Aerothermodynamics Response of Hypersonic Flow over a Blunt Cone under Distributed Rough Element

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Abstract. A direct numerical simulation method is used to simulate the hypersonic blunt cone flow field under the condition of smooth wall and distributed rough element. The effects of smooth wall and distributed rough element on hypersonic flow field and wall are compared and analyzed, and the aerothermodynamic response characteristics of hypersonic flow field to distributed rough element are studied. The results show that the effect of the distributed rough element on the hypersonic flow field and boundary layer is significantly higher than that of the smooth wall. The friction coefficient of the wall is directly proportional to the velocity gradient of the flow direction in the boundary layer, while the velocity gradient of the flow direction is inversely proportional to the thickness of the boundary layer. The heat flux density of the wall increases at the front edge of the rough element to promote the heating, and decreases at the second half of the rough element to inhibit the heating.

1. Introduction

Under the condition of high-speed aerodynamics, the shock, surface discharge effect, and vibration of the hypersonic vehicle in flight will make the wall roughness element widely exist on hypersonic vehicle surface [1-4]. The wall roughness can be generally divided into independent and distributed roughness element. The distributed roughness element refers to the roughness element with distributed group shape on the wall of the aircraft, which generally exists at the port of the hypersonic vehicle surface and distributed on the boundary layer surface. If it is controlled and measured, then a large number of parameters are needed [5]. Therefore, it is generally necessary to accurately describe the distributed rough element parameters under specific conditions, which is very difficult [2]. In the process of high-speed flight, hypersonic vehicles will be subjected to severe aerodynamic heat and aerodynamic force, which will accelerate the temperature rise of the aircraft surface. Meanwhile high temperature will lead to the weakening of the strength and stiffness of the collective material structure of the aircraft, which will damage the shape of the body and even cause out of control. Therefore, the research of the aerodynamic heating problem of hypersonic vehicles is the most advanced problem at present. A new idea is provided to study the influence of aerothermodynamics characteristics of
hypersonic flow field on hypersonic vehicle design. Based on the distributed rough element influence on hypersonic flow, many scholars have done a large number of researches [3-5]. It is found that the studies were mainly based on the influence of the rough element in the background of Reynolds average method on the aerothermodynamics of hypersonic flow, and many useful results were obtained. It can be found that these studies are mainly divided into two parts: the study of the stability and sensitivity of hypersonic flow by rough element and the study of the influence of rough element on the aerodynamic characteristics. The studies on the stability and sensitivity of hypersonic rough boundary layer are mainly carried out by high-precision numerical method. The influence of rough element on the aerothermodynamics characteristics of hypersonic flow field mainly is studied using the Reynolds average method; however the calculation accuracy obtained by the Reynolds average method is not high. Therefore, the high-order precision method is used to simulate hypersonic blunt cone flow. The characteristics of the flow field are studied by the flow factors of pressure, density, velocity and temperature. The aerothermodynamics characteristics are studied by analysing the flow parameters of wall friction coefficient and heat flux, which provides a new idea for the research of aerodynamic heating effect in hypersonic vehicle design.

2. Numerical method and computational conditions
The N-S equations can be divided into three parts for discretization. Using Steger warming splitting method, the convective flux is divided into positive and negative flux terms, and then the positive and negative flux terms are discretized using the fifth-weighted essentially non-oscillatory[6] scheme. Due to the existence of viscosity, the physical information of the flow field spreads everywhere, and so the viscous flux is discretized by the sixth-order central difference scheme. The three-step and three-order Runge-Kutta method is used for time marching. The computing model is shown in Figure 1. In this model, the half cone angle of the blunt cone is \( \theta = 5^\circ \) and the head radius is 1mm. The model is symmetrical about the x-axis. The number of grids is 401×151. The grids near the wall and the nose area are densified using the exponential stretching method. The wall is applied by no sliding and isothermal condition, and the wall temperature \( T_w = 650k \). The model takes the origin of coordinate system as the center of the arc at the head position. The freestream angle of attack \( \alpha = 0 \), the Reynolds number \( Re = 6000 \), the freestream Mach number \( Ma = 6 \), and the freestream temperature \( T_\infty = 169K \).

