Protection of pyrolysis gases combustion against charring materials' surface ablation

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ABSTRACT

Charring ablation materials are widely used for thermal protection systems in a vehicle during hypersonic reentry. The pyrolysis gases from the charring materials can react with oxygen in the boundary layer, which makes the surface ablation rate decrease. The problem of protection of pyrolysis gases combustion against charring materials' surface ablation is solved by the detached normal shock wave relations and the counterflow diffusion flame model. The central difference format for the diffusion term and the upwind scheme for the convection term are used to discretize the mathematical model of the counterflow diffusion flame. Numerical results indicate that the combustion of pyrolysis gases in the boundary layer can completely protect the materials surface from recession when the velocity of pyrolysis gases injecting to the boundary layer is higher than the critical velocity. There is an allometric relationship between the critical velocity and Mach number, and the combustion heat has little influence on the temperature distribution originating from the aerodynamic heating. This study will be helpful for the design of the thermal protection system in hypersonic reentry vehicles.

1. Introduction

Charring ablation materials is the first choice for the thermal protection system of a vehicle subjected to severe aerodynamic environment during hypersonic reentry [1–3]. The pyrolysis of charring ablation materials and the flow of pyrolysis gases in materials can bring off amounts of heat [4–7]. Meanwhile, the char on the materials surface usually ablates because it reacts with the oxygen in the boundary layer behind the shock wave. Based on the thermal protection mechanism of charring materials, researchers developed three types of physical and mathematical models for the materials [5,8–13]. A heat conduction equation combining with the Arrhenius law was widely used to estimate the pyrolysis of a charring materials avoiding seeking moving interfaces in the materials. The other two models – the pyrolysis interface model and the pyrolysis layer model – were built, reflecting the materials' multilayer phenomenon. Regrettably, the three types of models above assumed that the pyrolysis gases do not react with the oxygen in the boundary layer. Actually, when pyrolysis gases injected from the inner materials meet the oxygen in the boundary layer, a diffusion flame is formed. A starting reaction interface in the pyrolysis

gases combustion is defined as the position where the mole fraction of oxygen just shifts from a positive value to zero. If the starting reaction interface reaches or enters the materials surface, char on the surface could react with the oxygen. In this case, combustion of pyrolysis gases partly protects the materials surface. If the starting reaction interface stays outside the materials surface, char on the surface cannot react with the oxygen so that combustion of pyrolysis gases could completely protect the materials from surface ablation. Notably, the velocity of pyrolysis gases is called the 'critical velocity' when the starting reaction interface just reaches the materials surface. Up to now, research on the critical velocity has still been a longstanding challenge.

The counterflow diffusion flame model, describing a fundamental combustion configuration, can be applied for solving critical velocity problems [14–18]. The mathematical model of the heat and mass transport processes must take numbers of chemical reactions, gas-phase multi-component viscosities, thermal conductivities, diffusion coefficients, thermal diffusion coefficients, thermodynamics and chemical rates into consideration [19–31]. However, the combination of counterflow diffusion flame and surface ablation of charring materials has never been reported. In this paper, the problem of the protection of pyrolysis gases combustion against charring materials' surface ablation is solved by numerical methods on the basis of the counterflow diffusion flame.

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Nomenclature

L	thickness of boundary layer [m]	X	mole fraction [–]
x	spatial coordinate in axial direction [m]	$[X]$	molar concentration [mol/m^3]
r	spatial coordinate in radial direction [m]	D_{jk}	multi-component diffusion coefficients [m^2/s]
ρ	gas density [kg/m^3]	D_{km}	mixture averaged diffusion coefficients [m^2/s]
u	gas velocity/gas velocity in axial direction [m/s]	D_k^T	thermal diffusion coefficients [kg·m^{-1}·s^{-1}]
p	gas pressure [Pa]	υ'	stoichiometric coefficient of reactant [–]
h	specific enthalpy [J/kg]	υ''	stoichiometric coefficient of product [–]
T	gas temperature [K]	s	curvature radius at stagnation point [m]
c_p	specific heat at constant pressure [J·kg^{-1}·K^{-1}]	$\dot{m}$	mass injection rate [kg·m^{-2}·s^{-1}]
G	function of density, radial velocity and radial coordinate [kg·m^{-3}·s^{-1}]	Ma	Mach number [–]
		a	speed of sound [m/s]
F	function of density and axial velocity [kg·m^{-2}·s^{-1}]		
μ	dynamic viscosity [kg·m^{-1}·s^{-1}]	*Subscripts*	
v	gas velocity in radial direction [m/s]	s	surface
λ	thermal conductivity [W·m^{-1}·K^{-1}]	c	critical
Y	mass fraction [–]	f	the position before detached normal shock wave
V	diffusion velocity [m/s]	b	the position behind detached normal shock wave
ω	chemical reaction rate [mol·m^{-3}·s^{-1}]	k	species index
W	molecular weight [kg/mol]	i	ith reaction
$\bar{W}$	mean molecular weight [kg/mol]	g	pyrolysis gases
C_p	molar heat capacity at constant pressure [J·mol^{-1}·K^{-1}]	j	space point in x direction

