Dusty plasma of a dc glow discharge in different noble gases

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Abstract. A self-consistent non-local model of the positive column of a dc glow discharge in helium, neon and argon with dust particles is presented. A kinetic Boltzmann equation for the electron energy distribution function, drift-diffusion equations for ions and dust particles, the Poisson equation for electric field were calculated self-consistently for different discharge conditions. The radial distributions of the discharge plasma and the dust particles parameters were obtained for different discharge gases. The influence of the buffer gas sort is revealed and discussed.

1. Introduction
Dusty or complex plasma is the ionized gas containing neutrals, ions, electrons, and negatively charged particles of micron and submicron size [1–2]. Dust particles can be found in space (e.g., in interstellar clouds, in comet tails or planetary rings) or in different kinds of technical processes (e.g., plasma-chemical reactions used for etching or depositing of thin films, in nuclear fusion reactors, etc.). In chemically reactive plasma, e.g. in semiconductor industry, these particles are typically polydisperse particles with nano- and micro-sizes [3]. They are self-maintained due to molecular dissociation followed by formation of small clusters. These clusters undergo coagulation or polymerization of gas dissociation products. These particles form a cloud of dust particles inside the reactor which levitates above the substrate in the electric field. They can spoil the surface of a growing film when the electric potential is off [3]. In laboratory conditions dusty plasmas are studied intensively in a positive column of dc glow discharge and in rf discharge in low-pressure noble gases. Dusty plasma is a place for many fascinating phenomena, i.e. formation of dust particles structures, phase transitions between different states of dusty plasma (Coulomb crystals, liquids and gases), vortexes and waves, and different kinetic processes.

The laboratory dusty plasma in dc and rf discharges consists of ionized gas with electron and ion densities \( n_i \sim n_e \sim 10^7-10^9 \) cm\(^{-3}\), and the density of dust particles may vary in a wide range \( n_d \sim 10^6-10^8 \) cm\(^{-3}\). Besides, the charge of dust particles can be as high as \( eZ_d = (10^3-10^5) \) e. One of the key characteristics critical for dusty plasma behavior is the Havnes parameter \( P_H = Z_d n_d / n_e \). For low level of Havnes parameter, \( P_H \ll 1 \), the charge of dust particles depends only on plasma parameters. As the parameter \( P_H \) increases, the local parameters (electron density, energy distribution function for electrons (EEDF)) in the region of dusty cloud change. This, in turn, leads to a change in the mean charge of a dust particle, and, consequently, of all properties of dusty plasma.

There are many papers devoted to the influence of dust particles on gas discharge plasma parameters [4-21]. It was commonly accepted that every dust particle plays the role of electrons and ions sink. At high concentrations of dust particles in plasma, this fact must expose some influence on
plasma parameters and even on conditions of discharge sustaining. The loss of electrons and ions on dust particles must be compensated by a high frequency of ionization collisions in plasma that would require a higher average electric field in the region of dusty cloud.

In papers [5,6], with the help of a homogeneous self-consistent kinetic model it was shown that an increase of dust particles density leads to an increase of averaged electric field and ion density, and to a decrease of a dust particle charge and electron density in a dusty cloud. The influence of dust particles on radial distributions of gas discharge plasma parameters was studied by a non-local kinetic model in [7-10] and with the help of drift-diffusion approximation for electrons and ions in [11-14]. The radial distribution of dust particle density in a dusty cloud was taken in [7] as a self-consistent equilibrium Boltzmann distribution of charged dust particles in discharge potential radial distribution. In [8-10], the radial distribution of the dust particles density was considered with the help of drift-diffusion equation.

The influence of discharge gas type on dust particles in a DC glow discharge was investigated in recent experimental works [15-17]. In [15-17] the experiments were carried out in pure He, pure Ar and He-Ar mixture. In [18], the dusty plasma structures were obtained in He-Kr DC glow discharge. It was shown that gas composition strongly influences the dust plasma and gas discharge plasma parameters. The aim of the paper is to develop a model of the positive column of a DC glow discharge in different noble gases and to describe the influence of dust particles on radial distributions of the discharge parameters.

