Applied Thermal Engineering 49 (2012) 124–130

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

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

ARTICLE INFO

Article history:
Received 27 October 2010
Accepted 7 July 2011
Available online 21 July 2011

Keywords:
Cubic cell model
Thermal protection
Thermal conductivity
Theoretical prediction
Numerical solution

ABSTRACT

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.

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).

1359-4311/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.applthermaleng.2011.07.012