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PLASMA GUNS OF AN EROSION TYPE WITH THE PULSE-PERIODIC GAS-METAL INJECTION

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The design of the modular plasma guns of an erosion type that operate in the pulse-periodic mode has been described. The injection of the electrode and dielectric materials occurs due to the combination of many processes initiated by the high-voltage surface discharge. The guns with the dielectrics of $(C_2H_4)n$ and $(C_2F_4)n$ types have been compared. Optical spectrograms of discharges for a $(C_2F_4)n$ dielectric have been obtained. The radial and axial spread of sprayed components that are the part of plasma guns has been specified and the composition of the sediments deposited on the targets has been defined.

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INTRODUCTION

Plasma guns (PG), plasma emitters and plasma injectors find wide application in different industrial and science-intensive branches [1-6]. Different types of injectors can be used, in particular multigap, capillary, coaxial and those that are equipped with gas puffing system, etc. [1-8]. The latest scientific developments are devoted to the use of them as the sources of plasma jets for space vehicles, and also to spray materials onto different targets, to initiate ignition of combustible mixtures in internal combustion engines, detonation devices and charged particle accelerators [1-12]. Plasma guns of a coaxial type with the surface discharge have recently found wide application to provide the material injection using anode, cathode and dielectric. The breakdown development processes that occur on the dielectric surface were described in detail in scientific paper [13]. The discharge process is accompanied by the formation of nonequilibrium low-temperature plasma of a specified composition. The power supply sources used for plasma guns are the pulse current generators that are based on capacitive energy accumulators that provide an appropriate high-voltage discharge duration and energy. The geometric configuration and the dimensions of the PG that is one of the technological assemblies of the unit depend on the discharge input energy, structure and the designation of the equipment.

The particle flows in the plasma jet contain electrons, excited ions and neutral atoms, molecules and the clusters consisting of electrode atoms and molecules and the plasma gun dielectric.

This paper gives consideration to the plasma guns operating in the pulse-periodic mode that are the plasma generators for plasma breakers and plasma filled diodes. Radial and axial distribution of plasma jets in the evacuated chamber and the composition of their sediment on the targets have been described and the spectral plasma composition has been established.

The purpose of this paper was to analyze the get geometry, radial distribution of the components of plasma jets created by the plasma guns of an erosion type with different types of dielectrics in the evacuated chamber and to study the plasma composition and sediment morphology.

1. INITIAL EXPERIMENT SETTING UP CONDITIONS

The acceleration technique specifies a number of requirements for the created PGs in order to analyze plasma jets whose task is to create initial plasma that acts as a current breaker. These include:

- The possibility of the compact arrangement of the components in appropriate sequence in the accelerator chamber to provide uniform plasma distribution;
- Providing the injection of atoms, molecules and their compounds that possess the lowest ionization potentials for the creation of the appropriate conduction zone with a minimum energy input;
- Generating the current conduction plasma domain with the density providing the best conditions for the subsequent plasma disruption in plasma breakers and plasma-filled diodes;
- Availability of the modular structure for the fast replacement of individual functional elements, for example the dielectric exposed to the electric surface breakdown.

The plasma guns are arranged in the evacuated chamber of the Plasma Gun Rig (PGR) of 1100 mm long with the diameter of 600 mm [2] and the volume of 85 l. The PGR was designed to study physical processes observed in small-size heavy current electron accelerators that are based on the plasma current switching and to detect the specific features of the operation of the plasma guns of a different type using different diagnostic tools.

Consideration was given to the following mode of the PG operation: the emission surface of the used dielectrics is 300 mm^2. The power supply system and the capacitor bank IK 100/0.4 allow for the generation of pulses with the frequency of 0.1...1 Hz. The operating current range is 15...20 kA; the voltage is 19...22 kV, and the pulse duration is 2...4 μs. The average pulse energy is 80 J. The PG initiates powerful high-voltage pulsed discharges that advance on the dielectric surface in the vacuum chamber with the steam-oil pumping out in vacuum of $5\cdot10^{-4}...5\cdot10^{-5}$ Torr. The number of pulses in each individual experiment varied in the range of 500 to 10^3. The operating resource of the guns could exceed in this case more than 5000 discharges with no visible damages of the dielectric surface and the gun structure.

