Influence of boundary slip effect on thermal environment in thermo-chemical non-equilibrium flow

Wenbo Miao, *Junming Lv, Fei Huang and Xiaoli Cheng

China Academy of Aerospace Aerodynamics, P.O.Box 7201-16, Beijing 100074, China

*Corresponding author: junminglv@gmail.com

Abstract

A kind of new hypersonic vehicle makes long-time flight in transitional flow regime where boundary slip effect caused by low gas density will have an important influence on the thermal environment around the vehicles. Numerical studies on the boundary slip effect as hypersonic vehicles fly in high Mach number has been carried out. The method for solving non-equilibrium flows considering slip boundary, surface catalysis and chemical reactions has been built up, and been validated by comparing the thermal environment results with STS-2 flight test data. The mechanism and rules of impact on surface heat flux by different boundary slip level (Knudsen number from 0.01 to 0.5) has been investigated in typical hypersonic flow conditions. The results show that the influence mechanisms of boundary slip effect are different on component diffusion heat flux and convective heat flux; slip boundary increases the near wall temperature which diminish the convective heat; whereas enhances the near wall gas diffusion heat because of the internal energy's growing. Component diffusion heat flux takes a smaller portion of the total heat flux, so the slip boundary condition reduces the total wall heat flux. As Knudsen number goes up, the degree of rarefaction increases, the influences of slip boundary on convective and component diffusion heat flux are both enhanced, total heat flux grows by a small margin, and boundary slip effect is more distinct.

Keywords: Non-equilibrium, thermal environment, boundary slip, surface catalysis

Nomenclature

Symbols

C_i	mass fraction of species *i*
D_i	diffusion coefficient of species *i*
h_i	enthalpy of species *i*
K_n	Knudsen number
Ma	Mach number
P	Pressure
P_r	Prandtl number
q	heat flux
R	universal gas constant
T	temperature
U	velocity
α	accommodation coefficient for energy
ρ	density
μ	molecule viscosity

η	conductivity
λ	mean free path
γ	ratio of specific heat
σ	accommodation coefficient for moment
Subscripts	
i	species i
w	wall
s	slip boundary

Introduction

Continuum hypothesis will break down at high altitude where energy exchange between molecule and molecule, molecule and surface is inadequate. Scott (Scott, 1973) first presented the surface slip boundary conditions for a multi-component mixture with diffusion and surface recombination. In obtaining these boundary conditions, he used a first order velocity distribution function at the edge of the Knudsen layer next to the wall where velocity slips and temperature jumps. Gupta (Gupta, 1985) suggested that for an accurate prediction of the aerothermal environment of a hypersonic vehicle entering the Earth's atmosphere in low Reynolds number, or flight in high altitude regime, the multi-component, non-equilibrium gas chemistry, as well as the wall slip and catalysis effects, must be evaluated.

In the last three decades, a great deal of researches were undertaken to understand these surface slip effects. Based on STS-2 flight data, Zoby (Zoby, 1982), Scott (Scott, 1982), Daiß (Daiß, 1997) studied windward aero-heating of space shuttle with high angle of attack, when the flow condition is near rarefaction, Knudsen number from 0.001 to 0.03. Results show that besides the multi-component mixtures, non-equilibrium reactions and surface recombination, surface slip condition must be considered to obtain reasonable numerical results. Another typical research is validation of sharp and blunt 25° double cones. Several numerical methods were compared with a series of test data. Mesh distribution, difference schemes and surface slip conditions were analyzed. Results show that the pressure and heat transfer rate match well on the cone forebody, through the separation zone, and on the second cone, except that the heat transfer rate on the cone forebody is over predicted by about 20%.

In this paper, aeroheating mechanism of surface recombination with slip surface conditions was focused on. First of all, the numerical method applied in double cone and STS -2 flight mentioned above was evaluated. The validation showed good agreement with test data and flight data. Then aeroheating of a cone was studied with different surface catalytic conditions and different Knudsen number.

