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# Analysis of weakly ionized ablation plasma flows for a hypersonic vehicle

Chun Shao [a], Liang Nie [b], Weifang Chen [a,*]

[a] College of Aeronautics and Astronautics, Zhejiang University, Hangzhou 310027, China
[b] Science and Technology on Space Physics Laboratory, Beijing 100076, China

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ABSTRACT

Hypersonic vehicles are enveloped by a plasma sheath that affects the data transmission and object identification. This paper develops a numerical methodology based on Magnetohydrodynamics equations to study the electromagnetic environment of hypersonic vehicles under the condition of carbon-based thermal protection material ablation. A surface ablation model considering the oxidation and sublimation ablation process is coupled with a Navier–Stokes solver by a gas–solid interaction method to simulate the ablation plasma flows. A piecewise linear current density recursive convolution finite-difference time-domain method is applied to further analyze the interaction between the incident electromagnetic wave and the plasma sheath. The computational results for an HTV-2 type vehicle indicate that both ablation and non-ablation plasma sheaths have significant effects on the electromagnetic environment of the vehicle. Compared with a non-ablation plasma sheath, ablation results in a decrease in the number of electrons and increases the number of neutral particles and therefore changes characteristic parameters of the plasma. Details of the electromagnetic scattering characteristics are reported to highlight the influences of ablation on the reflectivity, penetrability, and absorptivity of the plasma sheath for incident electromagnetic waves over different bands.

## 1. Introduction

Strong shock waves form in front of hypersonic vehicles and translate part of the kinetic energy of the vehicles into internal energy of the air. As a result, the air temperature rises precipitously, and chemical reactions occur. Meanwhile, high temperature gas heats the vehicle surface, causing the ablation of thermal protection material covering the vehicle. A large number of neutral particles, free electrons and ions are produced in these reactions, and they form a plasma sheath around the vehicle. The plasma sheath results in the reflection, absorption and scattering of the electromagnetic wave. The complex electromagnetic environment significantly influences data transmission between base stations and vehicles as well as the object identification of vehicles. Many research studies have been carried out on the simulation of the plasma sheath, the interaction mechanism between the incident electromagnetic wave and the plasma sheath, and plasma density reduction techniques [1–4]. Despite recent progress, the simulation of the electromagnetic environment of a realistic hypersonic vehicle under the conditions of ablation is still a challenging issue due to the complex physical and chemical processes, as well as the sophisticated coupling relationships between the flow and electromagnetic fields in the governing equations.

The formulation of Magnetohydrodynamics (MHD) governing equations has become an effective prediction method for aerodynamics and electrodynamics coupled system [5]. Numerical solutions of MHD equations include two general categories, coupling and decoupling methods, each with their applicable targets. Coupling method is applied for the control of high-speed ionized flows with high-intensity magnetic fields [6,7]. However, multiscale stiff problems, as well as spurious magnetic field divergence introduced by numerical errors, influence the computational efficiency and accuracy of complete MHD equations solutions. Meanwhile, the decoupling method is commonly used in the simulation of plasma flows with low-intensity magnetic fields [8,9] but decoupling criterions have not yet been systematically evaluated. Consequently, the applicability of decoupling method is discussed as a focus of this study.

In the study of the ablation plasma flow field, a thermal protection material ablation reaction model is the research focus. Based on the JANAF sublimation carbon group model [10], two types of surface ablation models named after the chemical equilibrium model [11] and the finite rate model [12,13], have been devel-

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* Corresponding author.
*E-mail address:* chenwfnudt@163.com (W. Chen).

