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# Effects of weakly ionized hypersonic flow on propagation of terahertz wave

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**Abstract:** The plasma sheath produced in the progress of entry or reentry flight has attracted much attention as it would impact the propagation of electromagnetic wave. This plasma sheath is a group of weakly ionized gas in general and has the ability to influent the communication between aero craft and ground. Sometimes the existence of this plasma sheath even cloud cause the communication blackout which is not desirable. To improve this problem plenty of researches have done, some of the researches mentioned that raising the wave frequency could be one way. The development of intensive terahertz sources broke up the restrain of electromagnetic wave in microwave range, there comes out several researches on the interaction between terahertz wave and plasma. Computational fluid dynamics was used in numerical simulating of a thermodynamics and chemical nonequilibrium flow over the aero craft to calculate the electromagnetic characteristics of plasma layer. Four flight scenes and different incidence forms were taken to discuss the interaction between terahertz wave and plasma sheath. And the propagation of terahertz wave along with different paths was discussed. From the simulating results, terahertz wave is capable to transmit in the plasma sheath with high electron density when the flight height is lower.

**Key words:** terahertz wave;　hypersonic;　plasma

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# 弱电离高超声速流场对太赫兹波传播影响

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**摘　要:** 在再入飞行过程中生成的等离子体鞘套对电磁波传播的影响引起了很多的关注。包覆飞行器的等离子体鞘套通常为一团弱电离的气体。等离子体鞘套的存在会影响飞行器与地面间的通信,甚至带来通讯黑障问题。为了解决这一问题,进行了大量的研究并提出提高电磁波频率可以成为一种解决方式。随着可以生成高强度太赫兹源的设备出现,电磁波与等离子体间相互作用在微波波段

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的研究局限被打破，高频率的太赫兹波与等离子体间的相互作用也引起了更多关注。通过计算流体力学方法对包覆飞行器的热力学和化学动力学非平衡流体进行数值计算可以得到包覆高超声速飞行器的流场分布，以此可以得到等离子体鞘套的电磁特性。通过数值计算得到四种飞行场景下的等离子体鞘套，并分析了不同传播路径下太赫兹波与等离子体鞘套的相互作用，结果表明：当飞行高度较低，鞘套等离子体密度较大时，太赫兹波具有穿过等离子体鞘套的能力，可以为通讯黑障问题的解决提供理论支持。

**关键词：** 太赫兹波； 高超声速； 等离子体

## 0 Introduction

During the hypersonic flight such as entry of spacecraft or reentry of vehicle, a shock wave forms and much of the kinetic energy would be converted into heat therefore increases the temperature. The high temperature cause the dissociation and ionization of molecules in air. Thus a plasma layer which is referred to as the plasma sheath is created around the leading edge of the aerocraft. Unfortunately, this plasma sheath could impact the transmission of information even causes "communications blackout"[1-2]. Works have done in different aspects such as plasma control or utilizing the nonlinear properties[3] to improve this situation. Due to the exploration of researches on terahertz wave[4-6], EM wave in terahertz range could be used to solve this problem as it has the ability to penetrate the over dense plasma. Therefore the investigation of interaction between EM wave and plasma would be a significative work. In our previous works[7], effects of inhomogeneousity of collision frequency were discussed. As many works have pointed out the improvement of un-uniform of electron density, there is a conclusion that for better results profiles of both the parameters are needed. As the developing in numerical simulation of flows, it could be used to simulate the producing of plasma sheath. By introducing the simulating results of flow field, the electromagnetic characteristics of the plasma layer could be got. Then the interaction between EM wave and plasma sheath could be investigated.

In this paper, numerical simulating result of flow field around a blunted cone is promoted and four flight scenes are chosen for discussion. The incident wave propagate through plasma layer achieves at the surface of spacecraft and reflected, then get out through the layer again. Frequency of incident wave is in the terahertz range and it is assumed that the EM wave launches on the plasma layer at different angels and locations.

## 1 Numerical simulation of flow

### 1.1 Modeling

In this section the method used in numerical simulating of flow field is afford. It is assumed that the fluid accords with the continuum approximation and can be weakly ionized. Two-temperatures model is applied that $T$ is assumed to describe the rotational and translational energy modes of all species and the electron energy and vibrational energy are described by $T_v$. The conservation equations for the two-dimensional system can be written as[8]:

$$\frac{\partial U}{\partial t}+\frac{\partial(F-F_v)}{\partial x}+\frac{\partial(G-G_v)}{\partial y}=W \tag{1}$$

where $U$ is the vector of conserved variables; $F$, $F_v$ describe the inviscid and viscous flux vector components in the $x$ direction respectively; $G$, $G_v$ are in the $y$ direction which calculated similarly with $F$, $F_v$. They are given as following:

$$U=\left\{\begin{matrix}\rho_{1\cdots ns}\\ \rho u\\ \rho v\\ E\\ E_v\end{matrix}\right\},F=\left\{\begin{matrix}\rho_{1\cdots ns}u\\ \rho u^2+p\\ \rho uv\\ (E+p)u\\ E_v u\end{matrix}\right\},$$

$$F_v=\begin{Bmatrix} -J_{x,1\cdots ns} \\ \tau_{xx} \\ \tau_{xy} \\ \tau_{xx}u+\tau_{xy}v-q_{tx}-q_{rx}-q_{vx}-\sum(\rho_s h_s u_{d,s}) \\ -q_{vx}-\sum(\rho_s e_{vs} u_{d,s}) \end{Bmatrix} \tag{2}$$

where $\rho_{1\cdots ns}$ are the species densities; $u$ and $v$ are the bulk velocity components; $\tau$ is the viscous stress component. $E$ is the total energy per unit volume of mixture and given by

$$E=\sum_{s\neq e}\rho_s C_{v,s}T+\frac{1}{2}\rho(u^2+v^2)+\sum_{s\neq e}\rho_s h_{s0}+E_v \tag{3}$$

where $C_{v,s}$ is the species specific heat at constant volume; $h_{s0}$ is the species heat of formation at 0 K and $h_s$ is the species enthalpy; $E_v$ is the vibrational energy per unit volume. $q_t$, $q_r$ and $q_v$ are translational, rotational and vibrational heat fluxes which are modeled according to Fourier′s law, the mixture and species thermal conductivities are determined by Eucken′s relation. The species mass diffusion fluxes are modeled as:

$$\vec{J}_{s\neq e}=\vec{I}_s-Y_s\sum_{r\neq e}\vec{I}_r,\ \vec{J}_e=M_e\sum_{s\neq e}\frac{\vec{J}_s C_s}{M_s},\ \vec{I}_s=-\rho D_s\nabla Y_s \tag{4}$$

where $\vec{J}_e$ is in order to guarantee the charge neutrality of the flow field; $D_s$ is the species diffusion coefficients calculated assuming that the Lewis number is constant; $Y_s$ is the species mass fraction; $C_s$ is the species charge.

The source term is given by

$$W=\{\omega_{1\cdots ns},0,0,0,\omega_v\}^{\mathrm{T}} \tag{5}$$

where $\omega_{1\cdots ns}$ describe the species mass production rates which are modeled using a standard finite-rate chemistry model for reacting air. Park′s two-temperature model is account for thermal nonequilibrium effects. The forward and the backward reaction rates used in this work is Park90. $\omega_v$ is the vibrational energy source term calculated by

$$\dot{\omega}_v=S_{epq}+S_{c-v}+S_{t-v}+S_{h-e}+S_{e-i} \tag{6}$$

where $S_{epq}$ stands for the approximation work electric field does on electrons; $S_{c-v}$ is the vibrational-electron-electronic energy generated by chemical reactions; $S_{t-v}$ is the energy transfer between translational-rotational and vibrational-electron-electronic modes; $S_{h-e}$ is the energy transfer between heavy particles and electrons; $S_{e-i}$ is the energy removed from free electrons during impact ionization reactions.

## 1.2 Simulation of blunted cone

In this section, blunted cone spacecraft which is most useful for numerical comparisons is taken for validation[8]. The flow condition is set as 71 km in height, Mach number is 25.9; temperature of incoming flow is 216 K. Contours of translational-rotational temperature and pressure over the spacecraft are shown in Figure 1. And Figure 2 shows the electron number density comparisons along the body for blunted cone fight test at 71 km altitude.

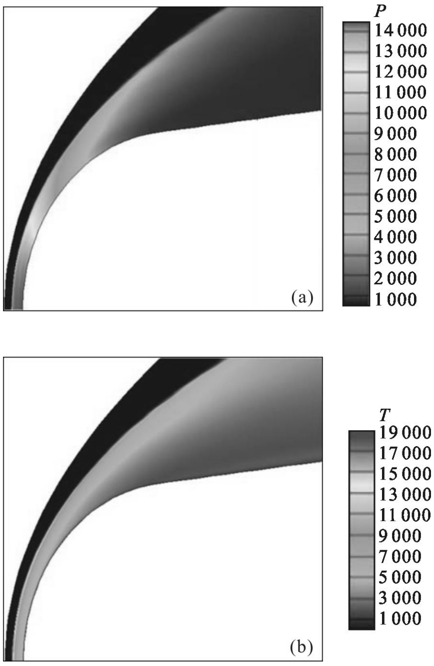

Fig.1 Translational-rotational temperature and pressure over the blunted cone

From the picture the numerical simulation could accord with the experimental data which validate the method we used in this paper. Based on above discussion, different altitudes in the reentry of blunted cone fight are taken to explore the effects of plasma sheath produced in this progress on the propagation of terahertz wave.

