doi: 10.56761/EFRE2024.S4-O-000601

Numerical modeling of the dynamics of gas and plasma jets in the application of a magnetic field

V.V. Kuzenov, S.V. Ryzhkov[*]

Bauman Moscow State Technical University, Moscow, Russia
[*]*svryzhkov@gmail.com*

Abstract. The presented work describes an element of the hierarchy of radiation-plasmadynamic mathematical models that are designed to study sources of pulsed electrical discharge of various classes. As a result of the conducted computational studies, data were obtained on radiation-plasmadynamic processes and phenomena in pulsed erosive electric discharge sources of ultraviolet radiation and various types of shock waves.

Keywords: gas, magnetic field, plasma dynamics, thermal physics, energy.

1. Introduction

Thermophysical processes play an important role in many scientific and technical fields in various types of discharges and circuits [1–8]. The use of electric discharge plasma sources is primarily associated with the need to develop and obtain energy sources and particles of different ranges [9–15].

Ohmic-heated radiation sources, or, in another way, high-current emitting discharges (HCED), are discharges in which the action of their own electromagnetic forces is directed at the magnetic localization of plasma formation forming in the interelectrode gap [16–23]. In this case, the role of the kinetic energy of the plasma in the energy balance of the discharge should be minimal with the most efficient conversion of Joule energy directly into the internal energy of the plasma. It should be noted that the ohmic plasma heating mechanism will be effective provided that the rate of energy transfer from electrons to ions exceeds the rate of energy transfer from an electric field to electrons. This condition is fulfilled by limiting the discharge current density j to a value of

$$j_{cr} \approx en_e \left(\frac{3kT}{M} \right)^{1/2}$$

which in typical cases ($n_e \approx 10^{18}$–10^{20} cm, $T \approx 10$–100 eV) is $j_{cr} \leq 1$ MA/cm^2. In addition, the effective introduction of Joule energy into the plasma of such discharges should be carried out under conditions of limiting the thermal expansion of the heated plasma, i.e. by limiting the characteristic transverse size b, since the highest values of the active resistance of the plasma $R_{pl} \approx L/[\pi b^2 \sigma(T)]$ are realized (where L is the length of the interelectrode gap, σ is the conductivity of the plasma with temperature T). In HCED, the transverse restriction of the plasma channel can be carried out not only by a magnetic field, but also by gas and solid walls.

The most promising, from the point of view of increasing the brightness temperatures of HCED plasma, are the so-called open discharges developing in an unlimited (or partially limited) medium with solid walls: open HCED in vacuum and gases. According to the factors limiting the rapid expansion of the plasma channel, all open HCED are divided into:

- vacuum open unbounded discharges where only compressive electromagnetic forces act;
- vacuum open surface discharges with the action of compressive electromagnetic forces and a solid dielectric surface;
- gas open unlimited discharges (OUD) under the action of compressive electromagnetic forces and back pressure of the gas surrounding the gas discharge;

- gas open surface discharges (OSD) in which the limitations of the thermal expansion of the plasma are carried out simultaneously by electromagnetic forces, the external gas environment and a solid surface.

2. Discharges and modes

One of the most important features of any radiative plasma dynamic (RPD) process is the presence of strong nonlinear interactions between the various processes that compose it: radiation, gasdynamic, electromagnetic and thermophysical. Due to the complexity of local diagnostics and experimental research of such processes and phenomena of RPD, in many cases experimental data on the parameters and characteristics of the process or phenomenon under study are integral, it is often insufficient to find cause-and-effect relationships that determine the basic physical patterns, and identify effective ways to optimize these processes and manage them. In such a situation, the success in creating high-energy RPD systems and installations for various purposes largely depends on the level of theoretical developments. Moreover, the most effective research method should be recognized as a computational experiment, which allows at some stages to replace expensive field experiments, and in a situation where experimental data are practically absent, numerical modeling remains the only way to obtain both qualitative and quantitative data about the process.

