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# Numerical investigation of dynamic properties of plasma sheath with pitching motion

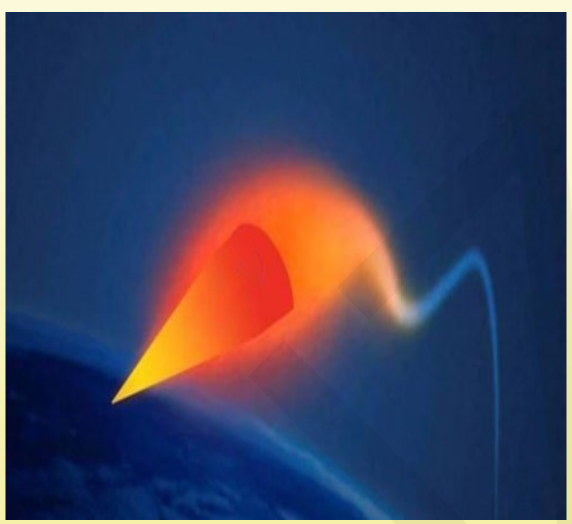
**Key words:**

plasma sheath; dynamic; thermodynamic non-equilibrium; rarefied flow

# Research background and significance

Key support technologies in the adjacent space vehicle technology and application research program

propulsion | aerodynamic | communication | measurement | structure | heat protection



ionization blackout problem

The first challenge of reliable communication and control of adjacent space vehicle: plasma sheath



➢Most previous research on the plasma sheath treats it as static, but the distribution of a plasma sheath for a reentry vehicle is definitely dynamic in practice.

➢ Research on the dynamic properties of a plasma sheath coupled with pitching motion of the vehicle has great significance in solving the problem of communication interruption in the process of vehicle reentry.

# Governing equations

The governing equations of a plasma flow field based on NS equations can be summarized as :

$$\frac{\partial \boldsymbol{Q}}{\partial t}+\frac{\partial \boldsymbol{E}}{\partial x}+\frac{\partial \boldsymbol{F}}{\partial y}+\frac{\partial \boldsymbol{G}}{\partial z}+\frac{\partial \boldsymbol{E}_{\mathbf{v}}}{\partial x}+\frac{\partial \boldsymbol{F}_{\mathbf{v}}}{\partial y}+\frac{\partial \boldsymbol{G}_{\mathbf{v}}}{\partial z}=\boldsymbol{S},$$

In order to simulate rarefied flow, the simplified conventional Burnett equations (SCB) (Zhao et al., 2015) are used, and these are applicable to the simulation of hypersonic rarefied flow. The high-order stress and heat flow terms can be written:

$$\tau_{ij}=\tau_{ij}^{(1)}+\tau_{ij}^{(2)}=-2\mu\overline{\frac{\partial u_i}{\partial x_j}}+K_1\frac{\mu^2}{p}\frac{\partial u_k}{\partial x_k}\overline{\frac{\partial u_i}{\partial x_j}}+$$

$$K_2\frac{\mu^2}{p}\left(-\overline{\frac{\partial u_k}{\partial x_i}\frac{\partial u_j}{\partial x_k}}-2\overline{\overline{\frac{\partial u_i}{\partial x_k}}\frac{\partial u_k}{\partial x_j}}\right)+K_6\frac{\mu^2}{p}\overline{\overline{\frac{\partial u_i}{\partial x_k}\frac{\partial u_k}{\partial x_j}}},$$

$$q_i=q_i^{(1)}+q_i^{(2)}=-\kappa\frac{\partial T}{\partial x_i}+\theta_1\frac{\mu^2}{\rho T}\frac{\partial u_k}{\partial x_k}\frac{\partial T}{\partial x_i}+$$

$$\theta_2\frac{\mu^2}{\rho T}\left[\frac{2}{3}\frac{\partial}{\partial x_i}\left(T\frac{\partial u_k}{\partial x_k}\right)+2\frac{\partial u_k}{\partial x_i}\frac{\partial T}{\partial x_k}\right]+$$

$$\left(\theta_3\frac{\mu^2}{\rho p}\frac{\partial p}{\partial x_k}+\theta_4\frac{\mu^2}{\rho}\frac{\partial}{\partial x_k}+\theta_5\frac{\mu^2}{\rho T}\frac{\partial T}{\partial x_k}\right)\overline{\frac{\partial u_k}{\partial x_i}}.$$

