Dynamics of pulse discharge in atmospheric pressure argon

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Abstract. In this paper, a complex study of the initial stage of the formation of a pulsed volume discharge in argon at atmospheric pressure under conditions of inhomogeneous preionization of a gas is performed. The features of the development of ionization waves between two plane electrodes in argon at atmospheric pressure are studied.

1. Introduction
The no equilibrium and no stationary plasma of pulsed volume discharges (VD) is widely used in high-power gas lasers, in optical radiation sources, etc. In addition, the formation of the initial stage of discharge development plays an important role in the study of the development of electric breakdown in liquids through a gas-vapor mechanism [1-3]. Despite the large number of works devoted to the study of pulsed volume discharges, many problems related to the physics of pulsed breakdown and mechanisms for the formation of initial stages have not been fully studied and cause scientific discussions [4-9].

In this connection, experimental and theoretical studies of the successive dynamics of the formation and development of a pulsed OP under conditions of preliminary ionization of a gas in inert gases of atmospheric pressure are of undoubted interest.

2. Research methods
2.1. Experimental installation and research methods
The experimental setup and research methods are given in [10]. The voltage across the gap varied in the limits 3÷20 kV. The space-time development of the discharge was photographed by a photoelectric recorder FER2-1. Preliminary maximum value of ionization of the gas (n0~10⁸ cm⁻³) was achieved by irradiating the gap through the grid anode with UV radiation from an external spark discharge [11]. The investigated interval of 1 cm in length was formed by a grid anode and a solid cathode 4 cm in diameter from stainless steel.

2.2. Model of the formation of a pulsed volume discharge in argon at atmospheric pressure
At present, there are three approaches for the numerical simulation of a plasma: kinetic, in which the Boltzmann equations are solved numerically either directly or using the method of macroparticles with Monte Carlo collisions [12, 13], hydrodynamic, in which equations for several the first moments of the Boltzmann equation [13, 14], and hybrid methods [15]. The choice of the model is determined by the
mean free path for each type of particles. For numerical modeling of discharges, at pressures on the order of atmospheric, hydrodynamic and hybrid models are usually used.

In this paper, a two-dimensional axisymmetric diffusion-drift model of the motion of electrons and ions is used to describe the discharge, together with the Poisson equation [16-19]. The calculation is carried out in an argon atmosphere at atmospheric pressure under conditions analogous to the experiment.

The number of cells along the radius was $N_r = 250$ (with condensation near the axis) and in the perpendicular direction $N_z = 300$ (with condensation near the electrodes), respectively. The grid convergence was verified in [24].

The gas-discharge plasma is regarded as a continuous multicomponent medium consisting of neutral atoms ($\text{Ar}$), electrons ($e$), excited atoms ($\text{Ar}^*$) with an excitation energy of 11.5 eV, atomic ($\text{Ar}^+$) and molecular ($\text{Ar}_2^+$) ions. The kinetics of the processes under consideration, the constants of the corresponding reactions, and the energy losses of the electron were taken from [20].

The system of equations (1) includes the balance equations for charged and excited particles, the equation for the electron energy, and the Poisson equation. Neutral gas heating was not taken into account. The temperature of heavy particles in the counting process was assumed to be equal to the temperature of the neutral gas 300 K.

$$\frac{\partial n}{\partial t} + \nabla \cdot \vec{\Gamma} = S$$
$$\vec{\Gamma} = q\mu E - \nabla (Dn)$$
$$\vec{F} = \frac{5}{2} k_b T_e \vec{v}_e - \nabla (\lambda_e T_e),$$
$$\lambda_e = \frac{5}{2} n_e D_e$$
$$\nabla \cdot \vec{E} = \frac{e(n_{de} - n_e)}{\varepsilon_0}$$

where $n$, $\vec{\Gamma}$, $\mu$, $D$ are the concentration, the flow, the mobility and the diffusion coefficient of the corresponding plasma components, $e$ is the electron charge, $k_b$ is the Boltzmann constant $T_e$, $\lambda_e$, $D_e$ are the temperature, the thermal conductivity and the electron diffusion coefficient, $n_e$, $n_{de}$, $n_{Ar^+}$, $n_{Ar_{2}^{+}}$ are the concentration of electrons, atomic and molecular ions, $Q_E$ is the work of an electric field $Q_{el}$, $Q_{in}$ are the elastic and inelastic energy losses of electrons, $S$ is the source of the birth and death of the particles in question in plasma, $\vec{E}$ is the electric field strength. For ions $q=+1$, for electrons $q=-1$, for excited particles $q=0$.