2. Models

2.1. Physical model

With charring materials of a vehicle subjected to severe aerodynamic environment, the aerodynamic heat transfers to the inner materials and the temperature of the materials increases. When the temperature at the surface reaches the temperature of commencing pyrolysis for phenolic resin, the materials start appearing two layers, namely a virgin layer and a pyrolysis layer. Meanwhile, the pyrolysis gases generated from the pyrolysis layer flow to the materials surface and inject to the boundary layer. Heating continues and the surface temperature reaches the temperature of completing pyrolysis for phenolic resin. At this time, three layers: the virgin layer, the pyrolysis layer and the char layer, are produced in the materials. Once the pyrolysis gases, which are usually hydrogen, methane, carbon monoxide, carbon dioxide, water and ethane, enter into the boundary layer of the high temperature and low pressure boundary, they can react with the oxygen.

A counterflow diffusion flame model can describe the combustion phenomena of pyrolysis gases in the boundary layer. In this model, the materials surface, where the pyrolysis gases spray, can be seen as the fuel nozzle; the detached normal shock wave as the oxidizer nozzle; and the region of the boundary layer as the range of diffusion combustion. Fig. 1 illustrates a schematic of a counterflow diffusion flame representing the pyrolysis gases reacting with the oxygen in the boundary layer.

In Fig. 1(a), a one-dimensional ablation model of charring materials is presented. With the increasing temperature of the inner materials, the pyrolysis gases generate and flow through the inner materials and inject to the boundary layer, whose thickness is L. The oxygen flows from the detached normal shock wave toward the materials surface. The bold dashed line in Fig. 1 represents the starting reaction interface. The pyrolysis gases and air flame in Fig. 1(b) describes the combustion phenomena in the boundary layer in detail. If we let x and r denote the independent spatial coordinates in the axial and the radial directions, respectively, the materials surface is located at $x = 0$ and the detached normal shock wave is located at $x = L$. At $x = 0$, the pyrolysis gases flow toward the positive x direction. At $x = L$, the oxygen flows toward the negative x direction.

2.2. Mathematical models

Based on the physical model, the mathematical model for the phenomena of pyrolysis gases combustion in the boundary layer can be considered as two parts: the detached normal shock wave relations and the counterflow diffusion flame model.

2.2.1. Detached normal shock wave relations

To obtain one of the boundary conditions in the counterflow diffusion flame, the temperature, pressure, gas density and gas velocity behind the detached normal shock wave, which are seen as the boundary conditions, should be calculated first. The mass conservation equation, the momentum conservation equation and the energy conservation equation of the detached normal shock wave can be written as

$$\rho_f u_f = \rho_b u_b \tag{1}$$

$$p_f + \rho_f u_f^2 = p_b + \rho_b u_b^2 \tag{2}$$

$$h_f + \frac{u_f^2}{2} = h_b + \frac{u_b^2}{2} \tag{3}$$

where ρ, u, p and h are the density, velocity, pressure and specific enthalpy of gas, respectively. And the subscript f and b, respectively, represent the position before and after the detached normal shock wave.

The thermodynamic properties of air with real gas effects may be denoted by [32]

$$h = h(p, \rho) \tag{4}$$

$$T = T(p, \rho) \tag{5}$$