Study of ionization waves in a pulse discharge in helium

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Abstract. The paper presents the results of experimental and numerical studies of the space-time dynamics of the formation of a discharge in helium under conditions of preliminary ionization of the gas. The effect of local field amplification regions on the discharge development is studied.

1. Introduction

Nonequilibrium and unstable plasma of impulse volume discharge can be widely used in power gas lasers, in optical sources, etc. In spite of a number of articles devoted to impulse volume discharges a lot of issues connected with physics of impulse breakdown and mechanisms of the initial stages formation are not still fully investigated and provoke the scientific discussions [1–7].

In this regard it is undoubtedly interesting to investigate the experimental and theoretical data of the consistent dynamics of impulse volume discharge formation and development in the preparatory gas ionization in helium of atmospheric pressure.

2. Methods of investigation

2.1. Experimental set-up and methods of investigation

Experimental setup and research methods described previously in [8]. For the formation of a pulsed volume discharge for the discharge gap consisting of two plane-parallel electrodes with an inter-electrode distance of 1 cm and a diameter of 4 cm, high-voltage voltage pulses with an amplitude of 20 kV produced by the voltage pulse were applied. The voltage and discharge current were recorded, respectively, by an ohmic divider and a low-inductive shunt using digital oscilloscopes such as Aktakom and Tektronix.

The registration of the space-time development of the discharge was carried out by an FER-2 electron-optical converter with a time resolution of ~ 0.1 ns, operating in frame-by-frame and in dynamic mode. Integral pictures of the glow were shot using a digital camera. The ultraviolet source for gas pre-ionization made it possible to create an initial electron concentration of \( n_0 \sim 10^8 \text{ cm}^{-3} \) and was located either behind the grid anode or laterally at a distance of 5–7 cm from the main gap.

2.2. Formation model of impulse volume discharge in helium of atmospheric pressure

In the article for discharge description we use a 2D axial-symmetric drift-diffusion model of electrons and ions movement along with Poisson equation [9–12]:
\[
\frac{\partial n_e}{\partial t} + \nabla \cdot \vec{\Gamma}_e = a_{nl} \left| \vec{E} \right|^2 - \beta n_e n_i \\
\frac{\partial n_i}{\partial t} + \nabla \cdot \vec{\Gamma}_i = a_{nl} \left| \vec{E} \right|^2 - \beta n_e n_i \\
\nabla \cdot \vec{E} = \frac{e}{\varepsilon_0} \left( n_e - n_i \right)
\]

Here the electron and ion fluxes which can be expressed like that \( \vec{\Gamma}_e = -n_e \mu_e \vec{E} - D_e \nabla n_e \), \( \vec{\Gamma}_i = n_i \mu_i \vec{E} - D_i \nabla n_i \), \( j \) is the current density; \( n_e \) and \( n_i \) are the density of electrons and ions, \( a_{nl} \) nonlocal first Townsend coefficient and \( \beta \) recombination coefficient, \( \mu_e(E/N) \) and \( \mu_i(E/N) \) electron and ion mobility, \( D_e = (kT_e \mu_e) e^1 \) and \( D_i = (kT_i \mu_i) e^1 \) electron and ion diffusion coefficients, \( \varepsilon_0 \) is the dielectric constant; \( \vec{E} \) is the electric field strength, \( \phi \) is the electric potential, \( N \) – concentration of neutral particles, \( T_e(E/N) \) – electron temperature, \( T_i = T_0 \) – ion temperature, \( e \) – elementary charge. Transport coefficients, ionization and deionization parameters are given by dependences from \[10, 11\].

Density of electrons and ions at the initial time inside the computational domain are: \( n_e(x, y, 0) = n_i(x, y, 0) = n_0 \) (\( x \) – dimension in radial direction).

Boundary conditions for the cathode are \( y = 1 \) cm, \( \vec{\Gamma}_e = \gamma \vec{\Gamma}_e \), \( \partial n_e / \partial y = 0 \), \( \phi_k = 0 \), where \( \gamma = 0.1 \) – secondary emission ratio, for the anode are \( y = 0 \) cm, \( \partial n_i / \partial y = 0 \), \( n_e = 0 \), \( \phi_k = U(t) - I(t)R_o \), \[ I(t) = 2\pi \int_0^r j_a(x, t) \, dx, \partial \phi / \partial y = 0. \]

\( I(t) \) – total current in electrical circuit, \( j_a(x, t) \) – distribution of current density on the anode.

The pre-ionization electron and ion concentration in the gap is set as follows:

\[
n_e(x, y) = n_{00} \cdot \exp\left(-k \cdot x^2\right) \cdot \frac{\exp\left(-k \cdot y^2\right)}{d^2} \quad \text{and} \quad n_i(x, y) = n_{00} \cdot \exp\left(-k \cdot x^2\right) \cdot \frac{\exp\left(-k \cdot y^2\right)}{d^2},
\]

Here \( r = 2 \) cm – discharge gap radius, \( d = 1 \) cm – interelectrode distance, \( k \) – coefficient, characterizing the level of in inhomogeneous pre-ionization: \( k = (1-10) \).

3. The results of the researches and their investigation

3.1. The results of the experimental researches and their investigation

Let us consider the experimental results of direct observations of the dynamics of the formation and contraction of a discharge with spatial and temporal resolution in the nanosecond time range with various methods of creating pre-ionization.

