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Analysis of energy characteristics of a transistor pulse generator in the process of electric spark dispersion of current-conductive granular media

Introduction. *Studies of electrophysical and technological aspects of electric discharge in reaction chambers with granular metal loading to obtain its highly dispersed states have been conducted for many decades, however, the power sources of electric spark dispersion installations today remain mainly classical in terms of the method of generating current pulses on the electric spark load. The main* ***problem*** *of using powerful current pulse generators and reaction chambers with a plane-parallel electrode system is to imitate the principle of the thermo-explosive mechanism of developing an electrical breakdown of dense intergranular gaps, which leads to deterioration of the dispersion of the eroded material, and the use of smaller energy ranges (<1 J) in such installations is complicated by the electrophysical limitations of the existence of plasma channels and the loss of energy efficiency of the electric spark treatment process.* ***Goal.*** *Research on the energy efficiency of the electric spark dispersion process of heterogeneous conductive granular media in a reaction chamber with a cylindrical electrode system, provided that it is powered by a transistor pulse generator.* ***Results.*** *Specific energy consumption in the process of electric spark dispersion of aluminum and titanium granules was determined, which correlate with the average power consumption indicators of processing depending on their bulk volume within a certain configuration of the electrode system.* ***Scientific novelty.*** *The flow of current through ohmic contacts until the formation of the main discharge in the intergranular volumes of the reaction chamber causes a voltage drop across the inductance of the discharge circuit, which accordingly reduces the amplitude of the applied voltage to the interelectrode gap, due to which the maximum of the average power consumption characteristic of the transistor pulse generator, which occurs before the beginning of the saturation section of the effective frequency curve of the discharge pulses, corresponds to the most consistent mode of energy input into the electric spark load. The* ***practical value*** *of the considered model of the electric discharge installation proves the feasibility of its use for the tasks of electric spark treatment of conductive granular media.* References 21, tables 2, figures 7.

Key words: **energy characteristics, electric spark dispersion, transistor pulse generator, cylindrical electrode system, layer of metal granules, ohmic contact current.**

Вступ*. Дослідження електрофізичних і технологічних аспектів електричного розряду в реакційних камерах з гранульованим металевим завантаженням для одержання його високодисперсних станів ведуться вже на протязі багатьох десятиліть, проте джерела живлення установок електроіскрового диспергування на сьогодні залишаються переважно класичними щодо способу генерації імпульсів струму в електроіскрове навантаження. Основною* ***проблемою*** *використання формувачів потужних імпульсів струму та реакційних камер з плоско-паралельною системою електродів є наслідування принципу термовибухового механізму розвинення електричного пробою щільних міжгранульних проміжків, що призводить до псування дисперсності еродованого матеріалу, а використання менших діапазонів енергій (<1 Дж) у таких установках ускладняється через електрофізичні обмеження існування плазмових каналів та втрату енергоефективності процесу електроіскрової обробки.* ***Мета.*** *Дослідження енергоефективності процесу електроіскрового диспергування гетерогенних струмопровідних гранульованих середовищ у реакційній камері з циліндричною системою електродів за умови її живлення від транзисторного генератора імпульсів.* ***Результати.*** *Проведено порівняльний аналіз поведінки характеристик середньої споживаної потужності транзисторного генератора імпульсів в залежності від насипного об'єму завантаження та діаметру зовнішнього електрода реакційної камери для металевих гранул з різною величиною їх міжконтактного активного опору до утворення у середовищі ланцюжків наскрізної провідності. Визначені питомі енергозатрати у процесі електроіскрового диспергування алюмінієвих та титанових гранул, що корелюють з показниками середньою споживаною потужністю обробки в залежності від їх насипного об'єму у межах певної конфігурації електродної системи.* ***Наукова новизна.*** *Присутність струму крізь контактний опір до формування основного розряду у міжгранульних об'ємах реакційної камери викликає падіння напруги на індуктивності розрядного контуру, що відповідно зменшує амплітуду прикладеної напруги до міжелектродного проміжку, через що максимум характеристики середньої споживаної потужності транзисторного генератора імпульсів, який виникає до початку ділянки насичення кривої ефективної частоти розрядних імпульсів відповідає найбільш погодженому режиму введення енергії в електроіскрове навантаження.* ***Практична значимість*** *отриманих результатів розглянутої моделі електророзрядної установки доказує доцільність її використання для задач електроіскрової обробки струмопровідних гранульованих середовищ.* Бібл. 21, табл. 2, рис. 7.

Ключові слова: **енергетичні характеристики, електроіскрове диспергування, транзисторний генератор імпульсів, циліндрична система електродів, шар металевих гранул, струм омічних контактів.**

Problem definition. One of the widely used methods for obtaining powders, both pure metals and compounds based on them, is the method of electric spark dispersion (ESD) of metal granules [1–3] immersed in a liquid with relatively low electrical conductivity. As is known, the peculiarity of the electric spark dispersion method is the presence of two most probable ways of developing a spark discharge between adjacent surfaces of contacting granules [4]: thermal breakdown in the area of contact microprotrusions caused by the flow of high current density and electrical breakdown due to the presence of surface oxide films or cavitation bubbles. Therefore, one or another breakdown mechanism will occur depending on the surface purity of the metal and the ability of the contacting surfaces of the granules to form conductive bridges between them. But regardless of the mechanism by which the spark discharge is formed, the process of forming erosion particles can mainly occur due to the heat of melting or evaporation of local zones of metal interacting with non-equilibrium plasma of high-energy electrons. The balance between the melting and evaporation energy will depend on the rate of energy input into the formed channel, its degree of ionization, temperature and electrical resistance. The regulation of this process is complicated by the fact that the volt-ampere characteristic of the spark discharge has a decreasing character and leads to an avalanche-like increase in current, which requires the use of parametric methods of controlling the process of energy transfer to the load. That is, a positive current feedback is formed between the power source and the load, which can lead to critical heating of the contact zones, their welding or, conversely, boiling and splashing out a significant amount of a large fraction of metal particles into the surrounding liquid. Most often, these phenomena occur due to the presence in the medium of a large number of dense contact zones between the surfaces of the granules, which have a low active resistance and counteract favorable conditions for the development of the electric spark treatment reaction. For their destruction in laboratory practice, accumulated high energies and long-term discharge currents are usually used. At the same time, in the work [5] it is reported that the energy in a more prolonged part of the pulse is mainly spent on heating the medium or electrochemical reactions in it due to the enhancement of recombination processes and extinction of plasma channels.

In the direction of improving the efficiency of energy transfer to the electric spark load (ESL), many approaches have been developed that use nonlinear, parametric or nonlinear-probabilistic models of its dynamic resistance [5–7]. Also, spectrometric methods of analyzing plasma channels have been recently practiced, which, due to the power and color of radiation, provide information about their number and energy distribution between them, on which the size of the particles and the efficiency of their production depend [8, 9]. On the other hand, for the synthesis of erosion particles with a controlled size and a reduced range of their dispersion, the plasma in a volume filled with many layers of metal granules (VMLMG) must be «colder», and this is possible by limiting the amplitude and duration of the discharge current pulses.

