

Проведеними дослідженнями високовольтного електрохімічного вибуху як об'єкта керування виявлено істотний вплив режимів керування введення електричної енергії в канал розряду на ефективність екзотермічного перетворення енергії. Отримано залежність питомої енергетичної ефективності виділення хімічної енергії екзотермічної суміші від розподілу повної електричної енергії між послідовними розрядними імпульсами. Це дозволяє за запропонованими авторами правилами визначати початкові умови алгоритму керування розрядноімпульсною установкою, яка реалізує технологічні режими високовольтного електрохімічного вибуху, що забезпечують максимальну ефективність екзотермічних перетворень.

Показано, що суттєва стохастичність процесів при екзотермічних перетвореннях в режимі вибухового горіння не дозволяє використовувати системи керування, що регулюють тільки початкові умови електрохімічного вибуху. Такі системи не забезпечують заданих режимів розряду при кожній реалізації. Обґрунтовано необхідність поточного керування в процесі екзотермічних перетворень з метою недопущення зниження тиску в каналі розряду нижче допустимого значення, яке підтримує екзотермічну реакцію вибухового горіння. Проведений кореляційний аналіз взаємозв'язку значень поточного тиску в каналі розряду і електричних характеристик розряду показав наявність досить щільного інформаційного взаємозв'язку між ними. Тому в якості інформаційних координат, які опосередковано визначають тиск в каналі розряду, запропоновано використовувати операційно визначені електричні характеристики розряду.

Розроблено алгоритм і систему керування високовольтною розрядноімпульсною установкою, що реалізує високовольтний електрохімічний вибух. Керування режимом введення енергії в процесі вибухового перетворення дозволяє уникнути згасання екзотермічної реакції при випадковому, через стохастичність процесу, зниженні тиску до гранично допустимого значення в період між розрядними імпульсами. За рахунок цього усуваються непродуктивні втрати екзотермічної суміші, зменшуються втрати хімічної та електричної енергії і збільшується кількість виділеної сумарної енергії, без збільшення введеної електроенергії, при кожній реалізації високовольтного електрохімічного вибуху

Ключові слова: розрядноімпульсна установка, алгоритм керування, інформаційні координати, високовольтний електрохімічний вибух

CONTROL OF A HIGH-VOLTAGE DISCHARGE-PULSE INSTALLATION WHEN IMPLEMENTING TECHNOLOGICAL MODES OF AN ELECTROCHEMICAL EXPLOSION

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1. Introduction

High-performance technological processes involving explosive energy conversion are widely used in various industries. The technologies of discharge-pulse treatment of materials and products employ a high-voltage electrical discharge in condensed environments as a source of concentrated, dosed impact within the specified local volumes with high specific energy indicators. The main factors affecting

the treated object include the pressure waves and hydraulic flows of liquid that propagate throughout a working environment, which are used for destruction, shape-formation, crushing, dispersing, etc. [1].

Most high-voltage discharge-pulse installations used in various technologies employ a capacitive drive as an energy source as part of a pulse current generator (PCG). When it is discharged to the intra-electrode gap, an expanding plasma channel is formed in a condensed environment, generating a

pressure pulse with a steep front and a descent close to exponential. However, for a series of discharge-pulse technologies (DPT), such as the destruction of natural and artificial oversized objects, loosening of strong bottom soils, a longer pressure pulse is required, with more energy [2, 3].

Such technologies exploit a high-voltage electrical discharge in chemically active condensed environments capable of exothermic conversions under an explosive combustion mode under the influence of high temperatures and pressures created in a discharge channel by electro-discharged plasma. Such a complex physical and chemical phenomenon is typically termed a high-voltage electrochemical explosion (HECE). The energy released during exothermal transformations is combined with the electrical energy of the discharge accumulated on the linings of capacitor batteries. As a result of this summation, the energy of destruction increases by several times without increasing the stored energy in the capacitor battery and, therefore, without increasing the number of capacitors and equipment dimensions [4].

