Dynamics of impulse volume discharge formation in atmospheric pressure helium

V S Kurbanismailov¹, O A Omarov¹, G B Ragimkhanov¹,³ and D V Tershonok²

¹ Dagestan State University, M Gadjieva st. 43a, Makhachkala, Russia 367003
² Joint Institute for High Temperatures of RAS, Izhorskaya st. 13 Bd.2, Moscow, Russia 125412
³ E-mail: gb-r@mail.ru

Abstract. In the article, we present the results of investigation of the initial stage of volume electric discharge formation in atmospheric pressure helium in inhomogeneous pre-ionized gas. The peculiarities of cathode-directed ionization wave development between two flat electrodes in atmospheric pressure helium are investigated.

1. Introduction

Nonequilibrium and unstable plasma of impulse volume electric discharge can be widely used in power gas lasers, optical sources, etc. Despite a number of articles that are devoted to impulse volume discharges, many issues that are connected with physics of impulse breakdown and mechanisms of the initial stages formation are still not fully investigated and provoke scientific discussions [1–6]. Therefore, it is undoubtedly interesting to investigate the experimental and theoretical data of consistent dynamics of the impulse volume discharge formation and development during the preparatory gas ionization in helium (He) at atmospheric pressure.

2. Methods of investigation

2.1. Experimental setup and methods of investigation

The experimental setup and methods of investigation have been presented in [7]. The voltage in the gaps changes within the limits of 3÷20 kV. The duration of electric pulse is determined by the discharge time of the charged capacitor, and the characteristic discharge time of the capacitor under the experimental conditions was \( \tau \geq 10^{-5} \). The space-time discharge development was recorded using a photoelectronic register (PER2-1). Preparatory gas ionization \( (n_0 \sim 10^8 \text{ cm}^{-3}) \) was obtained via gap radiation using a mesh anode via an exterior spark discharge UV radiation from a third-party discharge, which was located on the side at a distance of 5-7 cm from the axis of the main electrodes in the same gas [8]. The investigated gap (1-cm length) was formed via solid aluminium electrodes with a diameter of 4 cm.

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

Currently, there are three approaches for the numerical simulation of plasma: kinetic (in which Boltzmann equations are numerically solved either directly or using the microparticle method with respect to collisions according to the Monte Carlo method [9, 10]), hydrodynamical (in which the equations are solved numerically for the first several moments of Boltzmann equation [10, 11]), and a
hybrid method [12]. The choice of the model is defined by the free path length for every type of the particles. For discharge under the atmospheric-pressure, the hydrodynamical and hybrid methods are usually used for numerical simulation.

In this article, to describe the discharge, we use the 2D axial-symmetric drift-diffusion model of electron and ion movements along with the Poisson equation [13–16]:

\[
\frac{\partial n_e}{\partial t} + \nabla \cdot \vec{J}_e = \alpha_{nl} |\vec{F}_e| - \beta n_e n_i, \\
\frac{\partial n_i}{\partial t} + \nabla \cdot \vec{J}_i = \alpha_{nl} |\vec{F}_i| - \beta n_e n_i, \\
\nabla \cdot \vec{E} = \frac{e}{\varepsilon_0} (n_e - n_i)
\]

Here, the electron and ion fluxes can be expressed as \( \vec{J}_e = -n_e \mu_e \vec{E} - D_e \nabla n_e \) and \( \vec{J}_i = n_i \mu_i \vec{E} - D_i \nabla n_i \), respectively, where \( \vec{J} \) is the current density; \( n_e \) and \( n_i \) are the density of electrons and ions, respectively; \( \alpha_{nl} \) is the nonlocal first Townsend coefficient, and \( \beta \) is the recombination coefficient; \( \mu_e(E/N) \) and \( \mu_i(E/N) \) are the electron and ion mobility, respectively; \( D_e = \frac{kT_e \mu_e}{e} \) and \( D_i = \frac{kT_i \mu_i}{e} \) are the electron and ion diffusion coefficients, respectively; \( \varepsilon_0 \) is the dielectric constant; \( \vec{E} \) is the electric field strength; \( \varphi \) is the electric potential; \( N \) is the concentration of neutral particles; \( T_e(E/N) \) is the electron temperature; \( T_i = T_0 \) is the ion temperature; \( e \) is the elementary charge. Transport coefficients, ionization and deionization parameters are obtained from the dependences in [14, 15].

The non-local ionization coefficient was obtained from [16].

The densities of electrons and ions at the initial time inside the computational domain are:

\( n_e(x, y, 0) = n_{e0}, \quad n_i(x, y, 0) = n_{i0}, \quad (x - \text{dimension in radial direction}). \)

The boundary conditions for the cathode are \( y = 1 \) cm, \( \vec{J}_e = \vec{J}_+, \quad \partial n_+ / \partial y = 0, \quad \varphi_k = 0, \)

where \( \gamma = 0, 1 \) is the secondary emission ratio, and for the anode, \( y = 0 \) cm,

\[ \partial n_e / \partial y = 0, \quad n_+ = 0, \quad \varphi_k = U(t) - I(t) R_y, \quad I(t) = 2\pi \int_0^r j_a(x, t) x dx, \quad \partial \varphi / \partial y = 0. \]

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

The pre-ionization electron and ion concentrations in the gap are set as follows:

\[ n_e(x, y) = n_{e0} \cdot \frac{\exp(-k \cdot x^2)}{r^2} \cdot \frac{\exp(-k \cdot y^2)}{d^2}; \quad n_i(x, y) = n_{i0} \cdot \frac{\exp(-k \cdot x^2)}{r^2} \cdot \frac{\exp(-k \cdot y^2)}{d^2}, \]

where \( r = 2 \) cm is the discharge gap radius, \( d = 1 \) cm is the interelectrode distance, and \( k \) is the coefficient that characterizes the level of inhomogeneous pre-ionization \[ k = (1/10) \].
3. Results of the research and their investigation

3.1. Results of the experimental research and their investigation.

The most interesting are the experimental results of direct observation of the discharge formation dynamics with space and time resolution in the nanosecond time range, which were obtained using PER2-1.