In the standard case, the description of radiative magnetoplasmadynamic processes in the considered types of electric discharge sources should be carried out in a three-dimensional spatial approximation. The solution of the above system of equations in this case even now seems to be very problematic. Therefore, it is advisable to consider and build a hierarchy of spatially approximate models based on a complete system of equations, including the simplest one-dimensional models, which allow us to identify, first of all, the main qualitative features of dynamics and spectral brightness characteristics of discharges.

The magnetogasodynamic mode (MGD- mode) takes place in a certain range of values of the average specific electric power $P_{el} \in [P_{cr1}, P_{cr2}]$. The criterion determining the end of the MGD-mode, is the complete degradation of the gas dynamic gap (GD-gap) as the outer boundary of the discharges. The physical reasons for the discharge exit from the MGD – mode are associated with an increase (with an increase in P_{el}) in radiation fluxes and electromagnetic forces acting in the discharge zone.

At values $P_{el} > P_{cr2}$ the magnitude of the radiation fluxes that were absorbed by the GD-gap region should be sufficient to warm up the entire boundary region of the GD-gap during time $\leq t_1/2$ to temperatures at which current flows in it, and the resulting inhibitory electromagnetic forces will exceed the dynamic gas pressure in the GD-gap, thereby causing a radiation-magnetogasodynamic effect the disappearance of the GD-gap area and the transition of discharges into a quasi-pin mode.

The values of the critical values of the specific electrical power P_{cr2}, which are the upper limit of the existence of the MGD – mode, depend on the type of discharge and the properties of the environment. As calculations have shown, for OUD in argon P_{cr2} ~ 140 MW/cm, and for OSD in argon P_{cr2} ~ 300 MW/cm. That is, the P_{cr2} for OSD in argon is approximately twice as high as the P_{cr2} for OUD in argon.

The main reason for this difference in P_{cr2} is the difference in travel speeds GD-gap for OUD and OSD. For OSD higher velocities and levels of values of the velocity pressure $\rho_1 D_m^2/2$ of the gas in GD-gap require for its braking large values of electromagnetic forces acting in the region GD-gap, and, consequently, higher values of P_{el}.

The optical properties of the surrounding gas have a significant influence on the value P_{cr2}. A necessary condition determining the possibility of complete degradation of the GD gap is the condition for the penetration of radiation generated by the high-temperature plasma region of the discharge into the gas layer of the GD gap with intensity and spectral properties that ensure heating of this layer to temperatures T_1 ~ 20 kK, at which the inhibitory electromagnetic force effectively begins to act. A characteristic optical property of the air environment is the relatively low value of the spectral boundary of the "transparency window" of cold (T < 15 kK) air – $h\nu_1 \approx 6$ eV. An increase P_{el} leads to an increase in the temperature of the plasma zone T_2 and a shift of the maximum of the radiation spectrum to the area of the shortwave range ($h\nu_m \approx 3kT_2$ eV). At temperatures characteristic of the MGD mode (P_{el} > 40 MW/cm) the temperature values of the plasma discharge T_2 > 40 kK the main part of the thermal radiation generated by high-temperature plasma is in the region of short-wave radiation with quantum energy $h\nu_m \approx 12$ eV and, as can be seen, is outside the "transparency window" of cold (T < 15 kK) of air. Radiation cannot penetrate the GD-gap, heat it to a temperature T_1 ~ 20 kK and during the first half-period t_1 provide the conditions necessary for complete degradation of the GD-gap.

3. Description of the features

To identify the main qualitative features of the dynamics and spectral brightness characteristics of discharges in the main phase of Joule energy release, i.e. in the first half-period of the discharge current, we can limit ourselves to a one-dimensional approximation. At the same time, the direction perpendicular to the surface of the interelectrode insert is highlighted as a priority for OSD, and for OUD – the direction perpendicular to the axis of symmetry of the discharge. To ensure the identity of the conditions for comparing radiation-magnetoplasmadynamic processes in OSD and OUD, the simplest geometry was chosen for both discharges – a flat discharge with a simple Z-pinch configuration.

