

# Thermal Investigation of Charring Materials Based on Pyrolysis Boundary Representation

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**Abstract:** Charring thermal defense systems have been used to guard hypersonic vehicles from high heat loads. The pyrolysis of charring materials is an intricate corporeal and compound phenomenon. Based on the pyrolysis boundary model, a simulating advance for charring ablation has been calculated in order to acquire one dimensional transient thermal performance of homogeneous charring materials in reentry capsules. As the mathematical results designate, the pyrolysis rate and the surface warmth under a given heat flux rise abruptly in the commencement, then arrive at a plateau, but the high temperature at the bottom rises very gradually to avoid the structural materials from being passionate dangerously. Pyrolysis mechanism can play a significant role in thermal security systems subjected to severe aerodynamic heat. Ablation and pyrolysis of charring equipment were investigated through an ablation test motor. In addition, it is very significant to understand the physical and chemical performance of the TPS subjected to aerodynamic heat.

**Key words:** pyrolysis, pyrolysis interface model, charring materials, thermal protection system.

## I. INTRODUCTION

The presentation of the thermal protection system (TPS) is dangerous, since mass decrease trades directly with augment in science payload for a given reentry mass or reduction in launch vehicle cost by using a lighter entry system and a smaller launch vehicle. Charring materials are used in TPS for reentry vehicles such as Apollo and Orion capsules. TPS can maneuver by absorbing heat throughout decomposition and rejecting it via pyrolysis gas inoculation back into the boundary layer of gas. Conventionally, the design of a TPS has seriously relied on ground test. Ablation and pyrolysis of charring equipment were investigated through an ablation test motor. In addition, it is very significant to understand the physical and chemical performance of the TPS subjected to aerodynamic heat.

The pyrolysis interface is moving, so this is a moving boundary problem. Some researchers analyzed the temperature distribution, the mass loss rate and the surface recession through simulation. The central difference scheme to solve moving boundary problem in the one-dimensional thermal response. Conversely, there were a few discussions on the thermal response and the moving rate of pyrolysis interface in charring materials. This study will mainly focus on calculating the thermal response of polyester phenolic composites based on the pyrolysis interface model. Over 80% of the heating the orbiter experiences all through reentry is caused by density of the air ahead of the hypersonic medium,

in agreement with the basic thermodynamic relative between heaviness and high temperature.

Some high temperature metal alloys can withstand reentry warm; they basically get hot and re-radiate the fascinated heat. Nevertheless, the amount of high-temperature metal necessary to protect a large vehicle like the Space Shuttle Orbiter would have been very heavy and entailed a severe punishment to the vehicle's presentation. Correspondingly, ablative TPS would be heavy, possibly disturb vehicle aerodynamics as it burned off during reentry, and require significant maintenance to reapply after each mission. Heat flow is a predictable outcome of contact between objects of contradictory temperature. Thermal lagging provides a region of insulation in which thermal conduction is reduced or thermal radiation is reflected rather than absorbed by the lower-temperature body.

### **Pyrolysis Interface Model and Numerical Approach:**

The temperature incline vertical to the surface is much advanced than that in the other direction can be built on the base of the subsequent assumptions: pyrolytic response only occurs on the pyrolysis boundary that the pyrolysis layer connecting a char layer and a virgin materials layer, and pyrolysis gases do not react chemically with the porous char layer throughout which it flows.