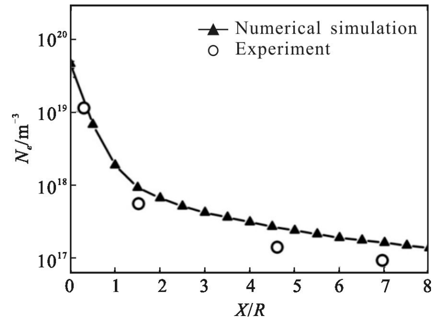

Fig.2 Electron number density comparisons along the body for blunted cone fight test at 71 km altitude

## 2 Propagation of EM wave

### 2.1 Modeling

In this section, the method used to investigate the interaction between plasma and EM wave is afforded and the validation of it is neglected because that it has been validated in a previous work. The plasma sheath is divided into a series of slabs according to its parameters. Varying of parameters in each slabs is small enough that can be molded as uniform ones. Therefore the multi-slabs assumption can be utilized in the analyses of interaction between EM wave and plasma sheath.

For a uniform plasma slab, the propagation equation of a plane EM wave along $z$ direction can be expressed as:

$$\vec{E}=E_0\exp(\mathrm{j}\omega t-\tilde{\gamma}z) \qquad (7)$$

$\tilde{\gamma}$ is the complex dielectric which defined as:

$$\tilde{\gamma}=j\frac{\omega}{c}\sqrt{\tilde{\varepsilon}_r}=\alpha+j\beta \qquad (8)$$

$\tilde{\varepsilon}_r$ here is the complex permittivity of high temperature plasma according to Heald et al.[9]:

$$\tilde{\varepsilon}_r=\left(1-\frac{\omega_p^2}{\omega((\omega-j\upsilon_e)\pm\omega_b)}\right)/\left(1+\frac{\omega\omega_p^2}{[(\omega-j\upsilon_e)\pm\omega_b]^3}\frac{K_bT_e}{m_ec^2}\right) \qquad (9)$$

where $\omega$ is the EM wave frequency; $\omega_p$ is the plasma frequency calculated by $\omega_p=(N_e\mathrm{e}^2/\varepsilon_0m_e)^{1/2}$; $\omega_b=\mathrm{e}B_0/m_e$ is the electron gyro frequency; $K_b$ is the Boltzmann constant; $m_e$ is the electron mass; $N_e$ is the number density of electron. In the plasma sheath, the electron temperature $T_e$ is assumed to be equal to $T_v$. As the plasma slabs are assumed to be uniform, the complex permittivity of the $i$th plasma layer can be written as Equation (9), so the reflection constant of the slab would be expressed as:

$$\lambda(i)=(\sqrt{\tilde{\varepsilon}_r(i-1)}-\sqrt{\tilde{\varepsilon}_r(i)})/(\sqrt{\tilde{\varepsilon}_r(i-1)}+\sqrt{\tilde{\varepsilon}_r(i)}) \qquad (10)$$

During the propagation of EM wave in plasma slab, it would be absorbed, transmitted and reflected at the interfaces of each two sub slabs. Reflection and transmission coefficient would be calculated as similar as[10]:

$$R=\sum_{n=1}^{N}\{|\lambda(n)|^2\cdot\prod_{i=1}^{n-1}[(\exp[-2\alpha(i)d(i)])^2(1-|\lambda(i)|^2)]\} \qquad (11)$$

$$T=\prod_{i=1}^{N}[\exp[-2\alpha(i)d(i)](1-|\lambda(i)|^2)] \qquad (12)$$

where $N$ is the total number of slabs; $d$ ($i$) is the length of the $i$th sub slab and when $i$=1 it is the layer is air. The absorption constant $\alpha$ could be evaluated by Equation (9)-(10). Then the absorption coefficient could be got as $A$=1−$T$−$R$.

### 2.2 Results and discussion

Combining with the electromagnetic characteristics calculated with the numerical simulating result of flow field, the absorption, transmission and reflection power could be evaluated. In this section, four flight scenes in blunted cone flight are taken to analyses the effects of plasma sheath. And the incident wave launches to the plasma slab at incident angles which are 0° and 60°. It also is assumed that incident wave arrives on the plasma at two locations one of which is the top of head (case 1) and the other one is the top half of head (case 2). It gets into the plasma and then reflected by the surface, finally gets out of the sheath again. The absorption and transmission parameters are induced in Figure 3.