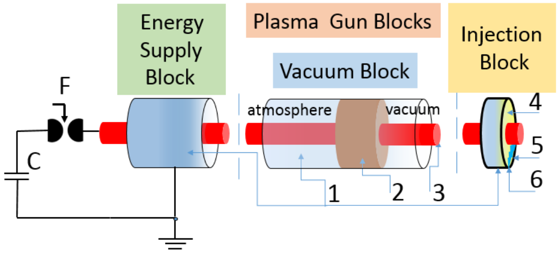


Fig. 1. Structural diagram of the coaxial plasma gun of an erosion type with the power supply unit where 1 – the gun body, i.e. anode; 2 – the vacuum sealing; 3 – the central electrode, i.e. cathode; 4 – the dielectric; 5 – a high-voltage surface discharge; 6 – is the anode in the form of the chamber wall

The plasma guns of an erosion type and coaxial geometry have been developed. Structurally the PGs can be represented in the form of three units and each performs a specific technological mission. The purpose of the power supply unit is clear. The power supply unit consists of the high-voltage power supply system, the pulsed capacitor IK100/0.4, air-driven (pneumatically-controlled) discharger, current inputs and the grounding system. The vacuum unit provides the sealing of the discharge section and appropriate vacuum conditions. The injection unit has the electrode system in the form of the rod that acts as the cathode and the chamber wall that functions as the anode with the emission dielectric surface (Fig. 1). General view of plasma guns outside and inside the evacuated PGR is given in Fig. 2. The chamber walls functions as the counter-electrode.

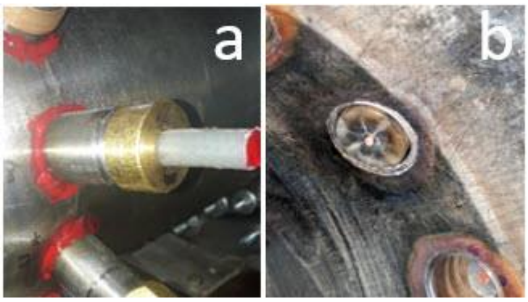


Fig. 2. General view of the PG, where a – outside and b – inside the PGR

To explain the propagation of plasma jets we need to have an idea of the arrangement of the force lines of electric and magnetic fields in the active zone of plasma guns during the surface discharge (Fig. 3) (consideration is given to the idealized case).

The nature of the arrangement of force lines shows that charged particles should follow the trajectories specified by them and the Lorenz force, i.e. up and to the side. In the case of the surface discharge, the normal component of the electric field snuggles up to the dielectric surface that results in addition to other things in the local heating and the evaporation of the particles of its material with the subsequent ionization and creation of the plasma channel.

Fig. 3,b also shows that the spoke-shaped structures are formed on the dielectric surface that runs from the center to the periphery with a sufficient degree of the symmetry. Black carbon sediment can be seen on the dielectric surface and it was formed by the dielectric material. It correlates with general ideas of the distribution of force lines of the electric field shown in Fig. 3.

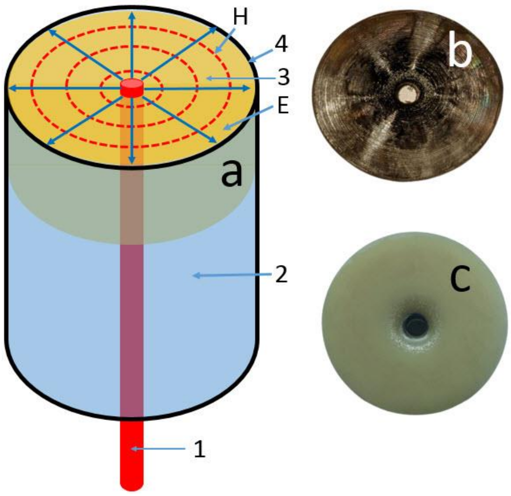


Fig. 3. Active zone of the plasma gun, where a is E and H force lines of electric and magnetic fields; 1 – the central electrode, i.e. the cathode; 2 – the PG casing, that is the anode; 3 – the dielectric surface; 4 – the domain of the triple interface: dielectric, air and metal; b is the general view of the surface of $(C_2H_4)n$ dielectric after 1000 pulses; c is a general view of the surface of $(C_2H_4)n$ dielectric prior to the breakdown

