High Frequency Feature of Pinhole-to-Plate Sinusoidal micro-DBD

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Abstract. The high (~ GHz range) frequency features of the sinusoidal axi-symmetrical micro-DBD discharge are studied with 2Dt numerical model. It was found that both in the negative and positive driving electrode polarities the electrode current reveals the rather regular “pulse” mode similar to the well-known Trichet pulse structure typically observed in the negative corona discharges in air. The preliminary analyses shown the reason of that is probably the strong nonlinear drift-diffusion-ionization interaction near the electrode surface.

1. Introduction
The surface DBD configuration is widely used in many plasma aerodynamics applications to control flow field or/and temperature distribution near the vehicle surface. The most popular configuration of sDBD is a 2D structure formed by the strip high-voltage electrode mounted above the grounded electrode covered by the thin insulator film (see, for example [1-3] and references there). The discharge is typically initiated by the voltage from couple to several tens of kV. In the case of the long duration experiment the sinusoidal shape of voltage applied can be considered as a good example. The applied voltage frequency is in a range of 1 – 100 kHz. In analysis, the sDBD configuration is usually assumed as 2D [1-4]. At the same time the experiments at high applied voltage and long duration have also shown that the discharge becomes constricted along the strip high voltage electrode edge and 2D consideration is now questionable. Nevertheless, the 2D based approach is still very popular because the 3Dt numerical simulation is enormously hard for everyday practice and, from the other hand, can provide acceptable accuracy to treat experimental characteristics.

In frame of such an approach, we performed earlier the analysis of the heat and dynamics effects of surface DBD actuators with the in-house created code PlasmAero [5,6] based on full self consisted solution of 2Dt Navier-Stokes equations, the drift-diffusion model for real gases, the physical-chemical kinetics and the Poisson equation. Used model has demonstrated the acceptable operability and flexibility to describe the in-time evolution of the electrophysical and thermo- and gas-dynamics fields in good correspondence with experimental observations under sinusoidal load in range from tens to thousands kHz.

The recent studies of long duration operation of the «classical» sDBD actuators proposed for practical applications [7] have revealed another non-2D effects - the formation of the micro structure on the oxidized aluminum electrode surface. This structure is characterized by the thin holes penetrating the oxide film normally to electrode surface to provide the contact of the discharge plasma with the metal electrode surface. This configuration is similar to the micro discharge panels used in some
applications [8]. One can expect the rather important role of the transfer process on these small scales. To focus on the discharge processes taking place in close vicinity of the effective “pinhole” electrode the simplified problem formulation is considered in this work.

2. Problem formulation
For well detailed description of the fast ionization and drift-diffusion processes in the electrode vicinity the rectangular computational region of $0.15 \times 0.075$ mm$^2$ is used (Fig. 1). We consider the first sinusoidal period of voltage applied for several frequencies from 0.1 to 10 MHz for positive and negative polarities.

![Figure 1](image)

**Figure 1** Computational domain.

The computational model is basically same as those described in paper [4,5]. We assume that the flow and electric discharge characteristics can be described by the set of equations reflecting conservation of mass, momentum and total energy for the whole fluid. Transport equations for charged particles, electrons and ions, as well as the Poisson equation for the electric field strength are solved assuming the drift-diffusion approach is valid. The set of governing equations is given below:

\[
\frac{\partial \rho}{\partial t} + \nabla (\rho \mathbf{U}) = 0, \tag{1}
\]

\[
\frac{\partial \rho \mathbf{U}}{\partial t} + \nabla (\rho \mathbf{U} \cdot \mathbf{U}) + \nabla \tau = \frac{\partial p}{\partial t} + \mathbf{F}_e, \tag{2}
\]

\[
\frac{\partial \rho e^0}{\partial t} + \nabla (\rho \mathbf{U} h^0) + \nabla (\mathbf{U} \mathbf{\tau}) + \nabla \mathbf{q} = Q_e. \tag{3}
\]

Here, $\rho$ is the density, $\mathbf{U} = (U_x, U_y)$ is the velocity, $P$ is the thermodynamic pressure, $e^0$ is the specific total energy, $h^0$ is the specific total enthalpy. Terms $F_e$ and $Q_e$ reflect the influence of plasma on the flow field and will be defined later. Equations of state are read as follows

\[
h^0 = e^0 + \frac{P}{\rho}, e^0 = e + \frac{u^2}{2}, (\gamma - 1)e = P/\rho, P = \rho R. \tag{4}
\]

Here, $\gamma = 1.4$ is the ratio of specific heats, and $T$ is the temperature.

