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RADIATIVE HEAT TRANSFER SOLUTIONS IN PLANE-PARALLEL PARTICIPATING MEDIA: - APPLICATION TO MULTILAYER INSULATIONS FOR SPACE VEHICLES

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14. Abstract/Notes

The ideas in the Galerkin method for the solution of radiative transfer in plane parallel participating media are extended to allow for both specularly and diffusely reflecting boundaries. The technique is then utilized to solve the transversal heat transfer in multilayer insulations (MLI) for aerospace applications. The relative accuracy of design-type, approximate formular are then established, and the effects of specularity are critically examined.

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ABSTRACT

The ideas in the Galerkin method for the solution of radiative transfer in plane-parallel participating media are extended to allow for both specularly and diffusely reflecting boundaries. The technique is then utilized to solve the transversal heat transfer in multilayer insulations (MLI) for aerospace applications. The relative accuracy of design-type, approximate formulae are then established, and the effects of specularity are critically examined.

INTRODUCTION

A multilayer insulation (MLI) for aerospace applications consists of several layers of reflecting shields separated by spacers, that can be made from materials such as nylon, dracon, silk or rayon nets, carbon fiber paper, or sometimes fiberglass batt. Such spacers are designed to serve the purpose of minimizing conductive heat transfer across the MLI; however, they might also play an important role in the radiative heat exchange between neighboring shields, characterizing a radiative transfer problem in plane-parallel participating media with specularly and diffusely reflecting boundaries. Therefore, the accurate evaluation of total heat transfer rates across the insulation is of major interest, related to cost and weight optimization needs. This typical, one-dimensional, radiative heat transfer problem has been treated quite extensively in the literature. Among the pioneering works that made use of approximate solution techniques, we list those by Viskanta & Grosh [1], Glaser [2], Love & Grosh [3], Usikin & Sparrow [4], and Viskanta [5]. These and related works have in common the fact that specular reflection at the boundaries was not considered. Among the most recent contribution that introduced formal and accurate solution techniques for this linear transport equation, we refer to those by Maiorino et al. [6], on the F_n method, Benassi et al. [7], on the P_n method, Yener & Özisik [8] and Cengel et alli [9], on the Galerkin method. The first two contributions included both diffuse and specular reflective boundaries, but had the drawback of requiring particular solution to the nonhomogeneous transport equation. The Galerkin method of [8,9], on the other hand, accomodates quite easily any functional form for the source term, but was restricted to diffuse reflection at the boundaries. Quite recently, however, the Galerkin method, coupled with a collocation scheme, was utilized to solve a two-dimensional radiative transfer problem in a rectangular enclosure with transparent boundaries [10], broadening up the range of applications that can be handled through extensions of the method. Therefore, based on such aspects, and since studies on both transversal and longitudinal heat exchange in MLI's, allthough yet quite limited, are now becoming available, it applies that the Galerkin method might be the basic tool for future developments. In such a context, the present contribution deals with the extension of the ideas in references [8,9], so as to allow for specularly reflecting boundaries on radiative transfer in plane-parallel participating media. Then, the method is applied to predict heat transfer rates in the most common configuration of MLI, under the quite well applicable assumption of radiative equilibrium, and numerical results are critically compared with those obtained from a couple of approximate, design-type formula, most of tem referenced in heat transfer manuals of Spacecraft Companies [11].

ANALYSIS

We consider radiative transfer in an absorbing, emitting, isotropically scattering, plane-parallel, gray medium of optical thickness a, enclosed between two infinite surfaces, S_1 and S_2, with emissivities ε_1 & ε_2, specular reflectivies ρ_1^s & ρ_2^s, diffuse reflectivities ρ_1^d & ρ_2^d, and prescribed temperatures T_1 & T_2. In addition, the participating medium is characterized by a thermal conductivity k, single scattering albedo w, and an extinction coefficient β, which defines the optical variable $x = \beta z$, where z is the physical coordinate. Under steady-state condition, the heat conduction equation to this one-dimensional problem is given by:

$$K \frac{d^2T(z)}{dz^2} - \frac{dq^r}{dz} = 0 \quad , \; 0 < z < L, \qquad (1)$$

where q^r is the radiative heat flux and T(z) is the temperature distribution in the medium.