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## Nomenclature

| | | |
|---|---|---|
| $\boldsymbol{B}$ | magnetic flux density | T |
| $C$ | species mass fraction | |
| $c$ | speed of light | |
| $c_p$ | specific heat capacity | J/(kg·K) |
| $D$ | diffusion coefficient | $m^2/s$ |
| $\boldsymbol{E}$ | electric field intensity | V/m |
| $e_t$ | total internal energy per unit mass | J/kg |
| $e_v$ | vibrational energy per unit mass | J/kg |
| $e$ | electronic charge, $1.6022 \times 10^{-19}$ C | |
| $f$ | incident wave frequency | Hz |
| $f_p$ | characteristic frequency | Hz |
| $\boldsymbol{H}$ | magnetic field intensity | A/m |
| $h$ | enthalpy | J/kg |
| $\boldsymbol{J}$ | polarization current density | $A/m^2$ |
| $Kn$ | Knudsen number | |
| $k_{f,j}$ | forward reaction rate | $m^3/(mole \cdot s)$ |
| $k_{b,j}$ | backward reaction rate | $m^3/(mole \cdot s)$ |
| $L$ | characteristic length | m |
| $M$ | species molar mass | |
| $m_e$ | electron mass, $9.1094 \times 10^{-31}$ kg | |
| $\dot{m}$ | mass flux rate | $kg/(m^2 \cdot s)$ |
| $n_e$ | electron density | $No./m^3$ |
| $n_m$ | neutral particle density | $No./m^3$ |
| $p$ | pressure | Pa |
| $Pr$ | Prandtl number | |
| $q_{vx}$ | vibrational heat flux terms in $x$ direction | $J/(m^2 \cdot s)$ |
| $q_x$ | translational–rotational heat in $x$ direction | $J/(m^2 \cdot s)$ |
| $\dot{q}$ | heat flux per unit area | $W/m^2$ |
| $Re$ | Reynolds number | |
| $Sc$ | Schmidt number | |
| $\boldsymbol{S}$ | strain rate | $s^{-1}$ |
| $T$ | translational–rotational temperature | K |
| $T_r$ | chemical reaction governing temperature | K |
| $T_v$ | vibrational temperature | K |
| $T_e$ | electron temperature | K |
| $v_e$ | collision frequency | Hz |
| $\boldsymbol{V}$ | velocity | m/s |
| $X_i$ | species mole fraction | |
| $Y$ | element mass fraction | |
| $\gamma$ | specific heat ratio | |
| $\eta$ | outward coordinate system normal to surface | m |
| $\eta_e$ | wave impedance | Ω |
| $\mu$ | viscosity coefficient | kg/(m·s) |
| $\mu_e$ | magnetic permeability | H/m |
| $\lambda_p$ | heat conductivity coefficient | W/(m·K) |
| $\lambda$ | mean free path of gas molecules | m |
| $\delta$ | grid size | m |
| $\tau$ | stress tensor | $N/m^2$ |
| $\rho$ | density | $kg/m^3$ |
| $\varepsilon_s$ | surface emissivity | |
| $\varepsilon_r$ | relative permittivity | |
| $\varepsilon$ | permittivity | |
| $\sigma$ | specific conductance | S/m |
| $\sigma_0$ | Stefan–Boltzmann constant | |
| $\upsilon$ | velocity component normal to surface | m/s |
| $\Phi$ | dissipation function | |
| $\dot{\omega}$ | species production rate | $kg/(m^3 \cdot s)$ |
| $\dot{\omega}_e$ | source term of vibrational energy and electronic energy | |

*Subscripts*

| | |
|---|---|
| $i$ | species |
| $j$ | the direction of $x$, $y$, or $z$ |
| $k$ | element |
| $s$ | solid property at gas–solid interface |
| $w$ | gas property at gas–solid interface |
| $\infty$ | freestream conditions |

oped. The predicted ablation rate and the surface temperature show a good agreement with experimental data for these models [14–16]. In addition, the collision integrals governing the transport properties as well as the rate coefficients of the reactions have also been measured [17] and several gas–solid interaction methods have been studied including uncoupled, partially coupled and fully coupled methods [18]. The details of the model construction are presented in the following sections.

In the research on the electromagnetic scattering characteristics, the finite-difference time-domain (FDTD) method, as a type of classic full-wave time-domain electromagnetic field analysis algorithm, is widely used because of its high versatility [19]. Since Yee [20] used a difference scheme for numerically discrete Maxwell curl equations with time variables in a structured grid discrete space for the first time, various types of FDTD methods have been developed [21–24]. Among these methods, the piecewise linear current density recursive convolution finite-difference time-domain (PLJERC-FDTD) method is a mature method and the accuracy and efficiency of this method have been confirmed by several studies about the interaction mechanism between the electromagnetic wave and the plasma [25–28]. As a result, we selected the PLJERC-FDTD method to predict the electromagnetic environment in this paper.

The objective of this paper is to develop appropriate computational methods for capturing the key parameters of the ablation plasma sheath and, furthermore, to reveal the mechanism by which the ablation influences the electromagnetic characteristics of a realistic hypersonic vehicle. The coupling terms between the fluid field and electromagnetic field in MHD equations are examined by magnitude analysis for further use in a hypersonic weakly-ionized plasma. Numerical approaches including a thermochemical nonequilibrium model, a surface ablation reaction model and the PLJERC-FDTD method are applied to simulate the characteristics of the complicated ablation plasma flows. The accuracy of the numerical methodology is tested and the simulation results for a Hypersonic Technology Vehicle #2 (HTV-2) type vehicle are discussed.

## 2. Computational methods

### 2.1. Governing equations

For the nonmagnetic and collisional plasma, the MHD equations can be represented in the following form:

$$\frac{d\rho}{dt} + \rho \nabla \cdot \boldsymbol{V} = 0 \tag{1}$$

$$\rho \frac{d\boldsymbol{V}}{dt} = -\nabla p + \nabla \cdot (2\mu \boldsymbol{S}) - \frac{2}{3}\nabla(\mu \nabla \cdot \boldsymbol{V}) + \boldsymbol{J} \times \boldsymbol{B} \tag{2}$$

$$\rho \frac{de_t}{dt} = -p\nabla \cdot \boldsymbol{V} + \Phi + \lambda_p \nabla^2 T + \boldsymbol{E} \bullet \boldsymbol{J} \tag{3}$$

$$\boldsymbol{J} = \sigma(\boldsymbol{E} + \boldsymbol{V} \times \boldsymbol{B}) \tag{4}$$

$$\nabla \times \boldsymbol{E} = -\mu_e \frac{\partial \boldsymbol{H}}{\partial t} \tag{5}$$