO_2–N_2 mixtures.

Nomenclature

B_e = rotational constant
B_ν = Planck function
$\bar{B}_\alpha$ = nondimensional Planck function, defined by Eq. (6)
C_0 = constant used in Eq. (2)
e = Naperian base
$E_n(t)$ = exponential function of order n
f_e = electronic oscillator strength
F_{el}'' = fraction of molecules in absorbing electronic state
$\bar{G}$ = vibrational term value, Eq. (1)
h = Planck's constant
k = Boltzmann's constant
N = particle number density
$\bar{q}$ = averaged Franck-Condon factor
$\bar{q}^r$ = nondimensional radiative heat flux
r = internuclear separation
r_e = equilibrium internuclear separation
r_0 = classical electron radius
r^+ = constant used in Eq. (2)
R_N = body nose radius at stagnation
t = dummy variable used in Eqs. (3) and (4)
T = absolute temperature
U_∞ = flight velocity
y = coordinate normal to vehicle surface
α = nondimensional frequency, $h\nu/kT_\delta$
δ = shock standoff distance
θ = nondimensional temperature, T/T_δ
μ = linear absorption coefficient
ν = frequency
ρ = density
ρ_0 = standard sea-level density
σ = Stefan-Boltzmann constant
τ = optical thickness
ω = wave number
ω_{00} = wave number of 0–0 transition
ω^0 = constant used in Eq. (2)

Subscripts

w = conditions at the surface
∞ = freestream conditions
α = at frequency α
δ = conditions behind shock wave
ν = at frequency ν
ω = at wave number ω

Superscripts

r = radiative
$'$ = upper electronic state
$''$ = lower electronic state

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I. Introduction

IN recent years, considerable effort has been devoted to determining the heat transfer to a body entering the Earth's atmosphere. The available experimental and theoretical studies[1–5] have convincingly demonstrated the necessity for a careful consideration of the effects of radiative cooling and nongray self-absorption if reliable predictions of the surface radiative flux are to be obtained. The analysis by Page et al.[5] is noteworthy because it shows that even with small amounts of cooling, a large reduction in the flux can be achieved. This result, which contrasts significantly with conclusions obtained from earlier transparent gas analyses, was attributed to strong absorption by the optically thick portions of the emission spectrum of high-temperature air.

For entry into the atmospheres of Mars or Venus, however, the influence of the aforementioned effects on the shock-layer structure and heat transfer apparently has not yet been examined. Most studies[6–9] were limited primarily to experimental measurements of radiative emission from a volume of gas with essentially a uniform temperature. These investigations indicate that CO_2–N_2 mixtures simulating the Martian and Venusian atmospheres radiate more energy than air at the equivalent flight conditions,[7,8] are highly nongray because of the dominance of molecular radiation, and that self-absorption is important, especially in the ultraviolet where the CO(4+) system is a major contributor.[6,9] Thus, it appears that radiative cooling and nongray absorption may also be important for a Martian or Venusian entry.

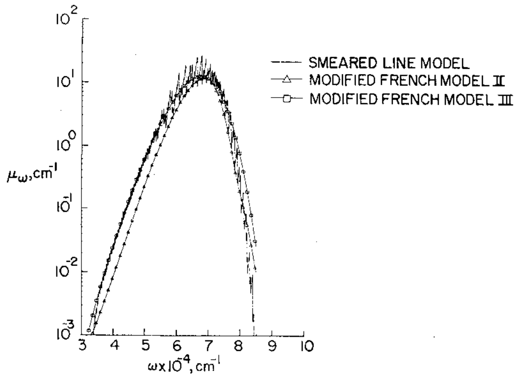

Fig. 1 Comparison of approximate and detailed spectral absorption coefficients for the CO(4+) band system at 8000°K.

