Unsteady Coupled Heat Transfer Simulation of Unsteady numerical simulation of slot flow in anti-heating tile

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Abstract. An unsteady coupled heat transfer solver is developed in the study. The coupled solver, solving the partial differential equations for fluid flow and thermal conduction in the solid, is employed to predict the unsteady heat and transfer in the anti-heating tile. The influence of gap depth on the fluid flow and solid thermal conduction is studied. The results show that the flow field distribution between the different gap depths is similar, otherwise reducing the gap depth is conducive to reducing the thermal load in the bottom plate.

1. Introduction

The gaps between the protection elements are widely used by the thermal protection systems (TPS) on the hypersonic aircraft to account for the thermal expansion. For the optimized design of gaps and protection elements it is necessary to predict the flow conditions and thermal loads as accurate as possible [1]. Compared with the fluid flow and heat transfer on the surface of the protection elements, it is rather complex in the gaps. There is small radiation heat flow on the side and the bottom of the gaps, and the aerodynamic heating in the aera is extremely serious. Meanwhile, the boundary layer flow on the gap is more complex, and the flight test results are obviously different from the predicted values in the wind tunnel. The experimental results show that the aerodynamic heating of the gap is closely related to the pressure distribution, pressure gradient and gap parameters [2].

From the literature, Charbonnier [3] has studied the boundary layer transition caused by the gap step difference, and obtained that there is a critical dimensionless step difference. Bertin [1] studied the influence of geometric parameters such as the number of gaps, the width, the depth, the scale and the arrangement direction of the gaps on the heat flow density of the wall gaps. Hinderkes [4, 5] coupled TAU and ANSYS, and carried out the gas thermal elastic coupling simulation analysis of slot flow, heat transfer of anti-heating tile and thermal deformation. Tang Guiming [6] took the plate control wing as the research object, carried out the shock wind tunnel test of slot heat flow distribution, which confirmed the feasibility of the shock wind tunnel for slot heat flow test. Zhang Haoyuan [7] carried out numerical simulation on a simplified model of slotted front, and found that the re attachment of the main vortex in the slot led to the existence of "unconventional" high heat flow area on the side wall. Shen Chun et al. [8] studied the overall flow and heat transfer characteristics of the gap cavity seal structure under the impact of high-speed air flow; Yin Kajun [9] carried out the size optimization design and analysis of the thermal protection system of the reusable aircraft ceramic tile.
An unsteady coupled heat transfer solver, HIT3D, is developed in the study. The solver employs the finite difference method (FDM). It is able to predict all arbitrary Mach number flow and unsteady coupled heat transfer problems. Then the developed solver is utilized to simulate the gap flow and heat transfer of TPS solid.

2. Numerical Method
The unsteady coupled solver solves the partial difference governing equations for unsteady fluid flow and solid heat transfer.

2.1. Governing equation
The dimensionless Reynolds-averaged Navier-Stokes (RANS) equation for the conservative variables in arbitrary, body-fitted coordinates is as follows:

$$\zeta \frac{\partial}{\partial \eta} \frac{\partial}{\partial \xi} = \frac{\partial}{\partial \eta} \frac{\partial}{\partial \xi} \frac{\partial}{\partial \zeta}$$

(1)

Where $Q = J \cdot (\rho u \nu \rho u \nu \nu e)$, $\rho$ is the density, $u$, $v$, $w$ are the velocity components; $E$, $F$, $G$ and $E_v$, $F_v$, $G_v$ are the inviscid flux and viscous flux respectively in curvilinear coordinate system; $t$ is time; and $\xi$, $\eta$, $\zeta$ are coordinate components in natural curvilinear coordinate system.

Making use of the Crank-Nicolson scheme, the RANS equations are approximated to the conservative equations in semi-implicit form.

$$[I + \tau \phi(\frac{\partial A^n}{\partial \xi} + \frac{\partial B^n}{\partial \eta} + \frac{\partial C^n}{\partial \zeta})] \Delta U^n = -\tau(\frac{\partial E}{\partial \xi} + \frac{\partial F}{\partial \eta} + \frac{\partial G}{\partial \zeta} - H)^n$$

(2)

where $A$, $B$, $C$ are the Jacobians of the inviscid fluxes $E$, $F$, $G$, respectively, $H$ is the sum of viscous fluxes, $\tau$ time step, and $\phi$ the scheme coefficient. And the new solution vector $U^{n+1}$ is obtained by $U^{n+1} = U^n + \Delta U$.

The inviscid term of equation (2) is discretized by an upwind difference scheme, the AUSM + -up scheme, which is with the 3rd accuracy with the MUSCL method. The central difference scheme is employed to discretize the viscous term. And the discretized RANS equations are solved by LUSGS [10] implicit scheme.

The B-L algebraic model [11] and the $\omega-q$ two equation turbulence model [12] are used to realize the closure of the time average N-S equation. The results of the algebraic model provide the initial turbulence parameters for the calculation with the two-equation turbulence model.

The unsteady heat conduction equation for the heat transfer in the TPS solid is provide as

$$\frac{\partial (\rho C T)}{\partial t} = \nabla \cdot (\lambda \nabla T)$$

(3)

Where $C$ is the specific heat capacity of the solid, $T$ is the temperature, and $\lambda$ is the thermal conductivity of the solid.

The above equation is discretized by the central difference scheme, since its diffusive characteristics. And the Douglas-Rachford alternative direction implicit (ADI) method is employed to solve the discretized equation.