After applying a high-voltage voltage pulse to a pre-ionized delay, the first recorded luminescence occurs at the anode (see figure 1a, photo 1), which then propagates to the cathode as a diffuse luminescence. With the advent of diffuse luminescence to the cathode, the discharge enters the next phase, the phase burning phase. At low breakdown voltages \( U_0 < 6 \) kV, the discharge burns stationary and is characterized by high uniformity of luminescence (see figure 1b, photo 1) and burning duration. At voltages \( U_0 > 6 \) kV and current densities of \( j \geq 40 \) A-cm\(^{-2}\), diffuse channels are formed that are tied to cathode spots (figure 1b, photo 2 and 3) and the discharge becomes channel form (figure 1b, photo 4), and the number of diffuse channels is greater, the higher and more uniform the field. The maximum specific energy input to the OR is \( \sim 0.1 \) J-cm\(^{-3}\).
3.2. The results of the numerical experiment and their consideration

As can be seen from figure 1a and 1b, the front of the diffuse glow is non-uniform and has an elongated shape, which can be attributed to the heterogeneity of gas pre-ionization. As follows from the calculation results (see figure 2a and 2b), the non-uniformity of gas pre-ionization both along and across the discharge gap leads to non-uniform distribution of the density of charged particles in the discharge gap, and the ionization wave front is not flat, but has an elongated shape. The rate of the ionization front decreases from the center of the discharge gap to the periphery.

**Figure 1.** Time-lapse pictures of the formation of OR in He ($d = 1 \text{ cm}, p = 1 \text{ atm}$). $U_0 = 18 \text{ kV}$ (a) – flat electrodes, the upper electrode is the anode (A), the lower one is the cathode (K); at different voltages on the gap (b) – stainless steel electrodes (cathode (K) – solid, anode (A) – mesh).

**Figure 2.** Character electron concentration distributions $n_e$, $10^{10} \text{ [cm}^{-3}]$ (a) and the longitudinal component of the field strength $E_y$, $10^4 \text{ [V} \cdot \text{cm}^{-1}]$; (b) in the interelectrode gap at $U_0 = 10 \text{ kV}$, $n_0 = 10^8 \text{ cm}^{-3}$, $k = 1$, $d = 1 \text{ cm}$, $p = 760 \text{ Torr}$.
As the ionization wave approaches the cathode, the electric field strength at the front increases, and the intensity of the ionization processes increases accordingly.

To study the effect of micro-inhomogeneities on the cathode surface on the discharge formation process, a rectangular protrusion with a height $\Delta h = 10 \mu m$ and a width of 100 $\mu m$ (from 1 to 3) was set on the cathode surface at a distance of 1 cm from the electrode axis. The distance between the micro projections was $\Delta x = 0.5$ cm. Micro-inhomogeneities distort the field in the cathode region and initially the development of the discharge begins in a spatially non-uniform field when the distribution of the pre-ionization electron concentration $n_0$ is uniform. As a result, the electron concentration distribution $n_e$ became non-uniform. An increase in the concentration of electrons in the region of increased field strength leads to the appearance of gradients $\nabla n_e$ and a decrease in field strength.

With the arrival of the ionization wave at the cathode and, accordingly, with a sharp decrease in the voltage on the electrodes and a high current growth rate, the electron concentration $n_e$ increased by two orders of magnitude, and its spatial distribution changes significantly. An increase in the electron concentration $n_e$ in regions with increased field strength occurred at a higher rate.

In particular, in figure 3a and 3b shows the characteristic distributions of the strength of the resulting field $E_p$ and the electron concentration $n_e$ over the discharge cross section at distances $\Delta y = 0.05$ cm and $\Delta y = 0.1$ cm from the cathode at time points: 88, 100 ns.

4. Conclusion

Thus, the results of experimental and numerical studies show that the homogeneity and stability of a volume discharge is determined not only by the initial conditions of discharge formation ($E/p$ and $n_0$), but also by cathode processes at the stage of formation and development of the ionization wave.

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References

[1] Tarasenko V, Baksht E and Burachenko A 2010 Technical Physics Letters 36 375
[2] Naidis G and Walsh J 2013 J. Phys. D: Appl. Phys. 46 095203
[3] Tarasenko V and Yakovlenko S 2004 Phys. Usp. 47 887
[4] Babich L, Bochkov E and Kutsyk I 2014 JETP Letters 99 386
[5] Osipov V V 2000 Phys. Usp. 170 225
[6] Kurbanismailov V, Omarov O, Ragimkhanov G et al 2016 Plasma Physics Reports 42 687
[7] Kurbanismailov V and Omarov O 1995 High Temperature 3 365
[8] Kurbanismailov V, Omarov O and Khachalov M 1989 Measurement technology 3 30
[9] Tereshonok D 2014 Technical Physics Letters 40(3) 83
[10] Raiser U 2009 Physics of gas discharge (MFTI. Dolgoprudny: Intellect) 736 p
[11] Surzhikov S 2006 Physical mechanics of the gas discharges (Moscow: Publishing house MSTU) 640 p
[12] Kurbanismailov V, Omarov O, Ragimkhanov G et al 2018 EPL 42 687