# Chemical Kinetic Models

The gas-phase chemical reaction in weakly ionized reentry flow fields are simulated using the Gupta's 7-species air model and the following species may appear in plasma sheath: O, N, O2, N2, NO, $NO^+$, and e, with the chemical reactions as follows:

$$O_2 + M \rightleftharpoons 2O + M \qquad (1)$$

$$N_2 + M \rightleftharpoons 2N + M \qquad (2)$$

$$N_2 + N \rightleftharpoons 2N + N \qquad (3)$$

$$NO + M \rightleftharpoons N + O + M \qquad (4)$$

$$NO + O \rightleftharpoons O_2 + N \qquad (5)$$

$$N_2 + O \rightleftharpoons NO + N \qquad (6)$$

$$N + O \rightleftharpoons NO^+ + e^- \qquad (7)$$

# Numerical Computation Methods

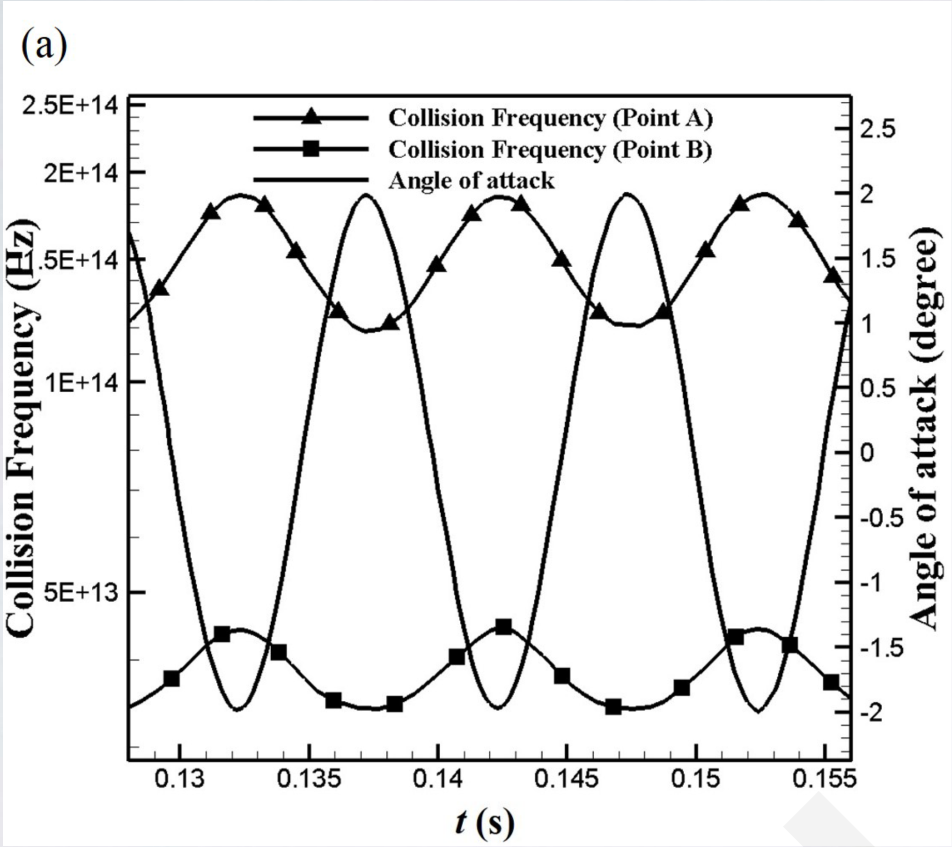
**Numerical Format**

- Refactoring Format ：MUSCL+Van Albada limiter
- Flux Format：Harten-Yee TVD
- Time Format：LU-SGS

