Absorption characteristic of arc plasma in the infrared region*

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In this paper, argon arc plasma is chosen as an example to study the absorption characteristics of arc plasma in the infrared region. Firstly, the phase and the attenuation constants are deduced for the given temperature, pressure and probe wavelength regions. Based on those constants, the dependence of the attenuation constant on the temperature and pressure in the vicinity of a certain probe wavelength is found. Then, theoretical analysis and discussion are conducted. Maximal absorption occurs at the position where the contributions of neutral particles and electrons come to a balance in a physical point of view, which may provide some measures to take for decreasing or controlling the plasma absorption of electromagnetic waves.

Keywords: absorption characteristic, arc plasma, attenuation constant

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1. Introduction

It is well known that aircrafts are exposed to the flow field of temperature, which is usually higher than 10000 K in the process of aircraft reentry into the aerosphere.[1] Hence, the gases surrounding the aircraft will undoubtedly be ionised, that is why they are usually called reentry plasma.[2,3] In order to clarify the phenomenon, the non-steady interaction of plasma with the aircraft in its near wake region has been studied.[4] Hoffman[5] indicated that the interaction of an electromagnetic wave with the flame and reentry plasma has received considerable attention because of the need to maintain the effective linkage between a station and a space vehicle. In the past, microwave and radio waves were widely used as the means of communication, thus much research was conducted on microwave and radio wave attenuation.[6−12] The research indicated that the linkage between aircrafts and the ground or a station would be badly affected, and that communication 'blackout' could even occur.[13,14]

Kim *et al.*[14] proposed that reducing the electron number density could be a solution to the microwave and radio wave blackout problem, as the plasma frequency is mainly determined by the electron number density of the plasma layer. However, the study is only discussed theoretically and it might be hard to realise in practice. Hereby, a feasible communication means should be considered. Many studies have suggested implementing optical communication technology[15−21] and the infrared region is the most popular signal source. Nevertheless, whether this method can be used during the aircraft reentry process must be based on the study of reentry plasma optical properties, especially the absorption characteristics in the infrared region.

It has been indicated that discharge produces a plasma layer with an electron density profile and other characteristics very similar to those of a reentry plasma sheath,[2] hence the argon arc plasma[22] is chosen as an example to simulate and study the absorption characteristic of reentry plasma in the infrared region.

2. Theories and deduction

2.1. Basic theories

The interaction between a material and the incident electromagnetic wave can be expressed as a

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function of either the complex refractive index $\tilde{n}$ or the complex dielectric constant ε of the material, as long as the material is not magnetic. The complex dielectric constant ε is expressed as[23]

$$\begin{aligned}\varepsilon &= \varepsilon_{\rm r} + {\rm i}\varepsilon_{\rm i} \\ &= 1 - \frac{\omega_{\rm p}^2}{\omega^2+\nu^2} - {\rm i}\frac{\nu\omega_{\rm p}^2}{\omega(\omega^2+\nu^2)} \\ &= 1 - \frac{(\omega_{\rm p}/\omega)^2}{1+(\nu/\omega)^2} - {\rm i}\frac{\nu}{\omega}\cdot\frac{(\omega_{\rm p}/\omega)^2}{1+(\nu/\omega)^2}, \end{aligned} \quad (1)$$

where $\varepsilon_{\rm r}$ and $\varepsilon_{\rm i}$ are the real and the imaginary parts of the complex dielectric constant, respectively; ν, $\omega_{\rm p}$, and ω represent the collision frequency, the plasma frequency and the probe frequency, respectively.

Based on the transverse wave's existence condition in the medium $k^2 - (\omega^2/c^2)\varepsilon = 0$, we can have

$$k^2 - \frac{\omega^2}{c^2}\left\{1 - \frac{(\omega_{\rm p}/\omega)^2}{1+(\nu/\omega)^2} - {\rm i}\frac{\nu}{\omega}\cdot\frac{(\omega_{\rm p}/\omega)^2}{1+(\nu/\omega)^2}\right\} = 0, \quad (2)$$

where k is the wave number and c is the speed of light in a vacuum.

Once the wave number k is given, the attenuation constant α and the phase constant β can be obtained. In fact, the attenuation constant α is generally used as the 'absorption coefficient', while the phase constant β represents the change in phase per meter along the path travelled by the wave at any instant. According to Eq. (2), in order to obtain the attenuation constant and analyse the absorption characteristic of reentry plasma further, the collision frequency ν, the plasma frequency $\omega_{\rm p}$ and the probe frequency ω should be determined initially.