Radiative heat transfer is then governed by the transport equation in the optical variable, x, given as:

$$\mu \frac{\partial I(x,\mu)}{\partial x} + I(x,\mu) = \frac{\omega}{4\pi} G(x) + S(x), -1 \leq \mu \leq 1 \quad \text{in } 0 < x < a, \qquad (2.a)$$

where

$$S(x) = \frac{n^2 \, \rho T^4(x)}{\pi} (1-\omega) \quad \text{is the source term,} \qquad (2.b)$$

$$G(x) = 2\pi \int_{-1}^{1} I(x,\mu)\, d\mu \quad \text{is the incident radiation,} \qquad (2.c)$$

and $I(x,\mu)$ is the radiation intensity, while n is the index of refraction of the medium.

The appropriate boundary conditions at surfaces S_1 and S_2, including specular reflection, are then written as:

$$I(0,\mu) = F(0) + 2\rho_1^d \int_0^1 I(0,-\mu) d\mu + \rho_1^s \, I(0,-\mu), \qquad (2.d)$$

$$I(a,-\mu) = F(a) + 2\rho_2^d \int_0^1 I(a,\mu) d\mu + \rho_2^s \, I(a,\mu), \qquad (2.e)$$

where

$$F(0) = \frac{\varepsilon_1 n^2 \sigma T_1^4}{\pi} \; ; \; F(a) = \frac{\varepsilon_2 n^2 \sigma T_2^4}{\pi} . \qquad (2.f,g)$$

Equation 2.a is now solved formally for the forward and backward radiation intensities, as described in reference [12], to yield:

$$I(x,\mu) = I(0,\mu)e^{-x/\mu} + \int_0^x e^{(x-\xi)/\mu}\Big[S(\xi) + \frac{\omega}{4\pi} G(\xi)\Big]d\xi. \qquad (3.a)$$

$$I(x,-\mu) = I(a,-\mu)e^{-(a-x)/\mu} + \int_0^x e^{(\varepsilon-x)/\mu}\Big[S(\xi) + \frac{\omega}{4\pi} G(\xi)\Big]d\xi . \qquad (3.b)$$

These formal solutions, following the procedure in the development of the integral equation for the incident radiation, G(x), are substituted back into the definition of G(x), eq. (2.c), as shown in [9]. In order to allow for the inclusion of specular reflection at the boundaries, we proceed by substituting the formal solutions (3.a,b) into the boundary equations (2.d,e) as well, resulting in the following system of algebraic equations for the incoming radiation intensities at the boundaries:

$$I(0,\mu) = \rho_1^s \; I(a,-\mu)e^{-a/\mu} + F_1 , \qquad (4.a)$$

$$I(a,-\mu) = \rho_2^s \, I(0,\mu) \, e^{-a/\mu} + F_2 , \qquad (4.b)$$

where

$$F_i = \rho_i^s \int_0 \Big[S(\xi) + \frac{\omega}{4\pi}G(\xi)\Big] \frac{\exp\{\big[(-1)^i\xi + (i-1)a\big]/\mu\}}{\mu} d\xi +$$

$$+ 2\rho_i^d \left\{ A_i + \int_0^a \Big[S(\xi) + \frac{\omega}{4\pi} G(\xi)\Big] E_2 \big((-1)^i + (i-1)a\big) \, d\xi \right\} ,$$

$$i = 1,2, \qquad (4.c,d)$$

$$A_i = \int_0^1 \mu I(a(i-1),(-1)^{i+1}\mu)d\mu, \; i=1,2, \qquad (4.e,f)$$

and $E_n(x)$ is the exponential integral function.

System (4) is readily solved to yield:

$$I(0,\mu) = \frac{F_1 + \rho_1^s F_2 e^{-a/\mu}}{1-\rho_1^s\rho_2^s \, e^{-2a/\mu}} ; \; I(a,-4) = \frac{F_2 + \rho_2^s F_1 e^{-a/\mu}}{1-\rho_1^s\rho_2^s \, e^{-2a/\mu}} . \qquad (5.a,b)$$

