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Thermal protection system gap analysis using a loosely coupled fluid-structural thermal numerical method

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ABSTRACT

A loosely coupled fluid-structural thermal numerical method is introduced for the thermal protection system (TPS) gap thermal control analysis in this paper. The aerodynamic heating and structural thermal are analyzed by computational fluid dynamics (CFD) and numerical heat transfer (NHT) methods respectively. An interpolation algorithm based on the control surface is adopted for the data exchanges on the coupled surface. In order to verify the analysis precision of the loosely coupled method, a circular tube example was analyzed, and the wall temperature agrees well with the test result. TPS gap thermal control performance was studied by the loosely coupled method successfully. The gap heat flux is mainly distributed in the small region at the top of the gap which is the high temperature region. Besides, TPS gap temperature and the power of the active cooling system (CCS) calculated by the traditional uncoupled method are higher than that calculated by the coupled method obviously. The reason is that the uncoupled method doesn't consider the coupled effect between the aerodynamic heating and structural thermal, however the coupled method considers it, so TPS gap thermal control performance can be analyzed more accurately by the coupled method.

1. Introduction

The space plane orbiter is subject to aerodynamic heating during the re-entry phase [1–3]. A thermal protection system (TPS) is necessary in order to ensure the internal structure of the orbiter within the sustainable temperature range [4–6]. The ceramic tile is the most widely used thermal insulation material, which is attached on the outer surface of structure through a strain-isolation-pad (SIP). Due to the deformation of the orbiter structure and the thermal expansion of the ceramic tile during re-entry phase, a gap is necessary to avoid the contact between the ceramic tiles, which is also the weakest point of the TPS. So, the detailed gap thermal control analysis must be carried out to ensure the safety of the TPS and orbiter.

The traditional TPS gap thermal control analysis method divides the aerodynamic heating and the structural thermal [7–11]. First, analyze the aerodynamic heating by the experiment or engineering algorithm, and then calculate the temperature field of TPS structure according to the wall heat flux. Due to the conveniences and high computational efficiency, this traditional analysis method has been widely used in the engineering. The aerodynamic heating results in the TPS structural temperature rise during the re-entry phase, so the temperature gradient between the boundary layer and the outer surface of TPS will decrease, and this decreased temperature gradient causes the decrease of the wall heat flux. The above analysis shows that the aerodynamic heating has a strong coupled effect with structural thermal. Obviously, the traditional TPS gap thermal control analysis method can't analyze the effect on the aerodynamic heating by the structural thermal rise, so it doesn't consider the coupled effect between the aerodynamic heating and structural thermal and can't calculate the TPS gap thermal control performance accurately.

In this paper, a loosely coupled method is introduced for the TPS gap thermal control performance analysis, and it can consider the coulped effect between the aerodynamic heating and structural thermal. In the coupled method, the aerodynamic heating is analyzed by the modern computational fluid dynamics (CFD) method [12,13] based on the Navier-Stokes equation, and the fluid field is discretized by the finite volume method (FVM). Besides, the structural thermal is calculated by the numerical heat transfer (NHT) method, and the structural temperature field is discretized by finite element method (FEM). An interpolation algorithm based on the control surface is used to achieve the data exchanges of the wall heat flux and wall temperature on the coupled surface. In order to verify the correctness and accuracy of the coupled method, a hypersonic circular tube example was analyzed in this paper. Finally, the TPS gap thermal control performance was studied by the loosely coupled method.

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Nomenclature

A	Three-dimensional physical space
B	Two-dimensional control surface
$C_{\max}$	Maximum power of CCS
$\boldsymbol{F}_c$	Convective flux vector
$\boldsymbol{F}_v$	Viscous flux vector
H	Gap depth [mm]
$\boldsymbol{K}$	Heat conductivity coefficient matrix
Ma	Mach number
$\boldsymbol{P}$	Temperature load vector
Q	Heat flux
Q_a	Heat flux from aerodynamic heating
Q_r	Heat flux from thermal radiation
Q_s	Heat flux at stagnation point
Q_1	Heat flux on the outer surface of coating
Q_2	Gap heat flux
R_1	Thermal radiation on the outer surface of coating
R_2	Gap cavity thermal radiation
T	Temperature [K]
$T_{\max 1}$	Maximum temperature of tile [K]
$T_{\max 2}$	Maximum temperature of SIP [K]
T_s	Stagnation point temperature [K]
T_w	Wall temperature [K]
T_0	Atmospheric temperature [K]

$\boldsymbol{T}$	Node temperature vector
$\dot{\boldsymbol{T}}$	Derivative of node temperature vector to time
W	Gap width [mm]
$\boldsymbol{W}$	Conservative vector
c	Specific heat [J/(Kg·K)]
k	Heat conductivity coefficient [W/(m·K)]
$\boldsymbol{n}$	normal unit vector
t	Time
t_{total}	Total time of analysis
Δt	Time step size
α	Gap local angle of attack
ε	Emissivity of coating
ρ	Density of material [Kg/m^3]
σ	Stefan-Boltzmann constant
$\Delta\tau$	Pseudo time step size

Subscripts

a	aerodynamic heating
c	Convective
max	Maximum
r	Thermal radiation
s	Stagnation point
v	Viscous