From the model, we know that the surface temperature rises up to the pyrolysis temperature  $T_p$  during  $0-t_0$  s, and materials start to decompose. Then the pyrolysis interface moves to the extended and a porous char layer appears, while pyrolysis gas flows throughout the char layer and injects back into the boundary layer of gas. After a char layer comes into connecting (heating time  $> t_0$  s), the surface temperature is more than  $T_p$  and there are two layers which are a char layer and a virgin materials layer. Based on the Fourier's law of heat conduction, the heat conduction equations of the two layers are, correspondingly, deduced as:

$$\rho_1 c_1 \frac{\partial T(x,t)}{\partial t} = k_1 \frac{\partial^2 T(x,t)}{\partial x^2} + \dot{m}_p c_p \frac{\partial T(x,t)}{\partial x} \quad 0 \leq x \leq X_c$$

$$\rho_2 c_2 \frac{\partial T(x,t)}{\partial t} = k_2 \frac{\partial^2 T(x,t)}{\partial x^2} \quad X_c \leq x \leq L$$

The boundary conditions are given in the form:

$$-k_1 \frac{\partial T(x,t)}{\partial x} = q \quad x=0 \quad (3)$$

$$T(x,t) = T_p \quad x = X_c \quad (4)$$

$$k_2 \frac{\partial T(x,t)}{\partial x} = 0 \quad x=L \quad (5)$$

where  $\rho$ ,  $c$ , and  $k$  are the density, specific heat capacity, and thermal conductivity, respectively, the subscripts 1 and 2 are a char layer and a virgin materials layer, correspondingly;  $\dot{m}_p$  is the mass flow rate of pyrolysis;  $c_p$  – the specific heat capacity of pyrolysis gas.

Pyrolysis mass rates are determined by the energy balance equation on a pyrolysis interface, which is represented by the relation:

$$-k_1 \frac{\partial T(x,t)}{\partial x} = -k_2 \frac{\partial T(x,t)}{\partial x} + \dot{m}_p h_p \quad x = X_c \quad (6)$$

$$\dot{m}_p = (\rho_2 - \rho_1) \dot{X}_c \quad (7)$$

Where  $h_p$  is the latent heat in pyrolysis and  $X_c$  is the moving rate of pyrolysis interface.

In adding up, there is only a virgin materials layer ( $X_c = 0$ ) before char layer arises. The surface

temperature is less than  $T_p$  in this epoch. The heat conduction equation is:

$$\rho_2 c_2 \frac{\partial T(x,t)}{\partial t} = k_2 \frac{\partial^2 T(x,t)}{\partial x^2} \quad 0 \leq x \leq L \quad (8)$$

The boundary conditions are:

$$-k_2 \frac{\partial T(x,t)}{\partial x} = q \quad x=0 \quad (9)$$

$$k_2 \frac{\partial T(x,t)}{\partial x} = 0 \quad x=L \quad (10)$$

The initial condition is given by:

$$T(x, 0) = T_0 \quad (11)$$

The heat transmission equations are perceptibly transient so that we have to discrete space domain and time domain, correspondingly. Here we use the central dissimilarity format for space domain and implied format for time domain as:

$$\frac{\partial T(x,t)}{\partial x} = \frac{T_{j+1}^n - T_{j-1}^n}{2\Delta x} \quad (12)$$

$$\frac{\partial^2 T(x,t)}{\partial x^2} = \frac{T_{j+1}^n - 2T_j^n + T_{j-1}^n}{(\Delta x)^2} \quad (13)$$

$$\frac{\partial T(x,t)}{\partial t} = \frac{T_j^n - T_j^{n-1}}{\Delta t} \quad (14)$$

We put equation. (12), (13), and (14) into eq. (1) and then let:

$$\frac{T_j^n - T_j^{n-1}}{\Delta t} = r \frac{T_{j+1}^n - 2T_j^n + T_{j-1}^n}{(\Delta x)^2} + z \frac{T_{j+1}^n - T_{j-1}^n}{2\Delta x} \quad (15)$$

