# Effect of Multi-rough Element Combination on Hypersonic Boundary Layer

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**Abstract.** In this paper, the influence of multi-rough element combination controlled by cubic polynomial on the flow field of hypersonic blunt wedge is studied by direct numerical simulation. The influence mechanism of six continuous rough element combinations on the flow parameters in the boundary layer is analyzed in depth, and compared with the influence of double rough elements. It is concluded that the first rough element of the continuous rough element combination has a great influence on the flow field pressure, and the influence of the latter rough element decreases in turn. The combination of six continuous rough elements on the wall can better suppress the incoming flow heating and reduce the wall friction compared with the double rough elements. Compared with smooth wall, wall friction and incoming flow heating are reduced by 25.23 % and 2.69 %, respectively.

**Keywords:** Rough element combination; high supersonic blunt wedge flow; numerical simulation.

## 1. Introduction

The research on boundary layer flow field of hypersonic vehicle is the difficulty and hotspot in the design of hypersonic vehicle. Due to the processing technology, material characteristics and other reasons, a large number of wall deformations inevitably exist in the skin of ultra-high-speed aircraft, and these wall deformations directly affect the flow state of the boundary layer, and even lead to early transition. In addition, wall bulges and depressions can cause some new physical phenomena, such as shock-shock interaction, shock-boundary layer interaction, flow separation and unsteady flow near rough elements [1-3]. Therefore, it is very meaningful to study the influence mechanism of wall roughness element on the flow field in boundary layer. Many scholars have focused on the influence of wall roughness element on supersonic flow field. Perry [4] divided the rough elements into two categories: the rough elements above the smooth wall are called K-type rough elements, and the rough elements below the smooth surface are called D-type rough elements. Duan et al. [5] proposed a high-order cut-cell method to study the influence of the position of the rough element on the stability of the boundary layer, and found that when the K-type rough element was located downstream of the synchronization point, the disturbance of S mode in the boundary layer was more stable. Riley and McNamara [6] think that the position and direction of K-type rough element and D-type rough element will affect the transition, and the effect of K-type rough element and D-type rough element is opposite. It should be noted that the above studies are concentrated on the influence of independent rough elements, but the random distribution of rough elements on the wall of hypersonic vehicles is more continuous and multi-type distributed rough elements. Sharma [7] used direct numerical simulation method to analyze the influence of different types of rough element combinations on the flow field in boundary layer, and considered that the disturbance interaction caused by two adjacent rough elements would affect the starting position of transition. Oliver et al. [8] studied the influence of the spacing and size of the rough elements on the laminar flow field at the downstream boundary, and compared the influence with that of the independent rough element. They found that with the increase of the spacing of the two rough elements, the boundary layer became turbulent under the interaction of wakes, and the transition of the boundary layer with two rough elements was more complex than that of the independent rough element. In the above studies, the shape of the rough element first considers the regular shape, such as rectangle or ellipse, and the study of multiple rough elements focuses on two different types of rough elements. There are few studies on the influence of multiple continuous rough elements on the boundary layer flow state.

In view of this, the high-order precision finite difference method is used to directly simulate the flow field around the hypersonic blunt cone. The influence of multi-rough element combination on the laminar flow field of the hypersonic boundary layer is studied. The influence of multi-rough element combination on the thermodynamic properties of the hypersonic boundary layer is deeply analyzed to supplement the influence mechanism of distributed rough element on the hypersonic boundary layer. The research results can provide some reference value for drag reduction and heat reduction of hypersonic vehicle.

## 2. Numerical Methods

The governing equation in this paper is a two-dimensional conservative N-S equation. The N-S equation is discretized in time and space by using the high-order refined rough finite difference method. For the non-viscous term, the Steger-Warming flow vector splitting scheme is used to decompose it into positive and negative flux terms, which is more stable than the central difference scheme, and has a certain inhibitory effect on confusion error and non-physical oscillation. The control equation after splitting as formula (1).

$$\frac{\partial \hat{\mathbf{U}}}{\partial t}+\frac{\partial \hat{\mathbf{F}}^{+}}{\partial \xi}+\frac{\partial \hat{\mathbf{F}}^{-}}{\partial \xi}+\frac{\partial \hat{\mathbf{G}}^{+}}{\partial \eta}+\frac{\partial \hat{\mathbf{G}}^{-}}{\partial \eta}=\frac{\partial \hat{\mathbf{F}}_{\upsilon}}{\partial \xi}+\frac{\partial \hat{\mathbf{G}}_{\upsilon}}{\partial \eta} \tag{1}$$

