Two-dimensional Aerodynamic Loads of Thermal Protection System Considering Different Widths of the Strain Isolation Pad

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Abstract. Thermal Protection System (TPS) is widely adopted to prevent aircraft substructure from the high environment temperature which is assembled by the ceramic tile, the strain isolation pad (SIP) and the substrate structure. The surface of shuttle is covered by individual ceramic tiles which are bonded to the substrate. The structure of SIP is the significant component of TPS which has important influence on the aerodynamic loads of TPS. To reveal the effect of the width of SIP on the aerodynamic loads, the two-dimensional TPS models considering various widths of SIP, 0.5mm, 0.7mm, 1.0mm, 1.3mm and 1.5mm, are founded and are simulated by computational fluid dynamic (CFD) method. The models are established by combining SIP and the ceramic tile on the surface of NACA0012. The flow around TPS, including flow around NACA0012 and internal flow, is simulated by solving Navier-Stokes (N-S) equation and Spalart-Allmaras (S-A) model. The pressure distributions around TPS are obtained and numerical results show: (1) In X and Y direction, with the width of SIP, $\triangle w$, being 1.0mm, the forces are minimum, 159.9N in X -direction and 313.3N in Y -direction, respectively; (2) The different force of tile-II is related to both the pressure distribution and the flow speed around tile-II.

1. Introduction
The surface of Space Shuttle will produce above 1220F in condition of ascent and re-entry which is the melting point of conventional aluminum aircraft structure [1]. To prevent the aircraft substructure from high temperature, some heat protection material, thermal barrier coating and the insulation structure are pointed out, such as the silica tiles and TPS structure. TPS structure is assembled by the ceramic tile, SIP and the substrate structure is widely adopted to protect the aircraft substructure to avoid the high environment temperature during the ascent and re-entry [2-4]. To protect the aircraft surface from high temperature and avoid the structural damage deriving from the excessive strain, TPS is designed in two ways [5-6]: (1) The aircraft surface is covered by individual ceramic tiles which allow the motion each other; (2) Simple tiles are bonded to the substrate by the deformable SIP. Both internal flows in tile-tile gaps and SIP are produced in this assembly structure. Widths of SIP have significant influence on the porous flow of SIP and the pressure distribution along SIP, which is the important component of the aerodynamic loads of TPS, especially in condition of shock wave on the surface of tile.

Lots of experts have some research on TPS. Lawing [7] obtained the permeability of both high density tile and SIP by performing lots of pressure drop experiments. Muraca [8] pointed out that during...
ascent environments; the biggest aerodynamic loads of tile are happened. Petley [9] calculated the aerodynamic loads of tiles during ascent steady-state by a modified heat-transfer program. However, the study about the influence of widths of SIP on the aerodynamic loads of tiles is still scarce. In this paper, CFD technology is utilized to calculate aerodynamic loads of TPS considering various widths of SIP, 0.5mm, 0.7mm, 1.0mm, 1.3mm and 1.5mm. The porous flow in SIP is simulated by adopting S-A turbulence model and solving N-S equation.

2. Internal Flow Model
The structure of TPS, which is assembly of the substrate structure, SIP and the ceramic tile, is shown in figure 1 [10]. SIP is utilized to conjunct the simple tile and the substrate. There is internal flows around TPS model, including porous flow of SIP and tile-to-tile gap flow. To eliminate the coupling effect of adjacent tile, the mechanical model of TPS with three tiles is simplified as the tile-airfoil model in figure 2, which assembles TPS and airfoil NACA0012 together. The shock wave is produced on the upper surface of tiles. The internal flow along with tile-tile gaps and SIP is produced from the high pressure zone on the downstream portion to the low pressure zone on the upstream portion, when the shock waves is on the upper surface of tile. In this paper, the force of TPS is obtained by tile-II which is on the middle tile of TPS.