Viscous stress tensor components and heat fluxes are specified as usually:

\[
\tau_{ij} = \frac{2}{3} \eta \delta_{ij} \mathbf{U} + \eta \left( \frac{\partial U_j}{\partial x_i} + \frac{\partial U_i}{\partial x_j} \right), \mathbf{q} = -\lambda \frac{\partial T}{\partial x}, \tag{5}
\]

where $\delta_{ij}$ is Kronecker symbol, $\eta$ is viscosity, $\lambda$ is heat conductivity. Gradient and divergence operators are defined as follows:

\[
\frac{\partial}{\partial x} = e_x \frac{\partial}{\partial x} + e_y \frac{\partial}{\partial y}, \nabla = \frac{\partial}{\partial x} + \frac{1}{\gamma} e_x \frac{\partial}{\partial y}, \tag{6}
\]

where $e_x$ and $e_y$ are unit base-vectors, $\xi = 0$ for Cartesian coordinate system, and $\xi = 1$ for axi-symmetric one.

The transport equations for concentrations and Poisson equation for electric field are read as follows:
\[
\frac{\partial n_i}{\partial t} + \nabla \cdot \mathbf{V}_{i} = \dot{Q}, \tag{7}
\]

\[
\frac{\partial n_e}{\partial t} + \nabla \cdot \mathbf{V}_{e} = \dot{Q}, \tag{8}
\]

\[
\varepsilon \mathbf{E} = \rho_e, \quad \mathbf{E} = \varepsilon_0 \nabla \phi, \quad \mathbf{E} = \varepsilon \nabla \Phi, \quad \rho_e = q(n_i - n_e). \tag{9}
\]

In equations (7) through (9) \(n_i\) is ion number density, \(n_e\) is electron number density, \(\rho_e\) is the electric charge density, \(\mathbf{E}\) is electric field, \(\mathbf{E} = -\nabla \phi\) is the electric potential, \(q\) is electron charge, \(\varepsilon\) is permittivity of vacuum, \(\dot{Q}\) is the source term defined later. Strictly speaking the Poisson equation with zero right-hand-side should also be solved in the bulk of dielectric. In this paper, simplified approach is used. Namely, the dielectric surface is considered via special boundary conditions on the plasma-dielectric boundary.

Ion and electron fluxes, \(\Gamma_i\) and \(\Gamma_e\), are defined as follows
\[
\Gamma_i = n_i(U + V_{di}) - D_i \frac{\partial n_i}{\partial r}, \quad \Gamma_e = n_e(U + V_{de}) - D_e \frac{\partial n_e}{\partial r}. \tag{10}
\]
Here, drift velocities \(V_{di}\) and \(V_{de}\) are defined as
\[
V_{di} = \mu_i E, \quad V_{de} = -\mu_e E, \tag{11}
\]
where \(\mu_i\) and \(\mu_e\) are ion and electron mobilities, respectively:
\[
\mu_i = \frac{q/m_i}{v_{i,e}}, \quad \mu_e = \frac{2\sqrt{2}}{3}\pi d_{i,e}^2 \e^{\frac{2kT_i}{\sqrt{\pi m_i e}}} \tag{12}
\]

In equation (12) \(d_{i,e}\) are mean collision cross-section diameters for ions and electrons, respectively. \(T_i\) and \(T_e\) are ion and electron temperature, respectively, \(m_i\) and \(m_i\) are ion and electron mass, \(v_{i,e}\) are mean collision frequencies for ion-neutral and electron-neutral collisions.

Diffusion coefficients, \(D_i\) and \(D_e\) in (10) are defined as
\[
D_i = \frac{u_i k_B T_i}{q}, \quad D_e = \frac{u_e k_B T_e}{q} \tag{13}
\]

In (13) \(k_B\) is the Boltzmann’s constant. In paper [2] we used an approximation for electron temperature as function of the reduced electric field, \(E_r = E/n (\text{Td})\), where \(n = P/k_B T\) is the total number density. Here, we simply take \(T_e = 2eV, \quad T_i = T\).