2. Numerical algorithm of aerodynamic heating

The Navier-Stokes equation is usually used in the numerical analysis of the hypersonic aerodynamic heating, and the equation in integral form is given by:

$$\frac{\partial}{\partial t}\int_V \boldsymbol{W}\,\mathrm{d}\Omega + \oint_S (\boldsymbol{F}_c - \boldsymbol{F}_v)\boldsymbol{n}\,\mathrm{d}S = 0 \tag{1}$$

where $\boldsymbol{W}$ is the conservative vector, $\boldsymbol{F}_c$ is the convective flux vector, $\boldsymbol{F}_v$ is the viscous flux vector, dS is the boundary surface of the control volume V, $\boldsymbol{n}$ is the normal unit vector of the boundary surface dS. According to the FVM, the semi-discretized equation can be written as:

$$\frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{W}_i V_i = -\sum_{N=1}^{N_F}(\boldsymbol{F}_c - \boldsymbol{F}_v)_N \boldsymbol{n}\Delta S_N \tag{2}$$

where $\boldsymbol{W}_i$ is the conservative vector of the element volume V_i, and ΔS_N is the area of the boundary surface dS.

In this paper, the NND [14] spatial discretization scheme with the total variation diminishing (TVD) property is used, and the semi-discretized upwind NND scheme is as follows:

$$\left(\frac{\partial \boldsymbol{W}}{\partial t}\right)_i = -\frac{1}{\Delta x}\left(\hat{F}_{i+\frac{1}{2}} - \hat{F}_{i-\frac{1}{2}}\right) \tag{3}$$

$$\hat{\boldsymbol{F}}_{i+\frac{1}{2}} = \frac{1}{2}(\boldsymbol{F}_i + \boldsymbol{F}_{i+1}) + \frac{1}{2}\left(\boldsymbol{A}^+_{i+\frac{1}{2}}\Delta\boldsymbol{W}^L_{i+\frac{1}{2}} - \boldsymbol{A}^-_{i+\frac{1}{2}}\Delta\boldsymbol{W}^R_{i+\frac{1}{2}}\right) \tag{4}$$

$$\begin{cases}\Delta\boldsymbol{W}^L_{i+\frac{1}{2}} = -\Delta\boldsymbol{W}_{i+\frac{1}{2}} + \min\operatorname{mod}\left(\Delta\boldsymbol{W}_{i+\frac{1}{2}}, \Delta\boldsymbol{W}_{i-\frac{1}{2}}\right)\\ \Delta\boldsymbol{W}^R_{i+\frac{1}{2}} = -\Delta\boldsymbol{W}_{i+\frac{1}{2}} + \min\operatorname{mod}\left(\Delta\boldsymbol{W}_{i+\frac{3}{2}}, \Delta\boldsymbol{W}_{i+\frac{1}{2}}\right)\end{cases} \tag{5}$$

where $\boldsymbol{A} \pm i+1/2$ is the Roe average between the elements i and $i+1$, and minmod is the limiter.

The viscous flux vector $\boldsymbol{F}_v$ in the Navier-Stokes equation can be discretized by the central difference scheme, and the Menter's SST two-equation turbulent model [15] is used for the turbulent simulation. Besides, the unsteady aerodynamic heating is analyzed by the dual time-stepping method [16] in this paper. A second-order accurate time discretization scheme is given by:

$$\frac{3\boldsymbol{W}_i^{n+1} - 4\boldsymbol{W}_i^n + \boldsymbol{W}_i^{n-1}}{2\Delta t} = \frac{1}{V_i}\boldsymbol{R}_i^{n+1} \tag{6}$$

where $\boldsymbol{R}n+1\ i$ is the residual. An internal iteration is added into the unsteady analysis by introducing a pseudo time term, and the first-order forward difference scheme is written as:

$$\frac{\boldsymbol{W}_i^{p+1} - 4\boldsymbol{W}_i^p}{\Delta\tau}\frac{3\boldsymbol{W}_i^{p+1} - 4\boldsymbol{W}_i^n + \boldsymbol{W}_i^{n-1}}{2\Delta t} = \frac{1}{V_i}\boldsymbol{R}_i^{p+1} \tag{7}$$

where p and n are the pseudo and physical time steps respectively, $\Delta\tau$ and Δt are the corresponding pseudo and physical time step sizes respectively. The internal iteration is analyzed by the LU-SGS scheme [17] in this paper, and the pseudo time term approaches zero when $p \to \infty$. So the steady solution calculated by Eq. (7) is the second-order accurate physical unsteady solution.

3. Numerical algorithm of structural thermal

The structural temperature field of TPS is solved by the transient heat conduction equation, which without the volumetric heat source is given by:

$$\rho c\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k_x\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_z\frac{\partial T}{\partial z}\right) \tag{8}$$

where ρ is the density of the material, c is the specific heat, and k_x, k_y and k_z are the heat conductivity coefficients in three directions.

The boundary conditions of TPS gap thermal control analysis contain the aerodynamic heating and thermal radiation.

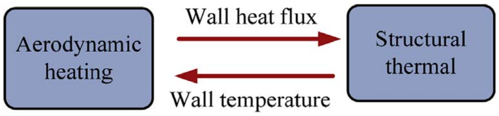

Fig. 1. Coupled effect between the aerodynamic heating and structural thermal.