3. Numerical Method
3.1. Governing Equation
Due to solve flows around TPS, the governing equation is as follows in Cartesian coordinates [11]:

$$\frac{\partial u}{\partial t} + \frac{\partial f}{\partial x} + \frac{\partial g}{\partial y} = \frac{\partial s_x}{\partial x} + \frac{\partial s_y}{\partial y}$$

Where $f$ and $g$ are the flow flux in $x$ direction and $y$ direction, respectively; $s_x$ and $s_y$ are the sum of heat exchange flux and viscous stresses in $x$ direction and $y$ direction, respectively; $u$ indicates flow vector.
S-A turbulent model is adopted. What’s more, it is chosen that a steady-state pressure-based implicit solver with coupled pressure-velocity and second-order upwind discretization.

3.2. Verification of Algorithm
There are both flow field mentioned above essential to be verified: (1) the porous flow in SIP; (2) the flow around NACA0012. The algorithm has been verified that the numerical method can solve both flow effectively, respectively [10-11].

4. The CFD setup
In this study, the multi-tiles-airfoil model is established. The ceramic tile is about 8.0 cm×1.0 cm and the chord length is 1.0 m. The mesh is all quadrilateral and the grid an O type, in figure 3 [10]. This domain is meshed with 67740 nodes and 68843 elements. Figure 4 shows tile-II in Cartesian coordinates [10]. Boundary conditions (BCs) of the far field are listed in table 1. Additionally, no-slip condition is adopted in this model.
Figure 3. Local mesh of multi-tiles-airfoil model.

5. Numerical Result
The widths of SIP have influence on the porous flow. Different models with various widths of SIP would be applied to obtain forces of tile-II. Widths of SIP, defined as $\Delta w$, are 0.5mm, 0.7mm, 1.0 mm, 1.3mm and 1.5mm, respectively. The forces of tile-II are shown in table 2. From table 2, it is easily seen that the forces in X and Y-direction are both minimum, when $\Delta w$ is 1.0mm. The force in conditions of $\Delta w$ 1.0mm is chosen to the basis data. As $\Delta w$ is increasing by, the force are increasing 5.4%~ 11.8% and 102.5%~ 127.3% in X-direction and Y-direction, respectively. As $\Delta w$ is decreasing by, the force are increasing 29.7%~ 48.6% and 57.1%~ 93.8% in X-direction and Y-direction, respectively. Compared to condition of $\Delta w$ 1.0mm, the maximum increment force in X-direction is 77.7 N in condition of $\Delta w$ 0.7mm, in Y-direction is 398.9N in condition of $\Delta w$ 1.5mm.

| $\Delta w$(mm) | Fx(N) | $\Delta Fx$(%) | Fy(N) | $\Delta Fy$(%) |
|----------------|-------|---------------|-------|---------------|
| 0.5            | 207.4 | 29.7          | 607.2 | 93.8          |
| 0.7            | 237.6 | 48.6          | 492.3 | 57.1          |
| 1.0            | 159.9 | 0.0           | 313.3 | 0.0           |
| 1.3            | 178.8 | 11.8          | 634.5 | 102.5         |
| 1.5            | 168.6 | 5.4           | 712.2 | 127.3         |

Notes: The force in conditions of $\Delta w$ 1.0mm is chosen to the basis data.

6. Discussion
It is easily to obtain that the forces of tile-II are related to the width of SIP. When $\Delta w$ is 1.0mm, the forces in X-direction and in Y-direction are all minimum. There are some factors lead to various forces of tile-II, such as flow field around airfoil and internal flow. The pressure around tile-II is shown in figure 5 and figure 6.

In figure 5, on front surface of tile-II, as $\Delta w$ is increasing by, the pressure distribution is increasing and the pressure distribution in condition of both $\Delta w$ 0.7mm and $\Delta w$ 1.0mm has little difference. On behind surface of tile-II, compared with condition of $\Delta w$ 0.7mm and $\Delta w$ 1.3mm, the pressure distribution is less in condition of $\Delta w$ 1.0mm. As a result, the force in X-direction in condition of $\Delta w$ 1.0mm is minimum.