It is well known that there are multiple collisions between particles in the plasma, such as the collision between electrons and ions, and the collision frequency is written as $\nu_{\rm ei}$. The collision between electrons and neutral particles is dominant in plasma,[24] which means that the effective collision frequency ν of the plasma may be nearly equal to $\nu_{\rm en}$. Hence, the collision frequency of the plasma can be written as[25]

$$\nu = \frac{4}{3}\pi a^2 N_{\rm n}\bar{v}, \quad (3)$$

where a (for argon atom, it is 3.4×10^{-10} m[26]) and N_n are the effective diameter and the number density of the neutral particle, respectively; $\bar{v} = \sqrt{8k_{\rm B}T/\pi m_{\rm e}}$ is the mean electron velocity, where T is temperature, $m_{\rm e}$ the electron mass and $k_{\rm B}$ is the Boltzmann constant.

The plasma frequency is[27]

$$\omega_{\rm p} = \left(\frac{N_{\rm e}e^2}{\varepsilon_0 m_{\rm e}}\right)^{1/2} \approx 5.64\times10^4\sqrt{N_{\rm e}}\ (N_{\rm e}:{\rm cm}^{-3}), \quad (4)$$

where $N_{\rm e}$ represents the electron number density, $e = 1.6\times10^{-19}$ C is the elementary charge, and $\varepsilon_0 = 8.85\times10^{-12}\ {\rm C^2\cdot N^{-1}\cdot m^{-2}}$ is the permittivity of the vacuum.

The probe frequency is

$$\omega = 2\pi\frac{c}{\lambda}, \quad (5)$$

where λ represents the wavelength of the probe signal.

The particle number density is determined by the temperature and pressure of the plasma. Both ν and $\omega_{\rm p}$ depend on the temperature and pressure. The dependence of the particle number density on the temperature and pressure can be obtained by the method implemented in Ref. [28]. Since the maximal temperature of reentry plasma is usually higher than 10000 K, the absorption characteristic will be discussed in the region 5000–20000 K. Because the practical pressure of the reentry plasma cannot be a constant, it is taken to be $(0.01\text{–}1.01)\times1.01\times10^5$ Pa which is derived from previous research.[11] Infrared rays, which are generated by the rotational and vibrational energies of molecules, would be absorbed by the homogeneous and inhomogeneous gases in the reentry plasma and atmosphere in the transmission along the path to the sensor.[29] Therefore, in order to avoid the polyatomic molecules, such as water vapour or carbon dioxide, absorbing the infrared rays (which may be used as the optical communication probe signals), the windows of atmosphere must be used to decrease such influence. Consequently, three atmospheric windows in the infrared region are considered, which implies that the absorption characteristic will be discussed in 1–3 μm, 3–5 μm, and 8–13 μm regions.

The collision frequency and the plasma frequency are shown in Fig. 1, they are basically of the order of magnitude of 10^{11} and 10^{13} Hz, respectively.

In the three atmospheric windows, the probe frequency ranges from 1.45×10^{14} Hz to 1.88×10^{15} Hz approximately, which indicates that $\nu \ll \omega$ and $\omega_{\rm P} < \omega$ in the given temperature and pressure regions. Hence, the probe signal can penetrate into the argon arc plasma and transmit successfully. Then, further deduction can be done.

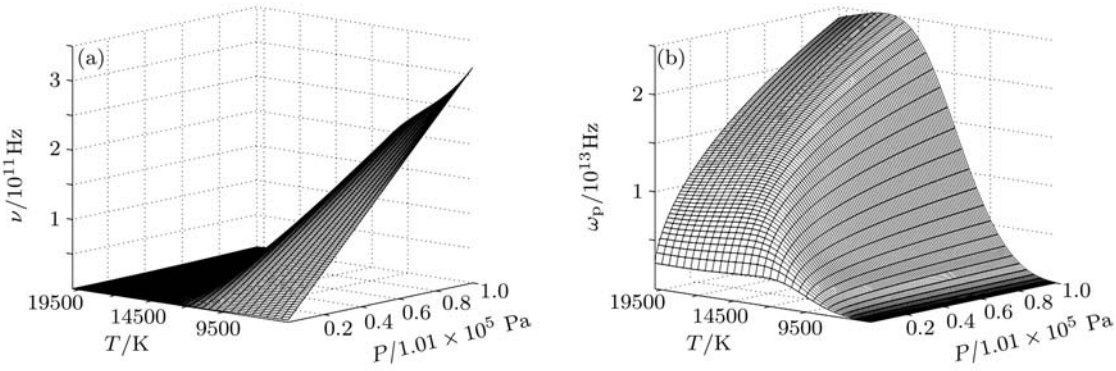


Fig. 1. The collision frequency ν (a) and the plasma frequency ω_p (b) versus T and P.