For the positive and negative flux terms, the fifth-order WENO scheme is used for discretization, because the WENO scheme has good resolution, especially for the high-order oscillation generated in the shock wave region. Therefore, the WENO scheme is widely used in the simulation of high-order fine-rough element flow field under complex flow conditions. The fifth-order WENO expressions for positive and negative fluxes are formula (2) and formula (3), respectively.

$$W'=\frac{1}{\Delta}(\sum_{N=1}^{6} l_N W_{j+4-N}) \tag{2}$$

$$W'=\frac{1}{\Delta}(\sum_{N=1}^{6} m_N W_{j+5-N}) \tag{3}$$

where $W'$ is the differential difference approximation of $W$, $l_N$ and $m_N$ are the weighting coefficients, and $\Delta$ is the grid spacing. For viscous terms, the sixth-order central difference scheme is used for discretization, such as formula (4).

$$f_j'=(45(f_{j+1}-f_{j-1})-9(f_{j+2}-f_{j-1})+3(f_{j+3}-f_{j-3}))/60\Delta \tag{4}$$

$f'$ is the differential difference approximation of $f$, and the time term is advanced by the three-step three-order TVD Runge-Kutta scheme. The expression is as follows:

$$u^{(\mathrm{i})}=\sum_{k=0}^{i}(\alpha_{ik}u^{(k)}+\Delta \mathrm{t}\beta_{ik}\,\mathrm{L}(u^{(k)})) \quad (i=1,2,3) \tag{5}$$

Where $\mathrm{L}(u^{(k)})$ is the time difference of the time term $u^{(k)}$, $\alpha$ and $\beta$ are weight coefficients.

## 3. Flow Conditions and Models

To analyze the influence of wall roughness element on aerodynamic heat and aerodynamic force in hypersonic boundary layer, the flow field around blunt cone is simulated directly. The calculation model and grid are shown in Fig.1. In order to avoid the occurrence of stagnation points, the rough element is controlled by a cubic polynomial, and the expression of curve CE is shown in Formula (6). The curves CE and CA are symmetrical about the straight line CF. For more convenient description, points B and D are called the first inflection point and the second inflection point, respectively. The six K-types rough elements have the same configuration. The parameters and positions of the rough elements are shown in Table 1 and Table 2, respectively.

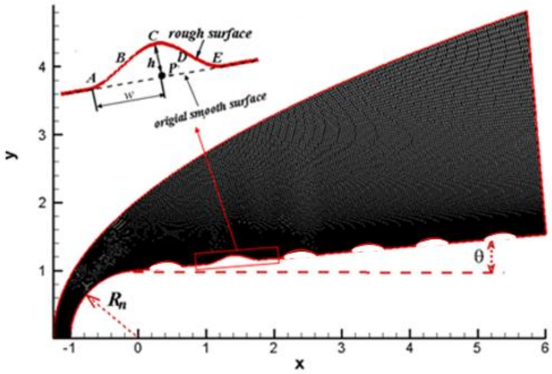


Fig.1. Computing model and grid

$$y=\frac{R_n+h}{\cos\theta}+x\tan\theta-\frac{3h}{\cos\theta}\left(\frac{x-x_F+h\sin\theta}{w\cos\theta+h\sin\theta}\right)^2+\frac{2h}{\cos\theta}\left(\frac{x-x_F+h\sin\theta}{w\cos\theta+h\sin\theta}\right)^3 \quad (6)$$

Table.1 Model parameters

| $R_n$/ mm | $\theta$ /° | h/ mm | d/ mm | w/ mm |
|---|---|---|---|---|
| 1 | 5 | 0.1 | 0.1 | 0.4 |

The number of grids is 550×150. The grids are stretched exponentially in the boundary layer and in the head region. The free flow Mach number of hypersonic flow is 6, the free flow temperature rough element and attack angle are 0° and 200 K, respectively, and the Reynolds number *Re* is 6000. The wall condition is non-slip condition and isothermal wall condition, and the wall temperature roughness element is 400K. Symmetrical condition, free flow condition and extrapolation boundary condition are respectively used in x-axis, upstream and downstream boundary.