In figure 6, on upper surface of tile-II, as $\Delta w$ is increasing by, the pressure distribution is almost same. Additionally, as $\Delta w$ is increasing by, the pressure gradient on lower surface of tile-II is diminished.
What’s more, the value of pressure distribution in condition of $\Delta w$ 1.0mm is minimum. As a result, the force in Y-direction in condition of $\Delta w$ 1.0mm is minimum.

**Figure 5.** The pressure distribution in X-direction.

**Figure 6.** The pressure distribution in Y-direction.

Not only there are various pressure distribution, but various flow speeds. The clouds of local speed in entrance and exit of internal flow are showed in figure 7 and 8, respectively. In condition of $\Delta w$ 1.0mm and $\Delta w$ 1.3mm, the internal flow speed have little difference, average velocity in entrance and exit is about 72.8m/s. Speeds in entrance and exit, in condition of $\Delta w$ 0.7mm, are different from condition of $\Delta w$ 1.0mm and $\Delta w$ 1.3mm, the velocity in entrance is 69.2m/s and in exit is 78.1m/s at table 3. So various pressure distribution and the flow speed around tile-II lead to various force of tile-II.

**Table 3.** Local flow speed considering various widths of SIP.

| $\Delta w$(mm) | The velocity in the entrance(m/s) | The velocity in the exit(m/s) |
|---------------|----------------------------------|-----------------------------|
| 0.7           | 69.2                             | 78.1                        |
| 1.0           | 72.8                             | 72.9                        |
| 1.3           | 72.8                             | 72.6                        |

**Figure 7.** Clouds of local speed in entrance of internal flow.

**Figure 8.** Clouds of local speed in exit of internal flow.
7. Conclusion
In this paper, the force around TPS has been studied considering various widths of SIP. The conclusions drawn are:

(1) In X and Y direction, when $\triangle w$ is 1.0mm, the forces are minimum, 159.9N in X-direction and 313.3N in Y-direction, respectively.

(2) The different force of tile-II is related to both the pressure distribution and the flow speed around tile-II.

References
[1] Cooper P A 1981 The shuttle tile story AIAA
[2] Rodriguez A C and Snapp C G 2011 Orbiter thermal protection system lessons learned AIAA 20 7308
[3] Monti R, Fumo M D S and Savino R 2006 Thermal shielding of a reentry vehicle by ultra-high-temperature ceramic materials Journal of Thermophysics and Heat Transfer 20 500-6
[4] Wu D, Wang Y, Gao Z and Yang J 2015 Insulation performance of heat-resistant material for high-speed aircraft under thermal environments Journal of Materials Engineering and Performance 24 3373-85
[5] Bertin J J and Cummings R M 2003 Fifty years of hypersonics: where we've been, where we're going Progress in Aerospace Sciences 39 511-36
[6] Blevins R D and Holehouse I 1993 Thermoacoustic loads and fatigue of hypersonic vehicle skin panels Journal of Aircraft 30 971-8
[7] Muraca R J, Coe C F and Tulinius J R 1982 Shuttle tile environments and loads AIAA 82 0631
[8] Lawing P L 1987 A prediction method for flow in the shuttle tile strain isolation pad AIAA 87 1510
[9] Petley D H, Alexander W, Ivey G W and Kerr P A 1984 Steady internal flow and aerodynamic loads analysis of shuttle thermal protection system NASA TP-2255
[10] Feng Y P and Xia W 2019 Two-dimensional aerodynamic loads of Space Shuttle thermal protection system considering steady internal flow APISAT 2018, LNEE 459 151–160
[11] Feng Y P, Xia W, Jiang J S and Hu S L 2016 Transonic aerodynamic loads of airfoil considering internal flow of gaps FLIGHT DYNAMICS 34 15-9 (in Chinese)