In particular, in fig. 1 (photos 1–4), the photos illustrate the volume discharge formation in He at different time periods. The discharges are made via preliminary gas ionization.

As can be seen in fig. 1 (photos 1–4), the first registered glow appeared on the anode after the outer field application, which then spreads to the cathode in the form of diffuse glow with a characteristic speed of $\sim 10^7$ cm/s. The glow front is inhomogeneous, and the intensity falls from the axis of discharge to the periphery. This shows the higher intensity of ionized processes on the discharge axis. After the glow front arrives to the cathode (photo 1–3), the discharge proceeds to the next phase – the overall combustion phase.

![Figure 1. Dynamics of volume discharge formation in He (photos 1–4) and the integral picture of discharge glow (photo 5): $p = 760$ torr, $d = 1$ cm, $U_0 = 9$ kV.](image)

For a small breakdown voltage $U_0 < 6$ kV, a volume discharge with a high glow homogeneity and combustion duration is formed. When the voltage is $U_0 > 6$ kV (look at fig. 1, photo 4) and the current density is $j \geq 40$ A/cm$^2$, the plasma channels, which are connected with cathode spots, are formed in the pre-cathode area.

3.2. Results of the numerical experiment and their consideration.

Let us look at the results of numerical experiment of the discharge formation stage in inhomogeneous gas preionization. As one can see from the results, after the high-tension impulse is applied, the electrons due to drift move to anode from the cathode region. Simultaneously, the electron concentration in the cathode region decreases, and their concentration in the discharge column increases due to ionized electron multiplication. The appearance of uncompensated positive electron cloud (look at fig. 2a) makes the field in the cathode region stronger and, at the same time, weaker in the positive column region (look at fig. 2b).

Gas preionization inhomogeneity due to both far and wide discharge gap leads to the inhomogeneity of electron concentration distribution when the discharge gap is wide. Thus, the ionization wave front is not flat, it has an oblong shape. The ionization wave formation mostly occurs in the discharge gap axis, where the field has the maximum value.

In the ionization wave development process, the uncompensated positive discharge on the front creates a high transverse electric field $E_x$. When it approaches the cathode, the field tension on the ionization front also increases, similar to the intensity of ionization processes. When there is a decrease in the preionization electron concentration, the time of the ionization wave formation increases as well as the discharge formation time.

In the formed plasma column, the concentration of charged particles on the discharge axis is higher, and it becomes smaller at the discharge periphery.
4. Conclusions
Discharge formation occurs during the propagation of cathode ionization wave. This is proven by the results of numerical experiments and by the results of experimental research of the space-time dynamics of the discharge initial stages development. Wide gas preionization homogeneity forms inhomogeneous ionization wave front, which is developed from the central zone of the gap.

The studies that are performed in this work show the complexity of the processes in the discharge formation stages. This generates interest for the further study of the problem.

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References
[1] Tarasenko V, Baksh E and Burachenko A 2010 Technical Physics Letters. 36(4) 375-78.
[2] Naidis G and Walsh J 2013 J. Phys. D: Appl. Phys. 46 (095203) 13
[3] Tarasenko V and Yakovlenko S 2004. Phys. Usp. 47(887)
[4] Babich L, Bochkov E and Kutsy 2014 JETP Letters 99(7) 386–90
[5] Osipov V V 2000 Physics-Uspekhi 170(3) 225-245
[6] Kurbanismailov V, Omarov O, Ragimkhanov G et al 2016 Plasma Physics Reports 42(7) 687-698
[7] Kurbanismailov V and Omarov O 1995 High Temperature 3(3) 365-369
[8] Kurbanismailov V, Omarov O and Khachalov M 1989 Measurement technology 3 30-37
[9] Birdsall C K 1991 IEEE Trans. Plasma Sci..19(2) 65-85
[10] Kim H C, Yang S S, etal. 2005 J. Phys. D: Appl. Phys. 38 283-301
[11] Georghiou G E, Papadakis A P, Morrow R A, and Metaxas A C 2005 J. Phys. D: Appl. Phys. 38 303–328
[12] Kushnier M J 2005 J. Phys. D: Appl. Phys. 38 1633-1643
[13] Tereshonok D 2014 Technical Physics Letters 40(3) 83-89
[14] Raiser U 2009 Physics of gas discharge MFTI. Dolgoprudny: Intellect 736
[15] Surzhikov S 2006 Physical mechanics of the gas discharges M.: Publishing house MSTU under the name of N.E. Bauman 640
[16] Soloviev V and Krivtsov V 2009 J. Phys. D: Appl. Phys. 42 13