2. Model
It should be noted that even without introduced dust particle a glow discharge in cylindrical tube is a complicated open non-equilibrium system consisting of neutral atoms, ions, and electrons. Under certain conditions, the low-temperature discharge plasma is capable of self-organization process, i.e. formation of striations [19-21]. For these conditions, a big role belongs to non-local effects [21]. As dust particles are introduced into a glow discharge, description of this type of discharge becomes more challenging.

Here we consider a simplified one-dimensional model of a glow discharge in a cylindrical tube with dust particles occupying a certain part of the tube. However, this simple model is called to explain the main problems of mutual influence between the dust particles and the discharge plasma. The previously developed models for radial distributions of a DC glow discharge in argon with dust particles [8-10] were modified to calculate the same distributions in other noble gases (argon, helium and neon).

To describe the mutual influence of dust particles and discharge plasma the following sub-models were used. For an electron component, a non-stationary Boltzmann equation for isotropic part of EEDF was used. The non-stationary drift-diffusion equations for radial distribution of ion density and dust particles density were calculated. The radial distribution of the electric potential $\phi(r)$ was determined from the Poisson equation. The dust particles charge number radial distribution $Z_d(r)$ was calculated with the help of the Orbital Motion Limited (OML) model. The radial and energy dependence of the electron distribution function was calculated with the help of Boltzmann equation.

In longitudinal direction we assume a homogeneous distribution of all plasma parameters including a constant value of axial electric field $E_z$. We set the value of the discharge current equal to $I_d$ as it could be done in an experiment. The value of axial electric field $E_z$ is then generated self-consistently by a feedback between $E_z$ and $I_d$.

In [6], radial distribution of negatively charged dust particles was assumed to have an equilibrium Gibbs-Boltzmann distribution (with some unique dust particle temperature $T_d$) in the effective potential $\phi_d(r)$. The effective potential energy $U_d(r)$ is equal to the sum of the electrostatic energy $U_d(r)$ of the dust particles placed in point $r$ in the radial electric potential of the discharge $\phi(r)$, average self-consistent potential energy of inter-particle interaction $U_{inter}(r)$, and the ion drag force potential energy $U_{drag}(r)$.
In this work, the time-dependent drift-diffusion equation for dust particles was considered. There are no source terms for dust particles. The Einstein relation between drift and diffusion coefficients was taken into account. As a result, it was shown that the equilibrium Gibbs-Boltzmann radial distribution of dust particles density coincides with the solution of drift-diffusion equation.

The cross sections of electron elastic and inelastic collisions with He, Ne and Ar were taken from [22]. It should be noted that the atomic masses of He, Ne and Ar differ greatly and, hence, the mobility coefficients differ several times. More detailed study of ion drift in an external electric field can be found in [23]. Another set of important parameters are the cross sections of elastic and inelastic electron-atom collisions and energy thresholds of inelastic collisions [22]. The thresholds of inelastic collisions in argon have the values starting from 11 eV (for neon 16 eV, for helium 20 eV). The energy threshold of argon atom ionization is about 15.6 eV (for neon 21.56 eV, for helium 24.6 eV). Depending on discharge parameters, the influence of metastable atoms on gas discharge plasma can play an important role. However, in this work we do not take metastable atoms into account.

3. Results
Below the converged solutions for equilibrium radial distributions of the discharge parameters are presented for the following conditions: gas pressure \( p = 1 \) Torr, discharge current \( I_z = 1 \) mA, the dust particle radius \( r_0 = 1 \) μm, the discharge tube radius \( R_w = 1.5 \) cm, the total dust particles number per unit length of the discharge tube corresponds to \( N_d = N_0 = 8 \times 10^4 \) cm\(^{-1}\).