CFD methods

The CFD codes have been applied for several hypersonic researches. Basic equations are 3-D full Navier-Stokes equations with 7 species of air using Park's chemical reaction model[2]. For the time integration, Lower-Upper Symmetric Gauss-Seidel (LU-SGS) scheme is applied. Convective terms are discrete by AUSM+ scheme (Liou, 2003).

Surface slip boundary condition follows Davis's slip model (Davis, 1970), where velocity, temperature and mass fraction at the Knudsen layer are described with equations below. Local mean free path is decided by molecule viscosity and gas density. α and σ is respectively the accommodation coefficient for moment and energy, and the value is between 0 and 1.

$$U_S = \frac{2-\sigma}{\sigma}\lambda\frac{\partial U}{\partial n}|_0$$

$$T_S - T_w = \frac{2-\alpha}{\alpha}\frac{2-\gamma}{(\gamma+1)P_r}\lambda\frac{\partial T}{\partial n}|_0$$

$$C_{i,s} - C_{i,w} = \frac{2-\alpha}{\alpha}\sqrt{\frac{\pi}{2RT}}(D_i\frac{\partial C_i}{\partial n})|_0$$

$$\lambda = \frac{\mu}{\rho}\sqrt{\frac{\pi}{2RT}}$$

Full catalytic and non catalytic surface conditions are involved to describe surface recombination. Considering low surface temperature, mass fraction of species on surface is set equal to that of free stream for full catalytic condition. Heat transfer rate are solved by equations below, where first term is convective heat flux and the second term is mass diffusion heat flux.

$$q_{flux} = \eta \left.{\partial T}/{\partial n}\right|_s + \sum_i \rho D_i h_i \left.\frac{\partial C_i}{\partial n}\right|_s$$

Sharp Double Cone Test Validation (Candler, 2002)

Data from Runs 35 of the Holden's experiment (Harvey, Holden and Wadhams, 2001) is compared at Mach number equals 11.3. The test was performed in an impulse shock tunnel with nitrogen as the test gas. Calibration runs were made ahead to verify the uniformity of the flow in test section. The tests were carried out at the same nominal conditions as in calibration test. Because of the high temperature and pressure, a kind of molecule vibrational excitation would occur, so thermal non-equilibrium may be considered. In the simulation thermal equilibrium and chemical reactions are assumed, both no-slip boundary and slip boundary are employed. The flow condition at the nozzle outlet is shown in Table 1. Outline of the double cone is shown in Figure 1, with a 25° first sharp cone and a 55° second cone. The diameter of the base is 261.02 mm. Grid condition of these simulations is set as a symmetric structural form, grid number of streamwise, normal direction and circular direction is 281×161×33.

Table 1. Flow condition at the nozzle outlet

Ma	*Radius* /m^{-1}	*U*/m•s^{-1}	*T*/K	T_W/K	*P*/Pa
11.3	1.33×10^5	2.71×10^3	138.9	297	22.05

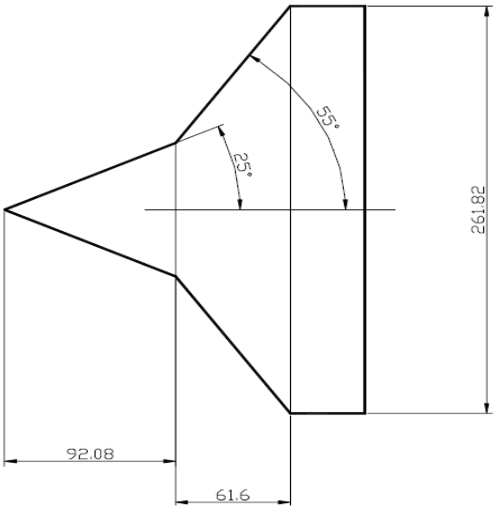


Figure 1. Outline of the sharp double cone (unit: mm)

Figure 2 shows the computed presure distribution and streamlines in the axisymmetric plane. An evident separate swirl can be seen in the corner. The pressure increases suddenly at the reattachment point.