Numerical studies of the plasmadynamic processes of discharges developing in argon (Ar) or atmospheric pressure air (Air) were carried out with variations in the length of the interelectrode gap, L = 25–100 cm the level of the amount stored in the capacitive storage, C = 3–10 μF energy

$$W_0 = \frac{CU_0^2}{2} \approx 1 \div 100 \text{ kJ} \quad (U_0 \approx 25 \div 300 \text{ kV}), \tag{1}$$

and the duration of the first half-cycle of the discharge current t_1 = 5–10 μs. The range of change in the average specific (per unit length of the interelectrode gap L) the electric power released in the plasma was P_{el} = 1– 400 MW/cm. The width of the discharge electrodes b = 1 cm. Corundum (AL_2O_3) ceramics, the thermophysical characteristics of which are taken from [14], was chosen as the material of the interelectrode insert for the OSD.

At the initial $t = [0–t_{in}]$, essentially non-stationary stage of the discharge, a transition occurs from the initial (t = 0, J = 0) state (simulating the situation after the breakdown of the interelectrode gap of the discharge) to a quasi-stationary state. The calculation results showed that the value t_{in}, for the studied conditions does not exceed the values ~ 1 μs. During the rest of the time of the first half–cycle of the current ($t_{in} - t_1$) – the phase of the main allocation of Joule power – the spatial distributions of the radiation-plasmadynamic parameters of plasma formation have a quasi-stationary character, by the type of which one can judge the features of the emerging structures and dynamics of the propagation of discharge plasma, and, consequently, talk about the modes of discharge.

Both types of considered HCED (OSD and OUD) are characterized by strong attenuation of the discharge current with maximum Joule energy release in plasma

$$W_1 = \int_0^{t_1} R_{pl} J^2 dt \approx \left(0.4 \div 0.99\right) \frac{CU_0^2}{2}, \tag{2}$$

in the first half-period $t_1 \leq 10$ μs of the discharge current J.

On the basis of analyses of the degree of influence of individual discharge parameters, it was found that the main physical parameter determining its radiative and plasmadynamic characteristics is the average (for the first half-period) specific (per unit length L) rate of energy input into the discharge plasma, $P_{el} = W_1 / L_{t1}$ the value of which in these calculations varied in the range of 1–400 MW/cm. In addition, it was found out that under the conditions of limitation of plasma expansion by the gas medium and its own magnetic field, the HCED in relation to P_{el} can exist in three different quasi-stationary regimes (explosive, magnetogasodynamic, and quasipinch) depending on the structure and parameters of the plasma.

We consider the specific features of the behaviour of radiation and plasmadynamic parameters of HCED in each of them. The boundary values of the average specific electric power P_{el}, which determine the regions of existence of the modes, depend on the properties of the surrounding gas and are different for OUD and OSD, reflecting the specific features of OSD associated with the presence of a solid dielectric surface, which is a rigid spatial limiter and a source of light-erosion plasma. The performed calculations and their analyses have shown that the HCED modes are related to the plasma parameters (velocity, density, etc.) in the boundary zones of the expanding plasma formation. With $P_{el} < P_{cr1}$ an "explosive" mode is carried out, in which the external boundary of the discharge is a gas-dynamic shock wave propagating in the surrounding gas at a speed of $D \sim P_{el}^{1/3}$. In the magnetogasodynamic mode ($P_{cr1} \le P_{el} \le P_{cr2}$) there is a limitation of the growth of the velocity D of the external boundary of the discharge with increasing specific electric power. In the magnetogasodynamic regime, there appears the effect of shock wave degradation, in which the gas compression rate behind the external rupture becomes less than the Hugoniot compression rate and continues to decrease as the power put into the plasma increases. The effect of the shock wave degradation was observed in experiments [15] under the action of strong external fields on the spark discharge plasma. In the quasi-spark regime with $P_{el} > P_{cr2}$ the external rupture transforms from a compression rupture into a radiation-magnetogasodynamic rarefaction wave. The values P_{cr2} are different for OUD and OSD, which reflects the specific features of OSD associated with the presence of a solid dielectric surface, which is a rigid spatial limiter and a source of plasma that causes light erosion. Such powerful discharges and radiation sources can be used for a wide range of applications [24–37].

