Study on the Influence of Isolated Roughness on Hypersonic Flow over Blunt Wedge

**Xiaojun Tang**, **Jingzhen Han**, **Mingfang Shi**, **Juan Yu**

1. Beijing Spacecrafts, China Academy of Space Technology, Beijing, 100094, China
2. Department of School of Mechanical and Electrical Engineering, North China Institute of Aerospace Engineering, Langfang, Hebei, 065000, China
3. College of Aerospace and Civil Engineering, Harbin Engineering University, Harbin, Heilongjiang, 150001, China
4. School of Civil Engineering, Inner Mongolia University of Science and Technology Baotou, Inner Mongolia, 014010, China
5. Consumer Goods Industry Research Institute, China Center for Information Industry Development, Beijing, 100846, China

*Corresponding author’s e-mail: yujuan@ccidthinktank.com*

**Abstract.** To investigate the problem of the influence of the depth of the isolated D-type roughness element on the hypersonic flow around the blunt wedge boundary, the high-order accuracy finite difference method is used to carry out the direct numerical simulation, the influence of the depth of the isolated D-type roughness element on the interaction between the free flow and the wall is analysed, and the influence of the D-type roughness element on the wall pressure, the wall friction resistance and the wall heat flow is discussed. The results show that the strength of compression wave and expansion wave increases with the increase of the depth of D-type roughness element, but the position of compression wave and expansion wave does not change; With the increase of the depth of the D-type element, the change speed of the flow parameters will be accelerated, the peak value will increase and the trough value will decrease, and the position of the peak and trough will gradually move away from the center of the element with the increase of the depth of the element. When the depth of the D-type element is greater than or equal to 0.08, a vortex will form in the D-type element, and the length of the vortex increases with the deepening of the element. The D-type element will not change the flow state of the shear layer near it.

**1. Introduction**

The flow state in the boundary layer of hypersonic vehicle directly affects the flight control, propulsion and thermal protection of hypersonic vehicle, which is a hot topic in current research. However, the flow state in the boundary layer is affected by many factors, such as wall temperature, wall deformation. These factors will change the flow state in the boundary layer and advance the transition [1]. In the process of practical application, there are a lot of wall deformations on the surface of hypersonic vehicle, such as fish scale crater, thermal protection system gap, skin seam and so on. Generally, the wall deformation higher than the smooth wall is defined as K-type rough element, on the contrary, the wall deformation lower than the smooth wall is defined as D-type rough element.
Although there are a lot of D-type and K-type wall roughness elements on the surface of hypersonic vehicle, the research on the influence of D-type roughness element on the boundary layer is far less than that of K-type roughness element. In 2003, the Columbia space shuttle accident was identified as a gap in the thermal protection system at the leading edge of the left wing. Therefore, the influence of D-type rough element on transition and hypersonic vehicle design has attracted more attention.

In 2006, berry [2] and Horvath [3] conducted an experimental study to analyse the effect of wall cavity on the transition of space shuttle orbiter. However, this experiment only supports the cavity with selected geometry, so it is difficult to predict the transition position caused by D-type roughness element. Ohmichi and Suzuki [4] used direct numerical simulation method to analyse Mach 7 laminar flow through a flat plate with a cavity, and found that the cavity would enhance the laminar turbulent transition. Xiao [5] used the improved delayed detached eddy (IDDE) method to study the hypersonic boundary layer transition induced by a square cavity, and found that the depth of the square cavity will directly affect the flow state in the hypersonic boundary layer, but did not mention the influence of the cavity depth on the pressure and heat flux. Riley and McNamara [6] used the linear stability theory and parabolic stability equation to study and found that the position and direction of the wall bulge / cavity can promote or delay the transition. To sum up, the research of D-type rough element on the flow state in the boundary layer is not comprehensive, especially the research of geometric parameters of D-type rough element on the blunt wedge boundary layer is rare. The blunt wedge structure is widely used in hypersonic vehicles, so it is necessary to study the influence of geometric parameters of D-type rough element on the blunt wedge boundary layer.