Figure 3 shows the temperature profile with two different surface conditions. Flow structure is almost the same, but the separation area of slip wall is somewhat bigger than that of nonslip wall. Surface velocity slip makes more gas stay in the separation cornor that causes a bigger vortex. A depressed region on the separation bow shock is obsered where free stream forces separation shock moving towards the wall, pressure and heat transfer rate enhanced at streamwise *x*=0.13m as presented in Figure 4.

Figure 4 plots total heat transfer rate with two silp conditions along x direction, agreement between calculation and experiment is obained. Note that the length of separation zone and the peak heat rate match the test data well, except that 10% over prediction at the first cone. The difference between slip wall and nonslip wall is not significant. Surface slip decreases the heat transfer rate along the full cone.

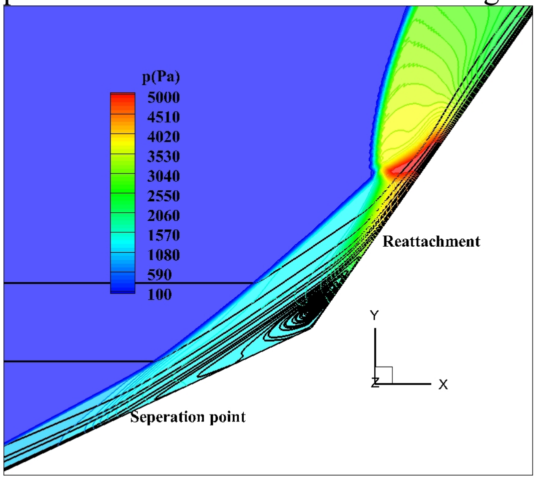


Figure 2. Pressure distribution and streamlines in the separation area

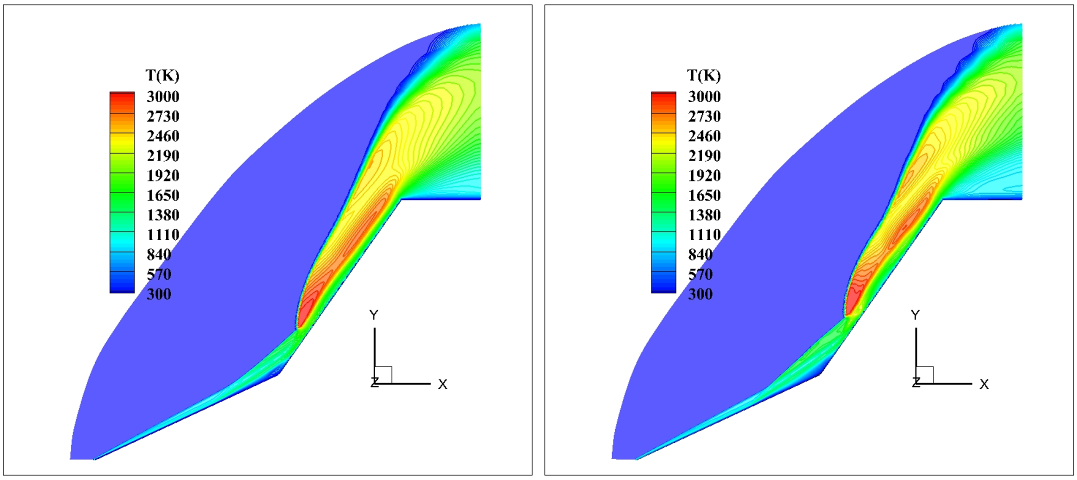


Figure 3. Temperature distribution in the flow field

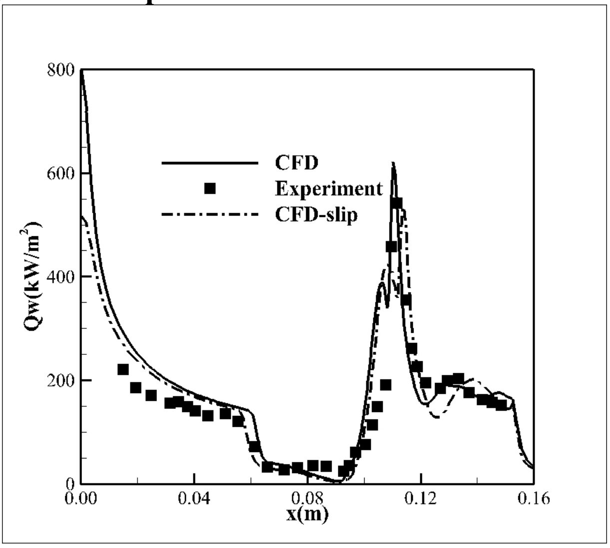


Figure 4. Heat transfer rate of double cone

Results and Discussion

STS-2 Flight Data Analysis

According to the trajectory of space shuttle, simulations are taken at H=92.35km and H=79.11km, where Knudsen number are 0.028 and 0.0023. Accommodation coefficients of 0.5 and 1 are considered with both full catalytic and non catalytic conditions. The flow at the trajectory point of Knudsen number equals 0.028 can be considered as a typical slip flow case.

