Topic number: 10

DYNAMIC INTERACTION BETWEEN LIQUID DROPLETS AND ATMOSPHERIC PRESSURE DISCHARGE

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We consider a discharge plasma in a recombination dominated equilibrium with spatially uniform ion $n_+^{(0)}$ and electron $n_e^{(0)}$ densities at atmospheric pressure. Suppose a spherical liquid droplet is immersed in this plasma and the recombination start occurring on the surface of droplet. So, the dynamic flow of charged particles is developed towards the droplet surface and the droplet acquires a negative potential in order to balance the flow of electrons and ions. It is very important to understand the behavior of macroscopic charged particles interacting with the discharge plasma in the presence of liquid droplets.

In this situation, the electrons follow the Boltzmann distribution and can be mathematically expressed as

$$n_e = n_+^{(0)} \exp\left(e\Phi / k\mathrm{T}_e \right) \quad (1)$$

where kT_e is the electron temperature expressed in eV and Φ is the electrostatic potential. The simplified form of transport equation for the ionic species in the quasi-neutral plasma can be written in one-dimensional spherical coordinates as

$$\frac{1}{r^2}\frac{d}{dr}\left(r^2 u_+ n_+\right) = \nu_i n_e - k_R n_+ n_e = n_+^{(0)}\left(\nu_i - k_R n_+\right)\exp\left(e\Phi / k\mathrm{T}_e \right) \quad (2)$$

where r is the radius of the droplet, ν_i is the ionization frequency and k_R is the recombination rate constant in the helium gas. The ionic drift velocity u_+ is given by

$$u_+ = \frac{e}{m_+\nu_+}E = -\frac{e}{m_+\nu_+}\frac{d\Phi}{dr}$$

where E is the electric field, m_+ is the ion mass and ν_+ is the ion collision frequency. Therefore, the electric field is evaluated by using Poisson's equation as

$$\frac{1}{r^2}\frac{d}{dr}\left(r^2 E\right) = \frac{e}{\varepsilon_0}\left[n_+ - n_+^{(0)} \exp\left(e\Phi / k\mathrm{T}_e \right)\right] \quad (3)$$

After simplification and elimination of u_+ and E, So

$$\frac{1}{r^2}\frac{d}{dr}\left(r^2 \frac{d\Phi}{dr}\right) = \frac{e}{\varepsilon_0}\left[n_+^{(0)} \exp\left(e\Phi / k\mathrm{T}_e \right) - n_+\right] \quad (4)$$

The dimensionless form of Continuity (2) and Poisson's equation (4) can be written as

$$\varepsilon \frac{dn}{d\rho} = (1-n)\exp(\psi) - \frac{1}{\alpha^2}\left[n - \exp(\psi)\right]n \quad (5)$$

$$\frac{d\varepsilon}{d\rho} = \frac{1}{\alpha^2}\left[n - \exp(\psi)\right] - \frac{2\varepsilon}{\rho} \quad (6)$$

$$\frac{d\psi}{d\rho} = -\varepsilon \quad (7)$$

where the normalized variables can be expressed as $\rho = r\sqrt{\frac{m_+\nu_i\nu_+}{kT_e}}$, $n = \frac{n_+}{n_+^{(0)}}$ and $\psi = \frac{e\Phi}{kT_e}$, α and β are evaluated for the helium gas. The useful and interesting information can be obtained from the above set of normalized fluid model equations (5 - 7) if the proper boundary conditions are applied. For example,

$$n \to 0 \text{ as } \rho \to \rho_0, \qquad \psi \to \infty \text{ as } \rho \to \rho_0$$

The floating potential is obtained by the balance of electronic and ionic fluxes at the surface of the droplet, which is assumed to be located at $\rho = \rho_0$. The flux balance condition for floating potential can be written as $u_+ n_+ = \frac{1}{4}\bar{v} n_e = \frac{1}{4}\bar{v} n_+^{(0)} \exp\left(e\Phi / kT_e\right)$, In normalized form, $\beta \varepsilon n = \exp(\psi)$ for the calculation of floating potential.

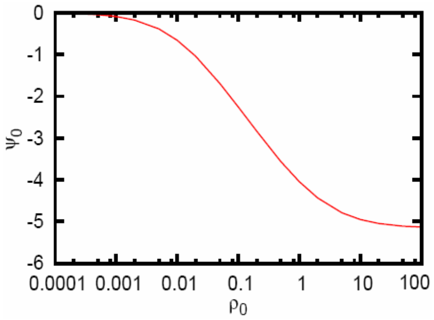

Fig. 1: Droplet floating potential obtained by solving Eqs. (5 - 7) with α = β = 0.01.

The structure of dimensionless floating potential (ψ_0) of droplet provides the range of dimensionless droplet radius, ρ_0 = 0.001 to 1, for the dynamic behavior of macroscopic species as shown in figure 1, which is decreased in this domain.

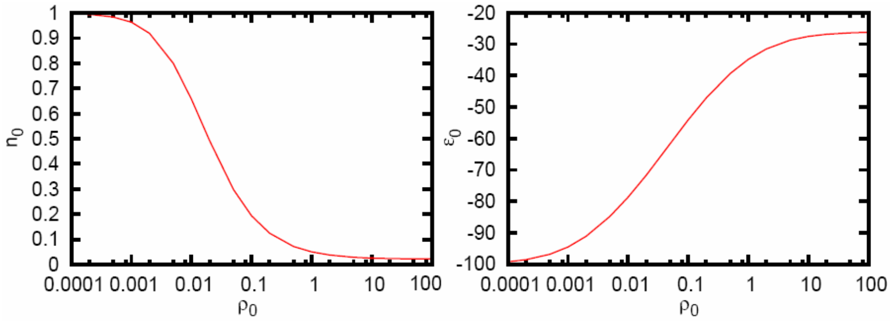

Fig. 2 (a, b): Dimensionless ion density and Electric field at the surface of droplet obtained by solving Eqs. (5 - 7) with α = β = 0.01.

The dimensionless species density (n_0) is sharply decreased from the dimensionless radius ρ_0 = 0.001 to 0.1, which illustrates the evolution of distinct distributions of ionic species in this domain. Corresponding, the dimensionless elecric field (ε_0) is decreased from the higher to lower values, which shows the strong dominance of of electric field near the surface of droplet. With the calculation of these parameters for quasi-neutral helium gas, $r_0 = r\sqrt{\frac{kT_e}{m_+ v_i v_+}}$, $\alpha = \frac{\lambda_D}{r_0}$ and $\beta = \frac{4 r_0 v_i}{\bar{v}}$, the range of the droplet radii is much less than the characteristic length r_0. The droplet size is expeced to be 10 μm or less by using the above mentioned parameters.

References

[1] R. Deloche, P. Monchicourt, M. Cheret, and F. Lambert. High-pressure helium afterglow at room temperature. Phys. Rev. A, 13(2), 1140 - 1176, March 1976.