44. MATHEMATICAL MODELING OF LINEAR-STABILIZED SURFACE DISCHARGE IN THE GAS

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One of perspective directions of creation powerful sources of radiation with ohmic heating, obeying of many practical requirements, is usage of high-current surface discharges. Considerable scientific and technical advance was reached in the last years in this direction [1]. An essential feature of surface discharges is that solid wall not only in many determines regime of an energy contribution and parameters of plasma, limiting a current channel and stabilizing its position in space, but also executes a function of an indispensable structural element of discharge, which accountable for its initiation. Among different effective ways of initiation of distributed surface discharges it is possible to secure a method pulse-periodic initiation offered in the work [2], on the basis of which one so-called the linearly-stabilized surface discharge (LSSD) is built.

The plan of LSSD is shown in a Fig.1a. In an interelectrode dielectric insert (IEDI), the sizes and material by which one have no principled value, on a straight line (or any other) line, connecting electrodes of the basic discharge with a step 5-15mms, set padding electrodes - metallic rods a dia 1mm, galvanic bound with auxiliary capacitances \( C_i \) (\( C_i = 100-1000 \mu F \)). Other plate of capacitors \( C_e \) is under an earth potential. there is a self-breakdown of a surface segment of dielectric between a high-voltage and first padding electrode at actuation of the commuting discharger, and the charge executes of the first auxiliary capacitor. When the voltage at it will reach value sufficient for a breakdown of an interval up to the second padding electrode, the charge of the second capacitor will begin, etc. The wave of a breakdown (ionization) is displaced along dielectric through line, given arrangement of padding electrodes, and at a final stage short-circuits all interelectrode interval. After that the basic capacitor \( C_0 \) with initial energy \( W_0 \) is discharged on an interelectrode interval and there comes stage of high-current discharge. On the plasma layer, appeared in surrounding gas, starts to flow a current, thus in plasma, at the expense of Joule heating, the energy from the capacitor is nested. Above IEDI surface is derivated plasma formation - straght-line, dilating in transverse direction, semicylindrical, consisting of plasma of surrounding gas and plasma of vapors of IEDI material, which is generated about a surface interelectrode insert under activity of radiation fluxes coming out of high-thermal areas of plasma discharge (Fig.1b).

LSSD, are carried out in gas media atmospheric pressure at a pulse discharge of the capacitor on an interelectrode interval \( L = 0.25-1m \), are characterized by a fading sinusoidal current pulse with duration of the first half-period \( t_1 \sim 10 \mu s \). The plasma of such discharge has temperature

Fig.1. Diagrams (a) of line-stabilized surface discharges (LSSD) and total structure (b) of LSSD plasma in cross-section.
1 - IEDI; 2 - power electrodes; 3 - igniter; 4 - commutator; 5 - area of light-erosive vapor; 6 - contact boundary; 7 - area of plasma-gas; 8 - front of external boundary of discharge with surrounding gas.
about $T=10$-100kK, density of electron $n_e=10^{18}$-$10^{20}$cm$^{-3}$ and reference transverse size $b=1$-5sm.

For achievement of brightness temperatures $T_{br}=20$-50kK, the demanded level of values specific (per unit length of interelectrode interval) electrical power allocated in plasma, should make $P_{el}=W_{el}/I_1 \geq 2\pi b g q=2\pi b q S_{BT} I_{el} \approx 1$-300MW/sm. The discharge currents, for execute of such energy contribution, should be $J_{el}(P_{el}/R_p)/2 \approx 10$-5000kA, and intensity of the own magnetic field - $H\sim J/b \approx 10^2$-5$\times10^3$ A/m.

LSSD are carried out in indicated ranges of the change of main parameters has specific features - limitation of dilating of plasma formation by dense gas medium, solid surface and own electromagnetic forces in conditions of operating power (1-102 MW/sm$^2$) flows of broadband heat radiation at limitation of a conclusion it from discharge area by “window of transparency” surrounding gas. At reference range $P_{el} \approx 1$-300MW/sm, as a result of operating radiation fluxes $q=1$-100MW/sm$^2$ from plasma, the intensive surface vaporization IEDI executes already on the initial phase of discharge during $t<1\mu s$. The light-erosive plasma “falling” in the field of operating electromagnetic forces can essential influence on structure and parameters of plasma discharge.

Known experimental results [2] demonstrate a capability of creation the power pulse-periodic sources of radiation with an extended homogeneous body of glow and brightness temperature in UV-range of spectrum $T_{br} \approx 40$K, with high reliability and resource ($\geq 106$ pulses) activity, manufacturability of design and low cost.

At analysis and subsequent optimization of such multiparameter systems, as LSSD, the theoretical investigations play the extremely relevant role. That in such composite plasmodynamic systems the analytical approach appears poor, there is a necessity of their numerical modeling.

