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Theoretical model of cylindrical Langmuir probe for low-pressure electronegative discharges

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The spatial distributions of the potential and the density and the velocity of positive ions in the surroundings of cylindrical probe immersed in electronegative plasmas is calculated. For simplicity, we consider that electronegative plasma consists of three charged species, which are positive ion, negative ion and electron. The continuity and momentum balance equations for the positive ion are

$$\nabla \cdot [n_+ \mathbf{v}_+] = \nu_{iz} n_e, \tag{1}$$

$$m_+ n_+ \mathbf{v}_+ \cdot \nabla \mathbf{v}_+ = e n_+ \mathbf{E} - \nabla p_+ - m_+ n_+ \nu_m \mathbf{v}_+, \tag{2}$$

where n_+, m_+, p_+ and $\mathbf{v}_+$ are the density, the mass, the pressure, and the velocity of the positive ion, n_e is the electron density, ν_{iz} and ν_m are the ionization frequency and the ion-neutral momentum transfer collision frequency, and $\mathbf{E}$ is the electric field. The Poisson's equation is written as

$$\varepsilon_0 \nabla \cdot \mathbf{E} = e(n_+ - n_e - n_-), \quad \mathbf{E} = -\nabla V, \tag{3}$$

where ε_0 is the permittivity of the vacuum, n_- is the negative ion density, e is the electron charge, and V is the electric potential. We assume that electrons and negative ions follow the Boltzmann energy distribution.

The equations are developed for cylindrical probe with radial motion of positive ions towards the probe. We have the dimensionless functions and parameters; $\xi = r/\Lambda$, $\tilde{n} = n_+/n_{e0}$, $u = v_+/c_s$, $\eta = -eV/kT_e$, $\alpha_0 = n_{-0}/n_{e0}$, $\gamma_- = T_e/T_-$, $\gamma_+ = T_e/T_+$, $q = \lambda_D/\Lambda$, $\delta = \nu_m/\nu_{iz}$, where c_s is the Bohm velocity ($= \sqrt{kT_e/m_+}$), λ_D is the Debye length and $\Lambda = c_s/\nu_{iz}$ is the ionization length. T_e, T_+, and T_- are the temperature of electrons, positive ions, and negative ions, respectively, k is the Boltzmann constant, the subscript 0 indicates the value at the plasma bulk region.

The equations are solved by using the fourth-order Runge–Kutta method with the boundary conditions at the bulk region $\tilde{n} = 1 + \alpha_0$, $u = 0$, $\eta = 0$ at $\xi = 1$, and the spatial distributions of the normalized potential, the normalized density, and the normalized velocity and flux of positive ions are calculated for various sets of q, α_0, δ, γ_+, γ_-. Especially, the effects of the δ and γ_+ are investigated.

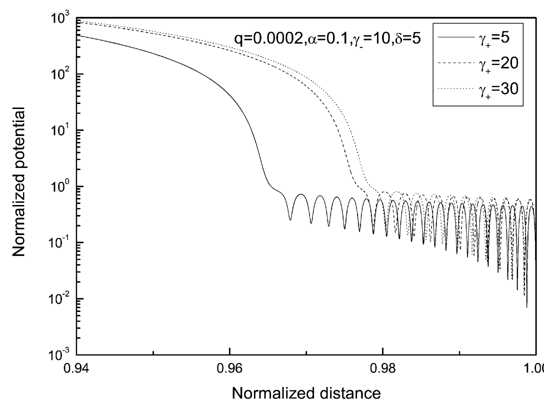

Fig. 1. Normalized potential along the normalized distance for several positive ion temperatures.

Fig. 1 shows the normalized potential along the normalized distance for several positive ion temperatures. For $q = 2 \times 10^{-4}$, if the positive ions have larger thermal motion (smaller γ_+), the electric potential increases more slowly (going from the plasma to the probe), the sheath is contracted, and the ion current collected by the probe increases. The increase of δ (collision term) causes the electric potential to increase more rapidly and the sheath to be enlarged.

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