Contrastive Research about Fluid-thermal Coupling of Carbon-phenolic Jet Vane in Terms of Two Different Numerical Models

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ABSTRACT: A numerical research on two-dimensional unsteady fluid-thermal coupling of carbon-phenolic jet vane was done through using secondary development by UDF. The main attention is on differences of surface temperature based on two models. The results show that, the highest temperature is always on stagnation point near by the leading edge of jet vane. Temperature of side face will decrease along the main flow direction. In jet vane coordinate system, at the same main flow position, temperature on upwind side is higher than leeward side, and the differences will become greater along the main flow direction. The escaping process of pyrolysis gas and chemical reaction on surface are in favor of reducing surface temperature. And two different numerical models can be used in study of jet vane made of charring materials on different attentions.

Keywords: carbon-phenolic; jet vane; fluid-thermal coupling; numerical model

1 INTRODUCTION

As one of the important means of thrust vector control (TVC) technology, the jet vane has the advantage of fast response, compact structure and high control efficiency. The jet vane was much more used in various types of missiles and rockets [1]. Throughout whole working process, jet vane is always in the atmosphere with high temperature and supersonic jet, therefore the working environment is extremely bad. At present, jet vane is mainly made of tungsten-copper in engineering application, although the tungsten-copper has high density, which can reduce the missile’s range [2, 3].

Carbon-Phenolic has the advantages of good resistance to erosion and ablation, good stability and low density. This article took the composite jet vane made of carbon-phenolic as research object, and the two-dimensional fluid-thermal coupling research was done with tightly coupled method. The variation of thermo-physical properties of carbon-phenolic with the changes of temperature, space and working time was declared by User Define Functions (UDF). Endothermic process due to pyrolysis of phenolic resin was simulated by adding energy source terms to interior cells in jet vane. And escaping course was simulated by adding mass, momentum, energy and components source terms to cells in fluid zone besides the boundary.

2 CALCULATION MODEL AND METHOD

In order to study the effect of pyrolysis gas’ escaping course and thermo-chemical reaction at surface on temperature of the wall and interior zones of jet vane, this article puts forward two different numerical models to study the same physical model: 1. Simplified model (hereinafter Mod.1)—the variation of thermo-physical properties of carbon-phenolic with the changes of temperature, space and working time was considered, and endothermic process due to pyrolysis of phenolic resin was simulated by adding energy source terms to interior cells in jet vane; 2. Thermo-chemical ablation model (hereinafter Mod.2)—escaping course of pyrolysis gas and thermo-chemical ablation process were added based on Mod.1. And concrete explanation is shown as follows.

2.1 Models of thermo-physical properties

(1) Density of carbon-phenolic
Based on “multi-component model”\(^{[4]}\), the density of carbon-phenolic at virgin state is:

\[
\rho_v = \Gamma \rho_h + (1 - \Gamma) \rho_b
\]  

(1)

Arrhenius equation is used to describe the pyrolysis rate of carbon-phenolic \(^{[7]}\), and the variation of density is:

\[
\frac{\partial \rho}{\partial t} = -A_b (\rho - \rho_{ch}) e^{\frac{E_a}{RT}} \Gamma (T > T_{th} \& \rho \geq \rho_{ch})
\]  

(2)

(2) Specific heat of carbon-phenolic

As specific heat can only be defined as temperature dependent function on Fluent platform, so specific heat of carbon-phenolic is modified according to literature \(^{[5]}\):

\[
c_p = a + b T + c T^2 + d T^3 + e \Gamma + f \Gamma^2 + g \Gamma^3
\]  

(3)

When \(300 \leq T < 212\), \(a = -1308.33\), \(b = 11.77\), \(c = -1.72e-2\), \(d = 9.86e-6\), \(e = -7.15e-11\), \(f = -1.83e-12\), \(g = 4.61e-16\). When \(212 \leq T < 500\), \(a = 2023.85\), \(b = 5.52e-2\), \(c = -1.72e-2\), \(d = 9.86e-6\), \(e = -7.15e-11\), \(f = -1.83e-12\), \(g = 4.61e-16\).

(3) Heat conductivity of carbon-phenolic

There are large amounts of porosity in charring layer and pyrolysis layer. Based on “effective heat conductivity” from the theory of porous media, heat conductivity of carbon-phenolic under different conditions is:

\[
k = \Gamma \kappa_h + \Gamma_b \kappa_b + \Gamma_c \kappa_c + \Gamma \kappa_y
\]  

(4)

\[
\begin{align*}
\Gamma_c &= (1 - \Gamma) \kappa_c \Gamma \\
\Gamma_h &= (1 - \kappa_h \Gamma) \\
\Gamma_b &= (1 - \kappa_b \Gamma) \\
\Gamma \kappa_y &= \Gamma \kappa_y \Gamma
\end{align*}
\]  

(5)

(4) Thermo-physical properties of pyrolysis gas and rocket gas

Pyrolysis products and their mole fractions are shown in literature \(^{[6]}\). Main flow is composed of rocket gas, which is combustion of propellant components of rocket gas is obtained by using the minimum free energy method, which is shown in Table 1:

Table 1. Components of main flow.