Table.2 Rough element location

| Rough element | center coordinates $x_F$ |
|---|---|
| $K_1$ | 0.4109 |
| $K_2$ | 1.4071 |
| $K_3$ | 2.4033 |
| $K_4$ | 3.3995 |
| $K_5$ | 4.3959 |
| $K_6$ | 5.3919 |

## 4. Result and Discussion

Fig.2 shows the pressure nephogram and streamline distribution of flow field under the action of six rough elements, and the vortex between $K_2$ and $K_3$ rough elements is amplified in the upper left corner. It can be seen that the influence of six rough elements on the flow field streamline on the wall is similar to the superposition of the influence of each independent rough element on the flow field streamline, and there are vortices between any two adjacent rough elements. The boundary layer streamlines also appear continuous fluctuations, and the compression wave and expansion wave in the flow field alternate with the arrangement of rough elements. The first rough element of the continuous rough element combination has a great influence on the flow field pressure, and the influence of the latter rough element decreases in turn.

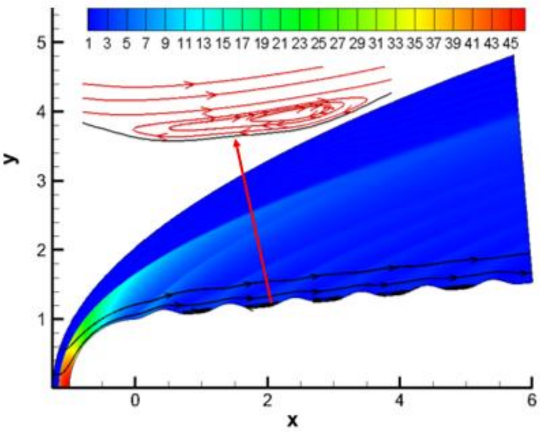


Fig.2. Wall pressure and streamline distribution under six K - type rough elements

Fig.3, Fig.4 and Fig.5 show the effects of six K-type rough elements on the wall pressure, heat flux rough elements and friction coefficient, respectively. The pressure distribution on the smooth wall and $K_2$+$K_3$ rough elements with the same configuration are also given. The wall pressure curves of the six rough elements oscillate along the pressure curve of the smooth surface, which is consistent with the pressure curve of the $K_2$+$K_3$ rough element between the $K_2$ and $K_3$ rough element centers. The results show that for $K_3$ rough element, two upstream rough elements ($K_1$ rough element and $K_2$ rough element) have the same effect as one upstream rough element ($K_2$ rough element). The pressure of $K_2$ rough element decreases at the front of $K_2$ rough element due to the existence of $K_1$ rough element. The existence of $K_2$ rough element reduces the wall pressure of $K_3$ rough element at the leading edge of $K_3$. The heat flux and friction coefficient distributions of the six roughness elements are similar to those of the wall pressure distribution. The curves of the six roughness elements oscillate on the smooth wall and coincide with those of the smooth wall in the same region. Compared with double rough elements, when there are K-type rough elements in the upstream region of $K_2$ rough element and the downstream region of $K_3$ rough element, the heat flux rough element and the friction coefficient decrease, as shown in $R_u$ and $R_d$ regions in Fig.4 and Fig.5.