For the diffusion term in the transport equation, and in the energy equation, instead of the generally accepted diffusion fluxes $\vec{\Gamma}_{df} = -D\nabla n$ and $\vec{F} = -\lambda \nabla T_e$ the correct expressions are used $\vec{\Gamma}_{df} = -\nabla (Dn)$ and $\vec{F} = -\nabla (\lambda_e T_e)$ [21].

The mobility coefficients for ions and the diffusion coefficient of the excited particles in the intrinsic gas were taken from [22].

The boundary conditions at the cathode for the potential, charged and excited particles $n_i$ (the index $i$ refers to atomic and molecular ions):

$$\varphi_e = 0, \quad \frac{\partial n_i}{\partial z} = 0, \quad \vec{\Gamma}_e = -\gamma \sum_i \vec{\Gamma}_i, \quad n^* = 0, \quad \frac{3}{2} k_b T_e = e (1 - 2\varphi_i);$$

on the anode:

$$\varphi_a = U(t), \quad \frac{\partial n_i}{\partial z} = \frac{\partial T_e}{\partial z} = 0, \quad n_i = 0, \quad n^* = 0.$$
on the lateral faces of the computational domain:

\[
\frac{\partial \varphi}{\partial r} + \frac{\partial n_e}{\partial r} = \frac{\partial n_i^*}{\partial r} = \frac{\partial T_a}{\partial r} = 0, \quad (4)
\]

where \( \gamma = 0.1 \) is the second Townsend coefficient, \( l = 15.76 \text{ eV} \) is the argon ionization potential, \( \varphi = 4.5 \text{ eV} \) – work function of the cathode, \( e \) is the electron charge, \( U(t) \) is the voltage in the discharge gap at different instants of time, taken from the experiment. For ion-electron emission, the flux to the cathode of both atomic and molecular ions was taken into account.

The integration was carried out explicitly [23] with a second order of accuracy in time and space with Courant number 0.1. The Poisson equation was solved by an iterative method of alternating directions.

The initial spatial distribution of electrons and atomic ions was specified as follows:

\[
\sigma_r = 10^{-3}, \sigma_z = 10^{-3}, z_0 = 5 \cdot 10^{-3},
\]

\[
n_e = n_0 \cdot \exp \left( -\left( \frac{r}{\sigma_r} \right)^2 - \left( \frac{z - z_0}{\sigma_z} \right)^2 \right), \quad n_i = n_0 \cdot \exp \left( -\left( \frac{r}{\sigma_r} \right)^2 - \left( \frac{z - z_0}{\sigma_z} \right)^2 \right)
\]

where \( \sigma_r, \sigma_z, z_0 \) are presented in meters, and determine the characteristic size of the plasma region the location of the position; \( n_0 = 10^8 \text{ cm}^{-3} \). The initial value for the excited particles in the entire design area was set at the level \( n(A^*) = 10^{-3} \text{ cm}^{-3} \). Voltage waveform was taken from [24] with a maximum amplitude of about \( U_0 = 6.8 \text{ kV} \).

3. Results and discussion

3.1. Results of experimental studies and their discussion

Of greatest interest are the experimental results of direct observations of the dynamics of discharge formation with spatial and temporal resolution in the nanosecond time range obtained with the use of FER2-1.

In particular, in figure 1 shows a spatio-temporal picture of the formation and development of OR in Ar in the presence of preliminary ionization of the gas \( (n_0 = 10^8 \text{ cm}^{-3}) \) in the slot-scan mode.

