Numerical Investigation of Hypersonic Slip Flow

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Abstract. Rarefied gas effects have to be considered when doing the research and design of hypersonic flight vehicle in near space, in which accurate prediction of flow field and surface properties such as pressure, shear stress and heat flux are needed. Research on the mechanism of hypersonic slip flow must consist of mathematical analysis, numerical analysis and experimental research. This study here has three main parts: CFD code debugging, physical model analysis and numerical experiments, focusing on the numerical investigation of hypersonic slip flow. Through the comparison with two experiments, the accuracy of computational model derived here are examined and certified.

1 Introduction

In 60km～100km high altitude, the flow lies between continuum regime and transitional regime, called slip regime. Because of the rarefied gas effects, flow field around hypersonic flight vehicle exhibits many new properties, with the phenomena that shock layer being thicker, boundary velocity slip and temperature jump, viscous interference, etc. The influence of real gas effect, rarefied gas effect, and Mach number effect on the flight vehicle cannot be simulated completely by the ground test, we can hardly confirm through experiment based on the ground the exact aerodynamic and thermo-aerodynamic properties of the vehicle, so research on the mechanism of hypersonic slip flow must consist of numerical analysis which is becoming more and more important recently. [1].

2 Computational model

In slip regime, non-slip boundary condition has to be replaced by slip boundary condition. N-S equation with slip boundary condition is generally adopted recently which can get satisfied accurate prediction while the computational cost is less expensive[2、3、4、5].

This study developed a general 3D, parallel, structured, finite-volume CFD code based on 3D N-S governing equations[6], using M-AUSMPW+ scheme [7]and LU-SGS implicit time integration scheme[8]. The comparison with experimental data verified the code accuracy[9].

We adopt the improved Maxwell slip model[10] that take into account surface curvature, the expression of slip velocity adds one part that indicates the tangential change of normal velocity, namely $u_s = \frac{2-\sigma}{\sigma}\lambda(\frac{du}{dy}+\frac{dv}{dx})$. The improved Maxwell slip model is relatively accurate and efficient, showing better applicability in hypersonic slip flow, while we find out that Gokcen slip model[11] have the slowest convergent process. Both Gokcen and Lockerby slip model[12] have to compute the thickness of the Knudsen layer every iterative step, and the computational costs increase rapidly with the growing grid number as well as complexity of geometry. The improved Maxwell slip model sees convergent speed with nonslip model[13].

In continuum regime, Fourier Law can be used to calculate the wall heat flux, but in slip regime, the wall surface sees the velocity slip and temperature jump so that the continuum consumption is invalidated, thus the Fourier Law based on this assumption cannot be used here. The hypersonic slip flow heat flux model $q_w = k\left(\frac{\partial T}{\partial y}\right)_w + \mu u_w(\frac{\partial u}{\partial y})_w$ is used here. The additional term in this improved model are definite: from the microscopic view, it shows the whole energy transferred to the solid surface unit time and area due to the molecular collision, at the same time, from the macroscopic view, it denotes the energy transferred by shear stress unit time, and the magnitude analysis indicates that the additional term cannot be neglected. This improved heat flux model in some sense improves the numerical results[14].

The boundary condition of hypersonic slip flow relies on the gas-surface interaction model, the accommodation coefficient is the parameter comes from the interaction model, it denotes the degree that gas molecular accommodates with wall surface from dynamic or thermo-dynamic point of view in gas surface interaction. Accommodation coefficient in slip model shows great influence in calculation. We usually set 1 in engineering[15], considering complete diffuse reflection in gas-surface interaction.

The grid effect has greater influence on the computation of heat flux than CFD scheme [16]. Grid effect is an important factor in numerical investigation of heat flux, of which the quality of surface grid is directly effective[17]. The accommodation coefficients have little impact on surface heat flux convergence which can be obtained using 1~2 grid Renold number in slip regime.

3 Numerical simulation

We carry out numerical simulation to verify the analysis above, so as to support the numerical investigation of the mechanism on hypersonic slip flow ahead of us. The experimental data on hypersonic slip flow are very small, in this study we search two typical correlative examples. The first example is flat corner flow [18]， results from calculation and experiment are compared. The experimental model and computational grid of this flat corner are shown in figure 1.

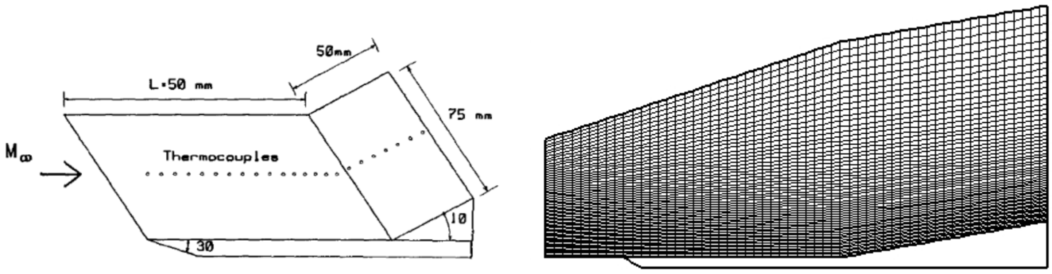

Fig.1. Experimental model and computational grid of flat corner

The length of the forepart and incline in the figure are both 50mm, with the incline angle 10°. The normal length of the first wall grid layer is 1.0×10-4m. Inflow condition：N2, $Ma_\infty = 20.2$, $T_\infty = 13.32K$, $T_w = 290K$, $\mathrm{Re}_\infty = 566$, $Kn_\infty = 0.047$, reference length $L_0 = 0.05m$ .We adopt improved Maxwell slip model, with the accommodation coefficient equal to 1 and using the improved heat flux model.