In the report the resutes of systematic numerical researches of radiation plasma-dynamic processes in electrodischARGE sources with the dominating ohmic mechanism of plasma heating - pulse high-current radiant discharges (HCRD) in gas media.

The analysis is conducted on the basis of a numerical solution of the system of unsteady equations of radiation magneto-gasdynamics [3], supplemented by the set of equations describing processes of heating and vaporization IEDI, and the set of equations of an electrotechnical contour of discharge [4]. The set of equations of gasdynamics was decided using the Godunov-Kolgan method. The electromagnetic processes are described by a set of equations of the Maxwell and Ohm in plasma with final conductivity (the calculations are carried out with usage data [5]). The radiation transfer equation was solved using the multigroup diffusion approximation [3]. The calculation of heating and evaporation of IEDI was performed on the basis of solution of unsteady heat equation with moving boundary of the evaporation front. The surface evaporation in the presence of backpressure was described by the model of Knudsen layer [6] with the solution of respective problem of conjugation of condensed and vapor media (using the iteration procedure), which makes it possible to determine the boundary conditions for the equations of gasdynamics. The loop equations were solved by the explicit Euler method.

The thermodynamic and optical parameters of the working media (vapour phase of IEDI material and surrounding gas) were defined within the framework of local thermodynamic equilibrium and were calculated using the MONSTR computer codes [7].

On the basis of common set of equations the hierarchy spatially one-dimensional and two-dimensional mathematical models of radiation plasma-dynamics is constructed, their numerical implementation is carried out and the programm complex is built.

The common qualitative legitimacies of radiation plasma-dynamic processes in HCRD in gas media of atmospheric pressure are established on the basis of designed one-dimensional models. Two basic types of discharges with the ohmic mechanism of heating (with the configuration of a flat simple Z-pinch) are selected for the analysis: the open discharge in unlimited gas medium (OUD) and the open surface discharge (OSD) limited from one-sided by a solid dielectric wall.

The calculations are conducted for discharges in argon or air media, at value of length of the interelectrode interval $L=25$-100sm, value stocked in the capacitor of energy $W_{el}=1$-100kJ and duration the first half-period of the discharge current $t_1=5$-10$\mu$s. The range of change average specific (per unit length of interelectrode interval $L$) electrical power allocated in plasma has compounded $P_{el}=1$-400 MW/sm.

Is shown, HCRD, depending on $P_{el}$, can exist in three different quasi-stationary regimes (“explosive” (ER), magneto-gasdynamics (MGDR) and quasi-pinch (QPR)) in conditions of limitation of dilating plasma formation by gas medium and own magnetic field. The regimes differ by structure and parameters of plasma.

The boundary values of average specific electrical power $P_{cr}$, determining areas of existence of regimes, depend on properties of surrounding gas and various for OUD and OSD, mirroring specific features OSD, bound with
availability of solid dielectric surface, which one is
the rigid spatial limiter and source of light-erosive
plasma. The regimes of HCRD are connected to
parameters of plasma (speed, density etc.) in
boundary zones of extending plasma formation is
established. The card of HCRD regimes is
constructed (Fig.2). The “explosive” regime at
$P_{el}<P_{cr1}$ is executed, at which one the outer
boundary of discharge is gasdynamic shock wave
distributing in surrounding gas with speed
$D=P_{el}/3$. At the magneto-gasdynamic regime
($P_{cr1}<P_{el}<P_{cr2}$) the limitation of increase of speed $D$
of the outer boundary of discharge takes place at
increase of specific electrical power (Fig.2). This
result confirms by experimental data obtained as
for discharges such as OUD and discharges such as
OSD. The effect of degradation external shock
wave appear in the magneto-gasdynamic regime at
which one the compression ratio of gas behind the
external break becomes less compression ratio till
Hugonio and prolongs to decrease in process of
increase of power, put in plasma. This effect
demonstrates on the Fig.3, on which one
calculation spatial distributions of basic plasma
parameters of OUD for MGD (a) and QP (b)
regimes are realized. The effect of degradation
shock wave was watched in experiments [8] in
conditions of operating strong external fields on
plasma of a spark discharge. In the quasi-pinchof
regime (Fig.3b), at $P_{el}>P_{cr2}$, the external break
transforms from a break of compression to a
radiation-magneto-gasdynamic rarefaction wave, in
which one the plasma density less than the
surrounding gas density.

