Kinetics of low-pressure discharge plasmas containing dust grains

I. B. Denysenko\textsuperscript{1,2}, M. Y. Yu\textsuperscript{1}, K. Ostrikov\textsuperscript{3,4}

\textsuperscript{1}Theoretical Physics I, Ruhr University, D-44780 Bochum, Germany; \textsuperscript{2}Kharkiv National University, Kharkiv, Ukraine; \textsuperscript{3}School of Physics, The University of Sydney, Sydney, NSW 2006, Australia; \textsuperscript{4}Plasma Sources and Applications Center, NIE, Nanyang Technological University, 637616 Singapore.

A spatially averaged model for low-pressure argon discharge plasmas containing dust grains is presented. Using the model we investigate the effects of the dust on the electron and ion number densities, the electron energy distribution, the dust charge, the effective electron temperature, as well as the power losses in the discharge.

An rf 13.56 MHz argon discharge of radius $R$ and of length $L$ (with $L \ll R$) containing dust grains is considered. The plasma is composed of electrons, singly charged positive ions $\text{Ar}^+$, and negatively charged dust grains. We assume that the dust particles are all of the same size and are uniformly distributed over the plasma slab and are absent near the plasma boundaries. We consider relatively small dust particles with the radius $a_d$ (50-200 nm), and the plasma conditions when the distance $d$ between the dust grains is much larger than the Debye length. For the present problem the Debye-Hückel potential can be taken as the shielding potential of a dust grain [1]:

$$\phi(r) = \phi_s \left( \frac{a_d}{r} \right) \exp \left[ -\frac{(r - a_d)}{\lambda_D} \right],$$

where $\lambda_D = \left[ 4\pi \left( n_e / T_{\text{eff}} + n_i / 2E_0 \right) \right]^{-1/2}$ is the Debye length, $\phi_s$ is the potential at the dust surface, $n_e$ and $n_i$ are the electron and ion densities, $E_0 = 0.06$ eV and $T_{\text{eff}}$ are the average ion energy and the effective electron temperature, respectively. To find the dust charge accumulated on the dust particles the orbit motion limited (OML) approximation is used. We also assume that the electron energy distribution function (EEDF) is essentially isotropic and stationary, and to find the isotropic part of the EEDF $F_0(u)$ (where $u$ is the electron energy) the Lorentz approximation is used [2].

For relatively high neutral gas pressures and plasma sizes considered here one can obtain the EEDF from the homogeneous Boltzmann equation[2]:

$$-\frac{2e}{3m_e} \frac{d}{du} \left( \frac{u^{3/2} E_{\text{eff}}^2(u)}{v_m(u)} \frac{dF_0}{du} \right) = S_{ea}(F) + S_{ee}(F) + S_{ed}(F), \quad (1)$$

where $E_{\text{eff}} = E_p \nu_m(u) / [2(\nu_m^2(u) + \omega^2)]^{1/2}$, $\nu_m$ is the collision frequency for momentum transfer, $\omega = 2\pi \times 13.56 \text{MHz}$, $E_p$ is the electric field sustaining the plasma, and

$S_{ea}(F), S_{ee}(F), S_{ed}(F)$ describe the electron atom, electron-electron, and electron-dust
collisions, respectively. The electron-dust collision term can be modeled by [3]

\[
S_{ed}(F_0) = \frac{d}{du} \left[ \frac{2m_e}{m_d} u^{3/2} v_{ed}^e(F_0 + T_d \frac{dF_0}{du}) \right] - v_{ed}^e F_0 u^{1/2},
\]

where \( v_{ed}^e(u) \) and \( v_{ed}^d(u) \) are the rates of momentum transfer and electron collection in electron-dust collisions, \( m_e \) and \( m_d \) are the electron and dust grain masses, \( T_d (=0.026 \text{ eV}) \) is the dust temperature (here it is equal to the neutral gas temperature). Here, \( v_{ed}^e(u) = n_d \sqrt{2e u / m_e} \sigma_{ed}^e \), \( \Lambda = -\lambda d T_{ed} / a_d \phi_s \), and \( \sigma_{ed}^e = \pi a_d^2 (-\phi_s / u)^2 \exp(2a_d / \lambda_d) \ln \Lambda \). Furthermore, \( v_{ed}^d(u) = n_d \sqrt{2e u / m_e} \sigma_{ed}^d \), where the electron-dust collection cross-section is \( \sigma_{ed}^d = \pi a_d^2 (1 + \phi_s / u) \) for \( u \geq -\phi_s \) and 0 for \( u < -\phi_s \).

