# Dynamic Interaction between Liquid Droplets and Atmospheric Pressure Discharge

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**Introduction:**

The direct introduction of liquid precursors or droplets in the atmospheric pressure discharges performs a dynamic role to modify the behaviour of discharge characteristics. When some chemically active liquid is nebulized into the plasma, or incidentally, as might be the case in some medical applications, for example. The interaction between the plasma and the liquid droplets may then be an important aspect of the process. The understanding of this complex interaction between the liquid droplet and plasma can probably create the APD applications in the categories of non-thermal plasma spraying and bio-medical equipments. The spatial response of ionic species density in the presence of droplet is numerically elaborated by using the coupled system of fluid model equations.

**Results and Discussion:**

We consider a discharge plasma in a recombination dominated equilibrium with spatially uniform density of ions $n_+^{(0)}$ and electrons $n_e^{(0)}$ at atmospheric pressure. Suppose a spherical liquid droplet ($r_d << \lambda_D$) is immersed in this plasma and the recombination prominently start occurring on the surface of droplet. As a result, the dynamic flow of charged particles is established towards the droplet surface and the droplet acquires a negative potential in order to balance the flow of electrons and ions. This is occurred due to the large thermal velocities of electrons than ions in the glow discharge plasma, which produce an intricate situation around the droplet. The spatial confinement of droplet is also effected with the imposed sinusoidal voltage in the parallel plate dielectric barrier discharge reactor. It is very important to understand the evolvement of macroscopic charged particles interacting with the discharge plasma in the presence of spherical liquid droplets.

The electron density $n_e$ is given by the Boltzmann relation as

$$n_e = n_+^{(0)} \exp\left( e\Phi / kT_e \right) \tag{1}$$

where $n_+^{(0)}$ is the initial density in the plasma, $kT_e$ is the electron temperature expressed in eV and $\Phi$ is the electrostatic potential. The simplified form of transport equation for the ionic species density 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, $\nu_i$ is the ionization frequency and $k_R$ is the recombination rate constant in the helium gas. The ionic drift velocity 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 mass of ions and $\nu_+$ is the collision frequency of ions. 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 $E$, the above Eq. (3) takes the form as

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

So, the dimensionless form of Continuity and Poisson's Eqs. (2, 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 $\rho = r\sqrt{\frac{m_+\nu_i\nu_+}{kT_e}} = \frac{r}{r_0}$, $n = \frac{n_+}{n_+^{(0)}}$ and $\psi = \frac{e\Phi}{kT_e}$, here $\alpha$ and $\beta$ are determined from the chemical reactions of 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 employed. For example,

$$n \rightarrow 0 \text{ as } \rho \rightarrow \rho_0 \text{ and } \psi \rightarrow \infty \text{ as } \rho \rightarrow \rho_0$$

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 $u_+ n_+ = \frac{1}{4}\bar{v}n_e = \frac{1}{4}\bar{v}n_+^{(0)}\exp\left(e\Phi / k\mathrm{T}_e\right)$. In normalized form, this takes the following shape, $\beta\varepsilon n = \exp(\psi)$ for the calculation of floating potential. The values of above mentioned parameters are estimated from the direct ionization, charge transfer and electron-ion recombination processes and they are represented in symbolic form of equations as

$$He + e \longrightarrow He^+ + e + e \tag{8}$$

$$He^+ + He + He \longrightarrow He_2^+ + He \tag{9}$$

$$He_2^+ + e \longrightarrow He + He \tag{10}$$

As these equations are not linearly independent, the ionic species density and ionization rate constant are calculated from the following formulae as

$$n_{He_2^+} = \frac{n_e}{1 + k_R n_e / \nu_A} \quad \text{and} \quad \nu_i = \frac{k_R n_e}{1 + k_R n_e / \nu_A} \tag{11}$$

From literature [1], $k_A \approx 10^{-31}$ cm$^6$ s$^{-1}$, $k_R \approx 10^{-9}$ cm$^3$ s$^{-1}$ and $T_e$ = 30000 K. Suppose $n_{He}$ = $2.41\times10^{19}$ cm$^{-3}$, $n_{He}^+ = 1.0\times10^9$ cm$^{-3}$. The mobility of $He_2^+$ ions is $\mu_{He_2^+} = \frac{e}{m_+ \nu_+} = 16.7\,\text{cm}^2\,\text{V}^{-1}\,\text{s}^{-1}$ and $r_0 = \sqrt{\frac{kT_e}{m_+ \nu_+ \nu_i}} = \sqrt{\frac{T_e \mu_+}{\nu_i e}} \approx 0.04\,\text{m}$, $\alpha = \frac{\lambda_D}{r_0} \approx 0.01$ and $\beta = \frac{4 r_0 \nu_i}{\bar{v}} \approx 10^{-4}$. These values provide an estimate of droplet radii, which are in the range much less than the characteristic length ($r_0$).