Analysis of recent research and publications. Today, laboratory installations for initiating the ESD process of heterogeneous conductive granular media use both high-voltage single-power pulse generators and semiconductor pulse generators of micro- and submicrosecond duration [10, 11]. The advantage of high-voltage electric spark treatment [12, 13] is the high speed of leading edges formation and the possibility of using a wide range of energies (0.1–10^3 J), as well as long interelectrode gaps (IEGs) of the reaction chamber. But the main disadvantage of such systems is the low frequency of reproduction of the ESD process due to the use of gas-filled switches or air dischargers. A more promising direction of high-voltage pulse technology in the direction of increasing the efficiency of ESD is the use of inductive energy storage in combination with drift diodes [14], which allows stabilizing the current in the load with a rapidly decreasing volt-ampere characteristic.

In contrast to these systems, thyristor or transistor converters are characterized by a high pulse frequency (0.1–10 kHz) and an energy range from a fraction to hundreds of joules. For example, dual-circuit charge-discharge circuits of thyristor generators [15] have proven themselves as a reliable solution for forming sufficiently long kiloampere pulses of aperiodic nature on a low-impedance load with a high rate of growth of their leading edge, provided that the inductance (1 μH) of the discharge circuit of the capacitive energy storage device (100 μF) is minimized. However, the main disadvantage of these converters is the limitation of the accuracy of current duration regulation, and the use of recharging circuits or circuits that shunt the load only increases additional energy consumption and reduces the efficiency of such devices. In addition, a stochastic increase in the equivalent resistance of the VMLMG can lead to emergency modes of operation of thyristor switches. In the case of a prolonged current pulse through the load, the discharge thyristor can remain in a conductive state until the next charging cycle arrives, which causes a through current to flow from the power source to the load. It should also be noted that the energy efficiency of such devices is significantly reduced when using a working capacitor capacitance of less than 20 μF and forming pulses with a duration of less than 15 μs. From the point of view of material dispersion, the main problem of introducing powerful pulses into the environment is the appearance of an undesirable microfraction (10–100 μm), which is formed mainly due to the droplet mechanism of condensation of metal particles.

Transistor converters for ESD tasks have not gained sufficient popularity to date, because they have much smaller limiting parameters for the current amplitude and rate of its growth than thyristor ones, however, their main advantage is the possibility of regulating the current duration under the condition of their rigid switching or dynamic adjustment to the period of circuit oscillations. For example, in work [16], a generator of quasi-rectangular current pulses with duration of 0.5 to 5 μs was used to obtain iron nanoparticles based on a sequential pulse-width-step down converter. As the authors of the work note, before the start of the experiment, the surface of the metal granules was thoroughly cleaned of unwanted oxide films. It can be assumed that under these conditions the mechanism of electric erosion formation mostly followed the path of thermal breakdown of the conductive bridges formed. Considering that the maximum current amplitude in the experiment was only 48 A, therefore, in the case of a large number of formed contacts along the length of the chamber and a short pulse duration, such a current strength may be insufficient to effectively initiate the thermal breakdown mechanism and form spark channels, and accordingly, the energy introduced into the medium will more likely go to thermal dissipation. As for the rational choice of the geometric parameters of the reaction chamber, the shape of the electrode system and the bulk height of the VMLMG from the position of their influence on the energy indicators of the ESD, many publications [15, 17] provide only an empirical assessment, referring to the range of stabilization of processing in the absence of idle and short-circuit modes.

Separation of previously unsolved part of the problems. In general, the considered problems of ESD of metallic materials can be divided into two ways - the use of longer pulses with high energy (1 J – 1 kJ) or shorter pulses with energy up to a fraction of a joule. The main problem with the introduction of a significant amount of energy into local zones is the damage of erosion particles due to their agglomeration. First, local overheating of contact microprotrusions causes thermal breakdown and initiates a blast wave, which in itself is an uncontrolled process. Second, the plasma formation reaction is stochastic in nature, and the number of plasma channels and the energy ratio between them in the VMLMG are randomly distributed, so there is a probability of introducing a significant amount of energy only into a separate local plasma formation zone, instead of its uniform distribution throughout the volume of the medium. On the other hand, when using low energies, plasma channels last less time, have a smaller diameter and, accordingly, a heating zone and allow for, so to speak, «point spraying» of the material surface, which accordingly improves the dispersion distribution and orderliness of the structure formation of erosion particles. But the main problem in this energy range is that short-pulse generators operate mainly by the mechanism of electrical gap breakdown and are extremely sensitive to the formation of conductive bridges in the medium, because for their destruction it is necessary to introduce much more energy to implement the thermal breakdown mechanism. Given the stochastic nature of the change in the ESL resistance, the amount of energy introduced into the plasma channels from pulse to pulse can vary significantly and depend on many factors such as the conditions of preliminary ionization of the contact gaps, the field strength between them, the roughness of the surfaces, the current density between the microprotrusions, etc. At the same time, to assess the efficiency of the ESD process, it is sufficient to rely on the average value of the energy introduced into the plasma channels for a certain period of time, which directly affects the total mass of eroded metal, which is removed from the contact local zones between the granules as a result of the supply of heat of melting or evaporation. Thus, the search for conditions for increasing the useful power from the pulse generator, which goes to heating the local zones and the formation of eroded metal particles in the direction of improving the energy efficiency of the ESD of a heterogeneous conductive granular medium remains an urgent task.

The goal of the work is to study the energy efficiency of the process of electric spark dispersion of heterogeneous conductive granular media in a reaction chamber with a cylindrical system of electrodes, provided that it is powered by a transistor pulse generator.

Features of the proposed ESD system. Unlike existing ESD reactors, which have a rectangular shape and the same flat shape of the electrodes in the form of plates, located at an average distance of 40–50 mm, in this work it is proposed to carry out processing in a reaction chamber with a cylindrical electrode system. The distance between the electrodes was set to be somewhat reduced within 20–35 mm to increase the energy input into the contact zones between the surfaces of the granules. The angular symmetry of the radial electric field strength of the cylindrical electrode system, in contrast to the flat system, where the field strength is highest at the edges of the electrodes, allows the use of smaller technological gaps provided that the plasma channels are evenly distributed over the volume of the reaction chamber. The design of the reaction chamber also includes a mechanical stirrer, which is a disk with vertically fixed rods at a certain distance relative to its axis of rotation, the edges of which are immersed in the VMLMG and practically lean against the bottom of the chamber. The disk with rods is mounted on the shaft of the gear mechanism and is driven by a stepper motor. In turn, the rods touch the adjacent granules with their edges and force them to move, giving them translational and rotational movements.