2.2. Deduction

From the above analysis, we have $\nu \ll \omega$ and $\omega_P < \omega$ in the given temperature (5000–20000 K) and pressure ((0.01–1.01)×1.01×10^5 Pa) regions, thus Eq. (2) can be transformed to

$$k^2 - \frac{\omega^2}{c^2}\left(1 - \frac{\omega_p^2}{\omega^2} - \mathrm{i}\frac{\omega_p^2\nu}{\omega^3}\right) = 0. \tag{6}$$

Then, the phase constant β and the attenuation constant α can be obtained

$$\beta = \frac{\omega}{c}\left\{\frac{1}{2}\left[\left(1 - \frac{\omega_p^2}{\omega^2}\right)^2 + \left(\frac{\omega_p^2\nu}{\omega^3}\right)^2\right]^{1/2} + \frac{1}{2}\left(1 - \frac{\omega_p^2}{\omega^2}\right)\right\}^{1/2}, \tag{7}$$

$$\alpha = \frac{\omega}{c}\left\{\frac{1}{2}\left[\left(1 - \frac{\omega_p^2}{\omega^2}\right)^2 + \left(\frac{\omega_p^2\nu}{\omega^3}\right)^2\right]^{1/2} - \frac{1}{2}\left(1 - \frac{\omega_p^2}{\omega^2}\right)\right\}^{1/2}. \tag{8}$$

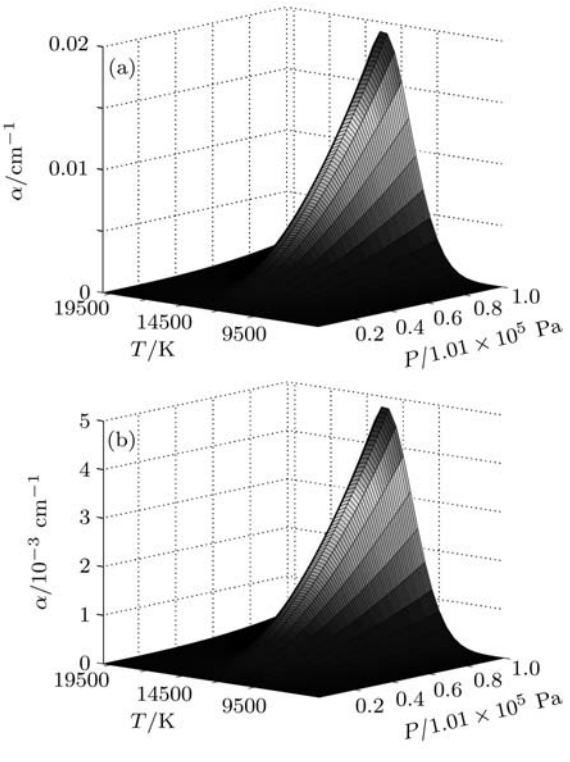
As a result we obtain $(\omega_p^2\nu/\omega^3)/(1-\omega_p^2/\omega^2) \approx \omega_p^2\nu/\omega^3 \ll 1$ in the given temperature, pressure and probe wavelength regions; using Taylor series expansion, we have

$$\beta \approx \frac{\omega}{c}\left(1 - \frac{\omega_p^2}{2\omega^2}\right), \tag{9}$$

$$\alpha \approx \frac{\omega}{c}\left(\frac{\omega_p^2\nu}{2\omega^3}\right) = \frac{\omega_p^2\nu}{2c\omega^2}. \tag{10}$$

Once the collision frequency, the plasma frequency and the probe frequency are known, the phase constant β and the attenuation constant α can be estimated using Eqs. (9) and (10), respectively. Evidently, if the probe frequency is chosen first, the phase constant β is only determined by the plasma frequency which depends on the electron number density, while the attenuation constant α is determined by both the plasma frequency and the collision frequency. The dependence of the attenuation constant on the temperature and pressure is shown in Fig. 2.

The order of magnitude of the attenuation constant indicates that choosing a suitable probe signal for the optical communication technology is quite important. Moreover, Fig. 2 manifests that the attenuation constant is nearly a linear function of pressure, whereas a nonlinear function of temperature. Figure 3 shows clearly the dependence of the attenuation constant on the temperature.