An important advantage of DPTs, which use a high-voltage electrochemical explosion to destroy the oversize, is their manageability, as opposed to technologies that apply explosives. Therefore, it is a relevant task to design control systems for discharge-pulse installations in order to provide the required technological modes of an electrochemical explosion.

2. Literature review and problem statement

Earlier studies at the Institute of Pulse Processes and Technologies (IPPT) of the National Academy of Sciences of Ukraine demonstrated that the use of a high-voltage electrochemical explosion (HECE) in various DPTs makes it possible to expand the scope of application of the technology of materials pulse treatment. This is predetermined by the fact that at identical characteristics of pulse current generators (PCG), used in discharge-pulse installations, the amplitude and duration of the generated compression pulse increase when HECE is applied. Paper [5] analyzes the pressure profiles that were derived considering the radiation caused by the reaction of exothermal additives at HECE. The authors determined the HECE electrical parameters and the amount of destruction depending on the strength of the destroyed soils. The calculation of force impact on the treated object confirms the increase in the amplitude and duration of the generated compression pulse at HECE.

Energy efficiency is important in the technological use of HECE. Study [6] explores the single-pulse input of energy into the HECE channel with disposable electrodes. The result is the savings through the reduction in the cost of the electrode system; however, the causes leading to incomplete combustion of the exothermal mixture are not eliminated. The combustion reaction of the exothermal mixture stops within a few tens of microseconds, resulting in the loss of potential chemical energy and exothermal mixture, which confirms the non-efficiency of single-pulse energy input into the HECE channel. Work [7] reports a diagram of the relationships of the main physical processes in the discharge-pulse treatment and their effect on the output indicators in the processing of minerals; however, there is no analysis of multi-pulse energy input. The use of single-pulse energy input is also considered in paper [8]. The authors estimated the volume of destruction and pressures generated by the use of HECE in the destruction of strong soils with single-pulse energy input. They

compared HECE with an electric explosion without the use of exothermal mixtures in terms of the volume of destroyed soils but did not perform analysis of the WEM combustion completeness and did not assess energy efficiency. Our analysis of works [6–8] reveals that the implementation of HECE at a single-pulse energy input and, therefore, when using a single-circuit scheme of PCG, is not effective due to incomplete combustion of the applied exothermal compositions because of a short-term nature of the pressure pulse generated by a high voltage discharge.

The shape of an electrical power pulse introduced into a discharge channel at a single discharge of the PCG capacitor bank is close to triangular, while the compression waves propagating in the working environment most often have a steep front and a decline close to exponential. This shape of a compression wave does not meet the needs of many discharge-pulse technologies. In order to study a possibility to generate a pressure pulse of the required shape and duration, in particular, a multi-pulsation pressure wave profile, the hydrodynamic processes were investigated at a multi-pulse power input into the channel of electrical discharge in a liquid [9–11]. The results of the numerical experiment [9] show that it is possible, based on combined electrical discharge energy sources, such as multi-contour PCG, to form pressure pulses with several successive pulsations whose number is equal to the number of electric power pulsations. Analysis of the results on the study of the introduction of electrical energy into the underwater spark discharge channel [10, 11] revealed that the numerical determination of the characteristics of electrically discharged technological installations should account for all the pulsations of power in the estimated multi-pulse energy input model. Each power pulse ensures an increase in the amplitude and duration of the pressure pulse. The reviewed literary sources reasonably demonstrate the advantages of multi-pulse energy input into the discharge channel. Implementation of a multi-pulse energy input requires the construction of control systems for energy input into the discharge channel.

