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Transient thermal radiation heat transfer in a reinforced plastic coating with anisotropic optical properties

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A R T I C L E I N F O

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A B S T R A C T

Advanced fiber reinforced plastics, such as carbon fiber reinforced polymers (FRP), offer many advantages over more traditional materials such as metals. Their characteristics make them ideal for use in many sensitive applications. To maximize the use of these materials, there is a need to gain a better understanding of heat and temperature distribution in these materials under different boundary conditions. In this study transient radiative and conductive heat transfer in a FRP medium with anisotropic optical properties is investigated. The solution includes the radiative transfer equation (RTE) within the material coupled to a transient energy equation that contains both radiative and conductive terms. Two different kinds of boundary conditions are treated: when the temperatures imposed on the boundaries vary with time and when the medium is subject to a radiation source which varies with time. It is shown that radiative heat transfer has significant effect on heat transfer and temperature distribution within the layer.

1. Introduction

Advances have been made in the design, manufacture and application of composite materials and much of this progress has been in the field of fiber reinforced plastics (FRP). Theses FRP materials are well known for their excellent mechanical and thermal and chemical resistance properties. They often have greater strength weight and stiffness/ weight ratios than traditional materials, such as metals, which makes them ideal for use in many applications. They are also stronger but much lighter than steel. They are being used for a variety of applications such as aerospace programs insulations and coatings [1–4] and for high temperature applications, [4–8]. Various types of reinforced plastics have been in use for many years as reinforcement in automobile tires, large balloons and dirigibles, electrical industries, automotive systems [8–12] and solvent resistant membranes applications [13–17]. They are widely known as protective and decorative coatings or films in broad range applications because of the wide range of physical properties and performance.

Accurate prediction of temperature distributions in FRP materials at high temperature, are essential during various fabricating operations. In FRP materials where radiative transport acts simultaneously with heat conduction, the radiation fluxes depends strongly on the temperature level. Hence, during transient calculations, accurate temperature distributions must be obtained of each time step or the error in the radiation terms will cause the results to become considerably in error as time advances. In addition the assessment of any insulating material under fire conditions requires evaluating the temperature field in the medium and its evolution with time.

For this purpose, this paper has considered a modeling of the coupled radiation and conduction heat transfer in a transient state inside a FRP plate, with a heat flux applied to one of its faces. A survey of the literature on coupled radiation and conduction in semi-transparent media shows that up to now, there exist rather few studies on the transient state and, that for the major part, the media considered are gray not scattering [18,19], or with an isotropic scattering, [20,21]. More over there exist, rather few studies dealing with flux boundary conditions. In addition note that in the quoted papers, FRP are practically not studied. In the present work the transient state is considered and the practical and economic stakes are investigated.

2. Analysis

A plane layer of thickness E, as shown in Fig. 1 is a heat conducting, emitting, absorbing and scattering medium with a refractive index equal to 1. The media is homogeneous, one-dimensional and axisymetric. The spectral radiation intensity $I_\lambda(x,\mu,t)$ is governed by the radiative transfer equation, (RTE), [22]:

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Nomenclature

C_p	specific heat capacity of the medium ($J \cdot kg^{-1} \cdot K^{-1}$)
E	medium thickness (m)
h	convective exchange coefficient ($W \cdot m^{-2} \cdot K^{-1}$)
I_λ	spectral radiation intensity ($W \cdot m^{-2}$, $\mu m^{-1} \cdot sr^{-1}$)
$I_{b,\lambda}$	spectral black body intensity ($W \cdot m^{-2} \cdot \mu m^{-1} \cdot sr^{-1}$)
k	thermal conductivity of the medium ($mW \cdot m^{-1} \cdot K^{-1}$)
Q_t	total heat flux ($W \cdot m^{-2}$)
Q_c	conductive heat flux ($W \cdot m^{-2}$)
Q_r	total radiative heat flux ($W \cdot m^{-2}$)
S_r	radiative source term ($W \cdot m^{-3}$)
t	time (s)
T	temperature (K)
T_∞	surrounding temperature (K)
x	position (m)

Greek symbols

λ	wavelength (μm)
μ	cosine of the polar angle
ρ	density of the medium ($kg \cdot m^{-3}$)
k_λ	spectral absorption coefficient (m^{-1})
$\sigma_{s\lambda}$	spectral scattering coefficient (m^{-1})
β_λ	spectral extinction coefficient (m^{-1})
ϕ_λ	spectral phase function