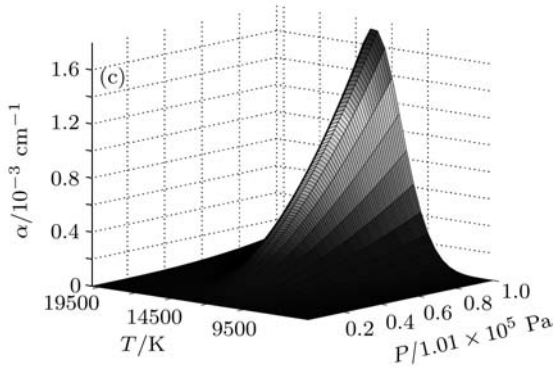


Fig. 2. The dependence of the attenuation constant on the temperature and the pressure at certain probe wavelengths (a) 10 μm, (b) 5 μm, (c) 3 μm.

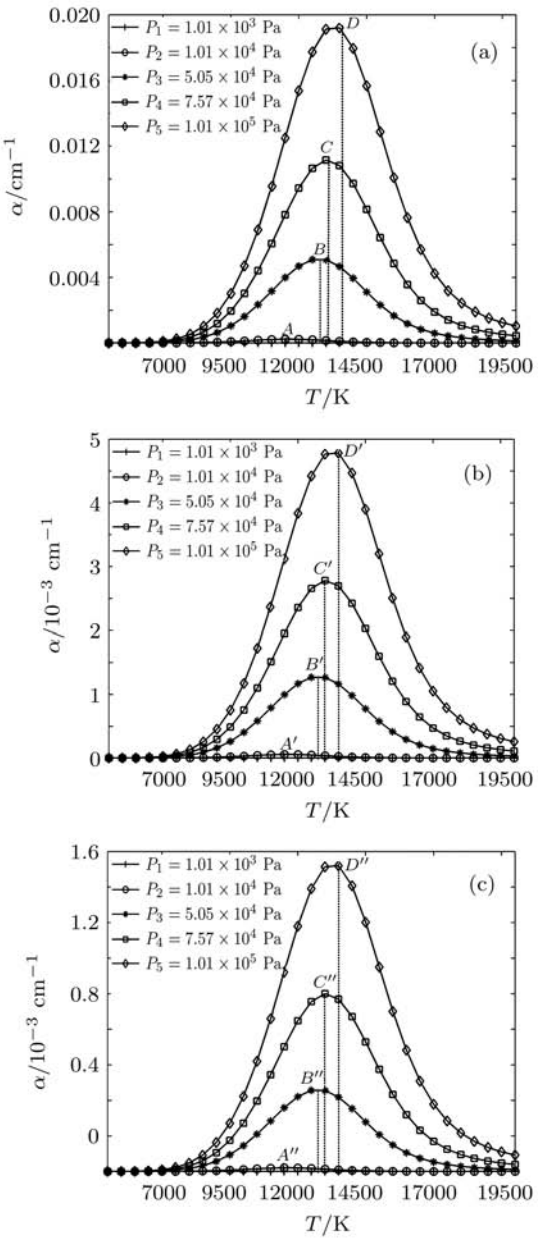


Fig. 3. The dependence of the attenuation constant on the temperature for different pressures at the probe wavelength (a) 10 μm, (b) 5 μm, (c) 3 μm.

As shown in Fig. 3, the maximal absorptions occur at the same temperature as long as the pressure is kept the same, whatever the probe wavelength may be. The physical mechanism of this phenomenon is worthy to be discussed seriously as follows.

3. Analysis and discussion

Based on Eq. (10), for a given probe frequency, the absorptive capability is only determined by the temperature of reentry plasma at a certain pressure. Hence, from the mathematical point of view, the appearance of the maximal absorption manifests that it must have a temperature $T_{\rm L}$ which can meet $\mathrm{d}\alpha/\mathrm{d}T|_{T_{\rm L}} = 0$. That is,

$$\begin{aligned}\left.\frac{\mathrm{d}\alpha}{\mathrm{d}T}\right|_{T_{\rm L}} &= \left.\left(\frac{\omega_{\rm p}^2\nu}{2c\omega^2}\right)'\right|_{T_{\rm L}} \\ &= \frac{1}{2c\omega^2}\left.\left(2\omega_{\rm p}\nu\frac{\mathrm{d}\omega_{\rm p}}{\mathrm{d}T}+\omega_{\rm p}^2\frac{\mathrm{d}\nu}{\mathrm{d}T}\right)\right|_{T_{\rm L}} \\ &= \frac{\omega_{\rm p}|_{T_{\rm L}}}{2c\omega^2}\left.\left(2\nu\frac{\mathrm{d}\omega_{\rm p}}{\mathrm{d}T}+\omega_{\rm p}\frac{\mathrm{d}\nu}{\mathrm{d}T}\right)\right|_{T_{\rm L}} \\ &= 0. \end{aligned} \tag{11}$$