Electric current density is determined as
\[
\mathbf{j} = j_i + j_e = q(\Gamma_i - \Gamma_e). \tag{14}
\]

Source-terms in equations (2), (3), (7) and (8) are determined as follows
\[
\mathbf{F}_e = \rho_e E, \quad Q_e = \eta_e j_e E + \eta_i j_i E, \quad Q = \alpha n_e - \beta n_e n_i. \tag{15}
\]

The approximations used for ionization coefficient, \(\alpha\), and recombination coefficient, \(\beta\), follow recommendations of the paper [5]:

At the dielectric surface, the jump condition for electric field strength projection is specified:
\[
\varepsilon_p(\mathbf{E}_p \mathbf{n}) - \varepsilon_d(\mathbf{E}_d \mathbf{n}) + \left(\frac{1}{q} \int \mathbf{j} \mathbf{n} \, dt\right) = 0. \tag{16}
\]

Here, \(\varepsilon_p\) is electric permittivity of plasma, \(\varepsilon_d = \varepsilon_0\) is electric permittivity of dielectric material. In the paper \(\varepsilon_p = 3\varepsilon_0(\mathbf{E}_p \mathbf{n})\) is projection of electric field strength onto normal-to-surface from the side of plasma, and \(\varepsilon_d(\mathbf{E}_d \mathbf{n})\) is projection of electric field from the side of dielectric. The latter term in equation (16) represents the accumulation of the charge on the surface due to the flux of charged particles onto the surface.

At the electrode surface potential is specified as: \(\varphi_{HV} = E_0 \cdot \sin(2\pi vt)\), where \(\varphi_0=3.5kV, \quad v=1-10\ \text{MHz}\). Cathode-type boundary conditions are set as follows. Zero normal gradient is set for ion number density. Relation \(\nabla \cdot \mathbf{J} = -\gamma_e \nabla \varphi\) is used for electrons. In this relation, \(\gamma_e\) is the coefficient of secondary electron emission. Calculations were carried out with \(\gamma_e = 0.02\).

The uniform grid with steps \(10^6\times10^8\ \text{m}\) is used in the simulation presented below. The air at the atmospheric pressure and the room temperature is specified as the initial condition, the background ionization as \(n_e = n_i = 10^6\ \text{m}^{-3}\) is specified in full domain, in thin sheet of 5 grid steps over pinhole.
electrode the initial ionization is increased up to $10^{16} \, \text{m}^{-3}$ to provide smooth start of calculations. It was found that there is no significant influence of the initial level of ionization degree on the studied phenomena. The time step integration is limited from above by $10^{-12} \, \text{sec}$ and automatically changed during the calculation to provide stability and accuracy and typically varied within the interval $10^{-12} – 10^{-14} \, \text{sec}$, lower time steps results in unacceptable total calculation time for desktop computing.

3. Results

The results of the simulation for two values of the power supply frequencies of 1 MHz and 10 MHz are presented below. These values are chosen to reduce the componential time requirement defined mostly by the physical time interval duration.

In figure 2 the evolution of the main integral characteristics: Voltage of driving (pinhole) electrode, $V_{ph}$, the total pinhole current $I_{ph}$, the total electrical charge extracted from the domain $Q_{ext}$, the average potentials of barrier $V_b$ and the isolator cover of the main electrode $V_s$. The important value of the gap voltage $V_g = V_{ph} - V_b$ will be also used in the analysis.

![Figure 2 V-I Evolution in 10 MHz discharge](image)

![Figure 3 The fine structure of the burst discharge mode](image)

The first regular mode corresponds to electric field formation through the hole domain with minor currents provided by initially introduced charged particles. In the system under consideration this linear mode exists until electric field will reach the value to start the fast ionization. In this model the only mechanism of ionization is included – electron impact ionization, and the maximal electric field is located at the pinhole outer edge. After the first breakdown newly produced electrons can support rather gradually developing current. At this quasi stable “glow” mode the electric field is reduced significantly due to charge deposition on the barrier and, consequently, the ionization production rate remains at low level. As it will be seen from the next pictures in figure 4 the glow mode is terminated first by the next three breakdowns producing high enough amount of electrons to provide the required level of charge deposition on the barrier for regular operation with rather stable level of the gap voltage $V_g$. The latter is more than an order of magnitude lower in compare with the applied voltage $V_d$. Further, the regular pulsating mode establishing as it is seen in figure 5.