As can be seen from figure 1, the first recorded luminescence appears on the anode after application of the external field, which then diffuses in the form of diffuse luminescence to the cathode with a characteristic velocity of \( ~10^7 \text{ cm/s} \).

![Figure 1](image)

**Figure 1.** The spatiotemporal picture of the development of luminescence in the interelectrode gap in Ar: \( p = 760 \text{ Torr}, d = 1 \text{ cm}, U_0 = 6.8 \text{ kV} \).

The front of the glow is non-uniform, the intensity falls off from the discharge axis to the periphery, which indicates a higher intensity of ionization processes on the discharge axis. After the arrival of the glow front to the cathode, the discharge passes to the next phase, the volume combustion phase. Based on the analysis of photos of the glow for argon at atmospheric pressure, it can be
concluded that at low breakdown voltages $U_0<7$ kV a discharge with a high uniformity of luminescence and a burning duration is formed. At voltages $U_0>7$ kV in the near-cathode region, plasma channels are formed, tied to cathode spots.

3.2. Results of numerical simulation and their discussion

In the case of heterogeneity of preionization, after the application of a high voltage pulse, the electrons leave the near-cathode region, depleting the electron concentration in the near-cathode region, while their amount in the volume increases due to ionization multiplication. This leads (figure 2a) to the formation in the discharge gap of an uncompensated positive and negative charge. Uncompensated charge increases the field strength (figure 2b), which leads to the formation in the discharge gap simultaneously of two ionization waves propagating in opposite directions to the anode and cathode.

![Figure 2](image_url)

**Figure 2.** Characteristic distributions of concentrations of uncompensated space charge (a) and field (b) in the interelectrode gap at different times on the discharge axis: $p=760$ Torr, $U_0=6.8$ kV.
In this case, the formation of an ionization wave occurs at the center of the discharge gap. During propagation, the transverse wave size increases, and the highest velocity is achieved on the axis of the discharge gap. It is also established (figure 2b) that the propagation velocity of the anodally directed ionization wave is higher and the first reaches the anode.

In this case, the maximum value of the field strength at the anode, which decreases with time (within ~5 ns) by more than an order of magnitude, and the maximum of the voltage shifts to the cathode (figure 2b).

Let us estimate the velocity of the ionization waves to the electrodes. To do this, consider the position of the two maxima of the electric field E at different instants \( t_1=36 \text{ ns} \) and \( t_2=42 \text{ ns} \) (figure 2b). As a result, we obtain the velocity of the front for an anodally-directed wave at a level of \( \approx 2.5 \times 10^7 \text{cm/s} \), and for a cathode-guided wave at a level of \( 10^7 \text{cm/s} \). In addition, over time, the cathode-directed ionization wave slows down, and on the basis of an estimate of the velocity of motion in the time interval \( t_1=44 \text{ ns} \) and \( t_2=48 \text{ ns} \), we obtain a velocity of \( \approx 1.5 \times 10^7 \text{cm/s} \). Similar results can be obtained if we follow the position of the maximum (for the cathode-directed wave) and the minimum (for the anodally-guided wave) of the space charge (figure 2a) at different instants of time. The obtained velocity of the ionization front agrees satisfactorily with the experimental data.

Figure 3 shows the concentrations of excited argon atoms in the interelectrode gap on the discharge axis at different instants of time. As we can see, at first the maximum of the concentration of Ar* excited by the atom moves to the anode. Then the concentration of Ar* grows on the discharge axis in the entire design area, with a local maximum being formed that advances to the cathode, which corresponds to the appearance of a glow first near the anode, and then to the growth of the glow front to the cathode.

**Figure 3.** Characteristic distributions of the concentration of excited argon atoms in the interelectrode gap at different times on the discharge axis; \( p=760 \text{Torr}, U_0=6.8 \text{kV} \).

4. Conclusion
A complex study of the initial stage of the formation of a pulsed volume discharge in argon at atmospheric pressure under conditions of inhomogeneous preionization of a gas was performed. The features of the development of ionization waves between two plane electrodes were studied.

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