The expression above, together with the formal solutions are now introduced into the definition of the incident radiation to yield the following integral equation for G(x), besides two additional equations for the quantities A_i's:

$$G(x) = 2\pi \int_0^1\int_0 R(\xi) \Big\{ \rho_1^s W_1(x+\xi,u) + \rho_1^s\rho_2^s\Big[W_1(2a - x + \xi,u) + W_1(2a - \xi + x,u)\Big]$$

$$+ \rho_2 \, W\,(2a - \xi - x, u)\Big\} d\xi du + 2\pi \int_0^1 R(\xi)\, E_1\big[x - \xi\big]d\xi$$

$$+ 4\pi\rho_1^d \left\{\int^1 W_2(x,u)du + \rho_2^s \int_0^1 W_2(2a - x,u)du\right\} \left\{\int_0^a R(\xi)E_2(a-\xi)d\xi + \right.$$

$$\left. + F(a) + 2\,\rho_2^d A_2 \right\}$$

$$+ 4\pi\rho_2^d \left\{\int^1 W_2(a-x,u)du + \rho_1^s \int_0^1 W_2(a + x,u)du\right\} \left\{ \int_0^a R(\xi)E_2(\xi)d\xi + \right.$$

$$\left. + F(0) + 2\rho_1^d A_1 \right\} \qquad (6.a)$$

$$A_i = \rho_{3-i}^s \int_0^1\int_0^a W_2(3a - a.i + (-1)^i\varepsilon,u)\, R\,(\varepsilon)du +$$

$$+ \int_0^1 W_3(a,u)du \left\{ F(2a - a.i) + 2\rho_{3-i}^d A_{3-i} + 2\,\rho_{3-i}^d \int_0^a E_2((-1)^i\varepsilon + \right.$$

$$\left. + 2a - a.i)\, R\,(\varepsilon)\, d\varepsilon \right\} + \rho_1^s \rho_2^s \int_0^1\int_0^a W_2(a + a.i + (-1)^{i+1}\varepsilon)R\,(\varepsilon)\, d\varepsilon du +$$

$$+ \rho_{3-i}^s \int_0^1 W_3(2a,u)du \left\{ F(a.i-a) + 2\,\rho_i^d \, A_i + 2\rho_i^d \int_0^a E_2(a.i - a + (-1)^{1+i}\xi) \, R(\xi)\, d\xi \right. \qquad (6.b)$$

Where

$$R(\varepsilon) = S(\varepsilon) + \frac{\omega}{4\pi} G(\varepsilon), \; W_i(x,u) = \frac{e^{-x/a} u^{i-2}}{1 - \rho_1^s \rho_2^s \, e^{-2a/u}} . \qquad (6.c,d)$$

The Galerkin method is now applied to equations (6.a-c), with G(x) represented as a polynomial expansion in the form:

$$G(x) = \sum_{n=0}^{N} \Psi_n \, x^n . \qquad (7)$$

where Ψ_n are the unknown expansion coefficients.

Equation (7) is substituted back into equations (6.a-c), while eq. (6.2) is operated on with $\int_0^a x^m dx$, $m = 0,1,\ldots,N$ to yield a system of (N+3) algebraic linear equations, that are solved for the (N+1) expansion coefficients and A_i's, i = 1,2.

Once Ψn's and A_i's have been obtained, the quantities F_i's are evaluated to yield the forward and backward radiation intensities, $I(x,\mu)$ and $I(x,-\mu)$, from eqs. (4.a,b) and (3.a,b). Besides, the radiative heat flux, q'(x), is then readily obtained from its definition

$$q'(x) = 2\pi \Big[\int_0^1 I(x,\mu)\mu d\mu - \int_0^1 I(x,-\mu)\mu d\mu \Big] . \qquad (8.a)$$

Then, substitution of the expression for $I(x,\mu)$ and $I(x,\mu)$ into eq. (8.a) yields the following working formula for the radiative heat flux inside the medium:

$$q(x) = \int_0^1\int_0^a R(\varepsilon) \Big\{ \rho_1^s W_2(\varepsilon+x,u) + \rho_1^s\rho_2^s W_2(2a - \varepsilon+x,u) - \rho_2^s\,(2a-x-\varepsilon,u)$$

$$- \rho_1^s\rho_2^s W_2(2a+\varepsilon-x,u)\Big\} d\varepsilon du$$

$$\left\{ -\rho_2^s \int_0^1 W_3(2a-x,u)du + \int_0^1 W_3(x,u)du \right\} \left\{ F(0) + 2\rho_1^d A_1 + 2\rho_1^d \int_0^a E_2(\varepsilon)R(\varepsilon)d\varepsilon \right\} \left\{ - \int_0^1 W_3(a-x,u)du + \right.$$

$$\left. + \rho_1^s \int_0^1 W_3(x+a,u)du \right\} \left\{ F(a) + 2\rho_2^d A_2 + 2\rho_2^d \int_0^a E_2(a-\varepsilon)R(\varepsilon)d\varepsilon \right\} + \int_0^1\int_0^a e^{-|x-\varepsilon|/u} . \mathrm{sgn}(x-\varepsilon)R(\varepsilon)d\varepsilon \qquad (8.b)$$

