Analysis of sheath formation and charged species density in collisional electronegative warm plasma

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Abstract

In this paper, the impact of positive ions' temperature, collisional parameter and power factor on the profiles of normalized potential and positive ions' velocity is examined for CF_4 collisional electronegative warm plasma. The concept of sheath thickness is also attempted herewith and is found to be modified significantly. The effect of the power factor on the system is dominated for higher collisional parameters. Here, probe of spherical geometry is entertained.

Introduction

In view of multi-component nature of plasma comprising ions, electrons and neutrals, collisions between different plasma species must be entertained. Moreover, energy and momentum are redistributed by the presence of collisions in plasma. The presence of negative ions in the system has a huge impact on the characteristics of various quantities like sheath thickness, density and potential profile. Also, their presence plays a crucial role in semiconductor industries, microelectronics industries, plasma cleaning, plasma etching, plasma propulsion and plasma nitriding [1–4]. In this paper, we accomplished a mathematical model to examine the behaviour of charged species present in electronegative plasma under the effect of their finite temperature and collisions with neutral atoms. It is found that collisional parameter as well as temperature have an intense effect on the plasma species profile. These result in the modification of sheath structure and hence, the sheath thickness. In this proposed mathematical model, both the ions, i.e. positive ions and negative ions, are described by fluid equations considering their drift term with collisional and pressure gradient terms. Here, we considered the CF_4 electronegative plasma [5], primarily composed of CF_3^+ and F^- ions where former ions are produced by the ionization and later ions by the attachment of electrons with neutral CF_4. CF_4 plasma is adopted because of its increasing applications in etching and film deposition processes.

Mathematical Model

The equations which govern the behaviour of charged species and analysis of sheath thickness are continuity and momentum transfer equations for both the ions and Poisson's equation. These equations for the case of collisional electronegative warm plasma are stated as follows:

$$\frac{1}{r^2}\frac{d}{dr}(r^2 n_P v_P) = 0, \quad (1)$$

$$\frac{1}{r^2}\frac{d}{dr}(r^2 n_N v_N) = 0, \quad (2)$$

$$m_P v_P \frac{d}{dr} v_P = -Z_P e \frac{d\varphi}{dr} - \frac{k_B \gamma_P}{n_P}\frac{dn_P}{dr} - m_P n_g \sigma_s \frac{{v_P}^{\gamma+2}}{C_{SP}}, \quad (3)$$

$$m_N v_N \frac{d}{dr} v_N = Z_N e \frac{d\varphi}{dr} - \frac{k_B \gamma_N}{n_N}\frac{dn_N}{dr} - m_N n_g \sigma_s \frac{{v_N}^{\gamma+2}}{C_{SN}}, \quad (4)$$

$$\frac{d^2\varphi}{dr^2} = -\frac{e}{\varepsilon_0}(n_P Z_P - n_N Z_N - n_e). \quad (5)$$

The electron density n_e is given by the Boltzmann distribution

$$n_e = n_{e0}\, exp\left(\frac{e\varphi}{k_B T_e}\right). \quad (6)$$

The probe/wall would correspond to the point where the floating wall condition is satisfied, which is stated as follows

$$n_P v_P = n_N v_N + \frac{n_e \bar{c}}{4} = n_N v_N + n_e \sqrt{\frac{k_B T_e}{2\pi m_e}}. \quad (8)$$

where n_i m_i, Z_i, T_i, v_i, C_{Si}, and v_i designates the density, mass, charge, temperature, collisional frequency, ion sound velocity, and velocity of positive ions ($i = P$) and negative ions ($i = N$). φ, T_e, and n_g are the electric potential, electron temperature, and neutral gas density, respectively. Here γ is a dimensionless parameter which is ranging from -1 to 0. σ_s is cross section at velocity C_{Si}. $\gamma = -1$ and 0 correspond to the case of constant mobility and constant collisional cross section of the ions, respectively.

The above defined equations will be represented in dimensionless form with the help of suitable normalization parameters, defined as follow:

$N_e = \frac{n_e}{n_{e0}}$; $N_P = \frac{n_P}{n_{P0}}$; $N_N = \frac{n_N}{n_{N0}}$; $\eta = -\frac{e\varphi}{k_B T_e}$; $x = \frac{r}{\lambda_{de}}$; $U_P = \frac{v_P}{C_{SP}}$; $U_N = \frac{v_N}{C_{SP}}$; $\alpha = n_g \sigma_s \lambda_{de}$; $\gamma_i = \frac{T_i}{T_e}$ for positive ions ($i = P$) and negative ions ($i = N$).

Here $C_{Si} = \sqrt{\frac{k_B T_e}{m_i}}$ and $\lambda_{de} = \sqrt{\frac{\varepsilon_0 k_B T_e}{n_{e0} e^2}}$ are positive ion sound velocity and Debye length, respectively. In the sheath, the degree of collisionality is given by collisional parameter α which is defined as the ratio of Debye length with the collisional mean free path.

The regime $x < 0$ corresponds to the plasma regime, whereas, $x > 0$ region corresponds to the sheath regime. The distance between sheath edge ($x = 0$) and the point where condition (8) is satisfied will lead to the sheath thickness for a particular set of parameters.