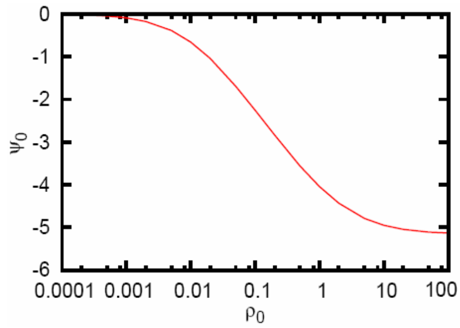


Figure 1. Profile of dimensionless droplet floating potential obtained by solving Eqs. (5 - 7).

The distribution of dimensionless droplet floating potential ($\psi_0$) illustrates that the value of floating potential is increased (in the negative sense) from 0 to ~ 5 in the domain of dimensionless radius from $\rho_0$ = 0.001 to 1 as shown in figure 1. It means that the dynamic behaviour of discharge participating species is evolved in the mentioned domain of normalized droplet radii.

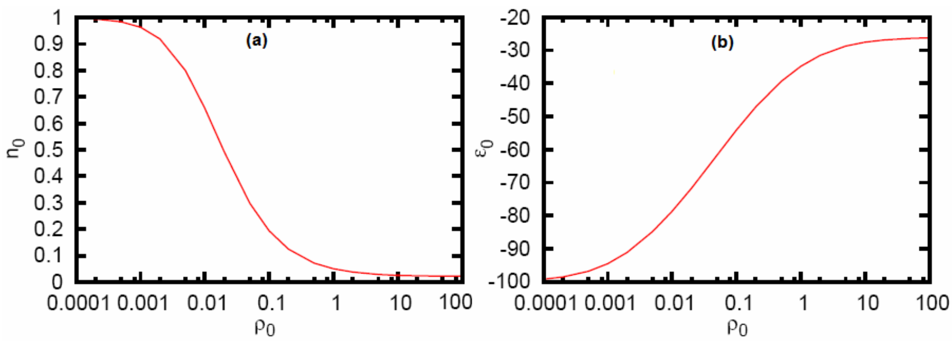


Figure 2 (a, b). Profiles of dimensionless ion density and electric field at the surface of droplet obtained by solving Eqs. (5 - 7).

The dimensionless ionic species density ($n_0$) is sharply reduced from 1 to very small values, when the dimensionless radius varies from 0.001 to 1 as shown in figure 2 (a). This means that the complex interaction between the droplet and plasma is emerged in the mentioned range. After the evolution of floating potential, the dimensionless electric field ($\varepsilon_0$) is reduced (in the negative sense) from the higher to lower values with an increase of dimensionless droplet radius as shown in figure 2 (b). To check the temporal profile of droplet temperature in the discharge plasma during charging of droplet, the temperature change of droplet ($T_d$) is found from the following relation as

$$\frac{dT_d}{dt} = \frac{1}{m_d c_p}(F) \tag{13}$$

Where $m_d$ is mass of the droplet, $c_p$ is the specific heat for the liquid and $F$ is the net heat flux to the droplet surface and composed of various terms [2].

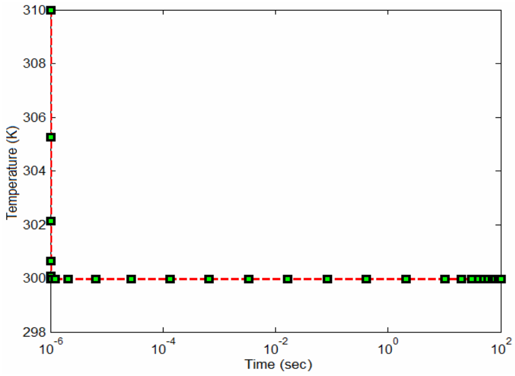


Figure 3. Profile of droplet temperature obtained by solving Eq. (13).

The temporal profile of droplet temperature is shown in figure 3 with a droplet radius $1.0\times10^{-5}$ m, indicating a slight change in the very start and then the steady state is achieved. This provides evidence that the droplet exists in the discharge plasma at room temperature (300 K) and smoothly interacts with other charged species. So, the distinct distribution of ionic species density is developed around the droplet due to the progression of floating potential. There are several issues that need to address in this area, for example, in-depth examination of droplet interaction with plasma and advancement of thin films and heterogeneous behaviour of droplets in the bulk and at the peripheral edge boundaries, which will be discussed in the future work.

References

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