Also, the divergence of the heat flux, which appears in the heat conduction equation, is readily obtained from:

$$\frac{dq'(x)}{dx} = (1-\omega)\Big[4n^2\sigma T^4(x) - G(x)\Big] . \qquad (8.c)$$

As shown in references [12,13], provided the conduction-to-radiation parameter $(4n^2\sigma\bar{T}^3/K\beta)$ is sufficiently large, the conductive and radiative transfer phenomena can be decoupled, requiring that $dq^{r(x)}/dx = 0$, which characterizes a radiative equilibrium situation. Besides, such a situation is also attained by a purely scattering medium, i.e., $\omega=1$. In MLI's due to the very low thermal conductivities and single scattering albedos very close to unity, the assumption of radiative equilibrium is indeed quite reasonable and suffices for most practical purposes. Therefore, this radiative transfer problem can be readily solved by setting $\omega=1$ in the expressions above, resulting in a uniform radiative heat flux distribution.

RESULTS AND DISCUSSION

Based on the expressions above, a computer code was developed for the calculation of radiation intensities, incident radiation and radiative heat flux distributions. All the related integrals were performed analytically, except for the calculation of integrals in the variable μ involving the functions W_i's, when an adaptive numerical quadrature routine was utilized. The results that follows were obtained with $N < 12$. Higher order expansions would involve convergence difficulties due to the ill-conditioning of the matrix in the linear system of equations, for the simple polynomial basis here chosen. The computer code was thoroughly validated against the results in reference [9] and, for the cases of specular reflection, against results from the P_N-method computer code developed in reference [7].

From the data available in reference [11], the most usual fibrous materials for spacers are listed in table I below, together with the relevant data for the radiative transfer calculations that follows.

Table 1. Relevant data of most usual MLI spacers

CASE	MATERIAL	CONSIDERED THICKNESS (m)	EXTINCTION COEFFICIENT	ALBEDO (	a)	TEMPERATURA K
1	Dexiglass	7.62×10^{-5}	2.73×10^4	0.952	2.08026	500
2	Tissuglas	15.2×10^{-5}	2.68×10^4	0.989	4.0736	500
3	Tissuglas	15.2×10^{-5}	2.92×10^4	0.9623	4.432	650
4	Refrasil A-100	9.83×10^{-5}	4×10^3	0.95	0.1932	500
5	Refrasil B-100	4.83×10^{-5}	3.1×10^3	0.94	0.169	500
6	Fibra de Carbono	3 a 10×10^5	3.89×10^4	0.990	1.167 a 3.89	5000

In addition, we examine the accuracy of a couple of approximate, design-type formulas, that were developed, respectively, by Glaser [2] and Deissler [14], for the radiative heat flux across the MLI, given by:

$$q_G = \frac{(T_2^4 - T_1^4)n^2\sigma}{\left[(1+\omega)\frac{a}{2} + \frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1\right]}, \quad \text{(Ref.2)} \qquad (9.a)$$

$$q_D = \frac{(T_2^4 - T_1^4)n^2\sigma}{\left[0.75a + \frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1\right]} \cdot \text{(Ref.14)} \qquad (9.b)$$

Therefore, in table II we list the results for the heat flux obtained form eq. (8.b), compared to the approximate ones from eqs.(9), for the MLI's listed in table I. Apparently, the results from Glaser's formula consistently underestimates the radiative heat flux, while Drissler overestimates it but provides better results than Glaser's. Both, however, in the MLI's investigated, performed quite well such simple, explicit expressions.

