Surface Recombination Effects on Surface Friction of Reentry Vehicles

Miao wenbo*, Huang fei, Zhang liang, Cheng xiaoli

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

Abstract

For the research needs on thermal environment of reentry vehicles, a simulation method is involved to study the surface recombination effect on surface friction by solving the 3-D Navier-Stokes equations. A CEV liked outline is involved to achieve the simulation. The results show that the surface friction differs from various catalytic conditions, and the difference is obviously around the high compressed area, but small in the major area and backward area. Surface recombination makes big molecule congregate to the wall, which causes larger velocity gradient and further surface friction. A flag flow is simulated to validate the hypothesis numerically. When Mach number and total enthalpy is equivalent, heavy gas leads to larger surface friction.

Keywords: Hypersonic; surface recombination; surface friction; Navier-Stokes equation

1. Introduction

As well as high speed and complicated flow structures, severe thermal environments are the typical characteristics of hypersonic vehicles. Taking moon exploration reenter for example, the capsule enters into the atmosphere at the speed of 12km/s, the Mach number is over 35, temperature after the shock is greater than 15000K where gas dissociate into atoms and electrons, a high enthalpy layer around the surface make the surface recombination effect ignorable.
NASA takes lot efforts on numerical simulation and experiment research of reentry vehicles, especially in Lunar Exploration Program and MARS Program, and knowledge of real gas effect on reentry vehicles is obtained [1-2], that is, surface recombination will dominate at the surface when gas after the bow shock dissociate evidently, atoms transform into molecule and release considerable energy, it is called surface recombination effect. Surface recombination will change the mixture composition and internal energy profile near the wall, the way and how it affects the thermal environment is known to a certain extent [3-5]. Surface recombination may increase the heat-flux on the wall by raise the gradient of mass diffusion, full catalytic heat rate may be 130% of non catalytic condition. How about the surface recombination effect on the local surface friction? That is a question and there are few literatures refer to this. Reynolds analogy theory mentions that there is a relationship between gradient of enthalpy and gradient of moment on the wall, which is the relation between heat transfer rate and surface friction. Surface recombination effect on surface friction of hypersonic vehicles is worth to study. The exact evaluation of surface friction will help to model and estimate shear resistance of thermal protection material.

A CEV liked reentry capsule is studied in this article to analyze surface recombination effect on surface friction, a numerical method is involved to simulate the hypersonic flows with different surface catalytic conditions. Full catalytic condition and non catalytic condition are considered in the research.

2. CFD method

Governing equation used here is based on 3-d reacting Navier-Stokes equations, hypothesis is involved that the flow is chemical non-equilibrium and thermo-equilibrium, gas radiation and inertial force is neglected, mass diffusion follows two-species gas diffusion model [6].

The CFD codes have been applied for several hypersonic researches. Park’ 7-species and 6-reaction model is involved to describe the chemical procession; the chemical kinetics includes gas dissociation and ionization [7-8]. For the time integration, Lower-upper symmetric Gauss-Seidel (LU-SGS) scheme is applied. Convective terms are modeled by AUSM+ scheme in the second order accuracy in space integration [9-11].

Validation of the CFD method is carried out with a test data of 2-d compressed corner [12]. Flow condition is set below, Mach number of free stream flow is 14.1, temperature is 72.2K and Reynolds number when reference length \( L = 0.439 \) m is 104000. Figure 1 shows profile of surface pressure and surface friction along x direction. Present calculations agree with Holden’s test data and Hung’s test data very well.

![Fig.1 Validation of compressed corner](image)

3. Results and Discussion

Firstly a CEV liked hypersonic blunt body is studied, four flight conditions covering large velocity and altitude range are involved[13]. This blunt body is like an inverted bell which contains a spherical crown and a 35° taper. Figure 2 shows outline and surface mesh of the blunt body. Flow configurations shown in Table 1, angle of attack is
20, surface temperature is set as 300K. Surface of the vehicle is set as isothermal wall and full catalytic condition and non catalytic condition is involved. When Ma=29.38, violent chemical reaction takes place after bow shock, dissociated gas provides enough surface recombination at the wall which leads to evident surface recombination effect. Reynolds analogy theory shows that there is a relationship between heat transfer rate and surface stress.