It is the purpose of this paper to report the results of a theoretical investigation of radiative energy transfer in the stagnation region of a blunt, axisymmetric body entering a CO_2–N_2 atmosphere. The analysis employs the assumption of local thermodynamic equilibrium and properly accounts for nongray effects by a spectral evaluation of the radiative flux. With the exception of atomic line radiation, all significant radiative processes are considered. Although attention is focused primarily on the radiative transport problem, the present analysis is combined with the approximate flowfield solution of Burns,[10] which was developed in conjunction with this investigation, so as to include viscosity, conductivity, dissociation and ionization. This study was undertaken to assess the relative importance of the various radiating species of high temperature CO_2–N_2 mixtures, particularly the CN and CO(4+) band systems, and to evaluate the effect of absorption by the CO(4+) band on the surface radiative flux. A further objective was to develop and determine the applicability of simplified absorption models for molecular band transitions that can be used for engineering calculations instead of the commonly employed smeared rotational line model.[11,12] This latter model is impractical to use in a fully coupled flowfield calculation because the spectral detail provided by the model requires a prohibitive amount of computer time for a spectral evaluation of the radiative energy transfer.

II. Absorption Coefficients

If the thermodynamic properties have been defined at each point in the shock layer, the radiative flux is readily calculated for the case of local thermodynamic equilibrium, once the dependence of the absorption coefficient on frequency and the state variables is known. For the gas mixtures and flight conditions considered in the present study, the following sources of radiation were estimated to make the major contributions to the optical properties: CN red, CN violet, CO(4+), NO^+ Miescher-Baer, NO gamma, NO beta, NO delta, NO epsilon, N_2 Birge-Hopfield, O_2 Schumann-Runge, and CO_2 electronic band systems; O_2 photodissociation continuum; and the free-bound and free-free continuum of neutral and singly ionized C, N, and O. (The criteria used in the selection of these sources are discussed in Ref. 13.)

Expressions for the continuum absorption coefficients of the C, N, and O atoms and ions were obtained from the approximate quantum defect theory of Biberman and Norman.[14] These expressions are not presented here since they are readily available in the open literature (in Refs. 15 and 16, for example). For the O_2 Schumann-Runge continuum and the CO_2 molecule, the Sulzer-Wieland model,[17,18] which assumes a Gaussian distribution for the frequency variation of the absorption coefficient, was utilized. A more detailed discussion concerning the application and adequacy of this model for these two transitions is given in Refs. 17 (CO_2) and 18 (O_2).

For the aforementioned diatomic molecules, it was previously noted that spectral absorption coefficients can be calculated using the smeared rotational line model,[11,12] which considers variations only in the vibrational band strengths by "smearing" the contributions of the rotational lines in order to give a continuous function of frequency within a vibrational band. However, when several molecules must be included, the detailed absorption spectrum given by the model greatly reduces its utility for a spectral evaluation of radiative heat transfer. In this study, the point of view adopted was that a simplified model retaining only the essential average characteristics of the spectral distribution can be employed to obtain results sufficiently accurate for engineering purposes. To achieve this, the approximate model, originally proposed by French[19] and later used by Deacon and Boughner[20] with a slight modification, was further modified and extended to improve computational efficiency and obtain better agreement with the results of the smeared line model. Other investigators[21] have also developed models very similar to French's, but the latter was selected because it predicts the correct temperature dependence of the absorption cross-section.

Simply stated, the basic assumption of the present (and French) model is that the main features of the spectral absorption curve can be derived by considering only the strong vibrational bands falling on or near the Condon parabola, which, according to the Franck-Condon principle,[22] is the locus of upper and lower states having equal internuclear separations at the classical oscillator turning points. In fact, since the Franck-Condon factors of these bands are about the same order of magnitude, the average spectral absorption coefficient is computed[19] as though due to a single strong band. This band is centered at the transition wave number ω and extends over the interval $\Delta\omega = 0.5(\omega_e' + \omega_e'')$, the average interval corresponding to a unit change in vibrational quantum number. This procedure yields

$$\mu_\omega = \frac{2\pi r_0}{\omega_e' + \omega_e''} f_e \bar{q} N F_{el}'' \frac{\omega}{\omega_{00}} \exp\left\{-\frac{hc\bar{G}}{kT}\right\} \times \left[1 - \exp\left(-\frac{hc\omega_e''}{kT}\right)\right]\left[1 - \exp\left(-\frac{hc\omega}{kT}\right)\right] \quad (1)$$