![Figure 1. Computing model and grid.](image1)

![Figure 2. Velocity contours under (a) smooth wall and (b) distributed rough element.](image2)

3. Response of hypersonic flow field to rough element
To study the aerothermodynamic characteristics of hypersonic flow field, the parameters of velocity, entropy, density, pressure and temperature are studied and analyzed. Figure 2 shows the isoline Contours comparison of the velocity V of the incoming flow field under the condition of smooth wall and distributed rough element, respectively. It can be seen from the figure that there is no difference in the amplitude of the incoming velocity under the two wall conditions as a whole, but the incoming velocity increases significantly in the head region and the shock boundary layer region, and it decreases gradually with the downstream movement. The isoline of the flow velocity in the smooth wall condition is gentle in the wall area, while it in the distributed rough element condition forms the same angular shape. The velocity near the wall is close to zero, and this is because the flow velocity is different at the peak and valley of the distributed rough element.
Figure 3, figure 4 and figure 5 show the comparison of entropy disturbance cloud, density cloud and pressure cloud under smooth wall condition and distributed roughness element condition. It can be found that under the two conditions, the entropy disturbance cloud contours are similar, and the magnitude of the disturbance amplitude is the same as the whole, which means that the entropy disturbance is the largest at the wall and increases with the downstream moving entropy disturbance amplitude. It can also be seen that there are drag waves near the wall of the distributed rough element, which are consistent with the number of rough elements. This is because the distributed rough element causes continuous compression waves and expansion waves in the flow field. Similar to the velocity cloud contours of the incoming flow field, the amplitudes of the density disturbance under the two wall conditions are the same as the whole.

![Figure 3. Contours of entropy disturbance under (a) smooth wall and (b) distributed rough element.](image)

![Figure 4. Density contours under (a) smooth wall and (b) distributed rough element.](image)

![Figure 5. Pressure contours under (a) smooth wall and (b) distributed rough element.](image)

To more accurately analyse the aerothermodynamics characteristics of the hypersonic flow field under the wall roughness element condition, figure 6 shows the influence of the smooth wall and distributed roughness element on the temperature of hypersonic flow field. The black line with arrow represents streamline. It can be seen that the effect of the distributed rough element on flow field is different from that of smooth wall. The influence of the distributed rough element on the flow field temperature will change with the change of wave crest and valley of the rough element, and this is because the change of heat flow density is caused by wave crest and valley of the rough element. However, the temperature variation ranges of the two are almost the same, and it can be found that the
streamlines near the wall flow along the wall, so there are no essential differences in the temperature change of the two. The shear structure of the area above the rough element is basically unaffected.

![Figure 6. Comparison of pressure contours under (a) smooth wall and (b) distributed rough element.](image)

![Figure 7. Wall pressure distribution under smooth wall and distributed rough element.](image)

4. Response of wall to rough element

To further explore the aerothermodynamic characteristics of hypersonic flow over a blunt cone under the condition of distributed rough element, figure 7 shows the comparison of the influence of the smooth wall condition and the distributed rough friction element condition on the wall pressure. The red and black curves represent the distribution curves of the distributed rough element and the smooth wall condition pressure along the X direction, respectively. The blue curve represents the change rate of the pressure along the X direction under the distributed rough element condition relative to that under the smooth wall condition. It can be seen from the figure 7 that the variation trend of the wall pressure under different wall conditions is relatively consistent, which tends to be gentle after decreasing. And the pressure disturbance value of the head position is far larger than that of the non-head area this is due to the amplification effect of the shock wave on the head area. However, it is also found that the pressure change rate at the leading edge of the first rough element is the largest, which is caused by the interaction between the rough element and the shock wave. The oscillatory phenomenon of wave crest and wave valley caused by the pressure fluctuation on the wall is obviously different from that on the smooth wall. The wave phenomenon between the pressure increases and decreases after the rough element appearing is caused because of the shape characteristics of the distributed rough element.

![Figure 8. Pressure along y-axis under (a) smooth wall and (b) distributed rough element.](image)