![Fig.2. Diagram of regimes and velocity external boundary HCRD propagation](image1)

![Fig.3. Effect of radiation-magneto-gasdynamics degradation of shock wave. a) $P_{el}=100$MW/sm (MGD-regime), b) $P_{el}=300$MW/sm (QP-regime); 1 - area of degradation of shock wave in the MGD-regime; 2 - area of RMGD rarefaction wave in the QP-regime](image2)

The analysis of mechanics of HCRD
formation radiation spectrums is conducted and
their connections with regimes and types of
discharges are established. Is shown, brightness
temperature and light output generated by the
surface discharge of UV-radiation, are increased at
transition in the energy-powerful regimes with
formation light-erosive plasma, the radiation by
which one can make an essential part in the
common light flux of discharge. Is established, the
availability of plasma light-erosive vapors provides the effect of amplification of flows UV-radiation and higher light efficiency in surface discharges, than in the open discharges through gases in the field of parameters, conforming to the explosive regime. The radiant characteristics of surface discharges succumb to the characteristics OUD at transition in the magneto-gasdynamic regime.

Fig. 4. Diagrams of LSSD regimes and dependence of average velocity of boundary discharge in argon from regime parameter $G$ in perpendicular $D_\perp$ and parallel $D_\parallel$ dimension to IEDI

On the basis of created closed unsteady two-dimension radiation plasma-dynamic model the systematic numerical researches of practically relevant type OSD - the linearly-stabilized surface discharge (LSSD) in gas media in wide range of change energy-powerful ($P_e=1-400\text{MW}/\text{sm}$) and design parameters of discharge in medium of argon and air are conducted. As has shown the analysis of the obtained results, main legitimacies on dynamics of formation, structure and parameters of LSSD plasma qualitatively correspond to legitimacies established in one-dimensional models. Differences of radiation plasma-dynamic processes in directions perpendicular and parallel to the interelectro dielectric insert surface and their nonlinear connection, causes complicating of reshaped LSSD plasma structure.

Is shown, in the first half-period of discharge $t_1\approx5-10\mu$s, when the current, the magnetic field and the radiation fluxes are max, LSSD can exist in the different quasi-stationary regimes depending on value of the regime parameter $G=P_e/(\rho d_1)$, describing average pace of allocation specific Joule power in plasma discharge. The calculation diagram of LSSD regimes and dependence of average velocity of boundary discharge in argon from regime parameter $G$ in perpendicular $D_\perp$ and parallel $D_\parallel$ dimension to IEDI are shown on the Fig.4. The “explosive” regime at $G\approx G_{cr}=\approx(4-5)\times10^{11}\text{m}^4/\text{s}^4$ is realized, at which one the plasma of discharge isotropically extends in all directions, and the border

Fig. 5. Features of structure LSSD in quasi-pinch regime. Level line of density $\rho\text{[kg/m}^3\text{]}$ and temperature $T\text{[KK]}$ at point time $t=2,03\mu$s the first maximum discharge current $J=1\text{MA}$ for LSSD in argon under consideration $W_0=375\text{kJ}$, $L=0.25\text{m}$, $G=100\times10^{14}\text{m}^4/\text{s}^4$
of discharge is strong gasdynamic shock wave. The magneto-gasdynamic regime is realized in area $G_{cr1}-G_{cr2}=(5-20)\times10^{14}(m/s)^2$, at which the anisotropy of plasmadynamic characteristics of discharge in directions perpendicular and parallel to the dielectric insert surface is essential. The rate of propagations of border discharge in directions perpendicular $D_\perp$ and parallel $D_\parallel$ to IEDI surface leave on some limiting values $D_\perp M=4\text{km/s}$ and $D_\parallel M=2.5\text{km/s}$ (for argon at normal conditions). The boundary area of discharge with surrounding gas is degrading gasdynamic break. The blended radiation-magneto-gasdynamic regime with the brightly expressed asymmetry of parameters plasma in different directions of dilating plasma formation takes place at $G_{cr2}-G_{cr3}=(20-100)\times10^{14}(m/s)^2$. In the areas of plasma discharge, accumbent to IEDI surface, the structure with availability radiation-magneto-gasdynamic rarefaction wave are derivated. Thus distribution of parameters plasma in the direction perpendicular to IEDI correspond to the MGD-regime. The quasi-pinched regime executes at $G>G_{cr3}=(100-1000)(m/s)^2$, for which one all boundary area of discharge is the front of radiation-magneto-gasdynamic rarefaction wave. There is magnetic and shock-oblated plasma “core” with reference density $(4-6)p_0$ and temperature about $8-10eV$ on a symmetry axis of discharge above the IEDI surface (Fig.5).

Is shown, brightness temperature of UV-range of LSSD spectrum are max in the first half-period approximately at the moment of maximum of the discharge current and reach limiting values $T_{brmx}$ at $G>100-10^{14}(m/s)^2$ (Fig.6).

The area of energy-powerful parameters discharge is determined, at which one its radiant efficiency is max, is minimum light-erosive breakup of IEDI, and brightness temperatures in UV-range reach values $20-30kK$, optimum for different practical applications of LSSD. On the complex of parameters and characteristics the satisfactory coincidence calculations and experimental data is obtained.

References