Results

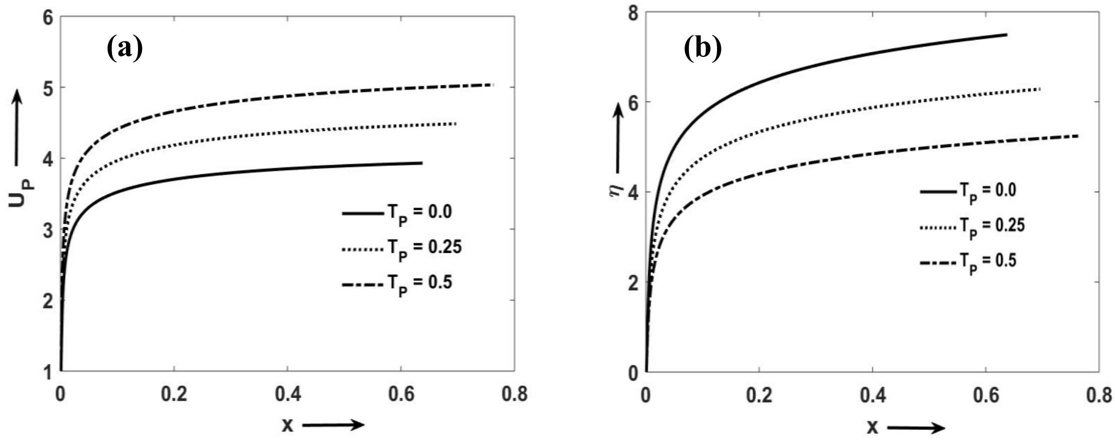

Figure 1. Normalized positive ion's velocity (a) and electric potential profile (b) for different positive ions' temperature as a function of distance from the sheath edge (x = 0) to spherical probe with α = 0.03, M_P = 69, M_N = 19, T_N = 0.1 and Z_P = Z_N = 1.

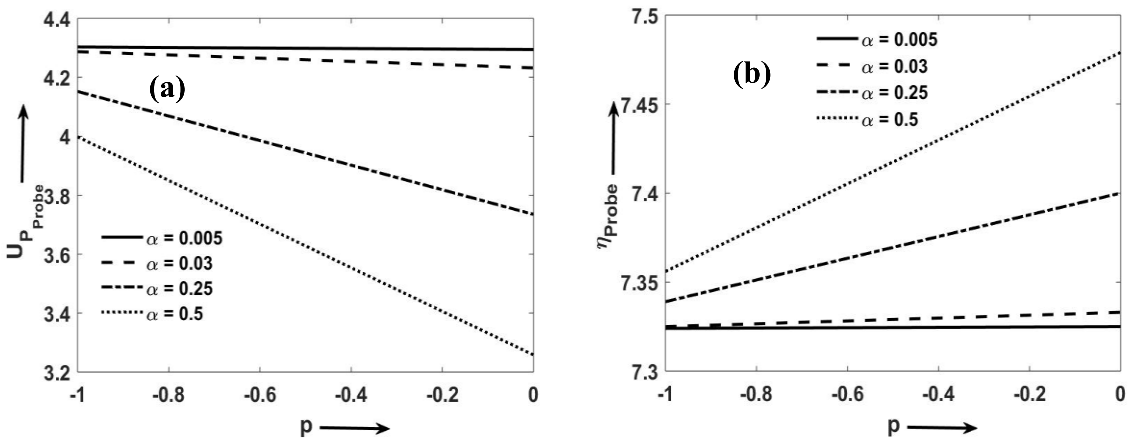

Figure 2. The magnitude of normalized positive ion's velocity (a) and electric potential (b) at the probe for different collisional parameters as a function of power factor with M_P = 69, M_N = 19, T_P = 0.1, T_N = 0.1 and Z_P = Z_N = 1.

Equations (1)-(6) are solved with the help of Runga-Kutta method of fourth order. Initial conditions are chosen by adopting the same methodology as discussed by Valentini [6] and Moulick et. al [7]. The behaviour of positive ions' velocity and electric potential as a function of positive ions' temperature is depicted in Figure 1. Here, the point on x-axis where solution terminates will belongs to the position of the probe and the distance between sheath edge and this point of termination determines the sheath thickness. Hence, we can conclude that an increment in positive ions' temperature results in enhancement of the sheath thickness.

Also, positive ions' velocity increases in magnitude with positive ions' temperature because of increment in thermal velocity of ions, whereas, magnitude of electric potential reduces with the positive ions' temperature. The magnitude of both profiles increases as we move towards the probe/wall. The impact of power factor at the magnitude of positive ions' velocity and electric potential at the probe as a function of different collisional parameters is attempted and depicted in Figure 2. As power factor changes from -1 to 0, the magnitude of positive ions' velocity decreases, whereas the magnitude of electric potential increases for all the collisional parameters. The change in magnitude is infinitesimal for lower collisional parameters whereas significant changes occurred for higher collisional parameters.

Conclusions

Sheath thickness is found to enhance with positive ions' temperature. Positive ions reach with more velocity at the probe for their higher temperature cases. The velocity of positive ions is more in magnitude for the case of constant mobility of ions, whereas the electric potential is more for the case of constant cross section of ions. Increasing collisional parameter results in the reduction of velocity of ions reaching at probe/wall.

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