To further find the influence of the distributed rough element on the hypersonic flow field, figure 8 shows the pressure distribution curve along y at different positions under the smooth wall and the distributed rough element condition. The selected positions are x=0.27978 (near the area of the distributed rough element) and x=2.19127, 4.12742, and 6.07573 (different areas of the distributed rough element), which also correspond to different areas under smooth wall. It can be found from the figure 8 that the intensity of the pressure change is different at different positions. The range of pressure intensity changes is smaller and smaller as it moves away from the wall. The pressure intensity changes in the flow field under the condition of the distributed rough element are basically consistent with that under the condition of the smooth wall, but the pressure changes under the condition of the distributed rough element show a spiral of change, which is due to the influence of the wave crest and wave trough generated under the condition of the distributed rough element on the pressure changes in the flow field. Through the analysis of figure 7 and figure 8, it can be found that
the boundary layer of the flow field will produce continuous wave peaks and troughs under the distributed rough element condition, which will affect the pressure distribution along the x and y direction in the boundary layer. This is one of the reasons for the change of heat flux in the flow field. The change of thermodynamics mechanism has a great influence on boundary layer stability. In order to deeply reveal the aerothermodynamics characteristics, figure 9(a) shows the comparison of the influence of the smooth wall condition and distributed rough element condition on the wall friction coefficient. The black and red curves represent the distribution of friction coefficient under the condition of the smooth wall and distributed rough element respectively, and the blue curve represents the change rate of friction coefficient under the distributed rough element condition relative to that under the smooth wall condition. It can be seen that the influence of the wall roughness element on the wall friction coefficient is obviously greater than that on the wall pressure. The variation trend of the wall friction coefficient near the head area under the distributed rough element is consistent with that under the smooth wall, which increases when \( x < 0.5 \), decreases significantly when \( x = -0.5 \), and reaches the peak value at \( x = -0.5 \). There is obvious difference when it comes out of the head area. The wall friction coefficient of the smooth wall decreases slowly when it comes out of the head area and then tends to be smooth and slow. The wall friction coefficient of the distributed rough element shows the same wave phenomenon as the shape of the distributed rough element when it comes out of the head area, and the wall friction coefficient is gradually gentle with the disappearance of the rough element. The maximum value of the wall friction coefficient appears in the centre of each group of rough elements, while the minimum value appears in the leading edge or trailing edge of rough elements. This is because the main difference between the flow field inside and outside the hypersonic boundary layer lies in the viscous effect of the boundary layer, which makes the flow smooth when flowing through the rough element, and this makes the boundary layer at the leading edge and the trailing edge of the rough element becomes thicker. The wall friction coefficient is directly proportional to the flow velocity gradient in the boundary layer, while the flow velocity gradient is inversely proportional to the thickness of the boundary layer. Therefore, the flow velocity gradient in the boundary layer around the leading edge and the trailing edge area of the wall roughness element becomes smaller, which makes the wall friction coefficient minimum at the leading edge and the trailing edge of the wall roughness element. However, the thickness of the boundary layer at the centre of the wall roughness element is the thinnest, and the wall friction coefficient at the centre is the largest. It can also be seen from the figure 9(a) that the friction coefficient is the smallest under the distributed roughness element condition at the position of \( x = 4 \). At this point, the change rate of the friction coefficient is the largest relative to that of the smooth condition, where the boundary layer is the thickest.

Figure 9. Distribution of (a) wall friction coefficient and (b) heat flux under smooth wall and distributed rough element.

Figure 9(b) shows the comparison of the influence of the smooth wall and distributed rough element on the wall heat flux. The black and red curves represent the distribution of heat flux under the condition of the smooth wall and the distributed rough element respectively, and the blue curves represent the change rate of heat flux under the distributed rough element condition relative to that under the smooth wall condition. It can be found that no matter what kind of wall conditions, the heat flux density of the wall at the head position is the largest. After the head area is out, the distributed rough element has a significant difference from the smooth wall. The appearance of distributed roughness element increases the influence of heat flux on the wall. Taking the first group of rough
elements as an example, it can be seen that the heat flux density of the wall increases at the front edge of the rough element, and then decreases at the centre of the rough element. It can be found from the blue curve that the change rate at the position of x=4 is the largest, and the heat flow density is the lowest under the distributed rough element condition. As you can see in Figure 9(b), at this point, the boundary layer is the thickest, the friction coefficient is the lowest, the heat flow density is the lowest, and the heat flux is the least. Due to the shape characteristics of the rough element, eddy current is generated at the leading edge of the rough element, which promotes the heating of the leading edge of the rough element, but suppresses the heating of the second half.

5. Conclusion
The effects of smooth wall and distributed rough element on the hypersonic flow field and boundary layer are compared and analyzed. The conclusion is that there is no difference between the smooth wall condition and the distributed rough wall condition, but there is drag wave in the distributed rough wall condition. In general, the wall roughness element will affect the hypersonic flow field and the boundary layer, but the influence range is limited. The influence of the distributed roughness element on the hypersonic flow field and the boundary layer is significantly higher than that of the smooth wall. Under the condition of smooth wall and distributed rough element wall, the pressure disturbance value of the blunt cone head is much larger than that of the non-head. In the case of the distributed rough element, the pressure disturbance on the wall is obviously different from that on the smooth wall. Under the distributed rough element, the maximum value of wall friction coefficient appears in the center of each group of rough elements, and the minimum value appears in the leading edge or the trailing edge of rough elements. The wall friction coefficient is directly proportional to the flow velocity gradient in the boundary layer, while the flow velocity gradient is inversely proportional to the thickness of the boundary layer. Therefore, the flow velocity gradient in the boundary layer around the leading edge and the trailing edge area of the wall roughness element becomes smaller, which makes the wall friction coefficient minimum at the leading edge and the trailing edge of the wall roughness element. The thickness of the boundary layer at the center of the wall roughness element is the thinnest, and the friction coefficient of the wall at the center is the largest.

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