The important advantage of HECE is manageability. One of the methods to control a discharge process to ensure fuller combustion of the exothermal mixture is to change the parameters of the pulse current generator (PCG) and the length of an intra-electrode interval [12]. However, in this case, the choice of the values for the adjustable quantities is made before the start of the energy input, so regulation is impossible in the discharge process; only discrete control from discharge to discharge is executed. To implement multi-pulse energy input in order to obtain the pressure waves of the required shape for a particular technology, multi-loop PCGs are used as part of discharge-pulse installations [13, 14]. The capacitive drives of each PCG circuit can have different capacities and may be charged to different voltages. Each subsequent circuit is enabled after the preset period relative to the beginning of the discharge of the preceding circuit. [14] proposed a scheme to automatically enable a second circuit in a two-circuit generator of pulse currents that provides for a fairly accurate delay in triggering the second circuit. However, it is impossible to change the length of the delay in the second pulse supply from discharge to discharge. Such multi-contour PCGs make it possible to generate a variety of shapes and amplitudes in current pulses and form an appropriate pressure pulse profile in the treatment area only if discharges are stable. Study [15] considers the use of two-circuit capacitive pulse generators in high-voltage electrical discharge installations

instead of conventional single-contour ones. The authors proposed a technique to regulate the energy accumulated in them by changing the capacity or voltages of their charge and the moments of input of this energy into the intra-electrode gap filled with an exothermic disperse environment. However, the proposed technique does not imply the possibility of control in the discharge process but makes it possible to change the initial conditions of energy input from discharge to discharge.

At a high voltage discharge, the exothermal disperse environments demonstrate considerable instability; the process is stochastic in character. Therefore, the use of the above deterministic methods of control over multi-contour discharge-pulse installations does not provide for the required mode at each HECE implementation. As a result, there are a certain number of ineffective discharges, leading to significant energy losses.

Our analysis of the scientific literature shows that there is an unresolved issue related to ensuring the effectiveness of exothermal transformations at each HECE implementation under conditions of discharge instability. One can conclude that a systemic study of HECE as a controlled object is needed in order to construct algorithms and control systems for HECE in the discharge process. A control system must be designed that would enable the operative control over a HECE process, which could improve the efficiency of exothermal transformations and the assigned technological regimes at each HECE implementation.

3. The aim and objectives of the study

The aim of this study is to synthesize a discharge-pulse installation control system for the process of the ongoing implementation of HECE in order to ensure the predefined technological modes and maximum efficiency of exothermal energy conversion at each discharge, as well as to rule out the non-effective discharges resulting in significant energy losses.

To accomplish the aim, the following tasks have been set:

- to investigate the impact of the modes of controlled input of electrical energy into a discharge channel on the efficiency of exothermal energy conversion in order to determine the initial conditions for a HECE mode control algorithm during a discharge;

- to explore the relationship between the electrodynamic and hydrodynamic characteristics of HECE with the controlled input of electrical energy in order to determine the information signals of the control system;

- to construct a control algorithm for a multi-contour discharge-pulse installation that would ensure the preset technological modes and the maximum efficiency of exothermal energy conversion at each HECE implementation.

4. Studying the effect of the modes of controlled input of electric energy on the efficiency of exothermal transformation during HECE

The goal to manage the HECE process is to improve the efficiency of exothermal energy conversion at each implementation, which determines the effectiveness of the technological impact on treated objects.

The effectiveness of exothermal energy conversion during HECE is determined by the completeness of the combustion of the WEM mass. When completely burned, the

amount of chemical energy released should be close to the potential energy of the exothermal mixture. However, under an unmanageable single-pulse energy input into a discharge channel, about 20 % of the total amount of the mixture, introduced to a discharge gap, participates in the reaction. The main reason for this is the termination of the exothermal self-sustaining reaction due to a sharp reduction in pressure in the HECE channel, ranging from hundreds of MPa to less than $P_{\min}=23$ MPa, the minimum level of pressure required for the course of an exothermic self-sustaining reaction.

In order to improve the efficiency of the release of WEM chemical energy, it is required to maintain the pressure level in a HECE channel above the minimum for a longer time. Based on the analysis of the physical processes taking place during HECE, a method has been proposed to improve the efficiency of exothermal transformations at each HECE implementation. The method is based on the sequential portioning of electrical energy into a discharge channel in line with the predefined algorithm, implying operative indirect control over the pressure level in the discharge channel, in order to prevent the extinction of the self-sustaining exothermal reaction. The implementation of this method requires the construction of an appropriate algorithm and a control system for the process of electrical energy input into the discharge channel.