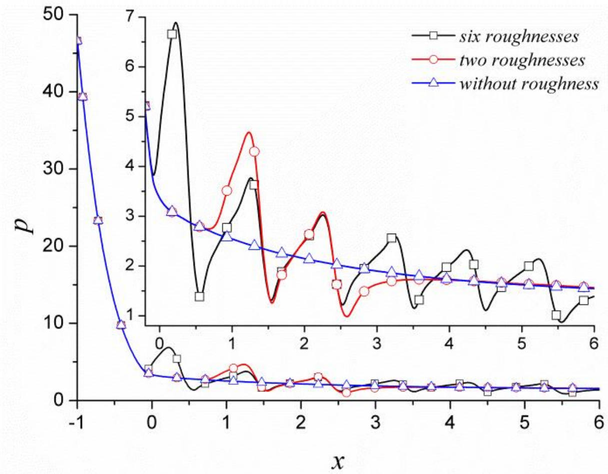


Fig.3. Influence of multi-rough elements on wall pressure

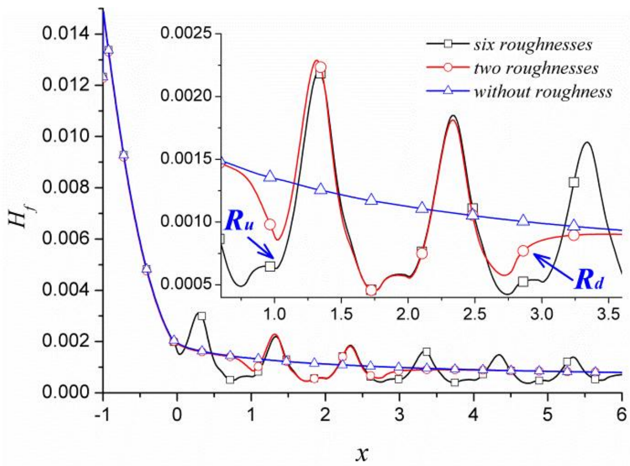


Fig.4. The influence of multi-rough elements on wall heat flux density

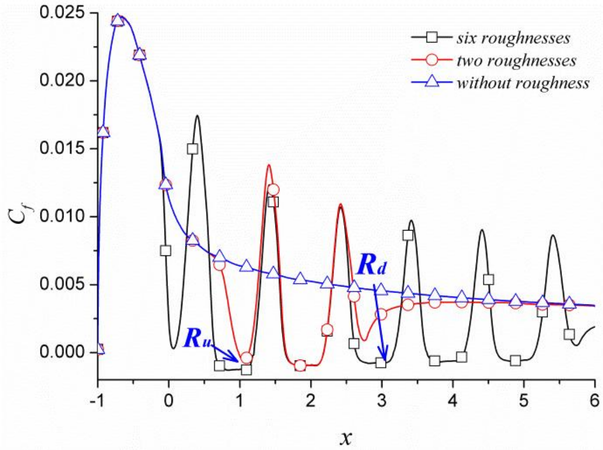


Fig.5. Effect of multi-rough elements on wall friction coefficient

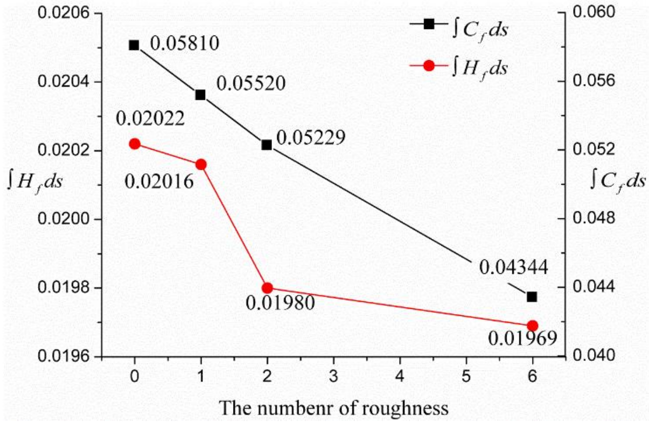


Fig.6. Effect of multi-rough elements on wall friction coefficient and wall heat flux integral

Fig.6 show the effect of multi-rough element combination on wall friction coefficient and wall heat flux integral. The results show that with the increase of the number of rough elements, the wall friction coefficient decreases gradually, and the wall heating decreases gradually. Compared with smooth surface, the integral values of wall friction coefficient and wall heat flux roughness element have reduced by 25.23% and 2.69%, respectively. This characteristic of wall roughness element provides a new idea for reducing drag and heat reduction of hypersonic vehicle.

## 5. Conclusion

The hypersonic blunt cone flow field is numerically simulated by high order accuracy finite difference method. The influence of cubic polynomial controlled continuous rough element combination on hypersonic boundary layer flow field parameters is studied and compared with that of double rough element. The following conclusions are obtained: the first rough element of the continuous rough element combination has a great influence on the flow field pressure, and the influence of the latter rough element decreases in turn. The combination of six K-type rough elements arranged on the wall can better suppress the incoming flow heating and reduce the wall friction compared with the double rough elements. Compared with smooth wall, wall friction and incoming flow heating are reduced by 25.23 % and 2.69 %, respectively.

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