Let  $A = 1 + 2r$ ,  $B = r + z$ ,  $C = r - z$ , and  $D = T_j^{n-1}$ . equation (15), can be printed as:

$$T_j^n = \frac{B}{A - CP_{j-1}} T_{j+1}^n + \frac{CQ_{j-1} + D}{A - CP_{j-1}} \quad (16)$$

$$P_j = \frac{B}{A - CP_{j-1}}, \quad Q_j = \frac{CQ_{j-1} + D}{A - CP_{j-1}}$$

The pyrolysis boundary is affecting with the heating. In order to use Thomas algorithm to compute the discrete equation, we introduce the technique which fixes the time step while altering space step to get the moving rate of pyrolysis interface. The energy balance eq. (6) becomes:

$$-k_1 \frac{T_{j+1}^n - T_j^n}{\Delta x} = -k_2 \frac{T_{j+1}^n - T_j^n}{\Delta x} + (\rho_2 - \rho_1) h_p \frac{\Delta X_c}{\Delta t} \quad (17)$$

From eq. (17), we can get the new moving distance  $\Delta X_c$  of a pyrolysis interface with every fixing time step:

$$\Delta X_c = \frac{\left( k_2 \frac{T_{j+1}^n - T_j^n}{\Delta x} - k_1 \frac{T_{j+1}^n - T_j^n}{\Delta x} \right) \Delta t}{(\rho_2 - \rho_1) h_p} \quad (18)$$

Based on the above arithmetical models and the iterative approach, we can write a computer code to determine the thermal reaction.

## II. RESULTS

Taking a polyester phenolic composite as an example, we can study one dimensional transient thermal behavior of homogeneous charring materials by means of the written computer codes. The temperature  $T_p$  on the pyrolysis interface is taken as 879 K, the latent heat  $h_p$  in the pyrolysis is 235.5 MJ/kg, and the initial temperature  $T_0$  is 350 K. The physical parameters of materials and pyrolysis gas are given in tab. 1.

	$\rho$ [kgm <sup>-3</sup> ]	$c$ [Jkg <sup>-1</sup> K <sup>-1</sup> ]	$k$ [Wm <sup>-1</sup> K <sup>-1</sup> ]	$L$ [mm]
<b>Char layer</b>	408.3	1596	64.7	
<b>Virgin materials</b>	1320	1509	0.2907	35
<b>Pyrolysis gas</b>		3275		

Table 1. Physical parameters

From the parameters, we have obtained the thermal response of charring materials under the aerodynamic heat flux  $q = 879200 \text{ W/m}^2$ . The surface temperature rises quickly to the pyrolysis temperature in the introduction time, and then keeps rising steadily, up to 942.2 K at 1000 s. The interior temperature distribution consists of two parts equivalent to the two layers. In preliminary heating time, the temperature distributions far absent from pyrolysis interface in virgin layer are  $T_0$ , comparing to which are of massive rising gradient adjacent to the pyrolysis boundary, which can be viewed on dot line. Heating continues and the char coating expands, while the virgin materials deposit diminishes, which can be establish in the other curves.

The moving rate of pyrolysis interface changing with the heating. In the initial heating time, the rate begins to rise rapidly from the pyrolysis at the beginning 0.55 s to 65.7 s, then keeps rising gradually. The moving linear rate of pyrolysis interface rises only 0.0042 mm/s during 100-1000 s, which is almost a steady state. Then it increasingly rises up to 306.5 K when the heating moment is 200 s. When it is 1000 s heating on the outside, the temperature at the bottom rises to 584.8 K. The high temperature at the bottom rises gradually with the occupation of pyrolysis to prevent the structural materials from being heated sincerely.

## III. CONCLUSIONS

Through simulating on the pyrolysis of polyester phenolic composites on the support of the Fourier's law of heat transmission and the pyrolysis apparatus, we have established the thermal reaction of charring materials beneath a heat flux. The consequences show that the touching rate of pyrolysis boundary and the facade warmth under a given heat flux rise unexpectedly in the commencement, then reaches a plateau, but the high temperature at the bottom rises very gradually to prevent the structural materials from being heated dangerously. With the fascinating heat through disintegration and rejecting it via pyrolysis gas vaccination back into the border layer gas, charring materials can play a significant role in thermal fortification systems subjected to severe smooth warmth.

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