The Role of Three-Dimensional Shock Wave Interaction in the Complex Hypersonic Heating

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Abstract The phenomena of complex gasdynamic heating exist in the hypersonic interaction region, such as the interaction region of body and wing of hypersonic aircraft. The main mechanism is the interaction of three-dimensional shock waves and boundary layer. This paper explored the role of three-dimensional (3D) shock wave interaction in the complex hypersonic heating based on the theory of 3D shock/shock interaction (SSI). The results show that complex 3D SSI configuration exists in the hypersonic interaction regions in different flight conditions, both regular interaction and irregular interaction. The contact surface induced by the 3D SSI represents the flow jet inclines to the boundary layer of aircraft surface, which always causes the high local heating flux. In the flight condition with a certain attack angle, complex 3D Mach interaction of shock waves in the interaction region of body/wing exists, which induces the complex flow around the wing; the jet bounded by two contact surfaces inclines to the surface of wing and causes the local heating peak, similar to the IV-type heating mechanism in two-dimensional interaction of shock wave and boundary layer.

1 Introduction

Since the development of hypersonic aircraft technology in the last century, the problem of hypersonic heating is one of the most important problems of hypersonic aerodynamics; there is a great deal of theoretic, experimental, and numerical work conducted to overtake the heat barrier of hypersonic aviation. Based on the theory of hypersonic boundary layer, the mechanism of gasdynamic heating in the nose

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of aircraft and that in the large area region of simple configuration of hypersonic vehicles has been clarified, several prediction formulae of hypersonic heating rely on the parameters of free stream, and wall incline angle and wall pressure have been built and well applied in the engineer practices. However, in the interaction regions of hypersonic vehicle, such as the interaction zones of body/wing and body/rudder, the gasdynamic heating is rather complex, the mechanism has not been well understood, and there is no generally accepted prediction formula. Plenty of experimental work is still necessary to simulate the complex gasdynamic heating, and it has been a critical problem for the design of new-type hypersonic aircraft. While the hypersonic aircraft flights in different conditions of flight Mach number and attack angle, the local heat flux in the interaction regions shows great difference which cannot be fully predicted in ground tests. Obviously, the hypersonic complex gasdynamic heating in the interaction region comes from the interaction of three-dimensional (3D) shock waves and boundary layer, which has not been well understood in the current hypersonic gasdynamics. Also the problem of steady 3D shock/shock interaction (SSI) is a key fundamental problem in hypersonic gasdynamics.

2 Theory of 3D Steady SSI Problem

3D steady SSI means the steady interaction of two shock wave planes, which can be widely observed in hypersonic inlet and wing regions. The problem of 3D steady SSI deals with the shock interaction configuration of two shock wave planes, which is different from the problem of shock reflection that often deals with steady or pseudo-steady shock wave reflecting on a wall surface.

According to our recent theoretic work on 3D steady SSI problem, the mechanism of 3D steady SSI is same as that of moving two-dimensional (2D) shock/shock interaction. Each shock configuration of 3D steady SSI problem has its correspondent shock configuration of 2D moving SSI problem [1, 2]. It has been known that there are several complex configurations in 3D steady SSI, for example, regular interaction and irregular interaction. In the irregular interaction configurations of 3D steady SSI problem, simple Mach interaction, complex Mach interaction, and weak interaction exist.

Figure 1 shows numerically simulated regular interaction and simple Mach interaction configuration in 3D steady SSI induced by two intersecting wedges, in which pressure contours show the 3D steady wave structures in both regular interaction and simple Mach interaction.

The above problem of 3D steady SSI can be transformed into that of 2D moving SSI, and then it can be theoretically analyzed with the shock dynamics in a two-dimensional plane. It should be noted that in the irregular 2D moving SSI, the theoretic approach of shock polar is not so applicable since it cannot be transformed to a fully steady problem; the theory of 2D moving SSI and shock dynamics is necessary.