The effects of plasma sheath at different altitudes on the propagation of EM wave are obvious. First we focus on case 1 of which the EM wave incidence into the plasma at the top of head. The transmission parameters approximate to 0.8 when the incident wave frequency is 1.5 THz at altitude of 70.1 km. However at the 51.82 km high, incident wave frequency should achieve to 35 THz to make the parameters close to 0.8. This phenomenon is due to the change of plasma sheath with the variation of fight scene. At altitude of 70 km, the density of air is lower and the reaction is weaker relatively. As the flight altitude declines, the higher air density leads to stronger reactions which make higher electron density and stronger collision. The incident angle also affects propagation of EM wave in plasma sheath. When the EM wave is assumed to achieve at top of spacecraft head, a larger incident angle would gain the length of propagation path. Although the electron density would be a bit lesser, the longer path which makes the whole plasma parameters larger could absorb more power.

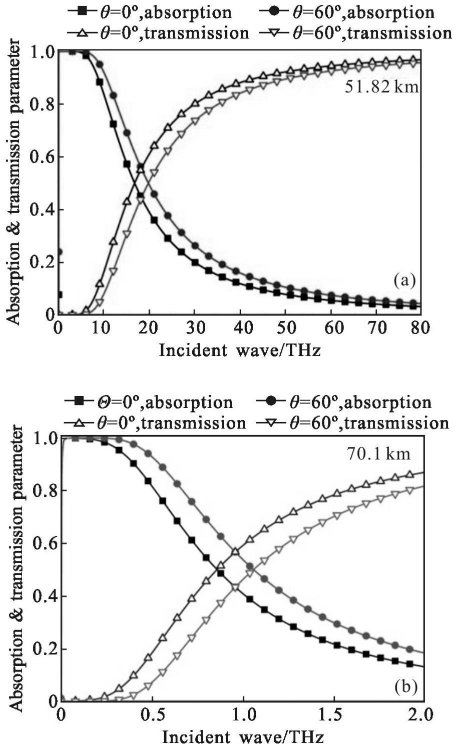

Fig.3 Absorption and transmission spectra in flight scenes of 51.82 km and 70.1 km

In Figure 4, comparison between case 1 and case 2 is shown at the altitude 39.62 km and 19.81 km. As the spacecraft declines to 39.62 km, incident wave in a range between 1 to 50 THz is mostly absorbed. In this scenes both the air density and velocity are large lead to strong reactions lead to large absorptions. When altitude is 19.81 km, a wave at frequency of 0.35 THz could mostly get through the sheath. It is because the spacecraft approaches to ground, its decreasing velocity result in a weaker reaction and the effects of plasma sheath weaken. Combine with the discussion above it could be summarized that adjust the wave frequency with the flight scenes could make the communication with terahertz wave more efficient and economical.

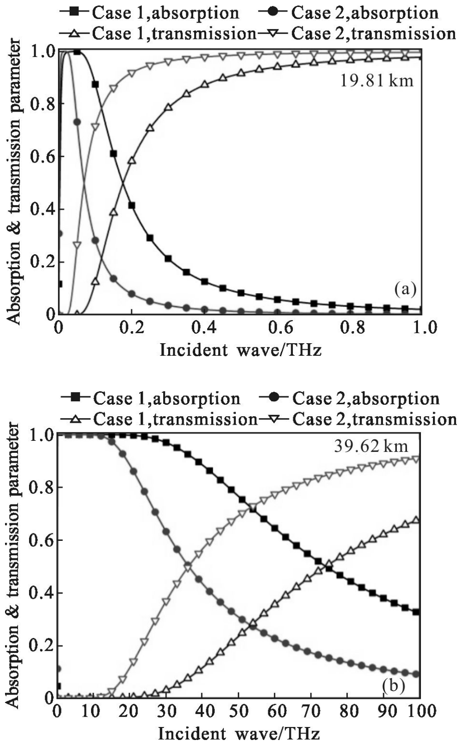

Fig.4 Absorption and transmission spectra in flight scenes of 19.81 km and 39.62 km

It is obvious that in case 2 of which EM wave incidence into the plasma at top half of head the absorption is much lower comparing with that in case 1. The reason is that the electron density and collision frequency are much lower along this path. It is more exactly when the altitude is 39.62 km. On conclusion is made that keep away from the aero with high plasma parameters could improve the transmission. It could be one way to avoid the strong absorption of plasma sheath.

## 3 Conclusion

In this paper, blunted cone is introduced to study the interaction between terahertz wave and plasma sheath produced in hypersonic flight is discussed. Absorption and transmission spectra are shown in different flight scenes and incident wave launches on the plasma layer at different angle and location. Due to the atmosphere condition and the velocity of flight, reactions of air would varying in differ flight scenes. However utilizing terahertz wave to realize getting through the plasma sheath is available. Unfortunately, at the altitude of 39.62 km the EM wave as high as 90 THz which is very high in communication could make the absorption parameter lesser than 0.6. Thus adjust the location at which the incident wave launches could be one way to improve this situation. What′s more, modifying wave frequency according to the flight scenes could make it more efficient and economical.

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