Figure 1a presents the electron energy distribution function \( f(U, r = 0) \) on the axis of the discharge tube. The dust particles parameters and discharge conditions were the same in all regimes, i.e. the number of dust particles \( N_d = N_0 \), the particle radius \( a = 1 \) μm, the tube radius \( R = 1.5 \) cm, discharge current \( I_z = 1 \) mA, gas pressure \( p = 1 \) Torr. It is seen that in argon the electrons have the lowest mean energy. The number of electrons with the energy higher the argon excitation and ionization thresholds (11 eV and 15.7 eV, correspondingly) is negligible. More energetic electrons present in EEDF calculated for neon (16 eV and 21.56 eV). The fastest electrons present in EEDF calculated for helium (20 eV and 24.6 eV). The electron temperature in the region of dust cloud is almost constant and is slightly lower than in the case of pristine plasma (see figure 1b). It reflects the fact that the high energy electrons recombine on the dust particles surface. It is also seen that at any radial position the electron mean temperature in neon is higher than in argon, and the highest in helium.

**Figure 1.** a) Electron energy distribution functions in different gases for the same discharge conditions \((I_d = 1 \) mA, \( a = 1 \) μm, \( p = 1 \) Torr, \( N_d = N_0, R = 1.5 \) cm). b) Radial distributions of mean electron temperature. Solid lines for neon, dashed lines for helium, dashed dotted lines for argon.
Figure 2 presents the radial distributions of dust particle density calculated for different buffer gases for the same discharge conditions. The narrowest radial distribution occurs in helium, and the widest one in argon.

The potential of a dust particle surface, \( \phi_d = -eZ_d/r_0 \), and the charge number, \( Z_d \), of the dust particle placed at the point \( r \) were calculated with the help of OML model taking into account the non-equilibrium EEDF. The potential of the dust particle surface (and the particle charge) decreases with the increase of the concentration of the dust particles inside the dust cloud. The dust particle surface potential on the axis of the discharge tube is equal to \( -e\phi_d(0) \approx 6 \) eV in helium, \( \approx 7 \) eV in argon, \( \approx 8 \) eV in neon. The dust particle surface potential is substantially lower in the region of dust cloud due to low electron energy in this region (see figure 1b).

Figure 3a presents self-consistent solutions for the discharge potential. The parameters of the dusty plasma adjust in such a way that electric potential becomes almost equal to zero in the region of the dust cloud. The radial electric field vanishes while remaining slightly negative. The self-consistent distribution of dust particles, ionization and recombination rates adjust in such a way that they compensate for each other inside the dust cloud. Thus, there is no net production of charged particles in a steady state cloud, no radial fluxes of ions and electrons, and the radial component of the electric field is almost equal to zero inside the cloud. The balance of ionization, recombination and charged particles fluxes to the tube wall is provided in every point of the discharge.

Figure 3b presents the radial distributions of gas ionization rate by an electron impact, \( k_{ion}N_gn_e \), in different buffer gases. The integral of total charge particle production over the whole cross section of the discharge tube has a positive value, which provides the electron and ion flows to the discharge tube walls. These values have the order slightly above the gas atoms ionization potential. For example, in argon \( |\phi_w| \approx 16 \) V, that has the order of argon ionization potential (\( I_{Ar} = 15.7 \) eV). For a smaller potential of discharge tube wall, all electrons created in ionization come to walls. Under higher wall potential, electrons begin to gather in the discharge tube. Outside the dust cloud, the potential \( (-\phi(r)) \) increases from zero level till values of order \( |\phi_w| \approx 26 \) V (\( I_{He} = 24.6 \) eV) for helium, \( |\phi_w| \approx 16 \) V (\( I_{Ar} = 15.7 \) eV) for argon, and \( |\phi_w| \approx 26 \) V (\( I_{Ne} = 21.56 \) eV) for neon.