Figure 5 plots the heat transfer rate of the calculation and flight data. Recombination coefficient of STS-2's TPS material is near zero, so the heat flux calculated with non catalytic condition is rational and close to the flight data. The agreement between the calculated and measured heat flux is poor when accommodation coefficient is set to 1. A possible reason for the discrepancies might be that the reasonable accommodation coefficient should be smaller than 1. Figure 5 shows that the agreement becomes better when accommodation coefficient is set to 0.5. Difference between two accommodation coefficients is large than 20%. When Knudsen number equals 0.0023, difference caused by accommodation coefficient is reduced to about 10%. It is guessed that the actual accommodation coefficient is close to 0 when flow is near free molecule flow.

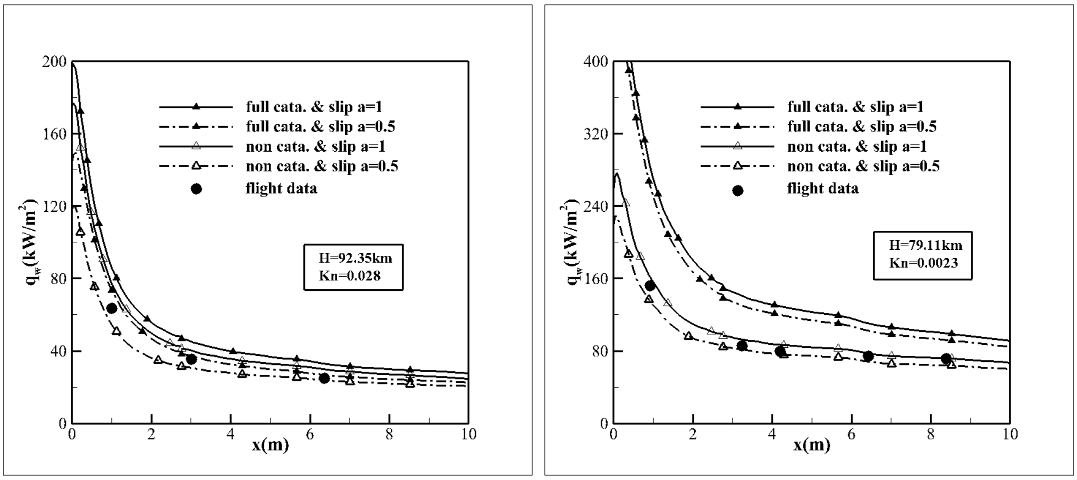


Figure 5. Comparison of heat transfer rate of STS-2 flight

Cone with Catalytic Conditions

Surface catalytic conditions with slip effect were studied. Based on a blunt cone, calculations were done with Knudsen number, which is the ratio of the mean free path to the cone diameter, equal 0.05, 0.01 and 0.00185. Both full catalytic and non catalytic condition was considered. For wall slip effect, accommodation coefficient was set to 1. Flow at *Ma* equals 20 involves intense chemical reactions behind the shock and increases the capability of atoms recombination near the wall. Table 2 shows the test configurations. Because the configuration is very simple grid number of streamwise, normal direction and circular direction is set as 61×161×33.