<table>
<thead>
<tr>
<th>Case</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mach number</td>
<td>29.38</td>
<td>25.25</td>
<td>18.19</td>
<td>12.81</td>
</tr>
<tr>
<td>Height(km)</td>
<td>64.92</td>
<td>59.</td>
<td>48.3</td>
<td>37.2</td>
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</tbody>
</table>

Figure 3 shows comparison of surface friction along windward generatrix between two catalytic conditions. The minimum locates at the physical stagnation where surface friction is almost zero and the maximum locates at the shoulder where gas begins to expand. There is evident gap between two catalytic conditions when Mach number is over 20, while violent chemical reaction occurs after the bow shock and surface recombination release giant heat. Difference between two catalytic conditions is over 20% when M=29.38. Surface friction with full recombination at the shoulder is almost 20 Pa higher than non recombination. Gas dissociation and surface recombination will abate when Mach number diminishes, thus the difference fall to zero when M=12.81. Figure 4 shows comparison of heat transfer rate along windward generatrix between two catalytic conditions. The figure verifies that Reynolds analogy theory is still valid when surface catalytic condition varies. Surface recombination affects the heat transfer rate and surface friction alike.
Reynolds analogy theory shows that heat transfer rate and surface friction is analogous in a certain extent, there is a similar mechanism between conductive heat transfer and Reynolds stress. When mass diffusion heat transfer is
considered, is the mechanism still available? Generally, surface recombination changes the distribution of mass fraction and temperature near the wall. Atoms recombine to molecule at the wall which increases molecule weight of the mixture. Because pressure and temperature is almost the same with different surface catalysis, higher molecule weight will lead to higher gas density at the wall. Figure 5 shows density distribution of two surface catalytic conditions at position $y=1\times10^{-6}$ m. Gas density differs distinctly. So we form a hypothesis that does inertia of motion help weighty gas keep higher velocity and produce higher surface friction.

![Fig. 5 Density distribution at position $y=1\times10^{-6}$m](image)

A flag flow is involved to validate the hypothesis advanced in the last paragraph. Considering that oxygen and nitrogen have similar physical and chemical characteristic, and oxygen is weight than nitrogen at same pressure and temperature condition. Medium of the flow is set as oxygen and nitrogen. Two flows have same Mach number, total pressure and total enthalpy. Table 2 shows the flow configurations of the validation. Length along stream direction is 1 meter, surface temperature is set as 300K, and the minimum grid scale is equal to $1\times10^{-5}$ m.

<table>
<thead>
<tr>
<th>Case</th>
<th>Medium</th>
<th>Ma</th>
<th>$T_\gamma$(K)</th>
<th>$P_\gamma$(Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$N_2$</td>
<td>6</td>
<td>200</td>
<td>100</td>
</tr>
<tr>
<td>2</td>
<td>$O_2$</td>
<td>6</td>
<td>228.57</td>
<td>100</td>
</tr>
</tbody>
</table>

Figure 6 shows comparison of surface friction of oxygen and nitrogen. Surface friction of oxygen is bigger than nitrogen. Figure 7 shows $U$ velocity distribution of two surface catalytic conditions at four $y$ positions. Bigger molecule keeps his velocity more easily in the boundary layer. Difference of the $U$ velocity between two flows decreases when flow leaves away from the surface. Thickness of boundary layer at $x=1$ m is almost $2\times10^{-2}$ m, difference of the $U$ velocity decreases to zero at the above of position $y=2\times10^{-2}$ m.
4. Conclusion

Surface recombination effect on surface friction of hypersonic flow with chemical reactions was studied. A numerical method is involved and a 2-d compressed corner case is simulated and compared with test data to verify the numerical method. A CEV liked vehicle is studied with different catalytic conditions, some specific conclusions are:

1. Surface recombination will increase surface friction. As soon as surface recombination release more energy on the wall, it produces larger surface friction. When $M=29.38$, it produces almost 20 Pa difference on the shoulder between full catalytic condition and non catalytic condition.

2. Surface recombination makes more molecules congregate on the wall, which have strong inertia and cannot be slowed down easily, a hypothesis is formed that inertia of motion help weighty gas keep higher velocity and produce higher surface friction.

3. A flag flow is simulated to validate the hypothesis numerically. When Mach number, total enthalpy and total pressure is equivalent, heavy gas leads to larger surface friction along x direction. U velocity of oxygen at the same y position is always bigger than nitrogen, and the two comes to equal outside of the boundary layer.

References