Table 2. Results for Radiative heat flux in the MLI's of table I

a	ρ^s	ρ^d	ε	q (Eq.8.b)	q_D	q_G	$\left\lvert\frac{q-q_D}{q}\right\rvert \times 100$	$\left\lvert\frac{q-q_G}{q}\right\rvert \times 100$
1.951	0.9	0.06	0.04	9.08	9.101	9.01	0.25	0.71
2.081	0.9	0.06	0.04	9.06	9.08	8.99	0.25	0.78
2.141	0.9	0.06	0.04	9.05	9.08	8.98	0.24	0.81
4.076	0.9	0.06	0.04	8.80	8.82	8.65	0.26	1.71
4.432	0.9	0.06	0.04	8.76	8.78	8.60	0.23	1.88
0.1923	0.9	0.06	0.04	9.34	9.35	9.34	0.07	0.02
1.951	0.7	0.1	0.2	43.4	43.9	41.9	1.0	3.6
2.081	0.7	0.1	0.2	43.0	43.3	41.5	0.6	3.8
2.141	0.7	0.1	0.2	42.9	43.5	41.2	1.5	4.0
4.076	0.7	0.1	0.2	37.7	38.1	35.2	1.0	7.3
4.432	0.7	0.1	0.2	36.9	37.3	34.2	0.9	8.0
0.1923	0.7	0.1	0.2	50.1	50.2	50.0	0.3	0.2
1.951	0.8	0.1	0.1	22.3	22.6	21.9	0.5	1.8
2.081	0.8	0.1	0.1	22.21	22.3	21.8	0.68	1.9
2.141	0.8	0.1	0.1	22.1	22.3	21.7	0.58	2.0
4.076	0.8	0.1	0.1	20.7	20.8	19.9	0.48	4.0
4.432	0.8	0.1	0.1	20.5	20.6	19.6	0.5	4.4
0.1923	0.8	0.1	0.1	24.0	24.0	23.9	0.16	0.09

Also of interest is the inspection of the relative importance of the specular reflectivity on heat transfer rates, and the effects on the assumption of purely, diffusely reflecting boundaries instead. Therefore, in table III we list heat flux results for a few combinations of reflectivities and emissivity, obtained from eq. (8.b) with $\rho^s \neq 0$ and $\rho^s = 0(\rho^d + \rho^d + \rho^s)$, and those obtained from Deissler's approximate formula.

Table 3. Effect of specular reflectivity – ($\omega=1$. $T_1 = 300^0K$; $T_2 = 0^0K$)

a	ρ_i^s i = 1 ou 2	ρ_i^d i = 1 ou 2	ε	q (Eq.8.b) $\rho s \neq 0$	q (Eq.8.b) $\rho s = 0$	q_D
2.090	0.9	0.06	0.04	9.06	9.07	9.08
2.141	0.9	0.06	0.04	9.05	9.06	9.08
1.951	0.9	0.06	0.04	9.08	9.09	9.01
4.0736	0.9	0.06	0.04	8.80	8.81	8.82
4.432	0.9	0.06	0.04	8.76	8.77	8.77
2.080	0.7	0.1	0.2	43.0	43.2	43.5
2.141	0.7	0.1	0.2	42.9	43.0	43.3
1.951	0.7	0.1	0.2	43.4	43.6	43.9
4.0736	0.7	0.1	0.2	37.7	37.9	38.1
4.432	0.7	0.1	0.2	36.9	37.1	37.3
2.080	0.4	0.1	0.5	99.3	98.8	100.7
2.141	0.4	0.1	0.5	98.3	97.8	99.7
1.951	0.4	0.1	0.5	101.4	100.9	102.9
4.0736	0.4	0.1	0.5	75.0	74.4	75.8
4.432	0.4	0.1	0.5	72.0	71.6	72.6

It appears that when the total reflectivity is very large (close to unity) for the MLI's investigated, the effect of disregarding specular reflection at the surfaces is not so significant, increasing in importance as the total reflectivity decreases. Therefore, depending on the shield materials being used, the effects of specularity might be neglected for the purposes of studying the transversal heat transfer. However, the effects of specular reflection are expected to play some role when the two-dimensional analysis, for the determination of longitudinal heat losses, is performed.

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RADIATIVE HEAT TRANSFER SOLUTIONS IN PLANE-PARALLEL PARTICIPATING MEDIA:
- APPLICATION TO MULTILAYER INSULATIONS FOR SPACE VEHICLES

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