In order to determine the initial conditions for a HECE control algorithm, which enable the release in a discharge gap of as much chemical energy as possible per WEM mass, it is necessary to establish the main factors influencing the efficiency of an exothermic transformation. While conducting an experimental study aimed at solving this problem, an important methodical point was to determine the energy released in the HECE channel through chemical exothermal transformations. The WEM potential energy could be calculated fairly accurately. However, since the total combustion of WEM in a discharge channel does not occur, the total energy released in the HECE channel would be less than the sum of potential energies accumulated in the capacitor bank and the WEM mass.

During HECE, the total energy consists of the electrical energy W_t and the thermal energy ΔW_{ch} , which is released through the oxidation of the exothermal mixture. This energy is used to change the aggregate and thermodynamic state of the substance in the HECE channel, to expand the channel, as well as for thermal and other losses. In the process of expanding the HECE channel, a wave of pressure is emitted and a post-discharge vapor gas cavity (VGC) forms with energy W_t , which is used to treat technological objects. In order to determine the effectiveness of the exothermal transformation of WEM in the implementation of the controlled HECE, it is necessary to determine the contribution of chemical energy ΔW_{ch} . To separate the contributions of electrical and chemical energies to the total HECE energy balance, we use the following expression [4]:

$$\Delta W_{ch} = W_t - \eta_t \cdot W_t, \quad (1)$$

where W_t is the full energy of VGC, J; η_t is the conversion coefficient of the electrical energy W_t , introduced to a discharge channel, into the VGC energy.

The energy of the post-discharge vapor gas cavity during HECE W_t could be calculated using a known Willis formula based on the duration of its pulsation T_p [4]:

$$T_p = \frac{1.14 \rho^{1/2} W_t^{3/2}}{P_0^6}, \quad (2)$$

where P_0 is the hydrostatic pressure at the depth of VGC pulsations, Pa; ρ is the density of a liquid, kg/m^3 ; T_p is the period of VGC pulsations, s.

In the experimental study, the amount of released energy in VGC (W_t) was determined based on the period of VGC pulsations T_p , the time interval between the peaks of pressure. The profile of a pressure wave in the $P(t)$ environment in the equatorial plane at a distance of 0.3 m from the discharge channel was measured using a piezoceramic pressure sensor and recorded by the memorizing oscillograph TDS 2024B.

The η_t magnitude was determined from the following empirical expression [4]:

$$\eta_t = 0.26 \exp(-2/3\beta) + 0.14, \tag{3}$$

where

$$\beta = l^{-1} \left(\frac{W_\tau}{P_0} \right)^{\frac{1}{3}},$$

– the coefficient of a VGC shape; l – the length of an intra-electrode interval, m.

An objective criterion for the efficiency of release of the WEM potential chemical energy could be the magnitude μ , the specific energy efficiency of an exothermal transformation, J/kg:

$$\mu = \frac{\Delta W_{ch}}{M}, \tag{4}$$

where ΔW_{ch} is the chemical energy, J. M is the WEM mass, kg.

To determine the μ magnitude from formula (4), we first determined, based on the experimentally recorded pulsation period of VGC T_p , the full energy of VGC W_t from formula (2). Based on the electrical characteristics $I(t)$ and $U(t)$, we determined the electrical energy W_τ and its conversion coefficient η_t from formula (3). Then, from formula (1), we determined the chemical energy ΔW_{ch} .

In the experimental study, during each discharge, we simultaneously registered voltage on the HECE channel $U(t)$, the discharge current $I(t)$, the profile of a pressure wave propagating in the $P(t)$ environment, and the period of pulsation of a post-discharge vapor gas cavity T_p (Fig. 1). The sensors used were the DN-50 voltage divider with a measurement range from 0 to 50 kV, as well as the S-100 shunt with a measurement range from 0 to 100 kA.