Table 2. Test configurations for catalytic and slip effects

Cases	Radius/m	Ma	Kn	T_W/K	Surface catalytic	Wall Slip
1	0.175	20	0.00185	300	Full catalytic/Non catalytic	Slip/Nonslip
2	0.175	20	0.01	300	Full catalytic/Non catalytic	Slip/Nonslip
3	0.025	20	0.05	300	Full catalytic/Non catalytic	Slip/Nonslip

Figure 6 shows comparison of slip and nonslip condition when Knudsen number is 0.05. Shock layer of slip wall is a little thicker than nonslip. The temperature behind the shock is higher. In contrast with the isothermal wall of 300K, slip temperature at the Knudsen layer is almost 2000K, which makes gas behind the shock dissociate more.

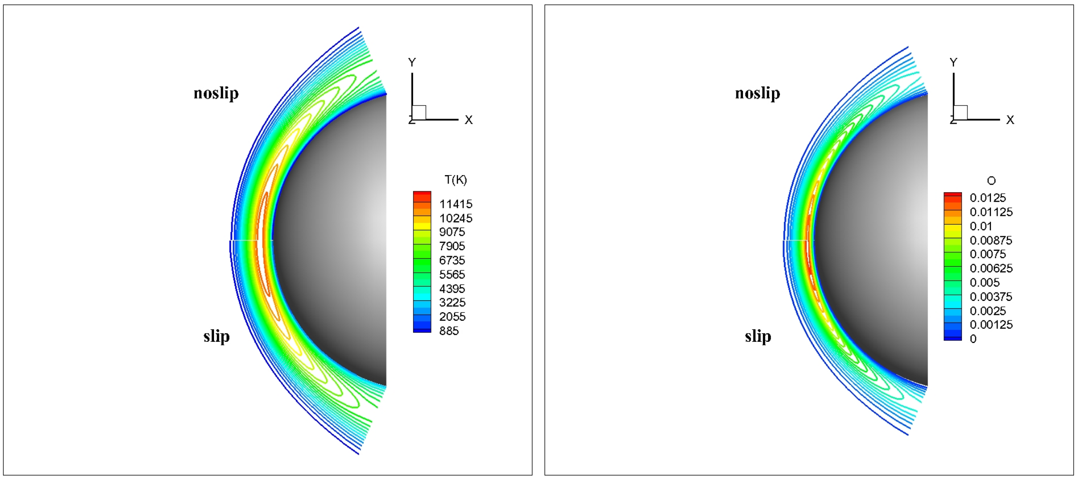
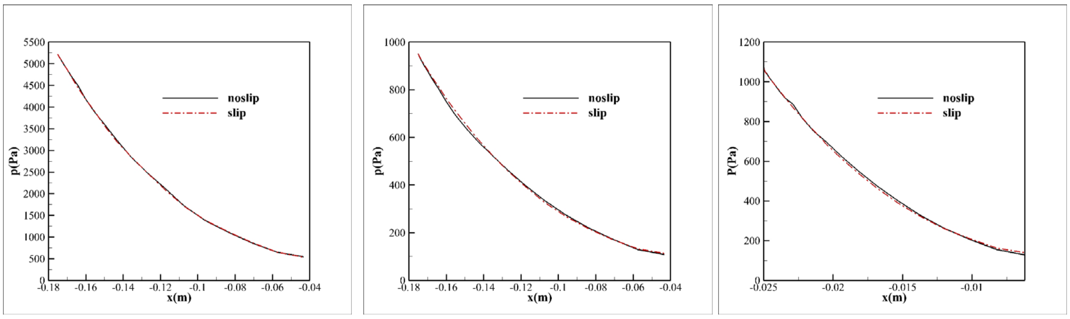


Figure 6. Comparison of temperature and O between slip and nonslip wall

Figure 7 shows surface pressure of different Knudsen number. Pressure with different slip conditions is almost the same at any Knudsen number. Considering slip surface effect is enhanced as Knudsen number goes up, the case of *Kn* equal 0.05 is chosen to analyze the mechanism.