4. Conclusion

The paper presents an element of the hierarchy of radiation-plasmadynamic mathematical models, which are designed to study pulsed electric discharge sources of various classes. With the help of computational studies, data on radiation-plasmadynamic processes and phenomena in pulsed erosive electric discharge sources of ultraviolet radiation and shock waves of various types were obtained. For electroplasma discharges, criteria have been established that determine discharge modes that differ in the degree of influence of electromagnetic processes and, as a result, the dynamics of formation and spatial distributions of plasma parameters. The effect of radiation-magnetic degradation of a shock wave is briefly described, which manifests itself in a decrease in the degree of compression of gas at the front and takes place under conditions of radiation ionization of gas in the front area and the action of inhibitory electromagnetic forces.

Acknowledgement

This research has been partially supported by the Russian Minobrnauki (GosZadanie Project, the cipher of the subject No. FSFN-2024-0022).

5. References

[1] N.A. Bulychev, Experimental Studies on Hydrogen Production in Plasma Discharge in a Liquid-Phase Medium Flow, *International Journal of Hydrogen Energy*, vol. **44**(57), 29933, 2019; doi: 10.1016/j.ijhydene.2019.09.177

[2] T. Raeder, V.A. Tenenev, M.R. Koroleva, O.V. Mishchenkova, Nonlinear Processes in Safety Systems for Substances with Parameters Close to a Critical State, *Rus. J. Nonlin. Dyn.*, vol. **17**(1), 119, 2021; doi: 10.20537/nd210109

[3] S.V. Ryzhkov, Magneto-Inertial Fusion and Powerful Plasma Installations (A Review), *Applied Sciences*, vol. **13**, 6658, 2023; doi: 10.3390/app13116658

[4] V.V. Kuzenov, S.V. Ryzhkov and A.Yu. Varaksin, The Adaptive Composite Block-Structured Grid Calculation of the Gas-Dynamic Characteristics of an Aircraft Moving in a Gas Environment, *Mathematics*, vol. **10**, 2130, 2022; doi: 10.3390/math10122130

[5] A.I. Shumeiko, V.D. Telekh, S.V. Ryzhkov, Probe Diagnostics and Optical Emission Spectroscopy of Wave Plasma Source Exhaust, *Symmetry*, vol. **14**(10), 1983, 2022: doi: 10.3390/sym14101983

[6] V.I. Khvesyuk, S.V. Ryzhkov, J.F. Santarius, G.A. Emmert, C.N. Nguyen and L.C. Steinhauer, D-^{3}He field reversed configuration fusion power plant, *Fusion Technology*, vol. **39**(1T), 410, 2021; doi: 10.13182/FST01-A11963492

[7] A.V. Rudinsky, D.A. Yagodnikov, S.V. Ryzhkov and V.V. Onufriev, Features of intrinsic-electric-field formation in low-temperature oxygen-methane plasma, *Technical Physics Letters*, vol. **47**, 519, 2021; doi: 10.1134/S1063785021050278

[8] V.S. Zarubin, V.S. Kuvyrkin, G.N., I.Yu. Savelyeva, Temperature state of the electrical insulation layer of a superconducting DC cable with double-sided cooling. *Herald of the Bauman Moscow State Technical University, Series Natural Sciences*, vol. **4**, 71, 2021; doi: 10.18698/1812-3368-2021-4-71-85

[9] S. Li, Y.I. Dimitrienko, Mathematical modeling for the local flow of a generalized Newtonian fluid in 3D porous media. *Applied Mathematical Modelling*, vol. **105**, 551, 2022; doi: 10.1016/j.apm.2022.01.003

[10] V.V. Kuzenov and S. V. Ryzhkov, Numerical simulation of the interaction of a magneto-inertial fusion target with plasma and laser drivers, *High Temperature*, vol. **60**, S7, 2022; doi: 10.31857/S0040364421040141