As a power source for the reaction chamber, a dual-circuit transistor pulse generator (TPG) circuit is used (Fig. 1), which contains the charging C_0-VT_0-VD_0-L_0-C_1 and the discharging C_1-VT_1-VD_2-L_1-R circuits. This converter is similar in structure to dual-circuit thyristor devices [6, 18], which use the recharging circuits of the working capacitor, but with the following feature of the circuit solution that the function of the current limiter of this circuit is performed by the charging choke L_0. High-speed diodes in series with the transistors prevent reverse integrated diodes from being blocked and limit electrical oscillations in each circuit to one half-cycle of current. The rectified voltage at the input of the converter is set from 400 to 500 V and is controlled by a laboratory autotransformer. Due to the resonant charging of the working capacitor C_1, the voltage on it can rise to 800 V.

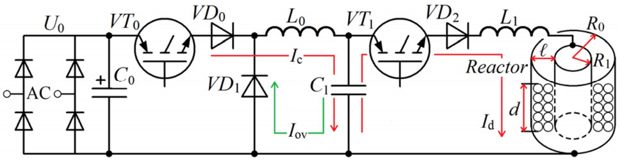

Fig. 1. Schematic diagram of a TPG with a load in the form of a reaction chamber with a cylindrical electrode system

Unlike the existing generally accepted practice of powering ESD reaction chambers using capacitors with a nominal value of at least 25 μF and an energy of 2 J and more, in the experiments performed, the range of energies operated by the generator did not exceed 1/3 J. The parameters of the discharge circuit were chosen such that its characteristic resistance was 4 Ω.

An important function of the reverse diode VD_1, which is placed in parallel with the working capacitor C_1, is to prevent an uncontrolled increase in voltage on it due to its resonant charge under non-zero initial conditions caused by the mismatch of the discharge circuit due to the stochastic nature of the equivalent resistance of the ESL. Despite the fact that the charging voltage on C_1 in the ESD process in a certain energy range of generator oscillations may have a modulation component, such a solution allows the generator to operate reliably from the idle mode to the short-circuit mode. For example, a characteristic feature of the short-circuit mode is the stationarity of its oscillations, during which the charge of the capacitor C_1 occurs under the condition of a constant positive residual voltage on it. The appearance of a negative residual voltage on C_1 indicates that the equivalent load resistance is lower than the characteristic resistance of the discharge circuit. Such a situation can occur both during the formation of conductive bridges and plasma channels. However, every time a negative voltage appears on C_1, diode VD_1 turns on, which causes the excitation of reverse oscillation and returns the voltage on C_1 to the polarity of the input DC source. Figure 2 shows the charge, discharge and recharge cycles of C_1.

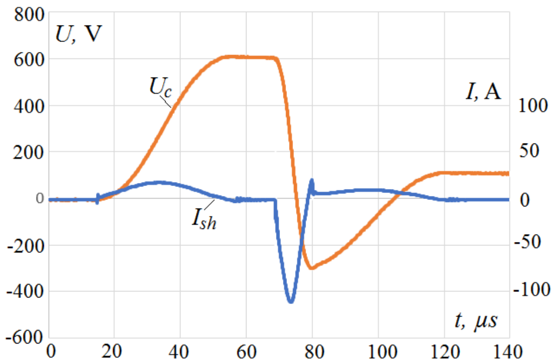

Fig. 2. Synchronous oscillograms of current and voltage of the working capacitor C_1 in the ESD process

Using a digital control system, the switching time intervals of each transistor can be set arbitrarily. However, unlike VT_1, the switching of the VT_2 lock-up can be carried out only if the discharge current reaches the zero point. The reverse fast diode VD_1 also plays a secondary function, similar to the circuit of a single-stroke step-down voltage converter, closing the residual magnetizing current of the charging choke L_0.

In the ESD process, plasma channels are formed chaotically, because of this, the energy invested in each pulse will be different, as indicated by the residual voltage on C_1 (Fig. 3), which has a step-like character. But this mode of generator oscillations is more pronounced only in a certain section of the energy curve, where the energy transfer processes in the ESL have a branched character.

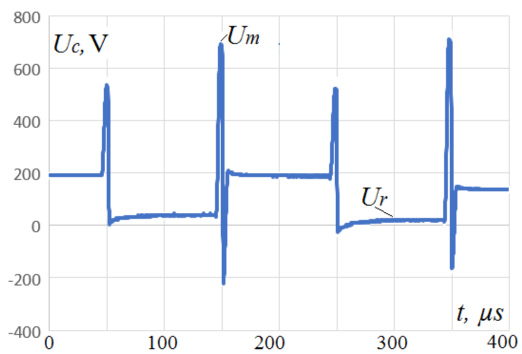

Fig. 3. Step-shaped voltage of the working capacitor C_1 in the ESD process

To measure the active instantaneous power and consumed energy in the installation, a household energy meter (model TM55) is used, which is connected between the generator input and the primary AC network. It has been experimentally established that for metal granules that are prone to the formation of conductive chains, such as *Ti*, *Cu*, *Fe*, as a result of the conditionally short-circuit mode, the generator power is approximately 2 times less (30 W) than for the mode when the electric spark treatment reaction is initiated with a minimum monolayer height of metal granules. In this case, the dynamics of voltage and current on the capacitor C_1 have a high stationary stability of the steady-state oscillation mode of the generator. Since the electrical resistance of the conductive bridges is much lower than the characteristic resistance of the discharge circuit, only a fraction of the energy of C_1 will be dissipated in the VMLMG and on the active elements of the circuit. In addition, the steady-state voltage on C_1 between energy conversion cycles will be close to the voltage of the power source. Otherwise, if *Al* granules, which are prone to the formation of oxide films on their surfaces, are loaded into the reaction chamber, the generator may experience a mode close to idle. In this oscillation mode, the voltage curve on C_1 will also be stationary, but will differ in the presence of only an added amplitude of pulsations and even lower power consumption. In addition, a small part of the accumulated energy C_1 will be dissipated in the environment due to losses in electrolysis and electrochemical reactions in the liquid.