Subscripts

O,E	boundaries
λ	spectral

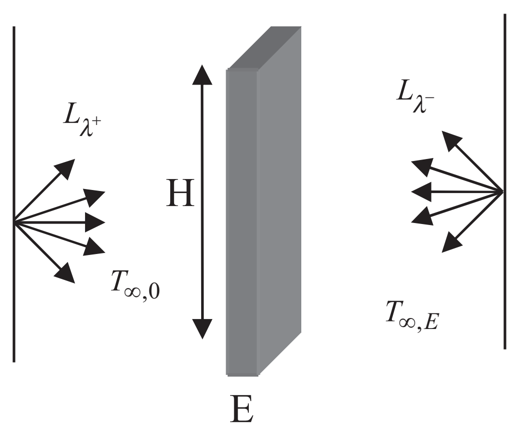

Fig. 1. Plane plate surrounded by two radiation source on its two surface.

$$\frac{\partial I_\lambda(x,\mu,t)}{\partial x} = \frac{-\beta_\lambda(\mu)I_\lambda(x,\mu,t) + J_\lambda(x,\mu,t)}{\mu} \quad (1)$$

With

$$\beta_\lambda = \kappa_\lambda + \sigma_{s\lambda} \quad (2)$$

And

$$J_\lambda(x,\mu,t) = k_\lambda(\mu)I_{b,\lambda}(T(x,t)) + \frac{1}{2}\int_{\mu'=-1}^{1} \sigma_{s\lambda}(\mu')\phi_\lambda(\mu' \to \mu)I_\lambda(x,\mu',t)d\mu' \quad (3)$$

For all $\mu \in [-1,1] \setminus \{0\}, \lambda > 0, 0 < x < E, \quad t > 0$

$I_{b,\lambda}(T)$ is the spectral intensity of black body emission at temperature T, given by, [23]:

$$I_{b,\lambda}(T) = \frac{C_1}{\lambda^5.[\exp(C_2/(\lambda.T))] - 1} \quad (4)$$

where

$C_1 = 1.19 \times 10^{-16}$ W m^2 sr^{-1} and $C_2 = 1.4388 \times 10^{-2}$m k

The total radiative heat flux in then given by:

$$Q_r(x,t) = 2\pi \int_{\lambda=0}^{\infty} \int_{\lambda=-1}^{1} I_\lambda(x,\mu,t)_\mu d_\mu d_\lambda \quad (5)$$

The transient behavior of the temperature within the layer is governed by the energy equation:

$$\rho c_P \frac{\partial T}{\partial t}(x,t) - \frac{\partial}{\partial x}\left(k(T(x,t))\frac{\partial T}{\partial x}(x,t)\right) = S_r(x,t) \quad (6)$$

The function k (T) is the medium thermal conductivity which is temperature dependent: It is derived using the Langlais and Klarsfeld relation, [24]:

$$k(T) = 0.2572T^{0.81} + 0.0527\rho^{0.91}(1 + 0.0013T) \quad (7)$$

The radiative source term in Eq. (6) is defined by:

$$S_r(x,t) = -\frac{\partial Q_r}{\partial x}(x,t) \quad (8)$$

The conductive heat flux is defined by:

$$Q_c(x,t) = -k(T(x,t))\frac{\partial T}{\partial x}(x,t) \quad (9)$$

The total heat flux in the sum of the conductive and radiative fluxes:

$$Q_t = Q_r + Q_c \quad (10)$$

In steady state, the energy equation becomes:

$$\frac{dQ_t}{dx}(x) = 0 \quad (11)$$

3. Temperature boundary and initial conditions

The medium boundaries are black surfaces with imposed temperatures. The temperature of the front face is assumed to be raised abruptly following a given time evolution f(t) to reach a constant value T_0. The cold face temperature T(E, t) remains constant with time:

$$T(0,t) = f(t) \text{ and } T(E,t) = T_E, \quad t > 0 \quad (12)$$

The radiative boundary conditions are for $t \geqslant 0$ are as follow:

$$I_\lambda(0,\mu,t) = I_{b,\lambda}(f(t)) \quad 0 < \mu \leqslant 1 \quad (13a)$$

$$I_\lambda(E,\mu,t) = I_{b,\lambda}(T_E) \quad -1 \leqslant \mu \leqslant 0 \quad (13b)$$

$$T(x,0) = T_E \quad 0 \leqslant x \leqslant E \quad (14)$$

4. Flux boundary and initial conditions

The layer is assumed to be vertically positioned between surroundings which are considered as two black surfaces, whose