2.2. Coupling method
The data transfer between the fluid and solid domains is carried out the direct coupling method, which is provided as following formula:

$$T_f = \left(\frac{\lambda_s / \lambda_f}{\Delta n_f / \Delta n_s}\right) T_f + T_f - q \Delta n_f / \lambda_f$$

(4)
To calculate the surface temperature $T_w$, one needs $T_f$ and $T_s$, which are the temperature at the cells adjacent to the fluid/solid interface, and one also needs the $\Delta n_f$ and $\Delta n_s$, the distance of the adjacent cells center to the interface. The subscript f and s denote the fluid and solid domains, respectively. $q_r$ is the radiation thermal flux.

2.3. Unsteady calculation method
The dual time step technique is adopted for the RANS equations, hence the implicit time scheme, the difference schemes for the inviscid and viscous terms, and the implicit LUSGS schemes are the same as mentioned above.

For the unsteady heat transfer equation for the solid part, the D-R ADI scheme is also employed. It is noted that the time in the ADI scheme is the real physical one, with the same value as the physical time in the dual time step scheme for the fluid domain, thus there is the uniform time marching in the fluid and solid domains.

3. Unsteady Gap Flow and Heat Transfer in Thermal Protection System
The unsteady coupled heat transfer simulations of hypersonic flow past the TPS gaps are carried out. The computational domain, consist of a fluid one and a solid one, is shown in fig. 1.

The tile dimension is set as 1000×1000mm, with thickness of 12mm, and there is an aluminum skin with thickness of 3mm. The width of the gap is 1.5mm. The shaded part in the fig.8(c) is the gap filler, and the thermal conduction coefficient of such filler is considered the same as that of the TPS material.

Fig. 2 presents the computational grids of the case. The grid interfaces between the blocks are full matched, and the mesh near the solid wall is refined, with the $y^+$ adjacent to the walls less than 5.

The inlet is set as supersonic one with free stream Mach number 6.0, the angle of attack is 0, and the outlet is set as supersonic outlet; BC set for the far-field boundary condition; set AE as the adiabatic wall condition; In the transverse flow direction, adopt the translational periodic boundary condition; In
the coupling calculation, the EF, DG and FG in the solid region are all set as adiabatic boundary conditions.

In order to consider the influence of radiation heat transfer, the radiation heat source term is added to the solid wall in the calculation, and the surface radiation coefficient is set as 0.8 for the solid wall in AE and DE, while for the gap, the non-closed cavity model is used to calculate the corresponding radiation angle coefficient for each wall in the gap to approximate the radiation effect.

Because the flow stability time is far less than the temperature field stability time, in the calculation, firstly, the flow calculation with wall temperature of 300K is carried out for the above scheme, then the flow calculation result is taken as the initial value, the initial temperature of solid is set as 300K, the unsteady gas heat coupling calculation is carried out, the calculation physical time is 600s.

3.1. analysis of flow field characteristics
The following figure shows the distribution of gas pressure and streamline near the gap on the transverse symmetry plane.

As shown in Fig.3, when the supersonic air flows through the gap, the flow area increases, and expansion wave occurs, and the pressure decreases. When the air flows through the seam, due to the reduction of the flow area, there is a strong compression wave, and the pressure increases. Under the condition of the same slit width, step height and TPS scale, the flow field distribution outside the slit obtained by the 2mm and 12mm slit depth schemes has little difference; there is a clockwise rotating vortex in the top region of the slit, and the flow field distribution obtained by the two schemes is very similar; the difference is that the 12mm slit depth scheme is a low-speed flow area at the bottom of the slit, which can be seen in the subsequent analysis. In this region, the air velocity is very low, and the heat conduction mode is mainly heat conduction.

3.2. temperature field of anti-heating tile changes with time
The solid temperature field in the transverse symmetry plane changes with time as follows:
Figure 4 shows the temperature contour of the anti-heat tile on the horizontal symmetrical plane at different time. Only those near the upstream gap region is provided. The heat gradually migrates from the surface of the anti-heat tile to the inner part and gradually reaches the bottom aluminum plate; while in the inner part of the seam, the heat gradually diffuses from the high temperature gas to the inner part of the anti-heat tile, the temperature gradient is uniform along the flow direction.

3.3. temperature field analysis of bottom aluminum plate

This section analyzes the influence of gap depth on the temperature field of TPS material and the temperature rise of key points of bottom aluminum plate. The selected characteristic positions are shown in Fig. 5.

The characteristic locations analyzed are on the surface of the bottom aluminum plate, including 6 lines. The characteristic lines, LH1 and LH3 locate at the bottom of upstream and middle cross joint, LH2 locates at the middle of these two lines. LZ1 and LZ3 locate at the bottom of two longitudinal joints, and LZ2 locates at the middle of these two lines.

The temperature on the characteristic line LZ1 is similar to that on LZ2. Along the flow direction, the temperature of aluminum plate decreases gradually. Compared with the calculation results of the two depth schemes, in the 2mm scheme, the presence of filler material is conducive to reduce the heat load of the bottom aluminum plate. In the analyzed calculation example, the maximum temperature difference between the two depth schemes at the same position is about 5K.
According to fig. 7, the transverse temperature distribution is relatively uniform, and along the flow direction ($x_{LH1} < x_{LH2} < x_{LH3}$), the temperature of the bottom aluminum plate decreases gradually.

![Figure 7](image1)

**Figure 7.** Temperature on the characteristic lines of transverse direction

4. Conclusions
The unsteady coupled heat transfer simulations of tile-to-tile structure on the hypersonic aircraft are carried out, and the conclusions are as follows:

1. The developed unsteady CHT solver is able to predict the unsteady hypersonic flow and heat transfer in the solid.

2. There is vortex flow on the tile-to-tile gap top in both the 2mm and 12mm gap depth cases, and there is similar flow field on the surface of the tiles. There is dead zone in the 12mm gap depth case.

3. The heat flux density at the bottom of gap with the depth of 12mm is higher than that with the gap depth of 2mm, which leads to higher local temperature of the bottom aluminum plate.

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