In view of this, taking the blunt wedge structure as the model, this paper discusses the influence of D-type rough element generated by cubic polynomial on hypersonic flow field and boundary layer, studies the influence of isolated D-type rough element on wall friction and wall heat flow at different depths, and reveals the more essential mechanism of the influence of isolated rough element on flow field.

2. The governing equation and numerical method
The governing equation in this paper is a two-dimensional conservative N-S equation, and the finite difference method is used to simulate the hypersonic flow field to analyze the influence of rough elements on the flow field and boundary layer of hypersonic blunt wedge flow. For non-sticking terms, Steger-Warming flow vector splitting format is used to decompose them into positive and negative flux terms. For viscous terms, a six-order central difference scheme is used for discretization. For time terms, three-order Runge-Kutta scheme is used for discretization.

3. Flow conditions and models
This paper adopts the blunt wedge structure as the calculation model, the half wedge angle $\theta = 5^\circ$, and the head radius $R_n = 1$ mm. The flow field around the hypersonic blunt wedge is simulated by direct numerical simulation. The free incoming flow conditions are shown in Table 1, where $\infty$ is the incoming flow parameters.

| parameter | $Ma_\infty$ | $T_\infty$ $(K)$ | $Re_\infty$ | $\alpha$ $(^\circ)$ |
|-----------|-------------|-----------------|-------------|-----------------|
| Value     | 6           | 200             | 6000        | 0               |

Figure 1 shows the blunt wedge model and calculation mesh including rough elements. The rough element boundary is generated by a third-degree polynomial. The expression of the CE segment curve in the figure is

\[ f(x) = \frac{R_n + h}{\cos \theta} + x \tan \theta - \frac{3h}{4 \cos \theta} \left( \frac{x - x_c + h \sin \theta}{w \cos \theta + h \sin \theta} \right)^2 + \frac{2h}{\cos \theta} \left( \frac{x - x_c + h \sin \theta}{w \cos \theta + h \sin \theta} \right)^3 \] (1)
In the formula, \( h \) and \( w \) are the height and half-width of the rough element respectively, and the curve CE and the curve CA are symmetrical about CP. \( S_c \) is the center of the rough element, which is determined by the following formula

\[
S_c = (\pi/2-\theta)R_n + x_p \cdot R_n
\]

where, \( x_p \) is the distance from the center of the roughness element to the edge of the ball head area. It is worth noting that points B and D in Figure 1 are the two inflection points of the cubic polynomial curve, and their abscissas are \( x_1 \) and \( x_2 \) respectively. In this paper, the number of grids is 600×150, and the exponential stretching method is used to refine the grids in the area near the head and the wall.

The following physical quantities are all dimensionless processing. The wall condition adopts the Kuta non-slip condition; the wall surface is an isothermal wall surface, and the wall temperature \( T_w = 400K \); the incoming flow and the calculated outlet adopt the incoming flow condition and the extrapolated boundary condition respectively. Table 2 summarizes the parameters of the rough element in the numerical simulation.

| case | \( x_p \) | \( x_1 \) | \( x_2 \) | \( d \) | \( w \) |
|------|----------|----------|----------|------|------|
| 1    | 1.4071   | 1.2057   | 1.6085   | 0.05 | 0.4  |
| 2    | 1.4071   | 1.2044   | 1.6098   | 0.08 | 0.4  |
| 3    | 1.4071   | 1.2035   | 1.6107   | 0.10 | 0.4  |
| 4    | 1.4071   | 1.2026   | 1.6116   | 0.12 | 0.4  |
| 5    | 1.4071   | 1.2013   | 1.6129   | 0.15 | 0.4  |