[11] A.G. Mozgovoy, I.V. Romadanov, S.V. Ryzhkov, Formation of a compact toroid for enhanced efficiency. *Physics of Plasmas*, 2014, vol. **21**, 022501; doi: 10.1063/1.4863452

[12] A.Yu. Varaksin and S.V. Ryzhkov, Particle-Laden and Droplet-Laden Two-Phase Flows Past Bodies (A Review), *Symmetry*, **15**, 388, 2023; doi: 10.3390/sym15020388

[13] V.V. Kuzenov, S.V. Ryzhkov and V.V. Shumaev, Application of Thomas-Fermi model to evaluation of thermodynamic properties of magnetized plasma, *Problems of Atomic Science Technol.*, vol. **1**(95), 97, 2015.

[14] A.Yu. Varaksin and S.V. Ryzhkov, Turbulence in Two-Phase Flows with Macro-, Micro- and Nanoparticles (A Review), *Symmetry*, vol. **14**, 2433, 2022; doi: 10.3390/sym14112433

[15] V.V. Kuzenov, S.V. Ryzhkov and A.Yu. Varaksin, Numerical modeling of individual plasma dynamic characteristics of a light-erosion MPC discharge in gases, *Applied Sciences*, vol. **12**, 3610, 2022; doi: 10.3390/app12073610

[16] V.V. Kuzenov, S.V. Ryzhkov and A.Yu. Varaksin, Simulation of parameters of plasma dynamics of a magnetoplasma compressor, *Applied Sciences*, vol. **13**, 5538, 2023; doi: 10.3390/app13095538

[17] V.V. Kuzenov, S.V. Ryzhkov, A.Yu. Gavrilova, E.P. Skorokhod, Computer simulation of plasmadynamic processes in capillary discharges, *High Temp. Material Processes*, vol. **18**, 119–130, 2014; doi: 10.1615/HighTempMatProc.2015015329

[18] V.V. Kuzenov, S.V. Ryzhkov and A.Yu. Varaksin, Calculation of heat transfer and drag coefficients for aircraft geometric models, *Applied Sciences*, vol. **12**, 11011, 2022; doi: 10.3390/app122111011

[19] V.V. Kuzenov and S.V. Ryzhkov, Thermophysical Parameter Estimation of a Neutron Source Based on the Action of Broadband Radiation on a Cylindrical Target, *Fusion Science and Technology*, vol. **79**, 399, 2023; doi: 10.1080/15361055.2022.2112037

[20] V.V. Kuzenov, S.V. Ryzhkov and A.Yu. Varaksin, Computational and experimental modeling in magnetoplasma aerodynamics and high-speed gas and plasma flows (A Review), *Aerospace*, vol. **10**, 662, 2023; doi: 10.3390/aerospace10080662

[21] A.Yu. Varaksin and S.V. Ryzhkov, Vortex Flows with Particles and Droplets (A Review), *Symmetry*, vol. **14**, 2016, 2022; doi: 10.3390/sym14102016

[22] V.V. Kuzenov and S.V. Ryzhkov, Estimation of the neutron generation in the combined magneto-inertial fusion scheme, *Physica Scripta*, vol. **96**, 125613, 2021; doi: 10.1088/1402-4896/ac2543

[23] A.Yu. Varaksin and S.V. Ryzhkov, Mathematical Modeling of Structure and Dynamics of Concentrated Tornado-Like Vortices: A Review*, Mathematics*, vol. **11**, 3293, 2023; doi: 10.3390/math11153293

[24] A.Yu. Varaksin and S.V. Ryzhkov, Mathematical Modeling of Gas-Solid Two-Phase Flows: Problems, Achievements and Perspectives (A Review), *Mathematics*, vol. **11**, 3290, 2023; doi: 10.3390/math11153290

[25] V.V. Kuzenov and S.V. Ryzhkov, Numerical Simulation of Pulsed Jets of a High-Current Pulsed Surface Discharge, *Computational Thermal Sciences*, vol. **13**, 45, 2021; doi: 10.1615/ComputThermalScien.2020034742