Suppose

$$M = \left.\left(2\nu\frac{\mathrm{d}\omega_{\rm p}}{\mathrm{d}T}+\omega_{\rm p}\frac{\mathrm{d}\nu}{\mathrm{d}T}\right)\right|_{T_{\rm L}}. \tag{12}$$

The maximal absorption should occur at temperature $T_{\rm L}$ that can fulfil $M = 0$. Of course, the temperature $T_{\rm L}$ will be different at different pressure. Equations (3) and (4) indicate that ν, $\mathrm{d}\nu/\mathrm{d}T$ and $\omega_{\rm p}$, $\mathrm{d}\omega_{\rm p}/\mathrm{d}T$ are functions of the neutral particle and the electron number density respectively. So, after a series of mathematical derivation, it can be known that $\mathrm{d}\alpha/\mathrm{d}T|_{T_{\rm L}} = 0$ or $M = 0$ means

$$\left.\left(\frac{1}{N_{\rm e}}\frac{\mathrm{d}N_{\rm e}}{\mathrm{d}T}+\frac{1}{2T}\right)\right|_{T_{\rm L}} = -\left.\left(\frac{1}{N_{\rm n}}\frac{\mathrm{d}N_{\rm n}}{\mathrm{d}T}\right)\right|_{T_{\rm L}}. \tag{13}$$

Obviously, Eq. (13) shows that the appearance of the maximal absorption is due to the contributions of the neutral particles and the electrons that come to a balance from the physical viewpoint. In order to verify this, the dependence of $\mathrm{d}N_{\rm e}/\mathrm{d}T$ and $\mathrm{d}N_{\rm n}/\mathrm{d}T$ on the temperature at certain pressures are shown in Fig. 4.

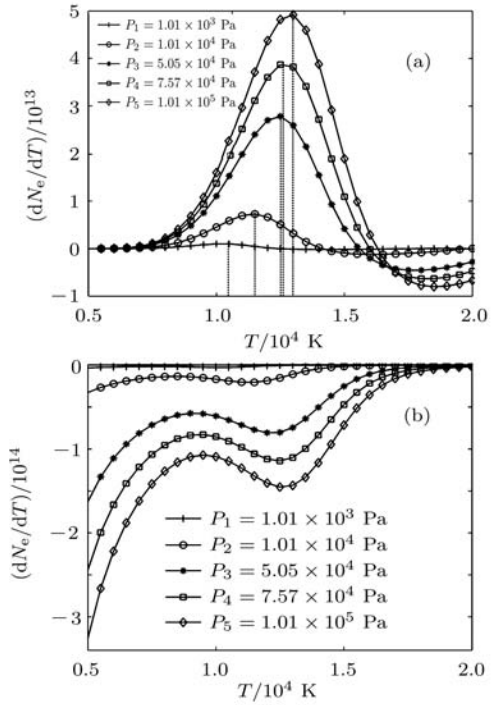


Fig. 4. The gradient of the particle number density with respect to temperature for (a) electron (b) neutral particle, as a function of temperature at different pressures.

As shown in Fig. 4, the electron has a positive effect on $d\alpha/dT$ in most part of the temperature range, while the neutral particle has a negative effect on $d\alpha/dT$ in the whole temperature region. Hence, it can be concluded that the maximal absorption is really attributed to the contributions of the neutral particle and the electron that come to a balance, as described by Eq. (13). For the sake of reducing the absorption of electromagnetic wave in the plasma, an effective way may be to keep away from the temperature at which the contributions of neutral particle and electron come to a balance at certain pressure.

4. Conclusion

The absorption characteristic of argon arc plasma has been studied by deducing the attenuation constant for the argon arc plasma in given temperature, pressure and probe wavelength regions. The results indicate that maximal absorption occurs where the contributions of the neutral particle and the electron come to a balance in physical point of view, suggesting a useful means to control or reduce plasma absorption of the electromagnetic wave; that is, trying to keep away from the temperature at which the contribution of neutral particle and electron come to a balance at certain pressure. In addition, this study may provide some theoretical aspects for judging whether optical communication technology can be introduced to the aircraft reentry process.

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