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Nonlinear analysis on thermal behavior of charring materials with surface ablation

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ABSTRACT

In-depth thermal responses and surface recession of charring materials are two main performances of the thermal protection system in reentry vehicles subjected to aerodynamic heating. To explore the thermal behavior of the charring ablator, we developed a new one-dimensional pyrolysis layer model with the heat and mass transfer through charring materials undergoing decomposition and surface ablation. Taking AVCOAT composites in an Apollo capsule during reentry as an example, the calculation codes are written to simulate its nonlinear thermal behavior caused by temperature dependent thermal properties, two moving interfaces and one moving boundary. Numerical results indicate that the pyrolysis layer model is suitable for solving the problem of the thermal behavior of the charring ablator. The nonlinear analysis is essential in the calculation process although it brings oscillations, which have little influence on surface ablation and decomposition. The thermal blockage effect of the pyrolysis gas from decomposition is significant in TPS during earth entry. This study will be helpful for the design of the thermal protection system in reentry vehicles.

1. Introduction

Thermal protection system (TPS) is essential for safety of vehicles subjected to severe aerodynamic heating [1]. Vehicles designed for earth entry typically use charring materials as TPS materials that can pyrolyze and ablate [2]. For example, AVCOAT 5026–39H/CG, which is epoxy novolac resin with special additives in a fiberglass honeycomb, has been successfully applied to TPS in the Apollo capsule. During the reentry, the material is able to operate by absorbing heat through decomposition and rejecting it via pyrolysis gas injection back into the boundary layer of gas. Furthermore, oxygen in the boundary layer may function with surface carbon generating gases at a high temperature, which is called surface ablation. As a result, the surface of material moves with recession, leading the original thickness reducing [3]. A lot of researches were carried out on both surface ablation and decomposition. On the one hand, surface ablation concludes oxidation and nitridation reaction between surface material and boundary gas, carbon diffusion and mass loss caused by mass-efficient from pyrolysis gas. Park [4] had developed the three-reaction equations to describe the chemical phenomena on the surface of material. There are papers keeping eyes on controlling mechanisms of oxidation on the surface and finding that different recession rates will be obtained by different controlling mechanisms [5]. Numerical simulations on surface ablation usually consider heat-flow coupling method using FIAT, CMA, TITAN and DPLR in the calculation [6]. On the other hand, decomposition of charring materials occurs in the internal of the material. Governing equations with Arrhenius law are utilized to analyze decomposition, which can obtain the mass change fraction, thermal properties and temperature distribution [7]. However, these methods utilize thermal analysis tests, and the test results depend heavily on the heating rate, which has great difference with the real heating rate of reentry. Even, these papers could not get the moving distances of interfaces between each different zone depending on temperature of inner material. To obtain the thermal response of charring material taking both surface ablation and decomposition into consideration, we have built a pyrolysis interface model, which regards the complex zone between virgin and carbonization as a pyrolysis interface yielding the energy balance equation [8]. Regrettably, this model cannot reflect the real situation of the material since that the mass injection rate of pyrolysis gas, change rate of density and enthalpy of thermal decomposition between the carbonized zone and the virgin zone are ignored in this model. To modify the pyrolysis interface model, we will develop a new pyrolysis layer model with considering surface ablation and decomposition, where ablator is divided into four layers with moving interfaces and boundary. By

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Nomenclature

ρ	density [kg/m^3]
c	specific heat [J$\cdot$kg$^{-1}\cdot$K^{-1}]
k	thermal conductivity [W$\cdot$m$^{-1}\cdot$K^{-1}]
$\dot{m}$	mass injection rate [kg$\cdot$m$^{-2}\cdot$s^{-1}]
h	enthalpy [J/kg]
q	heat flux [W/m^2]
ε	emissivity of ablation surface
σ	Stefan-Boltzmann constant[W$\cdot$m$^{-2}\cdot$K^{-4}]
T	temperature [K]
L	thickness of charring ablator [m]
x	space coordinate [m]
t	time [s]
F	heat flux difference [W/m^2]

Subscripts

1	virgin
2	pyrolysis layer
3	char
vp	interface between the virgin layer and the pyrolysis layer
pc	interface between the pyrolysis layer and the char layer
s	surface ablation
g	pyrolysis gas
cold	cold wall
w	surface
r	recovery
com	combustion

the way, thermal properties of charring ablators changing all the time with pyrolysis were researched by both test and theoretical methods [9–12], and the heat conduction equations with moving interfaces and boundary or temperature dependent thermal properties are strong nonlinear [13–17]. Taking AVCOAT composites in an Apollo capsule during reentry as an example, the computer codes will be written on the basis of the new model in order to simulate its nonlinear thermal behavior caused by temperature dependent thermal properties, two moving interfaces and one moving boundary.