However, it has been observed that the system shift from a conditionally quiescent state (idle or short circuit mode) towards the ignition of the plasma formation reaction and the initiation of the ESD process is possible due to the preliminary mechanical displacement of each metal particle of the VMLMG. That is, the forced destruction of conductive bridges or oxide films on the contact surfaces between the granules creates conditions for the preliminary ionization of the medium and the formation of plasma channels. For this purpose, the chamber design, as noted above, involves a mechanism of forced agitation and activation of the medium. To avoid the situation of blocking the movement of the mechanical stirrer due to the mutual adhesion of the granules to each other, their shape was chosen to be close to quasi-spherical. In addition, it was also observed that for granules that have a smooth surface and form more dense contacts with each other, it is difficult to finally reach the ignition limit of the self-pickup reaction of the EISD mechanism even by moving them. However, due to the continuous mixing of the medium from the mechanical stirrer and the support of the ESD reaction by the transistor pulse generator, the smooth surface of the metal granules (*Ti*, *Cu*, *Fe*) is gradually covered with erosion holes and becomes rougher with the formation of a larger number of microprotrusions. This allows, after some time of forced mixing of the medium, to initiate the self-catch reaction of «continuous» plasma formation of electric spark treatment, after which further mixing of the granules already has an indirect effect and can be suspended. During the studies on the example of Al granules, it was also noticed that the TPG power even increased with an increase in the rotation frequency of the rod mechanism. It should be noted that for the majority of the group of granules, additional disturbance was appropriate only at the stage of activation of their surfaces, because it caused some instability and intermittent ignition of the plasma channels. The implementation of such an additional processing method is also noted in the literature, but when using other mechanisms of medium disturbance. In particular, in [19] it is noted that the spatial oscillatory movement of granules relative to their static position as a result of the action of an additional source of mechanical disturbances (vibration, ultrasound) forcibly affects the length of plasma channels, restrains their development, limits the energy supplied to them, and enhances their migration along the surface of granules, which generally increases the dispersion of erosion particles and the energy efficiency of processing. But, on the other hand, the use of an additional mechanism and excessive agitation of the medium can significantly worsen the overall energy efficiency of electric spark processing.

Experiment setting. To achieve the goal, it is necessary to solve the following tasks:

- measurement of the power consumption of the electric discharge installation from the power supply network depending on the design parameters of the reaction chamber and the features of the VMLMG at other fixed parameters of the TPG (maximum charging voltage and energy of the working capacitor, frequency and pulse duration);
- assessment of the relationship between the power indicators of the electrical installation and the specific energy consumption of the ESD process of metal granules with different values of their intercontact active resistance (*Al*, *Ti*) in terms of kWh/kg;
- analysis of the electrophysical processes of EID to determine the effective modes of energy transfer from the TPG to the nonlinear ESL.

For clarity of the presentation of the experimental methodology, the input and output data operated by the electrophysical model of the TPG – ESL were determined.

Fixed parameters of the TPG and the reaction chamber: voltage on the input electrolytic capacitor C_0 – 420 V; maximum charging voltage and capacity of the working capacitor C_1 – 750 V and 1 μF; inductance of the discharge circuit L_0 – 14.6 μH; generator conversion frequency – 1 kHz; maximum current pulse duration – 12 μs; working fluid – water with a specific electrical conductivity of 30–50 μS/cm; diameter of the inner electrode 30 mm; duration of the ESD process – 10 min.

Adjustable installation parameters: technological gap between the cylindrical electrodes of the reaction chamber; mass of the granulated material before the start of dispersion – m_i, g; height and number of elementary layers of the VMLMG – h_i, mm, N_{sh}; diameter of the outer electrode; average diameter of the granule (quasi-spherical approximation).

Initial parameters of the technological process after processing: average power of the consumed energy of the electric discharge installation from the power supply network – P, W; residual mass of the granulated material after processing – m_{ex}, g; mass of dispersed material – Δm, g; specific electricity consumption for dispersion of granular material – Q, kWh/kg.

The concentration of metal granules (*Al*, *Ti*) was calculated using a measuring cup with a working volume of 50 ml, a height of 125 mm and a diameter of 22 mm. Then, after recalculating the number of granules in the bulk volume, their average N_a concentration per 1 cm^3 was determined, and after weighing, their bulk density. The average diameter of the granules was obtained in the approximation of their quasi-spherical shape and under the condition of their cubic model of location in space (d_{Al} = 2.4 mm, d_{Ti} = 3.5 mm). To calculate the bulk number of layers in the axial direction along the length of the reaction chamber with a cylindrical electrode system, the formula was used:

$$N_d = \frac{\sqrt[3]{N_a} \cdot V_t}{\pi \cdot \left(R_0^2 - R_1^2\right)}, \quad (1)$$

where R_0, R_1 are the outer and inner radii of the electrodes; V_t is the bulk volume of metal granules; $\sqrt[3]{N_a}$ is the number of granules per unit length in an arbitrary direction. The value $V_t / \pi \cdot \left(R_0^2 - R_1^2\right)$ is the height of the VMLMG in the axial direction along the length of the reaction chamber.

Measurement of the average TPG power in the process of electric spark treatment depending on the volume of each material was carried out in the range of their weights from 50 to 300 g with an analysis step of every 20 g and a processing duration of no more than 30 s, in such a way as to have the least impact on the previous initial state of the VMLMG in the ESD process.

Based on the obtained family of dependences of the average converter power on the bulk volume of granules and the diameter of the external electrode – d_0=72 mm, d_1=82 mm, d_2=98 mm (Fig. 4,*a*,*b*), both for aluminum and titanium loading, it can be stated that a common feature of all curves is the presence of distinct power maxima, which appear at approximately the same height of the VMLMG (for a certain number of layers) for each case of the geometry of the metal granular loading. In the range of the left section of the VMLMG experimental dependences also have a similar gradual growth pattern, close to linear. At the same time, with an increase in the diameter of the external electrode, the angular slope of each curve of the family decreases, and their maxima increase which is especially noticeable for titanium backfill. In addition, a distinctive feature is the electrophysical features of the behavior of titanium granules in the rear part of their dependences, where the power drops sharply. This is explained by the fact that the pulse energy at which the study was carried out (0.25 J) is no longer enough in this section of the VMLMG (to the right of the maximum) for continuous maintenance of the plasma formation reaction and a stable process of electric spark treatment.

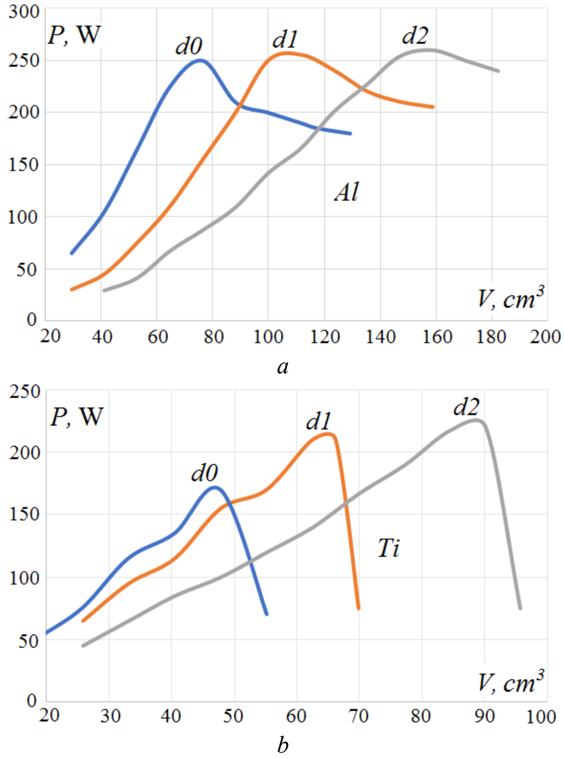

Fig. 4. Curves of dependence of generator power on the VMLMG of the reaction chamber for three values of the diameter of the external electrode:
a – *Al* granules; *b* – *Ti* granules