High-speed photography, in particular 1000 shots per seconds confirms that after the surface discharge the plasma jet propagates from the gun end to the chamber center with the gradual expansion and a partial spread along the adjacent chamber walls (Fig. 4).

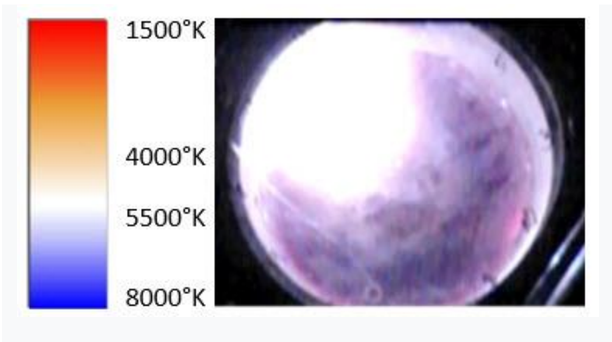


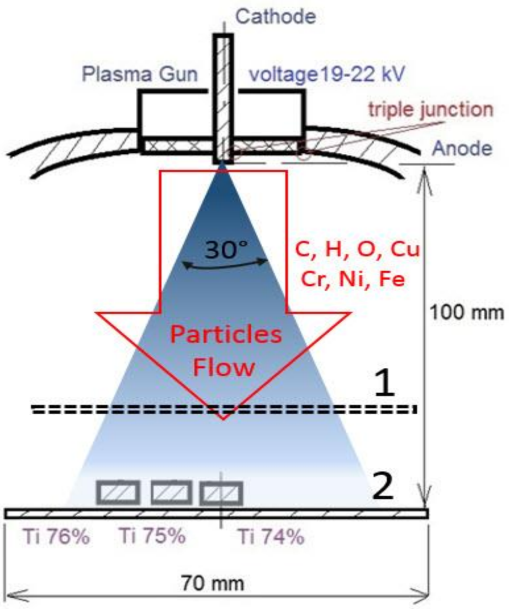
Fig. 4. General view of the plasma jet, the colored temperature scale

According to the color scale the plasma jet temperature is less than 4500 K.

2. MASS TRANSFER PROCESSES

Proceeding from the experimental data obtained in this paper and earlier in [2] we can give a general view of the propagation of the components of plasma jets (Fig. 5). The plasma jet sediment contours were defined in space using titanium plates arranged in the evacuated chamber (1, 2) with titanium targets arranged on them at a different distance from the pulse gun end.

The titanium target was selected proceeding from the non-availability of admixtures and alloyed dropes to provide a relative purity of the experiment. The triple interface domain that represents the transition zone between the electrodes and the dielectrics and includes inevitable vacuum gaps can have an effect on the breakdown development character and the breakdown voltage resulting in its increase. The given plates were arranged at a distance of 30, 70, and 100 mm from the gun end. The radial and axial spread of the plasma jet components was defined using the imprints of plasma jets formed on the plates during 1000 pulses.



(1, 2 are the target plates)

Fig. 5. The spread angles of the plasma jet components

Based on the analysis of the imprints obtained on the targets (Fig. 6,a,b) we determined the spread angles of the components of plasma jets that were equal to (50±5)° at a distance of 30, 70, and 100 mm with the imprint boundaries in the form of discoloration traces with the diameter of (25±2), (63±3), and (80±3) mm, accordingly.

The central region is relatively monotonous. In the center, the area of this homogeneous chromaticity is equal to 1200 mm^2. The color pattern varies more frequently approximately every 4 mm in the periphery exceeding 25 mm along the radius.

