International Journal of Heat and Mass Transfer 95 (2016) 720–726

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Numerical analyses of ablative behavior of C/C composite materials

Wang Chen *

Key Lab of Structures Dynamic Behavior and Control (Harbin Institute of Technology), Ministry of Education, Heilongjiang, Harbin 150090, China
School of Civil Engineering, Harbin Institute of Technology, Heilongjiang, Harbin 150090, China

ARTICLE INFO

Article history:
Received 1 April 2015
Received in revised form 1 December 2015
Accepted 15 December 2015
Available online 6 January 2016

Keywords:
C/C composite materials
Ablation
Spectrum diagnoses
Ablation model
Ablation recession rate

ABSTRACT

Ablation experiments of C/C composite materials were conducted by using arc plasma jet. The ablated surfaces of the C/C composite material samples were monitored by using the online spectrum diagnoses during the ablation experiments. Based on energy balance, mass conservation and chemical equilibrium equations, surface ablative model was established for the C/C composite materials to study the ablation process and the thermal environment parameters. The simulation results are in good agreement with the theoretical solution and experimental results. The ablative experiment and analytical model can be recognized as the basic research method for the thermal protection materials in the aerospace applications.

1. Introduction

Thermal protection materials and structures are the important part to protect the interior structural components of space vehicles during the re-entry stage. Polymeric composites have been widely used as ablative thermal protection systems (TPS) for a variety of military and aerospace applications. For thermal protective composites, C/C composites are widely used in the aerospace and aeronautic fields, such as in rocket throat lining, noze-tip, and brake pads materials etc. The ablation of C/C composites is a complex process in the high temperature environment, which plays an important role in the design of heat shield.

C/C composites exhibit thermochemical ablative characteristics in high temperature environments. When external heat flux is imposed on the polymeric composites, thermochemical ablation will be happened to induce surface recession phenomenon. When the material reaches a sufficiently high temperature, the matrix will begin thermochemical degradation or pyrolysis. The pyrolysis products include decomposition gases and solid carbonaceous char residue. Generally, ablation can be divided into two aspects, namely, superficial and volumetric ablation. Superficial ablation can change the geometrical dimensions of the thermal protection structures, and the volumetric ablation can decrease the density due to the pyrolysis of internal matrix and the release of gas generation. Thus the ablative evolution of surface and shallow surface layer of C/C composite material should be studied to understand their ablative mechanisms.

At present, the ablative behavior of material is mainly studied by experimental and numerical methods. The CORIA Center in France has developed plasma simulation equipment to study the ablative behavior of material in the ablative experiment [1–3]. Ablation products in the flow field of ground simulation system can be monitored and analyzed by spectral characteristics. It is helpful to study the ablative mechanisms of C/C composites by observing the mesoscopic ablation morphology of the ablative surface [4–11]. A numerical model was presented to predict the transient response of a one-dimensional ablative thermal protection system [12]. The oxidation and sublimation of charring ablator at a heated surface were taken into account in the model. Zabolotskiy and Roganov [13] analyzed the thermal interaction between a high-enthalpy incident gas flow and a thermal protection layer. The turbulent multicomponent boundary layer was described by the e–ε two-parametric turbulence model. In Chen et al.'s works [14–16], the flowfield and convective heat-transfer coefficients were computed using the flowfield code with species balance conditions for an ablating surface. The time-dependent in-depth conduction with surface blowing was simulated using the material response code with complete surface energy-balance conditions. A fixed domain numerical scheme was presented by Storti [17–19] to study the ablation problems, in which the enthalpy formulation with temperature was recognized as the main dependent variable. The basic idea of Storti's work is to introduce a fictitious phase in the region where the material has been removed. Jones and Shukla [20] used mathematical functions of thermal properties

* Address: Key Lab of Structures Dynamic Behavior and Control (Harbin Institute of Technology), Ministry of Education, Heilongjiang, Harbin 150090, China.

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.12.031
0017-9310/

to study the in-depth response of charring ablators exposed to high temperature environment. Two-dimensional ablation model with local boundary immobilization was established for cylindrical geometry [21] with temporal and spatial variations of the incident heat flux. In the (TITAN) program, Chen et al. [22–24] developed a method to predict the charring material ablation and shape change. The surface energy balance conditions were solved by a moving grid to calculate the shape change caused by surface recession. Murray and Russell [25] reported a process to calculate the surface temperature and thermal response of typical missile configurations in high-speed aero heating flows. Torre et al. [26–28] used thermogravimetric to characterize an ablative composite. The ablative behavior of silicon-based ablative composites for thermal protection shield was simulated based on mass and energy balance. The ablation mechanisms for thermal protection structures can be studied effectively by numerical method.

In the present study, the ablative experiment of C/C composites is conducted using ground simulation system. Based on the experimental observation and analysis, it is assumed that the ablative carbon surface satisfies the chemical equilibrium. The mass conservation, energy conservation, and chemical equilibrium for the chemical ablation model are established to describe the ablative process. Finally, it is found that the predicted results from the coupling algorithm are in good agreement with the experimental data by the arc jet tests. And the ablation mechanisms of C/C composites in different conditions can be studied by theoretical methods.