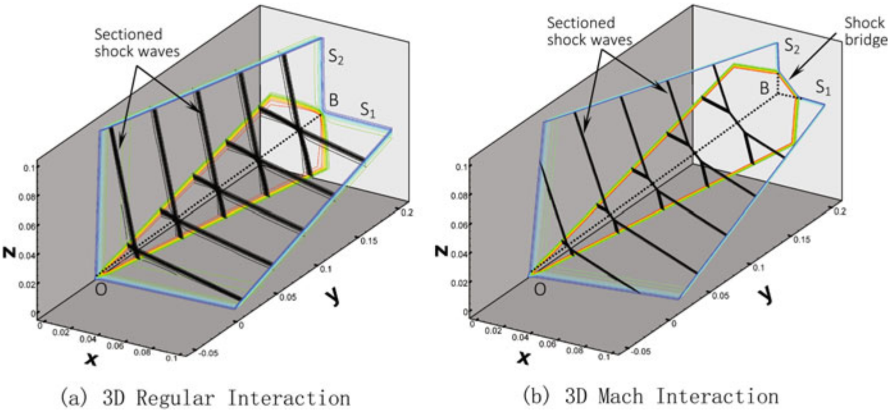
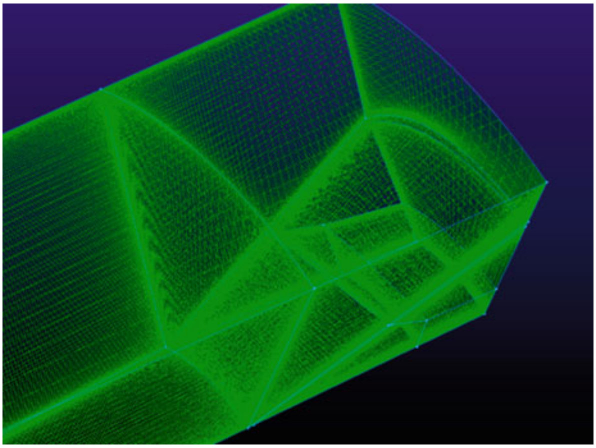


Fig. 1 3D steady SSI induced by two intersecting wedges (S_1 and S_2 denote the two planar shock waves and OB is the interaction line of S1 and S2)

Fig. 2 Meshes of numerical simulation



3 Complex Flows in Hypersonic Interaction Region

Figure 2 shows the numerical meshes of the interaction model of hypersonic body/wing. The interaction of 3D shock waves and boundary layer is mainly concerned. In numerical simulation, 3D Navier-Stokes equations with high-temperature reaction were solved; the fluid media is air. Turbulence simulation adopts the dual equation k-ε model, and fully turbulent inflow at the entrance is adopted. The high-temperature reaction model of air adopts the seven-species model proposed by Park [3], the species including O_2, N_2, O, N, NO, NO^+, and e^-.

The Mach number of the free stream is 10.11, and the cases of attack angles of 0° and 20° are simulated and discussed.

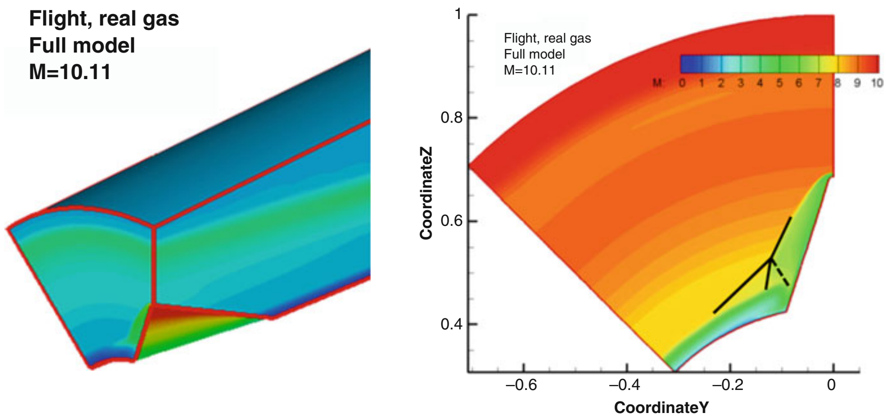


Fig. 3 The flow mechanism of interaction region with 0° attack angle

Figure 3 shows the numerical results of the case of 0° attack angle. In the case of 0° attack angle, 3D interaction of wing shock and boundary layer of body surface can be observed. The flow configuration exhibits 3D λ-type interaction of shock wave and boundary layer. The contact surface induced by 3D shock interaction represents the flow jet inclines to the wing surface, and it makes the boundary layer thin. We can deduce that the position on wing surface impinged by the contact surface has higher heating flux.

Figure 4 shows the numerical results of the case of 20° attack angle. In the case of 20° attack angle, the interaction of body shock and wing shock takes places. The 3D SSI further interacts with the boundary layers of body and wing and causes the complex flow mechanism in the interaction region of body and wing.