[26] S.V. Ryzhkov, Current state, problems and prospects of Thermonuclear Facilities Based on the Magneto-Inertial Confinement of Hot Plasma, *Bulletin of the Russian Academy of Sciences. Physics*, vol. **78**, 456, 2014; doi: 10.3103/S1062873814050281

[27] V.V. Kuzenov and S.V. Ryzhkov, Development of method to modeling physical processes in Combined Schemes of the Magneto-Inertial Confinement of High Temperature Plasma, *Bulletin of the Russian Academy of Sciences. Physics*, vol. **80**, 598, 2016; doi: 10.3103/S1062873816030217

[28] V.Y. Goryainov, A.V. Voronin, V.K. Gusev, A.N. Novokhatsky, S.A. Ponyaev, Investigation of plasma jet sources with high kinetic energy, *Journal of Physics: Conference Series*, vol. **1400**(7), 077020, 2019; doi: 10.1088/1742-6596/1400/7/077020

[29] V.F. Formalev, B.A. Garibyan, S.A. Kolesnik, Wave heat transfer in a nonlinear anisotropic plate under the action of a point source of thermal energy, *Herald of the Bauman Moscow State Tech. Univ., Nat. Sci.*, vol. **5** (110), 48, 2023; doi: 10.1134/S0018151X14050058

[30] V.F. Formalev, N.A. Bulychev, E.L. Kuznetsova, S.A. Kolesnik, The thermal state of a packet of cooled microrocket gas-dynamic lasers, *Technical Physics Letters*, vol. **46**(3), 245, 2020; doi: 10.1134/S1063785020030074

[31] N. Bulychev, W. Van Camp, B. Dervaux, Y. Kirilina, et al., Comparative Study of the Solid-Liquid Interface Behaviour of Amphiphilic Block and Block-like Copolymers, *Macromolecular Chemistry and Physics*, vol. **210**, 287, 2009; doi: 10.1002/macp.200800374

[32] A.D. Teresov, E.A. Petrikova, Y.F. Ivanov, O.V. Krysina, N.A. Prokopenko, Electron-Beam Surface Processing of Metal Materials Manufactured by Additive Methods, *Russian Physics Journal*, vol. **65**, 1971, 2023; doi: 10.1007/s11182-023-02858-8

[33] N.A. Bulychev. Obtaining Nanosized Materials in Plasma Discharge and Ultrasonic Cavitation, *High Temperature*, vol. **60**, Suppl. 1, S98, 2022; doi: 10.1134/S0018151X21040076

[34] E.A. Korznikova, I.A. Shepelev, E.L. Vardanyan, K.N. Ramazanov, P.V. Zakharov, Regimes of mass transfer in a 2D crystal in nonequilibrium states, *IOP Conference Series: Materials Science and Engineering*, vol. **1008**, 012034, 2020; doi: 10.1088/1757-899X/1008/1/012034

[35] V.M. Astashynski, H.M. Dzahnidze, E.A. Kostyukevich, A.M. Kuzmitski, P.N. Shoronov, V.I. Shymanski, V.V. Uglov, Generation of erosion compression plasma flows in a miniature plasma accelerator and their capability for formation of thin nanostructured coating. *High Temp. Mater. Process*, vol. **24**, 99, 2020.

[36] P. Popov, S. Poniaev, R. Kurakin, K. Tverdokhlebov, B. Reznikov, Peculiarities of the magnetic field distribution in the railgun channel, *Journal of Physics: Conference Series*, vol. **1400**, 077048, 2019; doi: 10.1088/1742-6596/1400/7/077048

[37] V.I. Shin, M.S. Vorobyov, P.V. Moskvin, V.N. Devyatkov, V.V. Yakovlev, N.N. Koval, M.S. Torba, R.A. Kartavtsov, S.A. Vorobyov, Latitude and Amplitude Modulation of the Beam Current for Controlling its Power during a Submillisecond Pulse, *Russian Physics Journal*, vol. **65**, 1979, 2023; doi: 10.1007/s11182-023-02859-7