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Theoretical prediction of thermal conductivity for thermal protection systems

F. Gori [a], S. Corasaniti [a,*], W.M. Worek [b], W.J. Minkowycz [b]

[a] University of Rome "Tor Vergata", Dept. of Mechanical Engineering, Via del Politecnico 1, 00133 Rome Italy
[b] University of Illinois at Chicago, Dept. of Mechanical Engineering, 842 West Taylor Street, Chicago, IL 60607-7022, USA

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A B S T R A C T

The present work is aimed to evaluate the effective thermal conductivity of an ablative composite material in the state of virgin material and in three paths of degradation. The composite material is undergoing ablation with formation of void pores or char and void pores. The one dimensional effective thermal conductivity is evaluated theoretically by the solution of heat conduction under two assumptions, i.e. parallel isotherms and parallel heat fluxes. The paper presents the theoretical model applied to an elementary cubic cell of the composite material which is made of two crossed fibres and a matrix. A numerical simulation is carried out to compare the numerical results with the theoretical ones for different values of the filler volume fraction.

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1. Introduction

The main problem in designing space vehicles, able to descend on the surface of planets with atmosphere, is to design reliable thermal protection systems. The re-entry vehicle system deserves special attention for security reasons and for its cost.

A wide range of applications is qualified by ground tests and flight experiments [1]. They include: flexible external insulation with limited aerodynamics or mechanics loads in the range between 300 °C and 1200 °C; surface protected flexible insulation, covered by a ceramic face sheet, extending the use to surfaces with higher aerodynamics and mechanics loads; metallic thermal protection system with new advanced titanium and super alloy materials, which can significantly reduce the specific mass of the system and provide advantages for reliability and operations; ceramic matrix composites available up to 1600 °C.

Heat protection design for spacecraft is a process involving different scientific fields, such as solid mechanics, aero-thermodynamics, physical chemistry and heat and mass transfer. Conservative design, usually carried out in order to have safe conditions for the re-entry vehicle, is no more enough [2], due to high-performance and low-cost requirements imposed on the development of future space vehicle.

Thermal behaviour of composite materials is extremely important in many applications as heat shields and heat guides [3–6]. Thermal protection blankets, consisting of fibre batting sandwiched between two sheets of woven ceramic fabric and alternative to rigid tiles, are interesting because of the low cost.

Blankets consisting of silica fibre fabrics and insulation are used to protect the upper surface of the Space Shuttle Orbiter. Advanced coating systems, based on an interface of oxide composites, are a mean to increase the service temperatures of thermal protection blankets for re-entry spacecraft. Preliminary experiments have been conducted in a modulated wind tunnel facility, including chemical compatibility, tensile strengths of coated, heat-treated fibres and fabrics, and durability [7].

Ablation is an auto-adjustment of heat and mass transfer where incoming energy is dissipated by loss of matter. The main class of ablative materials is polymer composites, made of matrix and filler. Ablative materials, used as thermal protection devices, change the thermal properties during the phenomenon because of the high thermal flux. Thermal conductivity of ablative material is dependent on physical and chemical phenomena, specifically the formation of char from the virgin material of the thermal protection.

Erosion rate of ceramic protection material with oxidation, defined as mass loss per exposed area and time, is especially high at low-pressure levels and, therefore, at high velocities [8].

The model of a cubic cell unit, representing a porous material with several phases, has been proposed first [9] and later on improved [10–13]. The cubic cell model has been applied to several heat transfer problems [14–16], and, among space applications, to thermal protections [17,18]. The present paper presents some unpublished results and new applications concerning different mechanisms of degradation.

* Corresponding author. Tel.: +39 06 72597130; fax: +39 06 2021351.
E-mail addresses: gori@uniroma2.it (F. Gori), sandra.corasaniti@uniroma2.it (S. Corasaniti), wworek@uic.edu (W.M. Worek), wjm@uic.edu (W.J. Minkowycz).

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Nomenclature

Latin variable (SI unit)

a	fibre thickness [m]
$a' = a/(a+2b)$	fibre thickness, dimensionless
b	matrix thickness [m]
$b' = b/(a+2b)$	matrix thickness, dimensionless
$f = S/S_t$	ratio between generic surface and total surface, dimensionless
k	thermal conductivity [W/m K^{-1}]
Q	heat flux [W]
S	surface [m^2]
T	temperature [K]
v	volumetric fraction, dimensionless
V	volume [m^3]
x	fraction of virgin material, dimensionless

Greek

$\varphi = V_p/V_{mv}$	pores volume fraction, dimensionless
ρ	composite material density [kg/m^3]

Subscript

c	char
eq	equivalent
f	fibre
g	gas
m	matrix during degradation
mv	virgin matrix before degradation
p	void pores
t	total
tf	total vertical parallel heat fluxes assumption
ti	total horizontal parallel isotherms assumption

2. Theoretical model

The composite material, made of fibre and virgin matrix, is arranged in a cubic cell unit as shown in Fig. 1. The fibre is present in the central layer of the cell and is drawn grey while the virgin matrix, surrounding the fibre, is drawn white.