Figure 8 shows the distribution of the heat transfer rate. Both differences between the mass diffusion heat flux and the convective heat flux are evident. Surface slip lead to higher surface temperature and better thermal conductivity which increases the mass diffusion heat transfer rate. On the other hand, the gradient of the temperature on the wall decreases when the surface slip temperature increases, which decreases the convective heat transfer rate.



***Kn*=0.00185** ***Kn*=0.01** ***Kn*=0.05**

Figure 7. Comparison of surface pressure

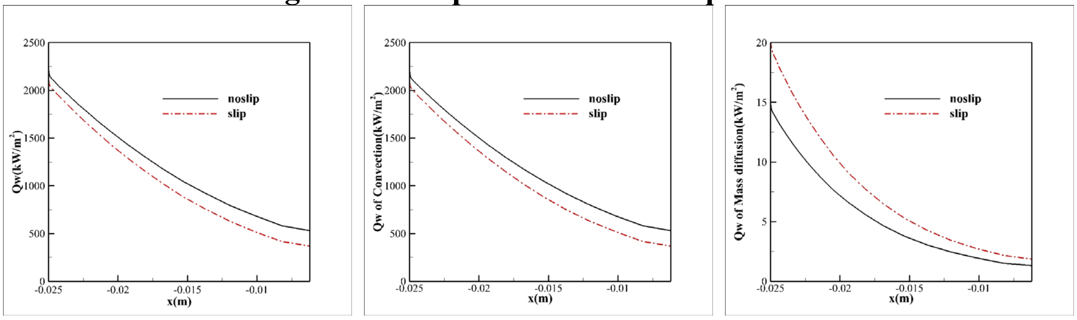
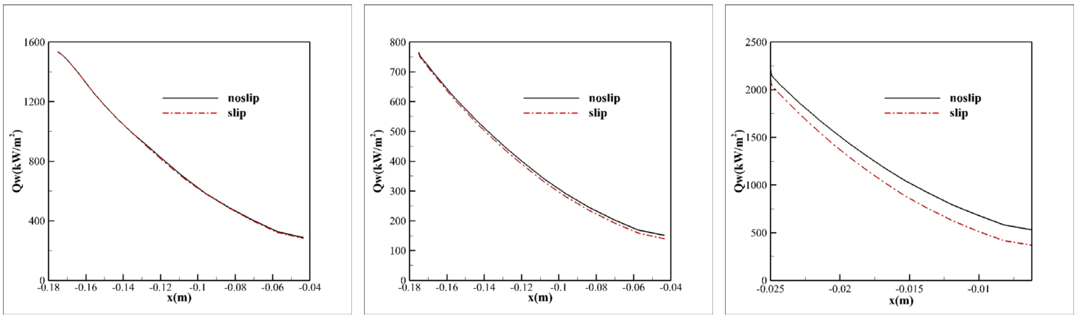