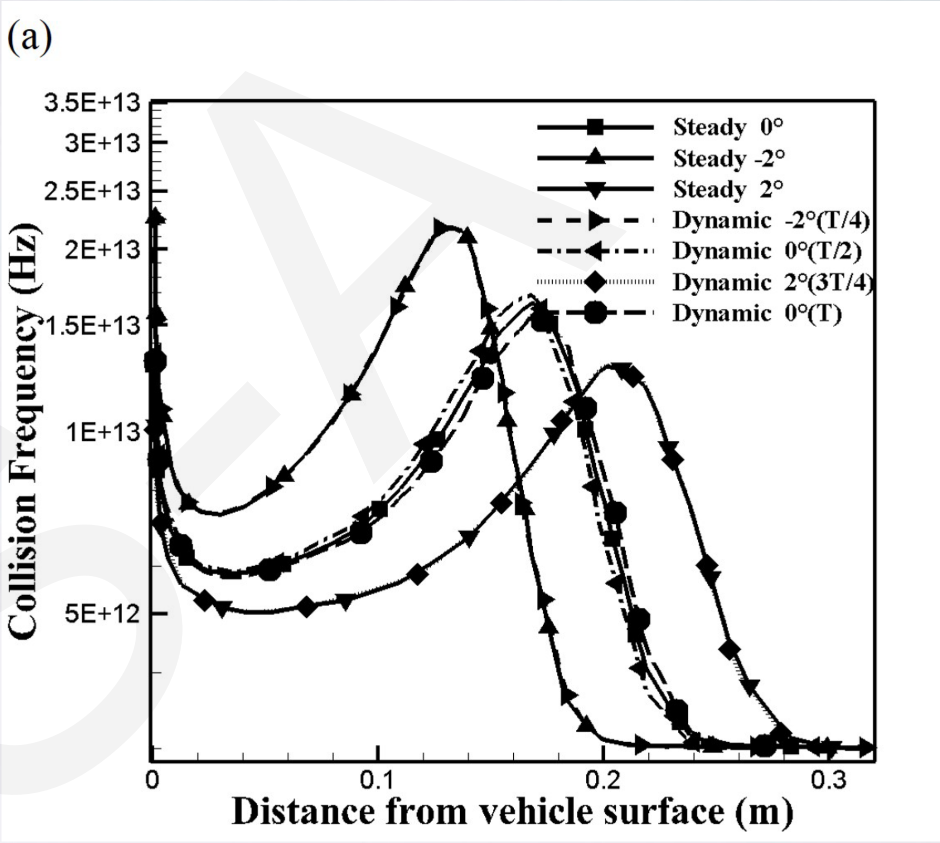
**Physical Model and Boundary Conditions**

- Viscosity Coefficient：Sutherland
- Boundary Condition：Supersonic Inflow/Outflow, first-order Maxwell slip isothermal wall

# Simulation Results and Discussions




Plasma collision frequency for RAM-C II vehicle at 71km (a)




Plasma collision frequency normal to the surface at 71km (a)

- After the introduction of vehicle pitching motion, the dynamic results are more consistent with the experimental data than the simulated results when treating it as static state.
- The plasma sheath characteristic parameters show periodic properties, whose changing period is the same as the pitching motion period.
- Because of the different velocity of the pitching motion, phase shifts exist in different positions of the vehicle.
- The enhancement of the rarefied effect weakens the disturbance to the plasma sheath.
- This research reveals the distribution and regularities of the dynamic plasma sheath.

# Perspectives and Research Priorities

Research Priorities:

- The method of steady and dynamic plasma sheath simulation for rarefied flow is proposed.
- The numerical comparison and verification are carried out by different chemical reaction kinetics models.
- The time-varying plasma sheath caused by the vehicle pitching motion is studied for the RAM-C II vehicle.

This research reveals the distribution and regularities of the dynamic plasma sheath. It has significance for solving the ionization blackout problem and the design of the reentry vehicle, and provides more reliable data for further research on the dynamic plasma sheath. However, this paper only studies the dynamic characteristics of the plasma sheath with pitching motion. More forms of dynamic properties can be studied to gain a more comprehensive understanding.