Fig. 6,a,b shows that plasma jets create sufficiently symmetric temperature field sectors and the main effect falls on the central region with the radius of 0 to 25 mm.

The distribution of the colors for the targets irradiated by the PG jets with fluoroplastic dielectric has a similar pattern. However, the pattern is less symmetric, the central region exposed to the jet action is shifted from the center and its area is 2 or 3 times smaller. It can be related to the type of the dielectric and the character of the breakdown development on its surface [13].

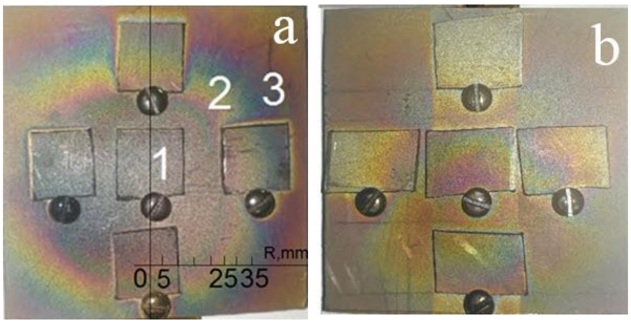


Fig. 6. General pattern of the plasma jet imprints on the targets where PG imprints of a – $(C_2H_4)n$ type; b – PG imprints of a $(C_2F_4)n$ type

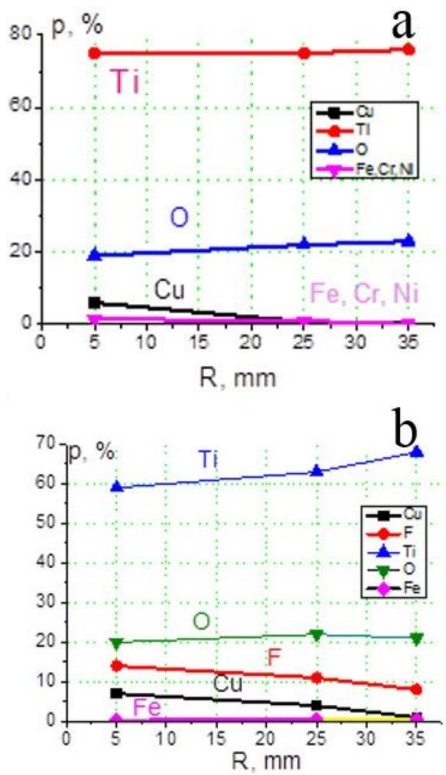


Fig. 7. The dependences of the element distribution along the target surface: a – PG of a $(C_2H_4)n$ type; b – plasma gun of a $(C_2F_4)n$ type

Further to the periphery the titanium percentage content is increased and it is well seen for the case (b) with the fluoroplastic dielectric.

This color distribution can be indicative of that the jet components have a similar energy level in the central domain. The central flow can be denser and more homogeneous. All the jet components have the energy distribution diminishing from the center to the periphery. In this case, the energy spread on the periphery is increased because the color sectors are changed more frequently.

Using the scanning electron microscopy, we defined the weight content of the elements sprayed on the target due to the erosion of the dielectric material and PG electrodes. Fig. 7,a,b shows the dependences of the distribution of the elements along the target surface. Based on the analysis of the data obtained using the scanning electron microscope we established that the thickest spray of the material is observed in the central region, up to 25mm for both types of the guns. The amount of registered titanium in the center is somewhat lower and it is indicative of the larger amount of components brought in from the active zone of the PG.