Figure 2. a) Dust particles density radial distribution in different gases for the same discharge conditions \((I_d = 1 \ mA, a = 1 \ \mu m, p = 1 \ Torr, N_d = N_0, R = 1.5 \ cm)\). b) Radial distributions of dust particles surface potential. Solid lines for neon, dashed lines for helium, dashed dotted lines for argon.
Figure 3. a) Radial distributions of electric potential potential in different gases for the same discharge conditions ($I_d = 1\ mA, a = 1\ \mu m, p = 1\ Torr, N_d = N_0, R = 1.5\ cm$). b) Radial distributions of gas ionization rate, $k_{\text{ion}}N_e\mu_e$. Solid lines for neon, dashed lines for helium, dashed dotted lines for argon.

4. Conclusion
A non-local hybrid model of a DC glow discharge in different noble gases with dust particles based on the non-stationary Boltzmann equation for EEDF, drift-diffusion equations for ions and dust particles, and the Poisson equation for a self-consistent electric field is presented. The model describes the influence of a cloud of dust particles on radial distributions of the DC glow discharge plasma parameters. As a result of a self-consistent evolution of plasma parameters to equilibrium steady state conditions, ionization and recombination rates become equal to each other in the region of the dust cloud, electron and ion radial fluxes become equal to zero, and the radial component of electric field is expelled from the dust cloud. It was shown that the electric potential at the discharge tube wall has the order that is slightly above the ionization potential of a buffer gas. It should be stressed that the present calculations were made for a self-consistent radial distribution of dust particles density. In this work, the drift-diffusion equation for dust particles was calculated. It was shown that the equilibrium Boltzmann radial distribution of dust particles density coincides with the solution of the drift-diffusion equation for the steady state.

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References
[1] Shukla P K 2001 Phys. Plasmas 8 1791-803
[2] Ishihara O 2007 J. Phys. D: Appl. Phys. 40 R121-47
[3] Boufendi L and Bouchoule A 1994 Plas. Source Sci. Tech. 3 262
[4] Boeuf J P 1992 Phys. Rev. A 46 7910
[5] Sukhinin G I et al. 2009 Contributions to Plasma Physics 49 781-5
[6] Sukhinin G I and Fedoseev A V 2010 Phys. Rev. E 81 016402
[7] Fedoseev A V et al. Thermophysics and Aeromechanics 18 615-27
[8] Sukhinin G I, Fedoseev A V 2012 Contributions to Plasma Physics 52 756
[9] Sukhinin G I et al. 2013 Phys. Rev. E 87 013101
[10] Fedoseev A V 2015 *Physical Review E* **92** 023106
[11] Shumova V V et al. 2017 *Plasma Sources Science and Technology* **26** 035011
[12] Polyakov D N et al. 2017 *Plasma Physics Reports* **43** 397-404
[13] Shumova V V et al. 2017 *Journal of Physics D: Applied Physics* **50** 405202
[14] Tian R. et al. 2018 *Journal of Applied Physics* **123** 103301
[15] Maiorov S A 2008 *Physics of Plasmas* **15** 093701
[16] Ramazanov T S et al. 2011 *Contrib. Plasma Phys.* **51** 505-8
[17] Maiorov S A. et al. 2015 *Physics of Plasmas* **22** 033705
[18] Antipov S N et al. 2011 *Journal of Experimental and Theoretical Physics* **112** 482-93
[19] Fedoseev A V and Sukhinin G I 2004 *Plasma Physics Reports* **30** 1061-70
[20] Fedoseev A V and Sukhinin G I 2008 *Journal of Engineering Thermophysics* **17** 74-79
[21] Sukhinin G I et al. 2008 *Journal of Physics D: Applied Physics* **41** 245207
[22] Morgan W L, Boeuf J P and Pitchford L, Siglo Data Base, CPAT and KINEMA software (http://www.siglo-kinema.com).
[23] Maiorov S A 2009 *Plasma Physics Reports* **35** 802-12