<table>
<thead>
<tr>
<th>Components</th>
<th>CO₂</th>
<th>CO</th>
<th>H₂O</th>
<th>H₂</th>
<th>N₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mole fraction/%</td>
<td>11.61</td>
<td>37.48</td>
<td>23.40</td>
<td>11.12</td>
<td>16.39</td>
</tr>
</tbody>
</table>

Thermo-physical properties of each component aforementioned are obtained from database of Fluent. By using weighted average method, thermo-physical properties of mixed gas (rocket gas) can be simulated.

2.2 Models of source terms

(1) Energy source in solid zone

Energy source contains pyrolysis heat of phenolic resin and heat carried out by pyrolysis gas:

\[
S = S_{py} + S_m
\]  

(6)

\[
S_{py} = -A_b (\rho - \rho_{ch}) e^{\frac{E_a}{RT}} \Gamma
\]  

(7)

\[
S_m = -A_b (\rho - \rho_{ch}) e^{\frac{E_a}{RT}} \Gamma
\]  

(8)

(2) Source terms in fluid zone

Source terms in fluid zone are caused by pyrolysis of phenolic resin and thermo-chemical reaction on the wall.

Mass source

According to the assumption that pyrolysis gas evolution direction is one dimension, the mass flow rate of pyrolysis gas is:

\[
m_{pyr} = -\int_{\Gamma} \frac{\partial \rho}{\partial t} \cdot Ad\eta
\]  

(7)

Kinetic parameters of heterogeneous reaction about carbon of charring layer with CO₂ and H₂O can be obtained from literature \(^{[7]}\). Carbon consumed by heterogeneous reaction is partial of mass source:

\[
m_{ch} = m_{C,H,O} + m_{C,CO}
\]  

(8a)

\[
m_{C,H,O} = k_{C,H,O} e^{\frac{E_{py}}{RT}} \cdot p_{H,0} \cdot |A_e|
\]  

(8b)

\[
m_{C,CO} = k_{C,CO} e^{\frac{E_{py}}{RT}} \cdot |p_{C,CO} \cdot |A_e|
\]  

(8c)

At last, total mass source is:

\[
S_m = m_{pyr} + m_{ch}
\]  

(9)

Energy source

Energy source is composed of heat from pyrolysis gas and thermo-chemical reaction.

\[
S_e = (\sum \dot{m}_j \cdot \int_{\Gamma} C_p(T) dT - m_{C,H,O} \cdot \Delta H_{C,H,O} - m_{C,CO} \cdot \Delta H_{C,CO}) / V_c
\]  

(10)

Momentum source

Pyrolysis products escaped from carbon-phenolic get in the mainstream with perpendicular direction to the jet vane. The momentum source in \(x\) and \(y\) directions is respectively shown below:

\[
S_{m,x} = -\frac{m_{pyr} \cdot \dot{A}_v}{\rho_c \cdot |A_e| \cdot V_c}
\]  

(11a)
\[ S_{m,y} = -\frac{\dot{m}_{m,y}^2 \cdot A_{m,y}}{\rho_c \cdot |A_y| \cdot V_c} \quad (11b) \]

**Components source**

There are nine gas components in this article, which are composed of four pyrolysis gas components and five rocket gas components.

Components source of pyrolysis gas:

\[ S_j = \sum_j A_{pe} \frac{E_{k,pe}}{RT_j} (\rho_j - \rho_{ib}) \cdot V_j \cdot \gamma_j(T_j) / V_c \quad (12a) \]

Components source of CO₂:

\[ S_{CO_2} = -k_{CO_2} \cdot e^{\frac{E_{k,CO_2}}{RT}} \cdot p_{CO_2} \cdot |A_y| \frac{M_{CO_2}}{M_c} / V_c \quad (12b) \]

Components source of CO:

\[ S_{CO} = (k_{CO,CO} - k_{CO,CH}) \cdot e^{\frac{E_{k,CO}}{RT}} \cdot p_{CO} \cdot |A_y| \frac{M_{CO}}{M_c} / V_c \quad (12c) \]

Components source of H₂O:

\[ S_{H_2O} = -k_{H_2O,CO} \cdot e^{\frac{E_{k,H_2O}}{RT}} \cdot p_{H_2O} \cdot |A_y| \frac{M_{H_2O}}{M_c} / V_c \quad (12d) \]

Components source of H₂:

\[ S_{H_2} = k_{H_2,CH} \cdot e^{\frac{E_{k,H_2}}{RT}} \cdot p_{H_2} \cdot |A_y| \frac{M_{H_2}}{M_c} / V_c \quad (12e) \]

2.3 Regression models

Regression of surface is a result from thermo-chemical reaction. In the course of working, reaction rate in different position is various, which causes the different regression rate. Assume that the direction of surface regression is vertical to local surface, the regression rate is:

\[ \dot{r} = (\dot{m}_{H_2,CH} + \dot{m}_{CO_2}) \cdot \Delta t / \rho_{ib} \quad (13) \]

3 PHYSICAL MODEL AND BOUNDARY CONDITIONS

Figure 1. Schematic of simulation model.