Weight content of the elements in the central part of the target for the both types of the guns

Element	Type of the plasma gun	
	Kapralon $(C_2H_4)n$	**Fluoroplast $(C_2F_4)n$**
	Weight %	
Ti	74.96	58.63
Cu	5.62	6.88
Fe	0.31	0.19
Al	0.3	0.32
O	18.83	20.40
F	–	13.59

The analysis of the surface morphology of the target specimens made of titanium shows that in comparison to the original pure titanium specimen Fig. 8,a with many pores the targets sprayed by the guns of $(C_2H_4)n$ and $(C_2F_4)n$ types have 70 to 80 times smaller number of the pores (some of them are marked with circles in Fig. 8,a,b,c and the area of the remaining pores is on average 10 times smaller in comparison to the original. The erosion traces of the active zone of the guns in the form of the drops of 5…30 µm consisting mainly of F, Fe, Ni, Cr are marked by the squares. It is seen that the same number of pulses and the same total energy input result in the smaller number and smaller size of erosion products deposited onto the target for the case with the dielectric of an $(C_2H_4)n$ type and it can be indicative of its higher electroerosion resistance.

The method of weighing was used for the estimation of the mass loss by the dielectric that was equal to 10 µg per pulse for the PG of a $(C_2H_4)n$ type and 12 µg per pulse for the PG of a $(C_2F_4)n$ type. The mass of discharge electrodes was measured using the scales of a VLP-200 type. In this case it was noted that the main increment in mass is observed on central targets. The 1000 pulses in the central part of the given target with the area of 100 mm^2 provide the deposition of 300 µg of the elements that are the components of the active zone of the PG and it corresponds to 300 ng/pulse. A maximum density of the sediment is peculiar for the central portion of the target with the area of 600 mm^2 (Fig. 9). It correlates with the color pattern given in Fig. 6,b. The shift of the area with a maximum increment in mass from the center corresponds to the actual experimental pattern comparable with that given in Fig. 6,b where the arrival of the jet is somewhat shifted relatively the target center due to the drawbacks of the alignment of the plasma gun-alignment system.

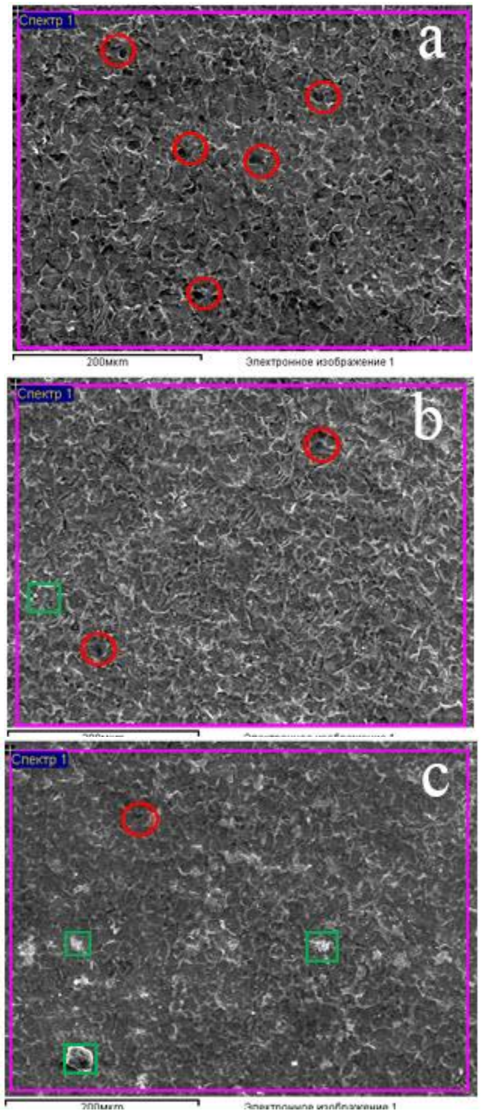


Fig. 8. Morphology of the titanium target treated by plasma jets. Marker of 200 µm. where a is an initial specimen; b is the PG with the $C_2H_4)n$ dielectric; c is the PG with the $(C_2F_4)n$ dielectric

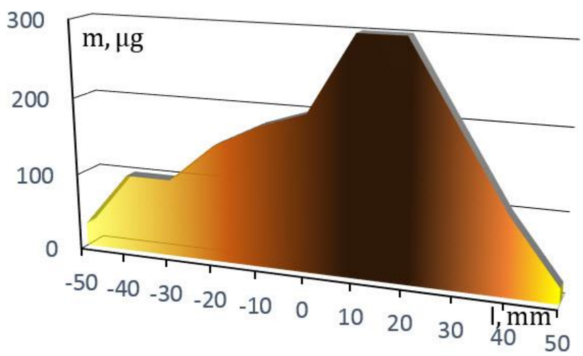


Fig. 9. An increase in mass along the target surface after 1000 pulses

The method of optical spectroscopy allowed us to determine the plasma composition using the two-channel spectrograph. Plasma jets contain the atomic hydrogen, molecular carbon C_2 and CN molecules and also singly charged and doubly charged carbon ions and hydrogen ions that are not detected using this spectral method (Fig. 10).