For a given EEDF, the electron current collected by a dust grain in the OML approximation is

\[
I_e = -\pi a_d^2 e n_e \int_{-\phi_s}^{\infty} (1 + \phi_s / u) \sqrt{2e u / m_e} F_0(u) \sqrt{u} \, du.
\]

The ion current is

\[
I_i = \pi a_d^2 e n_i \sqrt{2e E_0 / m_i} (1 - \phi_s / E_0).
\]

Here it is assumed that the ions are Maxwellian distributed. The dust surface potential is related to the dust charge \( Z_d \) by \( \phi_s = eZ_d / a_d \). The model assumes that the electron and ion current balance each other, or

\[
I_e + I_i = 0,
\]

and that the quasineutrality condition

\[
n_e + n_d |Z_d| = n_i
\]

is satisfied.

To find the averaged electron density, it is necessary to consider the particle and power balance in the discharge. The balance equation for the electrons can be written as

\[
D_a \pi^2 / L^2 \approx < \nu^i > - < v_{ed}^e >,
\]

where \( D_a \) is the ambipolar diffusion coefficient, \( \nu^i \) is the ionization frequency. The symbol \(< >\) denotes the energy-averaged value.

Multiplying both sides of the Eq. (1) by the electron energy and then integrating over the entire energy range one can obtain the electron power balance equation:

\[
\text{Re}(\sigma) E_p^2 / 2en_e \approx 2m_e / m_i < u \nu_m^e > + \sum_j V_j < \nu_j > + 2m_e / m_d < u \nu_{ed}^e > + < u \nu_{ed}^d >,
\]

where \( \text{Re}(\sigma) \) is the real component of the plasma conductivity, \( \nu_m^e \) is the electron-neutral momentum transfer collision frequency, \( < \nu_j > \) and \( V_j \) are the averaged frequency and
threshold energy for the $j$-th nonelastic process. In our study it is assumed that the power absorbed per unit area $P_{in} = L \Re(\sigma) E_p^2 / 2$ is fixed.

From Eqs. (1) — (5) the plasma properties were studied for different dust sizes $a_d$ and densities $n_d$. First, we compare the EEDFs in a dust-free plasma with that in a dust discharge. In Fig. 1 (a) the EEDFs are shown for the dust-free plasma (solid curve) and dust plasma (dashed curve) obtained at the same $n_e = 3.2 \times 10^{10} \text{ cm}^{-3}$ and $E_p = 200 \text{ V/m}$ as in the dust-free plasma case.

One can see from Fig. 1 (a) that in the dust contaminated plasma (at the same electric field sustained the plasma as in the dust-free discharge) the number of electrons with $u > -\phi_s$ is smaller than that in the pristine (dust-free) discharge. It is due to collection of the electrons by dusty particles. Compared with the pristine plasma in dusty plasmas there appears an additional region of inelastic collisions ($-\phi_s < u < V_{exc}$, where $V_{exc}$ is the excitation threshold energy) [Fig. 1 (b)]. To balance the enhanced electron loss, the electric field sustaining the plasma grows with $n_d$ and/or $a_d$. At the conditions corresponding to Fig. 1 (c) $E_p = 220, 359,$ and $459 \text{ V/m}$ for $n_d = 50, 150$ and $200 \text{ nm}$, respectively. The rise of $E_p$ increases the number of high-energy electrons in the EEDF tail (see, for example, Fig. 1 (c), where the EEDFs for different dust radii are presented). Due to an increase of the number of high energy electrons the averaged ionization frequency and the effective electron temperature grow with $a_d$ or/and $n_d$. For parameters of Fig. 1 (c) $T_{eff} = 3.87, 4.03$ and $4.17 \text{ eV}$ for $a_d=50, 150,$ and $200 \text{ nm}$, respectively. The electron density decreases and power
deposited on the dust particles increases with $a_d$ and/or $n_d$ (see, for example, Fig. 2, where the charged particle densities and power losses as a function of $n_d$ are presented).

![Graph](image)

Fig. 2. The charged particle densities (a) and power losses (b) in dependence on $n_d$ at $P_{\text{in}}=1.0$ W/cm$^2$, $p_0=0.1$ Torr, and $a_d=200$ nm. $P_d, P_{\text{el}}$, and $P_{\text{el}}/P_{\text{in}}$ are power loss in the nonelastic electron-dust, nonelastic electron-neutral, and elastic electron-neutral collisions, respectively.

At high dust densities the power deposited on dust particles can be about 30% of the input power. The decrease of the number of electrons with $u>-\phi_s$ may be also accompanied by changes of the EEDF shape. The Druyvesteyn-like electron energy distribution normally found in pristine plasmas (or at low dust densities and/or sizes) becomes nearly Maxwellian for sufficiently high grain density and/or size (Fig. 3).

![Graph](image)

Fig. 3. The EEDFs at $n_d=10^7$ cm$^{-3}$ (a) and $n_d=10^8$ cm$^{-3}$ (b). The other parameters are the same as in Fig. 2. The EEDF calculated from (1) is compared with Maxwell and Druyvesteyn distributions.

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