If the generator circuit enters a short-circuit mode or is close to it, then the discharge completely dies out in the reaction chamber or the plasma formation reaction occurs only near the central electrode-anode, and the power of the process still remains low (30–50 W). The maxima of the curves for aluminum backfill have a less pronounced growth pattern with increasing diameter of the external electrode, and their rear parts gradually decrease depending on the VMLMG. It should also be noted that all power maxima $P_{\max}$, both for aluminum and for titanium, arise at approximately the same height of the bulk volume of granules, or according to the number of their layers (1). Therefore, for *Al*: h_{Al} = 22 mm, N_l = 8 layers, for *Ti*: h_{Ti} = 13.5 mm, N_l = 5 layers. At the same time, the value of the power maximum tends to increase with increasing length of the IEG, on which a certain number of granules are placed depending on their diameter. For the average number of granules in the radial direction along the length of the IEG (R_0–R_1) of the reaction chamber, respectively, for the above-mentioned model of their packing, we have the expression:

$$N_l = \sqrt[3]{N_a} \cdot (R_0 - R_1). \qquad (2)$$

Therefore, guided by the above, it can be assumed that the average power consumption of the TPG in the process of ESD of metal granules is a unique function that depends to a certain extent on both the initial voltage on the IEG, the pulse energy and the frequency of their passage, and on the parameters of the packing of the VMLMG in the reaction chamber – the number of elementary layers in the bulk volume of metal granules and the number of granules in one of their layers. In addition, the surface tendency of titanium granules to form conductive bridges in the environment is manifested in a rapid decrease in the TPG power due to the onset of the short-circuit mode.

The next stage of the work is to determine the specific electricity consumption in terms of obtaining 1 kg of powder raw material. In this case, the accumulated value of the average power for a longer ESD period was already measured. For *Al* granules, the treatment was carried out with a 72 mm diameter of the external electrode and fixed system parameters, as indicated above. Experimental and calculated data on the ESD of *Al* and *Ti* granules are given in Table 1, 2 respectively. The electrical parameters of the ESD of titanium granules were chosen to be the same as for aluminum granules, but with the exception of the increased diameter of the external electrode of 82 mm.

Table 1

ESD results for aluminum granules

m_i, g	m_{ex}, g	Δm, g	V_i, cm^3	h_i, mm	N_l.	P, W	Q, kWh/kg
50	48,68	1,35	29,4	8,5	3,2	65	8,02
70	67,52	2,48	41,2	11,8	4,5	105	7,1
90	85,12	4,88	52,9	15,2	5,8	165	5,6
110	103,22	6,78	64,7	18,6	7,1	225	5,4
130	121,62	8,38	76,4	22	8,4	250	5
150	143,25	6,75	88,2	25,4	9,8	210	5,13
170	163,85	6,15	100	28,7	11	190	5,2

Table 2

ESD results for titanium granules

m_i, g	m_{ex}, g	Δm, g	V_i, cm^3	h_i, mm	N_l.	P, W	Q, kWh/kg
70	69,32	0,68	25,7	5,5	2	65	15,9
90	88,78	1,22	33,1	7,1	2,7	95	13
110	108,14	1,86	40,5	8,7	3,4	130	11,8
130	127,6	2,4	47,8	10,3	4	155	10,7
150	147	3	55,2	11,9	4,6	170	9,5
170	166,15	3,85	62,5	13,5	5,2	210	9
190	175,5	4,5	66,2	14,3	5,5	230	8,5

Thus, the obtained specific energy consumption indicators in the *Al-Ti* ESD process also correlate with the corresponding indicators of their average power. For *Al*, a lower dispersion energy consumption value was achieved than for *Ti* – 5 kWh/kg, but under the condition of a 20 W advantage. The obtained *Q* value correlates with the indicator given in [20] – 5.45 kWh/kg. However, this *Q* value was achieved at a very low productivity of electric spark treatment and power of the power source – during 3 h of treatment, the total mass of *Al* granules and electrodes decreased by only 1.8 g. The lowest value of the *Q* indicator for *Ti* – 8.5 kWh/kg was achieved only when the input voltage of the generator was increased to 450 V, which allowed stabilizing the plasma formation process, and despite the tendency in Fig. 4,*b* to increase the processing power. Taking into account the determined mass of the eroded material obtained during its processing time and the frequency of the generator pulses, it is possible to calculate the fraction of particles formed per one discharge pulse – $m_0 = \Delta m/(T \cdot f) = \Delta m/6 \cdot 10^5$. Accordingly, we have: m_{0Al} = 13.9 μg, m_{0T}=7.5 μg. Next, based on the thermodynamic equations [21] and the corresponding thermophysical coefficients for *Al-Ti*, the energy costs that go to melting E_m and evaporation E_v of this particle of eroded material are determined. Therefore, for *Al*: E_m=13.5 mJ, E_v=189 mJ; *Ti*: E_m=9 mJ, E_v=84 mJ. The average pulse energy for *Al* is 250 mJ, for *Ti* – 210 mJ. If we assume that all eroded particles completely pass the evaporation stage, then the efficiency of the ESD in relation to the energy E_v will be: *Al* – η = 76 %, *Ti* – η = 40 %. At the same time, the energy E_v for *Ti* in terms of the same mass of material is 17 % lower than for *Al*. If we refer to Fig. 4,*b*, the generator power tends to increase, but does not reach its saturation threshold due to the cessation of the plasma formation reaction. For example, with an external electrode diameter of 98 mm, the generator power drops after 90 cm^3 of the volume filled with metal granules. For this geometry of the VMLMG, energy consumption can be reduced to the level of 8.3 kWh/kg. Therefore, this indicator once again confirms the reality that with an increase in the number of contacts between granules along the length of the IEG and with an increase in the number of layers along the height of the reaction chamber, there is a gradual increase in the generator power and a decrease in the specific energy consumption of the ESD until its saturation threshold is reached.