for the absorption coefficient, including the correction for induced emission. $\bar{G}$ is the vibrational term value referred to the ground state vibrational level,[19,22] and $\bar{q}$ is an average Franck-Condon factor which is discussed further in the following paragraphs. If the potential energy curves of a diatomic molecule are represented by the Morse potential,[22] it is easily shown[19,13] that $\bar{G}$ and the transition wave number are determined by specifying the internuclear separation distance r. This quantity was chosen as the independent variable in the computational scheme of Ref. 19. In other words, for a specified value of r, $\bar{G}$ and ω were calculated and substituted into Eq. (1) to obtain μ_ω. However, since ω, rather than r, is known when the radiative flux is evaluated spectrally, the absorption coefficient computation would be simplified if r were expressed directly as a function of wave number. Such a relationship was determined empirically from plots of r vs ω, and is given by the following correlation

$$r = r^+ \exp[C_0(\omega - \omega^0)] \quad (2)$$

where the values of the constants r^+, C_0, and ω^0 depend on the band system being considered.

In Refs. 19 and 20, it was suggested that the quantity $\bar{q}$ appearing in Eq. (1) be taken as a constant equal to a representative value of the Franck-Condon factors for the bands along the Condon parabola. When compared to the results of the smeared line model, this approximation‡ generally

‡ This model, which is here labeled model I, provides a convenient method for estimating the relative importance of different band systems and was used for this purpose in the present study.

underestimates the value of μ_ω, the reason being that $\bar{q}$ is too small. Examinations of typical Franck-Condon factors arrays reveal that there are several vibrational bands of nearly equal strength that contribute to the absorption within the interval $\Delta\omega = 0.5(\omega_e' + \omega_e'')$, and this fact suggests that $\bar{q}$ be redefined as the sum of the Franck-Condon factors of these bands. However, in order to be consistent with the assumptions inherent in the basic model, only those bands having the same lower state vibrational quantum number as the most intense band situated on the parabola are included in the summation. If this procedure is followed, it is found that $\bar{q}$ varies with the transition wave number. For purposes of numerical computations, this variation was fitted with a simple analytical function. This change constitutes the modified French model II.

A third model can be derived by employing Eq. (1) to curve fit the smeared line model results, when they are available, to obtain an improved representation for $\bar{q}$.

Figure 1 compares the values of μ_ω predicted by the various models for the CO(4+) band system. In this case, the accuracy of the modified models is seen to be satisfactory for radiation calculations. However, in other situations, their validity depends on the band system to which they are applied. It was found that the modified French models provide a good representation to the results of the smeared line model whenever 1) the equilibrium internuclear separations r_e for the two electronic states involved in the transition are appreciably different, and 2) the rotational constants B_e of the two states differ substantially. When these conditions are not met, the absorption coefficient displays a large variation with frequency which is difficult to represent adequately with the modified models, although they do predict the correct wave number for maximum absorption and give the general shape of the spectral absorption curve. Since the effects of radiative cooling and self-absorption tend to reduce the sensitivity of the surface radiative flux to uncertainties in the radiative properties,[1,2,5] it is felt that the heat-transfer predictions based on the present models show the correct trends with respect to the important problem parameters and should provide data sufficiently accurate for design purposes.

III. Evaluation of Radiative Terms

The solution of the continuity, momentum, and energy equations provides a complete description of the flowfield within the shock layer formed around a blunt body in hypersonic flight. However, to make the problem amenable to analysis, simplifying assumptions are required. For the problem of interest here, the general conservation equations are reduced to the thin shock-layer conservation equations for laminar flow in the stagnation region of a blunt, axisymmetric body at zero angle of attack and then solved with the integral method discussed in Ref. 10. The integral forms of the momentum equations and the numerical procedures for solving them in conjunction with either the integral or differential energy equation have been extensively examined by other investigators,[4,10,13] and thus will not be further discussed here.

As a result of the long-range effect of radiation, the value of the radiative flux and its divergence at a specific position in the shock layer depends not only on properties at that position, but at every position in the layer. These properties are not known until the conservation equations have been solved. In addition, one of the boundaries, the shock wave, is determined as part of the solution. Consequently, the solution of the coupled momentum and energy equations requires an iterative procedure. The viewpoint adopted in the presentation here is that the shock detachment distance and the temperature and pressure distributions in the shock layer are given, and that the radiative contribution to the energy equation for the next iteration is to be determined.