The similar features are observed and in the case of the lower power supply frequency. Some examples of data for $f = 1 \, \text{MHz}$ are presented in figure 6 and figure 7. In addition to the evolution of the integral characteristics the behavior of the local parameters looks also very informative. The maximal value of the electric field strength is located as rule at the singularity of the “triple” point connecting plasma, insulator and electrode at the outer edge of pinhole electrode. In the considered configuration this point initiated as practically all ‘fast’ processes. This ‘hot spot’ is the location of maximal power dissipation, ionization production rate, temperatures and other local parameters.
**Figure 4** Details of the transition to the regular pulsating mode ($f = 10$ MHz)

**Figure 5** The fine structure of the regular pulsating mode ($f = 10$ MHz)

**Figure 6** Details of the transition to the regular pulsating mode ($f = 1$ MHz), dark blue for gap voltage, red – pinhole current.

**Figure 7** The fine structure of the regular pulsating mode ($f = 1$ MHz), dark blue for gap voltage, red – pinhole current, green – charge.

**Figure 8** The first pulse formation at the hot spot ($f = 10$ MHz)

**Figure 9** Details of the transition from glow to the regular pulsating mode at the hot spot ($f = 10$ MHz)
In figures 8–11 the transition process for the parameters at the hot spot from the initial stage to the fully developed pulsating mode are presented. In the figure 12 the effect of the power supply frequency is shown with comparison of the pulsating mode structure. Figure 13 shows the charge formation at the very beginning of the discharge inception. Finally, the framing of the selected current pulse development in terms of electron number density, current density and electric field vectors distribution in the region are presented.

4. Discussion

The particular goal of this publication to report the interesting features of the axisymmetric micro-DBD found during our study of the discharge characteristics for another application.

In the numerical simulation of the sinusoidal DBD with accurate and fine time resolution (time step from $10^{-12}$ to less than $10^{-14}$) we observed the well resolved pulsation of the driving electrode current. Pulsation is observed in both negative and positive polarity. At the negative polarity the pulses look very similar although not identical to the well-known Trichel pulses (see, for example, the work [3] and the good reference list there). The main difference is the frequency which is in two-three order of magnitude higher in compare with “classical” cases. As the preliminary explanation based on the results obtained in this study (only couple of cases are cited above because of the limited available space) is that the ionization process in this case governed by two physical factors – the local electric field defined by the...
global charge distribution and the local electron number density defined by ionization rate and electron drift-diffusion transfer. Micro scale configuration is considered: calculating domain linear scale is

**Figure 14** The discharge domain flashing at the regular pulsating mode ($f = 10$ MHz). Frame consequence from left to right and from top to down corresponds to the symbol order on the plot. Electron number density is represented by level line in blue, current density and electric field vectors in blue and red.
two-three order magnitude larger than the free path length and characteristics times are smaller than the electron collisional time. The framing of the (one of thousands) selected pulse in figure 14 may help us to preliminary suggest the rough model of the regular 10 GHz-pulsing as concurrent chain mechanisms: (a) ionization, (b) electron drift-diffusion, resulting in polarization of the strongly ionized area, (c) decrease of the electric field due to polarization (or screening effect), and (d) ionization rate drops catastrophically (practically stops), drift current becomes less than the diffusion flux (current can change the direction!), all process are stabilized , but (f) external voltage (slowly) recovers the electric field up to breakdown level – pulse start with the fast ionization, and so on. We found in the considered range of parameters that pulsating frequency is rather proportional to the frequency of the extremal applied voltage.

5. Concluding Remarks
1. The new very high frequency (1 – 10 GHz) pulsating electrode current is observed in the numerical simulation of the sinusoidal (0.1 – 10 MHz) micro-DBD in room air environment.
2. The regular (stable pulse shape and frequency) pulsating modes are observed both in the negative and positive polarities but they can differ significantly from each other.
3. The preliminary proposed mechanism can probable include several main processes: electric field induced ionization, drift/diffusion polarization, external circuit slow recovery action, capacity effects of surface and free charge reconfiguration.
4. The more detailed analysis using the wider simulation data based are in progress.

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