An important aspect of the study is still the explanation of the behavior of the obtained experimental dependences of the average power on each section of the VMLMG. Therefore, to solve this issue, measurements of the current-voltage characteristics were carried out both on the electrodes of the chamber and on the TPG elements. The conversion of electrical oscillations to the level of amplitudes of signals safe for oscillography was performed using a mixed-type voltage divider with a transfer ratio of 1:46.5 and a coaxial current shunt with an active resistance of 1.55 mΩ. Both signals are fed via coaxial lines to the inputs of a dual-channel storage oscilloscope SDS1022. The digitized data were stored in text format and transferred to Excel for mathematical calculations. The number of sampling points provided by the oscilloscope on each channel is 104 with an interval of 10 ns and an amplitude value in millivolts. The digitization results were converted taking into account the vertical shift and the transmission coefficient for each signal. After processing many synchronous pairs of oscillographic data, it was found that the efficiency of ignition of plasma channels increases with each added layer of metal granules of the reaction chamber. At the initial levels of the bulk volume, many ineffective discharges are observed and only a small part of it is taken from the energy of the working capacitor. In this interval, the effective frequency of discharge pulses (EFDP) is less than the frequency of the generator pulses. According to the step-like voltage diagram on C_1, it is possible to separate ineffective discharges from their total number for a certain period of time, and from the voltage drops from the charging to the residual at each switching cycle of the power switches, the average energy and conversion power can be calculated. To maintain the accuracy of signal digitization, the maximum width of the window for storing data on a time sweep of 1 ms/div. was 20 ms. In order to more accurately approximate the average power values, 5 voltage diagrams were processed with a total time of 100 ms. Therefore, according to the presented algorithm, the average effective discharge energy (AEDE) can be calculated as:

$$E_a = \frac{\sum_{i=0}^{N_{sp}} E_i}{N_{sp}} = \frac{C}{2}\cdot\frac{\sum_{i=0}^{N_{sp}}\left(U_c^2 - U_r^2\right)_i}{N_{sp}},\quad E_i \geq E_{th}, \quad (3)$$

where U_c, U_r are the charging and residual voltages on C_1; C is the capacitance of capacitor C_1, N_{sp} is the number of effective discharges for the measurement time interval; E_i is the energy of effective discharge; E_{th} is the minimum threshold energy of discharge current.

The measurements were carried out with preservation of the same geometry of electrodes as in the previous experiment. A distinctive feature of the obtained curve of dependence of EFDP for *Al* granules (Fig. 5,*a*) is the presence of a section of its saturation (75–100 cm^3), where the frequency of effective discharges coincides with the frequency of conversion of the generator 1 kHz. The average energy of effective discharges in this section of volumes after reaching its maximum (0.22 J) as well as the average power gradually decreases. In the case of *Ti* granules, the EFDP curve (Fig. 5,*b*) corresponds to the generator frequency only when it enters the short-circuit mode, and the maximum AEDE value is reached at the level of 60 cm^3 of the VMLMG.

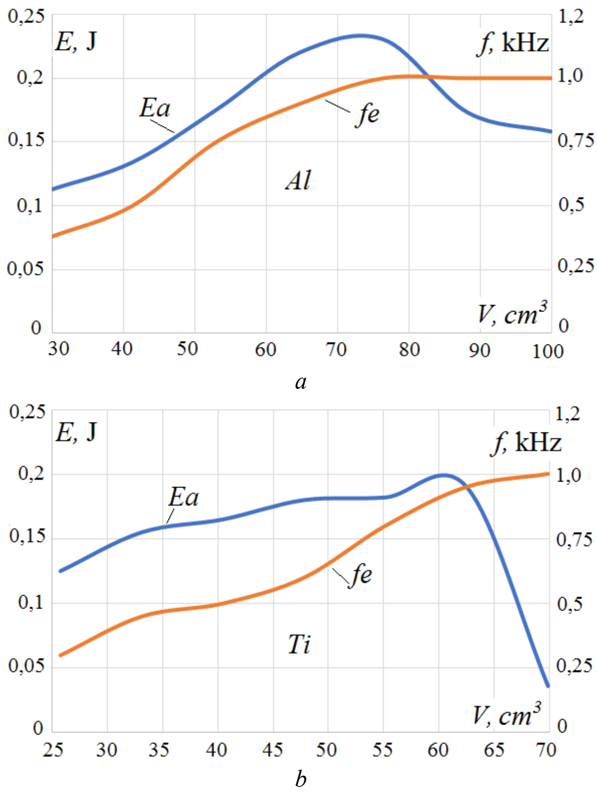

Fig. 5. Curves of the average energy and effective frequency of discharge pulses on the VMLMG of the reaction chamber:
a – aluminum granules; *b* – titanium granules

Stationary electrical oscillations in the TPG in the saturation region of the VMLMG curve for *Al*, in contrast to *Ti*, are characterized by greater stability and a smaller value of reverse oscillations. Therefore, provided that the frequency of discharge pulses and their amplitude are stable, it is possible to take the current-voltage characteristics at several points of the EFDP saturation region and calculate the instantaneous power and dynamics of the resistance on the load.

The equivalent value of the resistance R_{eq} of the VMLMG during the pulse duration is usually calculated by the formula [6], but the approximation to the integral expressions is performed using the trapezoidal approximation method:

$$R_{eq} = \frac{\sum_{k=0}^{n}\left(u_k \cdot i_k + u_{k+1} \cdot i_{k+1}\right)}{\sum_{k=0}^{n}\left(i_k^2 + i_{k+1}^2\right)}, \qquad (4)$$

where u_k, i_k are the instantaneous values of current and voltage in the discharge circuit at the k-th integration step.

The instantaneous power characteristics, which are allocated to the ESL, are calculated based on the obtained pairs of synchronous current and voltage oscillograms at 3 points of the saturation area of the effective discharge frequency (Fig. 6).

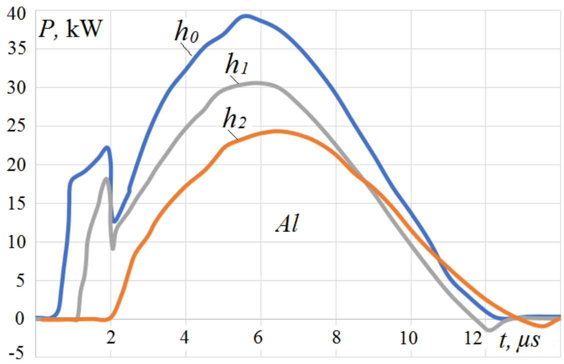

Fig. 6. Instantaneous power characteristics for 3 height levels of aluminum VMLMG

Synchronization of all characteristics was carried out on the first rapidly falling front of the voltage pulse on the IEG, which corresponds to the moment of the final electrical breakdown of the medium and the beginning of the development of the spark discharge with the subsequent transfer of the main part of the energy from the capacitive energy storage to the load. As can be seen from the characteristics for the filling levels h_0 = 22 mm, h_1 = 25 mm, their main feature is the presence of a significant power surge until the moment of development of the plasma channel. The power jump is mainly associated with the flow of current in ohmic contacts in local zones between the granules, the development of ionization avalanches and polarization of the working fluid in the intergranular volumes. It should be noted that the final voltage value, which is set on the IEG after the transistor key is completely unlocked, will be primarily determined by the current in the ohmic contacts of the load and the reactive parameters of the discharge circuit. The flow of current through the ohmic contacts causes a voltage drop across the choke L_1, which accordingly reduces the maximum amplitude of the applied voltage to the IEG, the value of which in turn affects the consistency of the energy input into the ESL. As found out based on the analysis of many synchronous pairs of volt-ampere data, the voltage on the IEG is maintained for some time and remains practically constant, while a voltage «plateau» is formed before the start of the development of the plasma discharge. In turn, the intensity of electron avalanche propagation and the further development of plasma channels will depend on the value of the ohmic contact current, which heats the contacting surfaces of the granules.