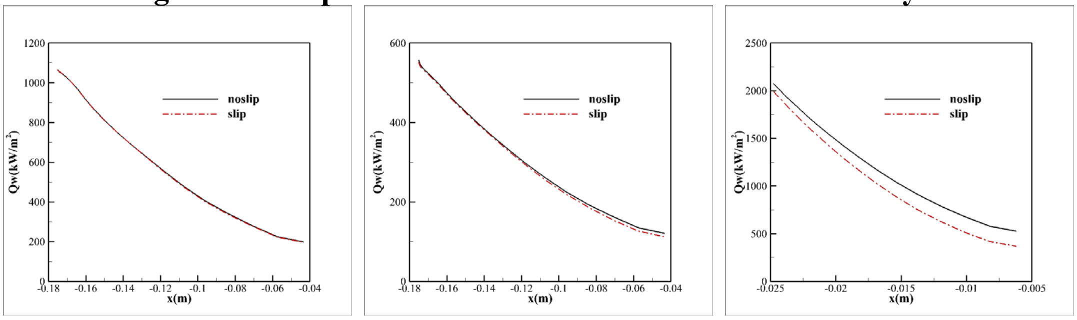
Figure 8. Heat transfer rate of *Kn*=0.05

Despite two mechanisms are widely divergent, total heat transfer rate keeps decreasing with slip wall condition. Figure 9 and Figure 10 show discrepancy between slip wall and nonslip wall with different catalytic surface. When Knudsen number is below 0.01, the difference of the total heat flux between two slip conditions is less than 5%. The difference increases to almost 20% when Knudsen number rises to 0.05. Meanwhile it can be found that the mass diffusion part of the heat flux decreases quickly as Knudsen number goes up. The reason is that low density reduces the chemical reaction rate and decreases the gas recombination on the wall.



***Kn*=0.00185** ***Kn*=0.01** ***Kn*=0.05**

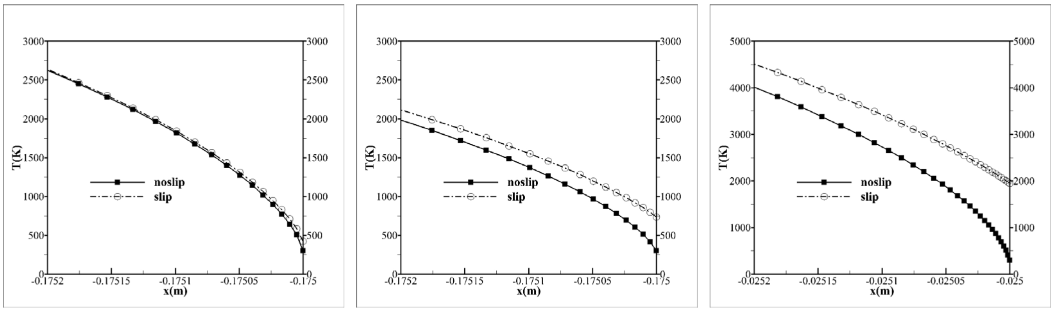
Figure 9. Comparison of heat transfer rate with full catalytic



***Kn*=0.00185** ***Kn*=0.01** ***Kn*=0.05**

Figure 10. Comparison of heat transfer rate with non catalytic

Figure 11 plots the temperature profile along the stagnation line. In despite of Knudsen number and chemical reaction, the temperature increases anyway. The discrepancy of temperature between slip wall and nonslip wall increases as Knudsen number rises.



***Kn*=0.00185** ***Kn*=0.01** ***Kn*=0.05**

Figure 11. Temperature along the stagnation line

Conclusions

Surface slip effect in hypersonic flow with chemical reactions was studied. Two cases were simulated and compared with test data to verify the numerical method. Slip and nonslip flow of a blunt cone were calculated to understand the mechanism of slip effect with different catalytic conditions. Some specific conclusions are:

1. Numerical method employed characterizes the double cone detail flow. The prediction of the heat transfer rate agrees well with the test data. Slip surface may somewhat enlarge the separation area and reduce the peak heat flux.

2. Accommodation coefficient in slip boundary model plays a key role in predicting the heat transfer rate. It functions importantly when Knudsen number get larger.

3. Surface slip leads to larger mass diffusion heat flux and smaller convective heat flux. When Knudsen number goes up, discrepancy between slip and nonslip wall get larger. Bigger Knudsen number which means smaller gas density slows down atoms recombination in chemical reactions.

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