In the leading edge of the wing, the interaction of body shock and wing shock is near 3D regular interaction, which causes the appearance of contact surfaces behind the shock interacting point. The direction of contact surface means the flow direction of local flow, that is, the contact surface represents a local flow jet. The local flow jet further impinges on the boundary layer of the leading edge of the wing and makes the boundary layer thinner. Inevitably, the position of flow jet impinging on the boundary layer is a region with higher local heating flux. In the case of 3D SSI, there is always a contact surface representing a local flow jet, so the region with the higher local heating flux always exists.

In the lateral region of the wing, the interaction of body shock and wing shock is near 3D Mach interaction, so there are two tripoints on the both ends of the Mach stem. Also, there are two contact surfaces are formed due to the appearance of 3D Mach interaction. The flow bounded by the two contact surfaces means the flow jet impinging on the boundary layer of wall surface. It will inevitably make the local boundary layer thinner and cause the wall surface region with higher local heating flux.

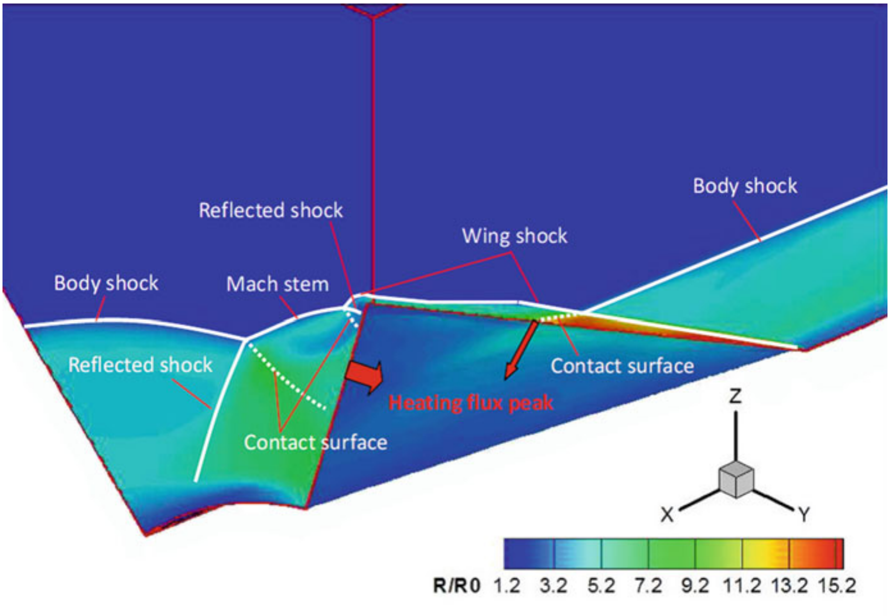


Fig. 4 The flow mechanism of interaction region with 20° attack angle

According to the theory of 3D steady SSI and the numerical flow filed of hypersonic interaction region, we can find that the 3D steady SSI configuration plays an important role on the complex gasdynamic heating in the hypersonic interaction region. As the direction of contact surfaces induced by the 3D steady SSI just represents the local flow direction, the contact surface in the flow field always means a flow jet impinging on the boundary layer of wing surface. The flow jet bounded by the contact surfaces makes the boundary layer thinner and further causes the local heating flux peak. The gasdynamic heating mechanism in the above situations is similar to the IV-type heating mechanism in two-dimensional interaction of shock wave and boundary layer.

Due to the pressure distribution on the wing surface cannot be used to distinguish the contact surface of 3D steady SSI, it is not suitable for the correlation of heating flux distribution. Also, in numerical simulation, the capture of contact surfaces is of great importance to find the local heating flux peak.

4 Concluding Remarks

Three-dimensional steady SSI plays an important role on the 3D steady SSI configuration which plays an important role on the complex gasdynamic heating in the hypersonic interaction region. Theoretical analysis and numerical results show that complex 3D SSI configuration exists in the hypersonic interaction regions in different flight conditions, both regular interaction and irregular interaction. The contact surface induced by the 3D SSI represents the flow jet inclines to the boundary layer of aircraft surface, which always causes the high local heating flux. In the flight condition with a certain attack angle, complex 3D Mach interaction of shock waves in the interaction region of body/wing exists, which induces the complex flow around the wing; the jet bounded by two contact surfaces inclines to the surface of wing and causes the local heating peak, similar to the IV-type heating mechanism in two-dimensional interaction of shock wave and boundary layer.

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