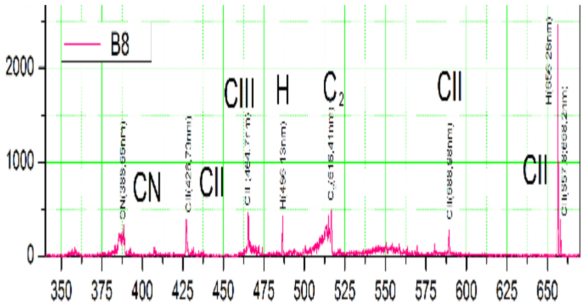


Fig. 10. The optic spectrogram of the plasma generated by the PG of a (C_2F_4)n type at U = 19 kV

CONCLUSIONS

The (C_2H_4)n and (C_2F_4)n PG dischargers develop according to the scenario for the dielectric surface discharge. These have the form of the sliding discharge and have the same spatial structure.

The plasma jet components structurally propagate in the form of cone and it is confirmed by the availability of the imprints of a different diameter on the targets arranged at different distances along the axis.

Observations and video data are indicative of the presence of the jets expanding to the center of the chamber. These jets consist of the ions and excited atoms and neutral gas.

This distribution can provide a good plasma filling both for the central part of the chamber and the regions adjacent to its walls. The temperature of the obtained plasma jet is at least of 4500 K. The main deposition of the PG material occurs in the target center on the area of 600…1200 mm^2.

The experimental data show that the mass losses of the (C_2H_4)n is equal to 90 µg/pulse. Whereas, the mass loss of the (C_2F_4)n is achieved 120 µg/pulse.

The dielectric of a (C_2H_4)n type has a higher wear resistance. It is confirmed by morphological studies. The number of the fluorine-containing clusters was respectively larger in comparison to that of the (C_2H_4)n gun.

It can be indicative of the larger resource of the guns made of caprolon in comparison to fluoiroplastic guns. The spraying in the central region of the target plate with the area of 100 mm^2 is equal to 300 ng/pulse. For the initial weight of the dielectric equal to 2…4 g the component composition of the material deposited on the targets consists mainly of Cu, Fe, O, F and it correlates with the components of the active zone of plasma guns. The hydrogen atoms as well as carbon atoms and ions (C^+, C^{++}) were recorded.

It was established that the suggested PGs generate plasma jets including ions, molecules and neutrals in gaseous and metallic phases. The presence of the drop phase in the form of the conglamarates of the erosion products was also established. The size of conglamarates is on average about 30 µm. These mainly consist of Fe, Ni, Cr, and F.

The arrangement of the sufficient amount of the PGs in the evacuated spaces can provide a reliable filling of the central part of the chamber with the plasma.

The PG resource is at least 5000 pulses with no failure and/or damages in pulsed-periodic modes with the frequency within range of 0.1…1 Hz and working voltages of up to 22 kV.

The block model of plasma guns of an erosion type and coaxial geometry operating in the pulsed periodic mode has been presented. Each block can be used by the acceleration equipment of other research plants of the same type. The PGR plant is the property of the NSC KIPT. It can be used for the injection of the primary plasma and also for plasma breakers and plasma-filled diodes.

REFERENCES

1. V.I. Tereshin, V.V. Chebotarev, D.G. Solyakov, I.E. Garkusha, V.A. Makhlai, S.A. Trubchaninov, N.I. Mitina, A.I. Morozov, A.V. Tsarenko, H. Wuerz. Powerful quasi-steady-state plasma accelerator for fusion experiments // *Brazilian Journal of Physics*. 2022, v. 32(1), p.165-171.