2. Ablative experiments

Fine-woven 3D C/C composites are composed of carbon fiber preforms and carbon matrix. In the carbon fiber preforms, the laminated carbon fiber clothes are laid in the *XY* plane, while carbon fiber bundles are punched in the *Z* direction as shown in Fig. 1. And the preforms are recognized as heterogeneous material. The preforms are impregnated with pitch precursor before heat treatment. Then the preforms are subjected to several high-pressure impregnation and carbonization to achieve a desired density. After a series of densification cycles, the C/C composites are treated by graphitization.

The ablation experiments of C/C composites were conducted by the ground simulation system, as seen in Fig. 2. The experiment was conducted in the air environment. As shown in Fig. 3, the heater equipment is an alternate current arc jet. During the ablative process, the heat flow, pressure, temperature, and ablation products were measured in the flow field of the ground simulation system. The enthalpy can be calculated by the heat flow and pressure.

By using the photoelectric pyrometer and thermal couple, the temperatures were measured on the ablative surface and the interior of the ablative specimens. The online emission spectrum diagnoses system can timely monitor ablative products. The specimens are a cylinder with a diameter of 24 mm and length of 100 mm.

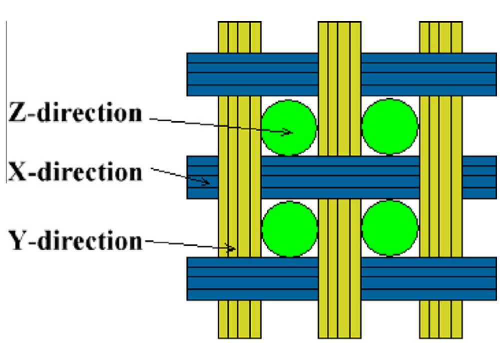

Fig. 1. Schematic of the fine-woven 3D composite preforms.

3. Theoretical analysis and ablative model

The ablative process of C/C composites can be divided into two stages, namely, oxidation and sublimation. Ablative velocity is generally dominated by superficial chemical kinetics at low temperature, and sublimation diffusion above sublimation temperature. With the diffusion controlling conditions, the ablation products of the material surface should satisfy the mass conservation and thermochemical equilibrium.

The mass transfer system with k kinds of components on the wall during ablation is described in Fig. 4.

The interface boundary conditions between a C/C material and its surrounding flowfield can be defined to solve the mass conservation and energy balance equations. Mass conservation equation on the surface of C/C material can be written as

$$\tilde{J}_{kw} + (\rho v)_w \tilde{c}_{kw} = \dot{m}_s \tilde{c}_{ks} \tag{1}$$

where $\tilde{J}_{kw}$ is the diffusion rate of k_{th} chemical component on the wall, ρ is the gas density on the wall, v is the velocity of injection gas on the wall, $\tilde{c}_{kw}$ is the mass fraction of k_{th} component on the wall, $\dot{m}_s$ is the mass loss rate of solids on the wall and $\tilde{c}_{ks}$ is the mass fraction of k_{th} component in mass loss of solids on the wall. By adding the k kind of components, the Eq. (1) can be rewritten as

$$\sum_k \tilde{J}_{kw} + (\rho v)_w = \dot{m}_s \tag{2}$$

Based on a chemical equilibrium computation for a C/C-air system, ten kinds of chemical gas phase components are studied to simulate the ablation of C/C composites. The chemical gas phase components have C_1, C_2, C_3, O, O_2, N, N_2, CN, C_2N and CO. The gas phase chemical reactions in the simulations include

1. $i\mathrm{C}(s) \leftrightarrow \mathrm{C}(g)$
2. $1/2\mathrm{O}_2 \leftrightarrow \mathrm{O}$
3. $1/2\mathrm{N}_2 \leftrightarrow \mathrm{N}$
4. $\mathrm{C} + 1/2\mathrm{N}_2 \leftrightarrow \mathrm{CN}$
5. $2\mathrm{C} + 1/2\mathrm{N}_2 \leftrightarrow \mathrm{C_2N}$
6. $\mathrm{C} + 1/2\mathrm{O}_2 \leftrightarrow \mathrm{CO}$

Based on the chemical equilibrium at the ablative material surface, the partial pressures of the gas components follows the Dalton's law as listed in Eq. (3). The expressions of component mass fraction and average molecular weight in the system are provided in Eqs. (4) and (5), respectively.

$$p_{\mathrm{C}} + p_{\mathrm{C_2}} + p_{\mathrm{C_3}} + p_{\mathrm{O}} + p_{\mathrm{O_2}} + p_{\mathrm{N}} + p_{\mathrm{N_2}} + p_{\mathrm{CN}} + p_{\mathrm{C_2N}} + p_{\mathrm{CO}} = p \tag{3}$$

$$\tilde{c}_k = \frac{M_k}{p\bar{M}} \sum_i x_{ki} p_i \tag{4}$$

$$\bar{M} = \frac{1}{p} \sum_i M_i p_i \tag{5}$$

where p is the total pressure of mixed gas, M_k is the molecular weight of the k_{th} component, p_i is the partial pressure of I_{th} gas, and x_{ki} is the atom number in the I_{th} chemical component.

It is assumed that mass transfer occurs in the boundary layer during the ablation process. thermochemical equilibrium system in the boundary layer should satisfy the conservation laws at the interfaces. Fig. 5 shows the energy balance on the wall.

The energy conservation equation at the surface of C/C can be expressed as