The radiative terms are evaluated using the one-dimensional slab approximation. It is convenient in this connection to introduce the dimensionless frequency $\alpha = h\nu/kT_\delta$, where T_δ is the temperature behind the shock wave; temperature $\theta = T/T_\delta$; and radiative flux $\bar{q}_\alpha{}^r = q_\alpha{}^r/\sigma T_\delta{}^4$. Thus, in terms of these nondimensional variables, the spectral radiative flux and its divergence become[23]

$$\bar{q}_\alpha{}^r = 2\bar{B}_\alpha[\theta(0)]E_3(\tau_\alpha) + 2\int_0^{\tau_\alpha} \bar{B}_\alpha[\theta(t_\alpha)]E_2(\tau_\alpha - t_\alpha)dt_\alpha - 2\int_{\tau_\alpha}^{\tau_{\alpha\delta}} \bar{B}_\alpha[\theta(t_\alpha)]E_2(t_\alpha - \tau_\alpha)dt_\alpha \quad (3)$$

and

$$\frac{d\bar{q}_\alpha{}^r}{d\tau_\alpha} = 4\bar{B}_\alpha[\theta(\tau_\alpha)] - 2\left\{\bar{B}_\alpha[\theta(0)]E_2(\tau_\alpha) + \int_0^{\tau_{\alpha\delta}} \bar{B}_\alpha[\theta(t_\alpha)]E_1(|\tau_\alpha - t_\alpha|)dt_\alpha\right\} \quad (4)$$

where

$$\tau_\alpha = \int_0^y \mu_\alpha' dy' \quad (5)$$

is the optical thickness and μ_α' the mixture linear spectral absorption coefficient corrected for induced emission. $\bar{B}_\alpha(\theta)$ is the normalized Planck function, defined as

$$\bar{B}_\alpha(\theta) = 15\alpha^3/\pi^4[\exp(\alpha/\theta) - 1] \quad (6)$$

and has been nondimensionalized such that

$$\int_0^\infty \bar{B}_\alpha(\theta)d\alpha = \theta^4 \text{ and } \sigma T_\delta{}^4\bar{B}_\alpha(\theta)d\alpha = \pi B_\nu(T)d\nu$$

In Eqs. (3) and (4), it is assumed that the vehicle surface is a black body at the constant temperature T_w, and the shock wave and freestream gas are transparent.

Integrated values for the radiative quantities were obtained numerically, employing approximately 50 frequency points, which provided a good compromise between reasonable accuracy and moderate computer run times. The evaluation of Eqs. (3) and (4) was simplified by dividing the shock layer into 20 equally spaced segments, and by assuming that the Planck function $\bar{B}_\alpha$ varied linearly with optical thickness between segments. This procedure permits the required spatial integrations to be performed analytically, and for typical shock layer profiles, gave the integrated flux to within 0.5% of that found by a completely numerical solution.

IV. Results and Discussion

As noted in the previous section, the present radiative analysis was combined with the integral procedure outlined in Ref. 10 to obtain stagnation region solutions for several flight conditions, body sizes, and CO_2–N_2 mixtures. Transport properties were taken from Ref. 24, whereas the thermodynamic properties and species equilibrium number densities were obtained from Ref. 25. The average Franck-Condon factors, spectroscopic constants, and electronic oscillator strengths used with the absorption coefficient models described in Sec. II are compiled in Ref. 13.

Figure 2 depicts the variation of the nondimensional wall radiative flux with body nose radius. Also shown are the ultraviolet ($\alpha \leq 10$, $h\nu \simeq 6ev$) and infrared-visible portions of the flux. At small radii, the ultraviolet contribution dominates whereas the infrared-visible radiation is predominant for large radii. This behavior is caused by the extreme differences in the magnitude of the absorption spectrum, which is characterized by a very high absorption coefficient level in the ultraviolet but at a considerably smaller level in the long wavelength region. As a result of absorption, the ultraviolet flux appears to approach, for the range of nose radii shown, an effective black body limit corresponding to a temperature in the outer portion of the thermal boundary layer. To illustrate this effect, the black body value is drawn on