2. Model

2.1. Physical model

The thermal response of charring materials under aerodynamic heating is as follows. First of all, charring materials can absorb heat by the heat capacity of materials themselves. When the surface temperature rises up to the beginning pyrolysis temperature T_{vp} of charring materials, the resin in surface materials starts to pyrolyze. Furthermore, when the surface materials are heated to the complete pyrolysis temperature T_{pc}, a char layer will form on the surface. Heating continues, the surface ablates and gradually moves into the virgin layer after it reaches the ablation temperature T_s.

We can develop a one-dimensional model (Fig. 1) since the temperature gradient vertically to the surface is much larger than those in the other orientations [18,19].

In Fig. 1, q is the hot wall heat flux with no mass transfer during reentry, x_{vp}, x_{pc} and x_s are coordinates of two moving interfaces and one moving boundary, which are functions of time, L is the thickness of ablator. Along the x direction, the ablator is divided into four layers, namely the virgin layer, the pyrolysis layer, the char layer and the ablation layer. The physical–chemical phenomena of the four layers are briefly introduced as follows

(a) The virgin layer: the zone where the temperature is lower than T_{vp}.

(b) The pyrolysis layer: the zone where the temperature varies from T_{vp} to T_{pc}. It is just an unsteady and complex zone of ablator with two moving interfaces. On the one hand, materials pyrolyze and release mixed gases which mainly consist of methane, ethylene, acetylene and hydrogen. On the other hand, loose solid carbon is gradually forming. In this layer, there exists the seepage of pyrolysis gas, the chemical reactions between pyrolysis gas and solid carbon, and the changes in density. Further, mechanism of absorbing heat mainly depends on the pyrolysis and the heat capacities.

(c) The char layer: the zone where the temperature is higher than T_{pc}, but lower than T_s. In this layer, there is a solid carbon structure through which the pyrolysis gases flow to the surface of the ablator. In addition, solid carbon and pyrolysis gases continue to absorb heat, and even the consequent cracking of pyrolysis gases is taken into consideration if necessary.

(d) The ablation layer: the surface recession zone where the temperature is higher than T_s. It becomes a part of the boundary layer with both absorbing and releasing heat. In this layer, there is convection and radiation phenomenon with the oxidation reaction; what's more, ejecting pyrolysis gases and combustion products can change the velocity and temperature of gas flow.

It is worth noting that the energy balance on the surface has to be discussed due to introducing surface ablation. Hot wall heat flux enters the material surface and is absorbed with mass transfer. Simultaneously, radiation heat flux releases outward the material surface. Besides, the combustion of carbon occurs on the material surface. The energy balance equation in detail can be seen in Section 2.2.

2.2. Mathematical models

To make the calculation easy, the two assumptions are the following:

(a) Pyrolysis gases do not react chemically with the porous char layer through which it flows.

(b) There is no secondary cracking of pyrolysis gases.

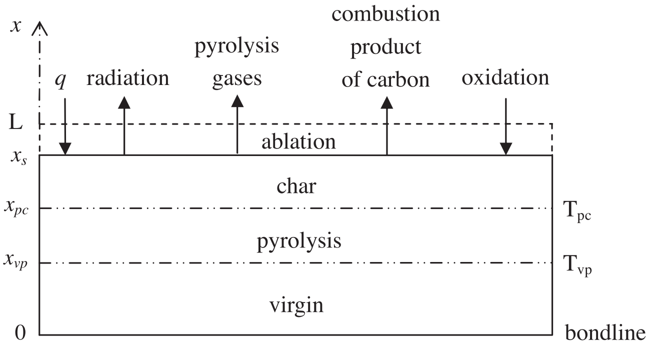

Fig. 1. One-dimensional pyrolysis model.