The increase in the ohmic contact current from the layer height is explained by the increase in the surface area of contact of the granules with the electrodes of the reaction chamber. But at some point, at the height of the VMLMG h_2 = 29 mm, the ohmic contact current becomes quite significant and merges with the spark discharge current, at the same time the voltage «plateau» – the ionization voltage shelf completely disappears, which worsens the development of plasma channels. Therefore, it is advantageous to perform the ionization process hold, when the voltage plateau on the IEG lasts for some time, on average several microseconds, which is important for increasing the number of plasma channels and the efficiency of their growth. The ohmic contact current in this sense heats the contacting layers of granules and stimulates thermionic emission from their surfaces, which in turn affects the ionization current, which is the trigger – the primary source for the formation of plasma channels. On the other hand, a sufficient potential difference between the heated surfaces of the granules will create conditions for the effective propagation of electron avalanches and the formation of plasma channels.

For the considered family of instantaneous power curves for the duration of the discharges (12 μs), the energy dissipated in the ESL is calculated. Again, if the power integral over time is approximated by the trapezoidal method, then we can obtain the expression:

$$E_a = 0.5 \cdot \sum_{k=0}^{n}\left(U_k \cdot i_k + U_{k+1} \cdot i_{k+1}\right) \cdot \Delta t, \qquad (5)$$

where Δt is the integration time step, Δt =10 ns.

From which we have that the energy for the curve h_0 is 240 mJ, h_1 – 190 mJ, h_2 – 160 mJ. These results also correlate with the values obtained by (3) for the generator power curve in Fig. 4,*a*.

Regarding the dynamics of the load resistance over time (Fig. 7), each curve has its own initial resistance value. However, a distinctive feature of the curve h_2 is the presence of a zero resistance value and its instantaneous jump in a short period of time from the zero mark to the initial value R_0.

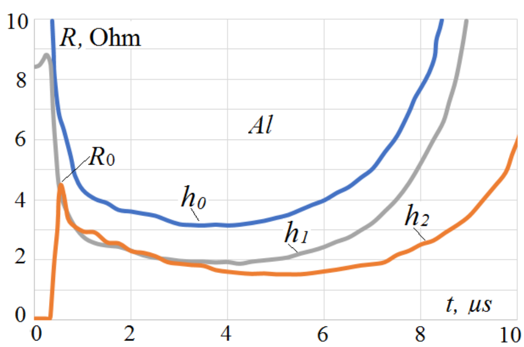

Fig. 7. Dynamics of the resistance of the electric spark load

At a layer height of at least 30 mm, the presence of the displacement current of the intergranular volumes of the working fluid becomes significantly noticeable, which causes the appearance of a reactive component in the dynamics of the load resistance. Further, using (4) for all 3 curves h_0–h_2, we have the following values of the equivalent load resistance: h_0 – 3.95 Ω, h_1 – 2.41 Ω, h_2 = 1.84 Ω. If the characteristic resistance of the C_1-VT_1-VD_2-L_1 circuit is 4 Ω, then it can definitely be stated that the main reason for the decrease in the AEDB with the increase in the VMLMG in the EFDP saturation region is the decrease in its equivalent resistance. Because of this, the transient process in this circuit becomes more oscillatory and branched [7].

At the same time, the R_{eq} values correlate with the initial resistance values at the time of IEG breakdown, which also tend to decrease – $R_0(h_0)$=25 Ω, $R_0(h_1)$=8.5 Ω, $R_0(h_2)$=4.5 Ω. The obtained relationship between the height of the VMLMG and the initial resistance of the ESL can also be an addition to the parametric model of the electric spark load [4], where the dependence of this resistance on the initial applied voltage to the IEG is established.

Another interesting circumstance is that the presence of ohmic contact current when switching the discharge circuit with a thyristor key is difficult to notice due to its inertial features – the process of heating the intergranular gaps and the formation of plasma channels merge in time. In addition, the low value of the circuit inductance only contributes to the rapid development of the plasma discharge and, in principle, makes it impossible to recognize this phenomenon. In [17], only approximate intervals of existence of each current are given, because the volt-ampere characteristics on the IEG are similar to a smooth curve of the pulse power at the point of a noticeable drop in the contact resistance of the ESL, which is shown in Fig. 6 (curve h_2). In this sense, the advantage of the transistor switch is the possibility of quickly applying voltage to the IEG and immediately separating several stages of the spark discharge development in the volume of the metal loading of the reaction chamber.

Conclusions.

1. The proposed model of an electric discharge installation – TPG with a maximum pulse voltage of up to 800 V and energy of up to 0.3 J in combination with a reaction chamber with a cylindrical system of electrodes confirms its effectiveness for ESD tasks of heterogeneous conductive granular media with different degrees of activity of intercontact resistance.
2. It was established that the average power consumption of the TPG when operating on the ESL under the condition of a fixed input supply voltage and pulse frequency is dependent on the geometric dimensions of the metal loading in the reaction chamber – the number of its layers and the number of granules along the length of the IEG in one layer. In addition, the nature of the TPG power after reaching its maximum in the saturation region of the effective frequency of the discharge pulses is influenced by the electrophysical features of the behavior of the intercontact resistance of the granules and their tendency to form chains of through-conduction in the medium.
3. The specific energy consumption Q in the ESD process of aluminum granules (5 kWh/kg) turned out to be lower than for titanium granules (8.3 kWh/kW), at the same time, the obtained power curve for the titanium load is characterized by the absence of its saturation area due to the onset of the short-circuit mode in the TPG. In the case of increasing the outer diameter of the reaction chamber and, accordingly, the inter-contact gaps along the length of the IEG, provided that there is a certain number of layers of the VMLMG, the maximum power also increases, which accordingly correlates with the Q indicator in the direction of its decrease.
4. It was found that the effective frequency of ESD discharge pulses depends on the ohmic contact current, the direct flow of which before the start of the main discharge causes heating of the contact surfaces of the granules, which affects the ionization processes of the development of electron avalanches and the formation of plasma channels.
5. It was established that the main reason for the decrease in average power with increasing bulk volume of metal granules in the saturation region of the curve of the effective frequency of discharge pulses is the decrease in both its initial and equivalent resistance, which is caused by an increase in the surface area of contact of the granules with the electrodes of the reaction chamber, therefore the transient process in the discharge circuit becomes more branched.

Conflict of interest. The author declares no conflict of interest.

REFERENCES

1. Monastyrsky G. Nanoparticles formation mechanisms through the spark erosion of alloys in cryogenic liquids. *Nanoscale Research Letters*, 2015, vol. 10, no. 1, art. no. 503. doi: https://doi.org/10.1186/s11671-015-1212-9.