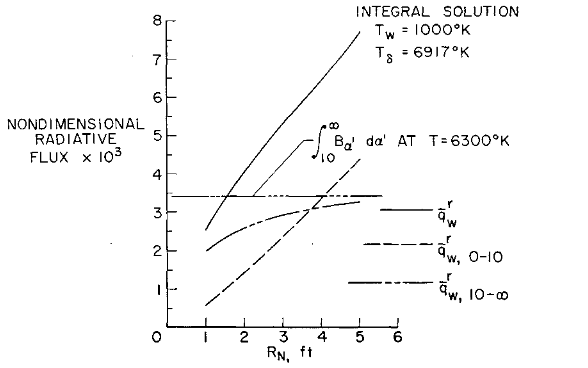

Fig. 2 Variation of radiative heat flux with body nose radius for 50% CO_2 = 50% N_2, $\rho_\infty/\rho_0 = 10^{-3}$, and U_∞ = 26,000 fps.

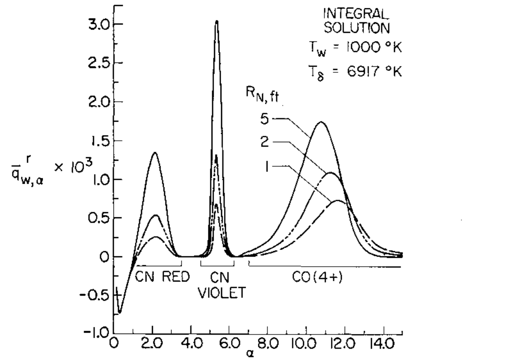

Fig. 3 Spectral radiative flux distribution for 50% CO_2–50% N_2, $\rho_\infty/\rho_0 = 10^{-3}$, and U_∞ = 26,000 fps.

Fig. 2 for a temperature of 6300°K, which is the gas temperature at $y/\delta = 0.1$ in the shock layer for $R_N = 5$ ft. The results previously discussed were also noted by Anderson[1,2] for radiative heat transfer in high-temperature air.

Figure 3 shows the spectral flux distribution for three values of R_N, and also identifies the major sources of radiation; the CN red, violet, and CO(4+) band systems. For the indicated conditions, the contribution of these three molecular transitions is 80% or more of the total radiative heat transfer. Below $\alpha = 10$, the flux is approximately proportional to the body nose radius, indicating that the shock layer is transparent to radiation in this spectral region. In fact, in the far infrared ($\alpha < 1$), the flux emitted by the black surface exceeds the incident flux from the shock-layer gas to give a negative flux to the surface.

In the ultraviolet region, strong absorption by the CO(4+) band, which is maximum at $\alpha = 14$, produces the peak in the flux shown in Fig. 3. This peak value occurs at about the same frequency for which $\tau_{\alpha_\delta} = 0.5$. At larger frequencies, the surface flux decreases because τ_{α_δ} becomes much greater than one; so only radiation from the relatively cool regions of the shock layer reaches the surface. As R_N is increased, the shock layer thickens and τ_{α_δ} reaches the value 0.5 at a lower frequency, resulting in a corresponding shift of the peak.

The fifth and sixth columns of Table 1 summarize the results of additional calculations that were made to examine the relative importance of the CN and CO(4+) band systems. These results were obtained in an approximate manner using the thermodynamic profiles computed without the inclusion of these bands. It is believed that this procedure does not introduce any significant errors because the amount of radiative cooling was small for the flight conditions investigated in this study. (Less than 5% of the flow energy crossing the shock front was lost by radiation.) As expected on the basis of Fig. 3, omission of CO(+4) in the 50% CO_2–50% N_2 mixtures causes the greatest reduction in the flux because of its large absorption coefficient values and broad spectral extent. Consequently, in accordance with Kirchoff's law, emission is very strong in the optically thin portions of the band ($\alpha = 7$ to $\alpha = 11$ in Fig. 3). For the 90% CO_2–10% N_2 mixture, the lower CN concentration is mainly responsible for the small decrease in the wall flux when the CN bands are deleted.