This article does numerical simulation about carbon-phenolic jet vane at 0°, 5°, 10°, 15° and 20° based on two different numerical models respectively. Figure 1 shows the schematic of simulation model, boundary conditions and jet vane coordinate system.

Pressure far field: Static pressure is 101325Pa, static temperature is 1245K, mainstream Mach number is 3.2237. As solid zone, in carbon-phenolic jet vane there is only heat transfer simulation. Leading edge, trailing edge, upwind side and leeward side are defined as coupled wall.

4 RESULTS AND DISCUSSION

![Temperature distribution in and around jet vane based on Mod.1, when t=2.0s.](image)
Figure 2 shows the temperature distribution in and around jet vane when \( t=2.0s \) at different drift angle based on Mod.1. Under a supersonic jet, the bow shock is formed on leading edge of jet vane and increases rapidly through the shock wave temperature. Near the railing edge, vortex is formed due to the flow separation, and the local high temperature is formed there. Once jet vane deflecting, wave angle on upwind side is larger than which on leeward side. So the temperature after the shock wave on upwind side is higher than which on leeward side.

For thermal protection of jet vane, the temperature of the wall is the key point of the research. Figure 3 shows the temperature distribution on wall of jet vane at different drift angle when \( t=2.0s \) based on Mod.1. The highest temperature of the entire wall of jet vane is about 2583K, and the position of highest temperature is on leading edge because of the stagnation of the flow. When the flow passes the arc transition between leading edge and side of jet vane, the temperature reduces rapidly. After the point aforementioned, the temperature distribution will evolve the differences between upwind side and leeward side. Differences of temperature on double sides aforementioned will become larger along the main flow direction with the increase of drift angle.

Figure 4 shows the temperature distribution on wall of jet vane at different drift angle when \( t=2.0s \) based on Mod.2. The trend between temperature distribution on wall of jet vane based on Mod.2 and which based on Mod.1 is consistent. As the evolution process of pyrolysis gas is considered in Mod.2, which forms heat blockage of boundary layer by pyrolysis gas and has an effect on heat transfer, the thermo-chemical reaction on surface of jet vane can also reduce the wall temperature effectively. As a result, the highest temperature of the wall is lower than stagnation temperature of rocket gas, and just reaches 2300K.

As a more detailed analysis, Figure 5 shows the wall temperature contrast between those obtained based on Mod.1 and Mod.2 when \( t=2.0s \) and the drift angle is 0°, 10° and 20°. In Figure 5, the right side of \( x \)-coordination zero point means upwind side, and the left side means leeward side. Obviously, wall temperature at the same position based on Mod.1, which is hollow tagged in Figure 5, is higher than that based on Mod.2, which is solid tagged in Figure 5. The difference aforementioned between upwind side and leeward side is obvious. First, at the same \( x \) position, temperature difference in upwind side is larger than which in leeward side, and the difference increases with the rising at drift angle. Second, as the increase of \( x \) position, the difference of temperature based on two models reduces. As what mentioned before, the cause of such difference is that evolution process of pyrolysis gas and thermo-chemical reaction on the wall are considered in Mod.2.

Surface regression due to thermo-chemical reaction is considered in Mod.2. The regression rate on middle and posterior area of jet vane is rare. Figure 6 shows the erosion graph on front area of jet vane when \( t=2.0s \) at different drift angles and, Figure 7 shows erosion distribution. The serious erosion is on stagnation point due to the highest temperature and pressure along the whole wall. Erosion on upwind side increases with drift angle increase, and the erosion is virtually nil on leeward side.
1. Heat blockage of pyrolysis gas and thermo-chemical reaction can reduce the wall temperature of jet vane.

2. The highest temperature along the whole of jet vane is at the point of stagnation position. And the wall temperature decreases along the mainstream direction. Once the jet vane drifting, the temperature of upwind side is higher than that of leeward side. And the temperature difference increases with the increase of drift angle.

3. The most serious erosion position is on leading edge of jet vane followed by upwind side, and the erosion is virtually nil on leeward side.

REFERENCES


5 CONCLUSION

With the study on heat transfer and erosion based on two different numerical models, the conclusions are shown below.