One dimensional heat conduction is solved under two thermal assumptions for a given configuration of the cubic cell unit. If the composite material is not degradable the form the cubic cell is independent of time and the solution of heat conduction is steady state.

With reference to Fig. 1, the first thermal assumption is of horizontal parallel isotherms, corresponding to the hypothesis of an infinite thermal conductivity in the horizontal direction. The second thermal assumption is of vertical parallel heat fluxes, corresponding to the hypothesis of zero thermal conductivity in the horizontal direction.

Under the assumption of horizontal parallel isotherms the cubic cell unit can be split in three horizontal layers, as shown by Fig. 1. The total heat flux Q_t through the virgin matrix is

$$Q_t/S_t = k_{mv} \cdot (T_2 - T_1)/b \qquad (1)$$

for the top layer and

$$Q_t/S_t = k_{mv} \cdot (T_3 - T_4)/b \qquad (2)$$

for the bottom layer, where k_{mv} is the thermal conductivity of virgin matrix and S_t is the surface of the cell unit.

The total heat flux Q_t through the central layer, where is present virgin matrix and fibre, is

$$Q_t/S_t = k_{\mathrm{eq}} \cdot (T_3 - T_2)/a \qquad (3)$$

The equivalent thermal conductivity of the central layer, k_{eq}, is

$$k_{eq} = k_f \cdot S_f/S_t + k_{mv} \cdot S_{mv}/S_t = k_f \cdot f_f + k_{mv} \cdot f_{mv} \qquad (4)$$

where k_f is the thermal conductivity of the fibre while S_f and S_{mv} are the surfaces relative to fibre and virgin matrix.

The total effective thermal conductivity of the cell unit, k_{ti}, under the assumption of horizontal parallel isotherms is finally:

$$k_{\mathrm{ti}} = \left(b'/k_{mv} + a'/k_{eq} + b'/k_{mv}\right)^{-1} \qquad (5)$$

where $a' = a/(a+2b)$ and $b' = b/(a+2b)$ are the dimensionless fibre and matrix thicknesses respectively. Equation (5) shows the separate contribution of each of the three horizontal layers of the composite material in the cell unit.

Under the thermal assumption of vertical parallel heat fluxes the total heat transfer can be split in two parts, Q_1 and Q_2, where Q_1 is the heat transfer through the virgin matrix, which is present on the four sides of the cubic cell, while Q_2 is the heat transfer through the virgin matrix and the fibre in the central part of the unit cell, as shown in Fig. 2.

The heat transfer flux Q_1/S_1 through the virgin matrix is:

$$Q_1/S_1 = k_{mv} \cdot (T_4 - T_1)/(b + a + b) \qquad (6)$$

The heat transfer flux Q_2/S_2 through the virgin matrix and the fibre in the central part is

$$Q_2/S_2 = k_{eq} \cdot (T_4 - T_1)/(b + a + b) \qquad (7)$$

where k_{eq} is the equivalent thermal conductivity of the central layer

$$k_{eq} = \left(b'/k_{mv} + a'/k_f + b'/k_{mv}\right)^{-1} \qquad (8)$$

The total heat transfer through the cell unit, Q_t, under the assumption of vertical parallel heat fluxes, is finally the sum of Q_1 and Q_2:

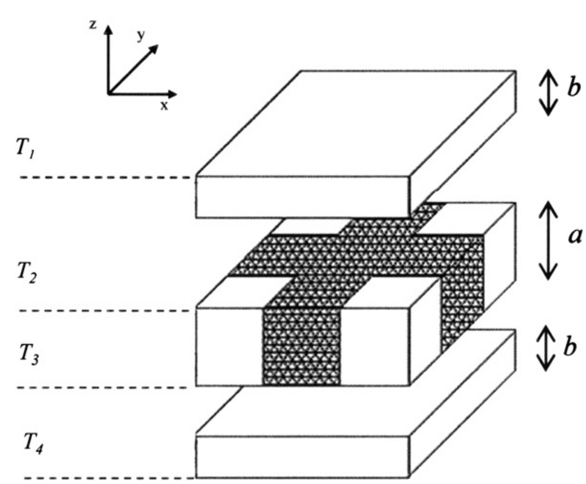

Fig. 1. Cubic cell unit with virgin matrix (white) and fibre (grey).

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