2. D.V. Vinnikov, V.V. Katrechko, V.B. Yuferov, V.I. Tkachev, S.A. Petrenko, V.T. Fomin. Experimental testing bench for the diagnostics of plasma generated by pulsed guns with the dielectric surface breakdown // *Problems of Atomic Science and Technology. Series "Plasma Electrons and New Methods Acceleration" (134)*. 2021, № 4, p. 18-23.

3. I. Beilis. Spot Plasma and Plasma Jet // *Plasma and Spot Phenomena in Electrical Arcs. Springer. Series: "Atomic, Optical, and Plasma Physics"*. 2020, v. 113.

4. Ju. Ružbarský, A. Panda. Plasma and Thermal Spraying // *Springer Briefs in Applied Sciences and Technology*. 2017, v. 107.

5. Yu.Yu. Protasov. A Laser Plasma Injector. January // *Instruments and Experimental Techniques*. 2003, № 46(2), p. 194-198.

6. A.F. Sorokin, A.M. Tsyukh, V.I. Maslov. Plasma injector for space technology // *Kosmìčna Nauka Ì Tehnologìâ*. 2002, № 8(2s), p. 369-374.

7. Prabir Basu Biomass Gasification, Pyrolysis and Torrefaction (Third Edition). *Practical Design and Theory*, 2018, p. 263-329

8. Michael J. Taylor. Ignition of Propellant by Metallic Vapour Deposition for an ETC Gun System // *Propellants Explosives Pyrotechnics*. 2001, v. 26(3), p. 137-143.

9. K.V. Korytchenko, V.I. Golota, D.V. Kudin, S.V. Rodionov. Experimental study of spark-discharge initiation of detonation // *Journal of Engineering Physics and Thermophysics*. 2013, v. 86(3), p. 577-586.

10. K.V. Korytchenko, V.F. Bolyukh, O.L. Rezinkin, S.G. Burjakovskij, O.P. Mesenko. Axial Coil Accelerator of Plasma Ring in the Atmosoheric Pressure Air // *Problems of Atomic Science and Technology*.

Series "Vacuum, Pure Materials, Superconductors" (119). 2018, № 1, p. 120-123.

11. K.V. Korytchenko, P. Krivosheyev, D. Dubinin, A. Lisniak, K. Afanasenko, S. Harbuz, O. Buskin, A. Nikorchuk, I. Tsebriuk. Experimental research into the influence of twospark ignition on the deflagration to detonation transition process in a detonation tube // *Eastern-European Journal of Enterprise Technologies*. 2019, v. 4/5 (100), p. 26-31.

12. C.W. Mendel, D.M. Zagar G.S. Mills, S. Humphries, S. A. Goldstein. Carbon plasma gun // *Review of scientific instruments*. 1980, v. 51(12), p. 1641-644.

13. N. Khamidov. *Electric Discharge Along the Surface of Solid Dielectrics in Vacuum*. Tashkent: "FAS", 1985, p. 258.

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ПЛАЗМОВІ ГАРМАТИ ЕРОЗІЙНОГО ТИПУ З ІМПУЛЬСНО-ПЕРІОДИЧНОЮ ГАЗОМЕТАЛЕВОЮ ІНЖЕКЦІЄЮ

Д.В. Вінніков, В.В. Катречко, В.Б. Юферов, В.І. Ткачьов

Описано влаштування плазмових гармат ерозійного типу модульної конструкції, що працюють у імпульсно-періодичному режимі. Інжекція матеріалу електродів та діелектрика відбуваються за рахунок комплексу процесів при високовольтному поверхневому розряді. Проведено порівняння гармат з діелектриками $(C_2H_4)n$- та $(C_2F_4)n$-типу. Отримано оптичні спектрограми розрядів для $(C_2F_4)n$-діелектрика. Визначено радіальний та осьовий розліт розпилених компонентів, що входять до складу плазмових гармат. Визначено склад осаду на мішені.