The spectral radiative surface fluxes calculated with the present analysis and for a plane-parallel isothermal gas layer with temperature T_δ and thickness δ are compared in Fig. 4. In the spectral interval near $\alpha = 3.5$, the behavior of the curves is due to the local variation of the NO(β) band system emission. For the nonuniform temperature situation, the emission from this band reaches a maximum within the shock layer rather than at the shockwave, and this variation, in turn, is primarily a reflection of the NO mole fraction distribution which shows a similar peak[25] as a result of its dependence on temperature. Therefore, since the shock layer is optically thin in this spectral region, the surface flux, which equals the local emission integrated across the shock layer, is larger for the nonisothermal case.

The close agreement between the nonisothermal and isothermal flux in the long wavelength region indicates that this radiation is governed primarily by the hot, inviscid portions of the shock layer. In addition, the figure shows dramatically the influence of CO(4+) absorption. For $\alpha > 9$, the isothermal curve corresponds to the Planck function evaluated at T_δ. The minimum value in the nonisothermal flux ($\alpha \simeq 12.54$) is equivalent to an effective black body at approximately $T = 4200$°K, demonstrating that the ultraviolet contribution is strongly dependent on the thermal structure within the boundary layer. By failing to account for this strong temperature dependence, the isothermal calculation overestimates the radiative heat transfer, amounting to 35% for the case shown in Fig. 4. Further comparisons between the isothermal and nonisothermal radiative flux predictions are given in the last column of Table 1.

For the 50% CO_2–50% N_2 mixtures, the trends exhibited by the data are due to two factors. First, as R_N and/or ρ_∞ increases, the thermal boundary layer becomes a smaller

Table 1 Relative influence of the CN and CO(4+) band systems on the radiative flux[a]

				$\bar{q}_w{}^r$ with change$/\bar{q}_w{}^r$ without change			
Mixture CO_2–N_2	U_∞, fps	ρ_∞/ρ_0	R_N, ft	No CN		No CO(4+)	Isothermal
50–50	26,000	10^{-2}	1	0.645		0.415	...
				0.787[b]			
					0.060[c]		
			2		0.079[c]		1.49
			5		0.103[c]		1.35
50–50	26,000	10^{-3}	2	0.718		0.210	1.54
90–10	32,000	10^{-3}	2	0.984		0.107	2.22

[a] Integral solution with T_w = 1000°K.
[b] Represents omission of CN violet system only.
[c] Represents omission of both the CN and CO(4+) bands.

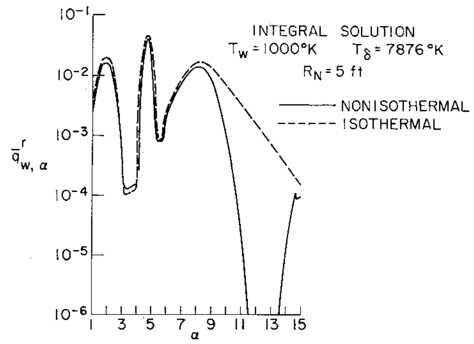

Fig. 4 Comparison of isothermal and nonisothermal spectral radiative flux distributions for 50% CO_2 -50% N_2, $\rho_\infty/\rho_0 = 10^{-2}$, and U_∞ = 26,000 fps.

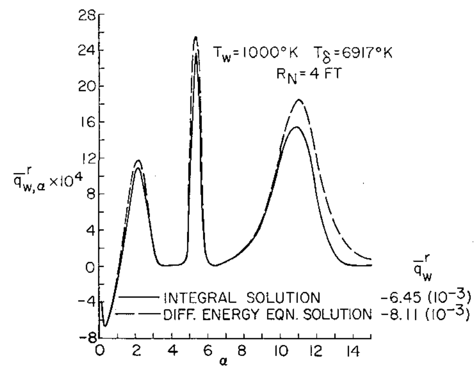

Fig. 5 Comparison of spectral radiative flux distributions for integral and differential energy equation solutions; 50% CO_2-50% N_2, $\rho_\infty/\rho_0 = 10^{-3}$, U_∞ = 26,000 fps.

fraction of the shock layer. Second, as illustrated in Fig. 3, the CN bands increase in importance relative to the CO(4+) system. This latter effect occurs because absorption decreases the CO(4+) contribution. Furthermore, the CN equilibrium mole fraction depends on temperature in such a way that the higher temperatures associated with a nearly isothermal shock layer lead to a higher mole fraction level, resulting in an increased CN contribution. In the 90% CO_2–10% N_2 case, the CO concentration is larger, and consequently absorption produces a greater reduction in the radiative flux. Again, as noted earlier, radiative cooling is small, so the decrease in $\bar{q}_w^r$ is due to absorption. Page et al.[5] observed a similar reduction in air when cooling effects were negligible.