4. Result analysis and discussion

The influence of D-type roughness element depth on the temperature field near the roughness element is shown in Fig.2. It can be seen that when the depth of the D-type rough element reaches 0.08, vortices will be formed in the D-type rough element, but when the depth of the K-type rough element is 0.08, no flow separation is formed in the boundary layer. The flow separation becomes easier as the depth of the D-type roughness element increases. In addition, the D-type roughness element has a relatively small influence on the flow field, and the shear layer near the D-type roughness element does not change significantly.
Figure 3 shows the influence of D-type roughness element of different depths on the wall pressure. The increase of the depth of D-type roughness element will expand the influence range of roughness element. The positions of the wave crest and the wave trough of the wall pressure curve change. The wave crest moves back with the increase of the depth of the rough element, while the wave trough moves forward with the increase of the depth of the rough element. Because the position of the pressure extreme point is determined by the position of the wall inflection point, from the inflection point position of the D-type rough element with different depths in Table 2, it can be found that the position of the first inflection point of the D-type rough element moves forward with the increase of the depth of the rough element, and the position of the second inflection point moves backward with the increase of the depth of the rough element, so the position of the pressure extreme point changes. The peak value of wall pressure increases with the increase of the depth of the rough element, but the valley value does not decrease with the increase of the depth of the rough element. When \( d = 0.1 \), the wave valley reaches the minimum value.

Figure 4 shows the distribution of friction coefficient along the direction of the wall under different depth conditions. The three maximums of the friction coefficient increase with the increase of the roughness element depth. When \( d = 0.05 \), the wall friction coefficient curve does not bend, the vortex does not form in the D-type rough element, and the flow does not separate; When \( d \geq 0.08 \), the friction coefficient curve of the wall is bent, and the length of the bending region increases with the depth of the rough element, that is, the width of the vortex increases with the depth of the rough element. This shows that the increase of the depth of the D-type rough element leads to the separation of the flow field, and this separation will become more and more serious with the increase of the depth of the rough element. In general, the increase of roughness element depth will reduce the wall friction resistance. Different from the recirculation flow in the square cavity, with the increase of the length depth ratio of the square cavity, the recirculation flow in the square cavity can not be completely filled, but the flow in the D-type rough element does not separate with the increase of the length depth ratio, and is always filled with the D-type rough element [7].

![Figure 2. Temperature distribution near D-type rough element](image-url)
Figure 5 shows the influence of roughness elements with different depths on the distribution of wall heat flux along the flow direction. The increase of D-type roughness element depth expands the influence range of wall heat flux. The wave crest of wall heat flux increases with the increase of roughness element depth, while the wave trough decreases with the increase of roughness element depth. The curve of wall heat flux changes sharply with the increase of roughness element depth. The increase of the depth of the rough element makes the heating of the second half of the rough element more serious, but it also suppresses the heating of the first half of the cavity. Generally speaking, the increase of the depth of the rough element reduces the heating of the wall to a certain extent.

Figure 3. Comparison of influence of roughness element depth on wall pressure

Figure 4. Effect of roughness element depth on wall friction coefficient

Figure 5. Comparison of the influence of the depth of D-type rough element on the wall heat flux

5. Conclusion
A high-precision finite-difference method is used to simulate the hypersonic flow around a blunt wedge under the condition of wall roughness element. The influence of the position of the isolated K-type wall roughness element on the flow field and boundary layer is analyzed, and the effect of the roughness element on the mechanical and thermal properties of the wall is given: With the increase of the depth of D-type roughness element, the intensity of compression wave and expansion wave in the flow field will be enhanced, but the position of compression wave and expansion wave will not change;
With the increase of the depth of the D-type element, the change speed of the flow parameters will be accelerated, the peak value will increase and the trough value will decrease, and the position of the peak and trough will gradually move away from the center of the element with the increase of the depth of the element. When the depth \( d \) of the D-type rough element is \( \geq 0.08 \), a vortex will be formed in the D-type rough element, and the length of the vortex will increase with the deepening of the rough element, and the D-type rough element will basically not change the flow state of the nearby shear layer.

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