2. Jin C.H., Si P.Z., Xiao X.F., Feng H., Wu Q., Ge H.L., Zhong M. Structure and magnetic properties of Cr/Cr2O3/CrO2 microspheres prepared by spark erosion and oxidation under high pressure of oxygen. *Materials Letters*, 2013, vol. 92, pp. 213-215. doi: https://doi.org/10.1016/j.matlet.2012.10.126.

3. Vinnychenko D.V., Nazarova N.S., Adamchuk Y.O., Vinnychenko I.L., Vyshnevskyi O.A. Synthesis of Tungsten Carbides Submicron Powders by High-Frequency Electrospark Treatment Method. *Springer Proceedings in Physics*, 2024, vol. 312 SPPHY, pp. 385-395. doi: https://doi.org/10.1007/978-3-031-67527-0_27.

4. Shydlovska N.A., Zakharchenko S.M., Cherkaskyi O.P. Physical prerequisites of construction of mathematical models of electric resistance of plasma-erosive loads. *Technical Electrodynamics*, 2017, no. 2, pp. 5-12. (Ukr). doi: https://doi.org/10.15407/techned2017.02.005.

5. Shydlovska N.A., Zakharchenko S.M. Discrete nonlinear-probabilistic model of the equivalent electrical resistance of a layer of metal granules. *Technical Electrodynamics*, 2021, no. 2, pp. 3-12. (Ukr). doi: https://doi.org/10.15407/techned2021.02.003.

6. Shcherba A.A., Suprunovska N.I. Cyclic transients in the circuits of electric discharge installations taking into accounttheinfluence of magnitude and rate of discharge currents rise on resistance of electric spark load. *Technical Electrodynamics*, 2018, no. 2, pp. 3-10. (Ukr). doi: https://doi.org/10.15407/techned2018.02.003.

7. Shcherba A.A., Suprunovska N.I., Ivashchenko D.S. Modeling of nonlinear resistance of electro-spark load for synthesis of discharge circuit of capacitor by time parameters. *Technical Electrodynamics*, 2014, no. 3, pp. 12-18. (Ukr).

8. Shydlovska N.A., Zakharchenko S.M., Zakharchenko M.F., Kulida M.A., Zakusilo S.A., Yakovenko R.A. Distribution of volumes of plasma channels components between metal granules in working liquids. *Electrical Engineering & Electromechanics*, 2025, no. 1, pp. 73-85. doi: https://doi.org/10.20998/2074-272X.2025.1.10.
9. Shydlovska N.A., Zakharchenko S.M., Zakharchenko M.F., Kulida M.A., Zakusilo S.A. Spectral and optic-metric methods of monitoring parameters of plasma channels caused by discharge currents between metals granules in working liquids. *Electrical Engineering & Electromechanics*, 2024, no. 6, pp. 72-83. doi: https://doi.org/10.20998/2074-272X.2024.6.10.
10. Petrov O., Petrichenko S., Yushchishina A., Mitryasova O., Pohrebennyk V. Electrospark Method in Galvanic Wastewater Treatment for Heavy Metal Removal. *Applied Sciences*, 2020, vol. 10, no. 15, art. no. 5148. doi: https://doi.org/10.3390/app10155148.
11. Khrysto O.I. Current-voltage characteristics of single-stage semiconductor magnetic pulse generators with a distinctive structure of the conversion link in the input circuit. *Electrical Engineering & Electromechanics*, 2023, no. 6, pp. 41-47. doi: https://doi.org/10.20998/2074-272X.2023.6.07.
12. Syzonenko O.M., Tashev P., Torpakov A.S., Lypian Ye.V., Prystash M.S., Kandeva M., Dyakova V. Influence of the High-Voltage Discharge Treatment of Powders on the Properties of Metal Matrix Composites of the Ti–TiC System. *Materials Science*, 2022, vol. 58, pp. 165-174. doi: https://doi.org/10.1007/s11003-022-00645-3.
13. Khrysto O. Energy transfer processes in high-voltage circuits based on magnetic pulse compression. *Acta Electrotechnica et Informatica*, 2020, vol. 20, no. 3, pp. 3-10. doi: https://doi.org/10.15546/aeei-2020-0013.
14. Khrysto O.I. Energy characteristics for nanosecond current interrupter of semiconductor-magnetic pulse generator's terminal stage. *Electrical Engineering & Electromechanics*, 2023, no. 3, pp. 59-65. doi: https://doi.org/10.20998/2074-272X.2023.3.09.
15. Petrichenko S., Malyushevskaya A., Ivanov A., Mitryasova O., Salamon I. Improving the Efficiency of Water Purification from Heavy Metals using the Electric Spark Method. *Journal of Ecological Engineering*, 2024, vol. 25, no. 8, pp. 1-9. doi: https://doi.org/10.12911/22998993/189230.
16. Zakharchenko S.N., Kondratenko I.P., Perekos A.E., Zalutsky V.P., Kozyrsky V.V., Lopatko K.G. Influence of discharge pulses duration in a layer of iron granules on the size and structurally-phase conditions of its electroerosion particles. *Eastern-European Journal of Enterprise Technologies*, 2012. vol. 6, no. 5 (60), pp. 66-72. (Rus).
17. Zakharchenko S.N. Modelling of dependence of electrical resistance of granulated current-carrying mediums from a pulse current proceeding in them. *Technical Electrodynamics*, 2012, no. 5, pp. 17-27. (Ukr).
18. Shcherba A.A, Suprunovska N.I., Shcherba M.A. Features of the formation of multi-channel pulse currents and fast-migrating electric sparks in the layer of current-conducting granules of electric-discharge installations. *Tekhnichna Elektrodynamika*, 2022, no. 2, pp. 3-11. doi: https://doi.org/10.15407/techned2022.02.003.
19. Liu Y., Zhu K., Li X., Lin F., Li Y. Analysis of multi-scale Ni particles generated by ultrasonic aided electrical discharge erosion in pure water. *Advanced Powder Technology*, 2018, vol. 29, no. 4, pp. 863-873. doi: https://doi.org/10.1016/j.apt.2018.01.003.
20. Zakharchenko S.M., Shydlovska N.A., Perekos A.O., Zakharchenko M.F. Power Efficiency of Electrophysical Methods of Dispersion and Electrochemical Dissolution of Several Metals. *Metallofizika i Noveishie Tekhnologii*, 2021, vol. 43, no. 4, pp. 465-487. (Ukr). https://doi.org/10.15407/mfint.43.04.0465.
21. Gulbinowicz Z., Goroch O., Skoczylas P. Mathematical Modeling of Material Erosion During the Electrical Discharge. *Advances in Science and Technology Research Journal*, 2020, vol. 14, no. 2, pp. 27-33. doi: https://doi.org/10.12913/22998624/114959.

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