In the discussion concerning Fig. 4, it was observed that the ultraviolet radiation is extremely sensitive to variations in the temperature distribution. This influence is further emphasized in the comparison of results predicted by an integral method of solution and by a differential solution of the energy equation. The integral method used[10] provides an approximate solution to the conservation equations in an average manner across the shock layer. The velocity and temperature profiles thus obtained satisfy the conservation equations in a global manner but do not necessarily agree with the actual profiles. In Ref. 10, it was clearly demonstrated that in the region of the shock layer near the surface, the approximate temperature profile from the integral solution was a poor representation of the more exact result found from the differential equation solution. The latter method predicts a higher temperature level in the thermal boundary layer, and consequently, the wall radiative flux is larger, as illustrated in Fig. 5. The ultraviolet contribution is seen to be appreciably affected, while the long wavelength radiation is influenced only slightly, providing additional evidence that the source of this radiation is the inviscid portion of the shock layer. The difference between the values of $\bar{q}_w{}^r{}_{,10-\infty}$ for the two cases accounts for 83% of the total variance in the $\bar{q}_w^r$ values shown in Fig. 5.

All the results presented thus far were obtained with f_e = 0.24 for the CO(4+) band system. However, the value 0.15 has also been reported in the literature. Additional computations were performed to determine the effect on the radiative heat transfer of changing to the lower value of f_e. These results are presented in Table 2 and were found with the same approximation used to obtain the values given in columns 5 and 6 of Table 1. As expected, the wall flux is reduced, but because of strong absorption in the ultraviolet, the decrease is less than a 40% difference between the two f-numbers.

Table 2 Effect of a change in f_e of the CO(4+) band system on the radiative heat transfer for 50% CO_2–50% N_2, $\rho_\infty/\rho_0 = 10^{-3}$, U_∞ = 26,000 fps[a]

Frequency range	$\bar{q}_w^r$ (f_e = 0.15)/$\bar{q}_w^r$ (f_e = 0.24)	
α	R_N = 2 ft	R_N = 5 ft
0–∞	0.858	0.862
0–10	0.855	0.835
10–∞	0.853	0.896

[a] Integral solution with T_w = 1000°K.

V. Conclusions

In this paper, an analysis of equilibrium radiative heat transfer in the stagnation region of a blunt, axisymmetric body has been presented. A spectral evaluation of the radiative flux has been employed to account for nongray effects, including photoionization, free-free electron interactions, and molecular band transitions. For the molecular bands, simplified absorption models that smooth out the detailed vibrational-rotational structure, but preserve the general shape of the absorption curve, were developed and compared with the results of the more exact smeared line model to establish their accuracy and range of applicability. These models were then used to determine the relative contributions of various radiating species and to obtain stagnation point spectral and integrated radiative heat-transfer rates for several flight conditions, body sizes, and CO_2–N_2 mixtures.

The results indicated the following: 1) The emission spectrum is dominated by the CN red, violet, and CO(4+) band systems which contribute 80% or more of the total radiation for the 50% CO_2–50% N_2 atmospheres. 2) Relative to the CN bands, the CO(4+) band is a more important source of radiation. This latter system is a particularly strong contributor in the ultraviolet region of the spectrum. As a consequence, the ultraviolet dominates the radiative flux at small body nose radii. However, for larger R_N, the long wavelength radiation becomes predominant because strong self-absorption decreases the CO(4+) contribution in comparison to that of the CN bands. 3) The source of the long wavelength radiation is the inviscid region of the shock layer. The ultraviolet radiation, on the other hand, is governed by the viscous region near the wall. Furthermore, this latter contribution is extremely sensitive to temperature variations in the thermal boundary layer. An isothermal slab calculation greatly overestimates the wall radiative flux by failing to account for this dependence. 4) Because of strong absorption, a 40% reduction in the electronic oscillator strength used for the CO(4+) system results in only about a 15% decrease in the surface radiative flux for the two cases considered in this study.

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