Heat flux distribution of slip boundary condition and non-slip boundary condition are compared with experiment in figure 2, which shows that our CFD project has a perfect match with the experiment.

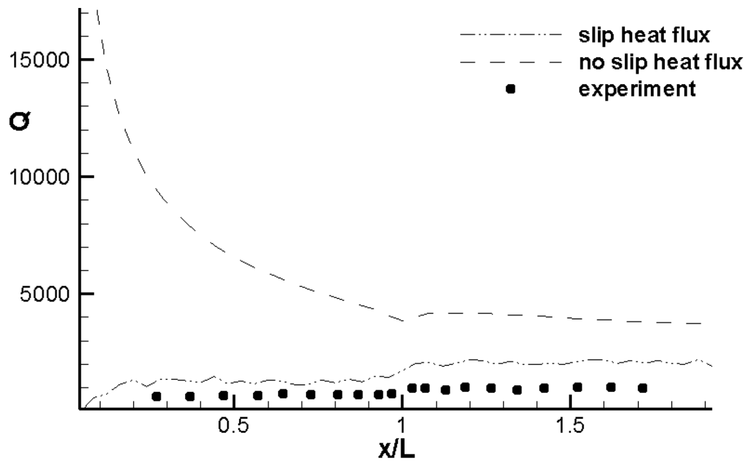

Fig.2. Comparison of heat flux distribution

The second example is spherical cone flow [19]，figure 3 shows the size and computational grid of this spherical cone, and experimental condition are set out in table 1.

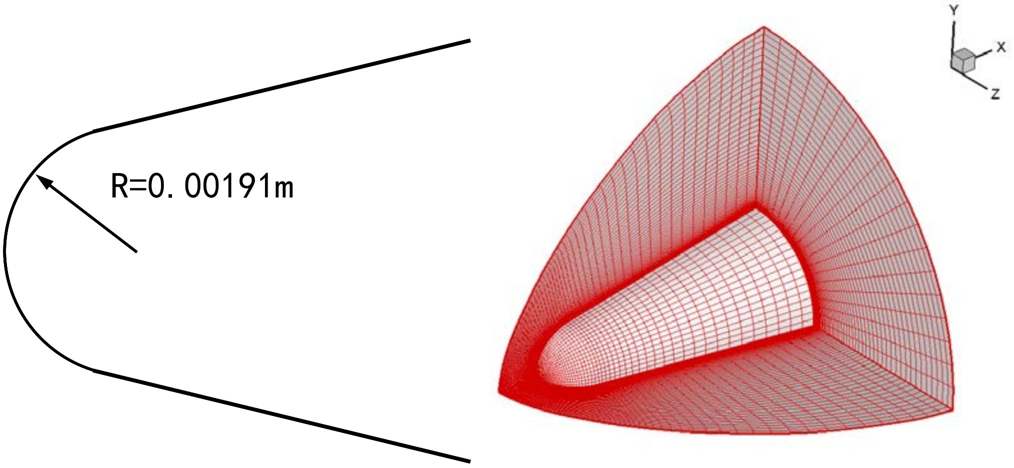

Fig.3. Spherical cone size and computational grid

Table 1 Experimental condition

Ma	18.2
Inflow temperature（K）	374.4
Inflow pressure（Pa）	177.9
Inflow Re	1017
Inflow density（kg/m3）	1.628e-03
Wall temperature（K）	1405
Inflow Kn	0.025

We can see from the isoline of Ma number and distribution of St number came out of calculation in figure 4 that airflow are severely compressed in the head of the spherical cone, and the arched shock nearly attached to the wall. The results of generatrix St number from calculation are comparatively consistent with experiment.

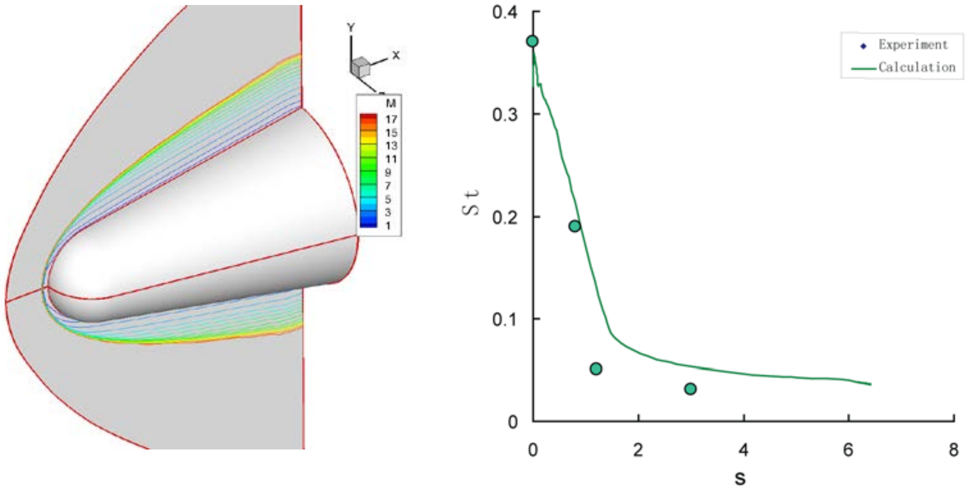

Fig.4. Isoline of Ma number and distribution of St number

4 Conclusion

In this study, we analysis the CFD code debugging, physical model analysis and numerical experiments on the numerical investigation of hypersonic slip flow. The comparison with experimental data above verified the accuracy of computational model and code derived here which can be used for further research.

5 Acknowledgement

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