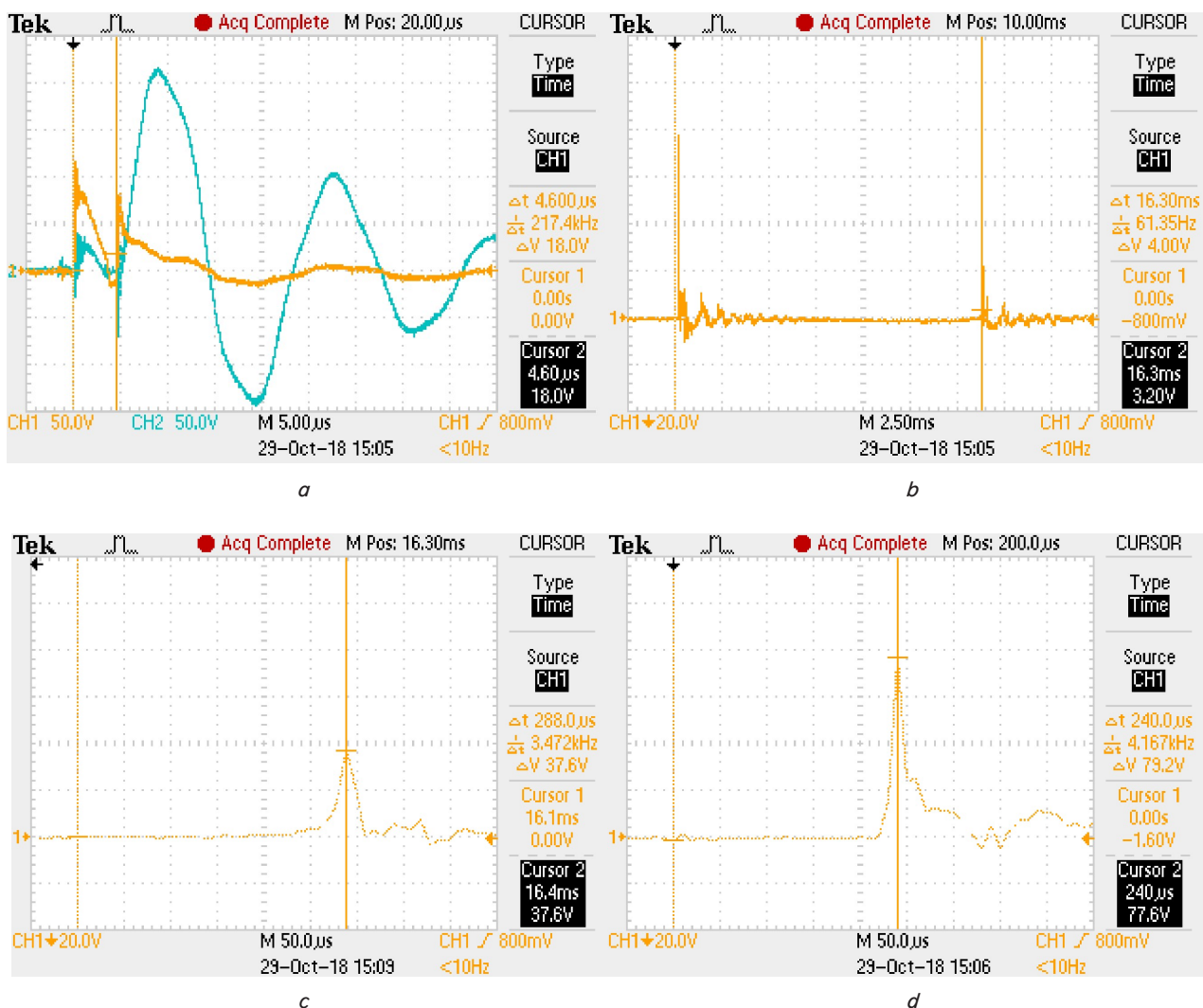


Fig. 1. Results of HECE parameters registration in the discharge process: *a* – electrical characteristics $U(t)$, $I(t)$; *b* – VGC pulsation period T_p ; *c* – pressure wave profile $P(t)$; *d* – profile of the second pulse of VGC pressure

Since the breakdown processes, the release of energy in a discharge channel and the generation of compression waves are stochastic in nature [12, 16], then, in order to improve the degree of reliability and the estimation of the statistical variance of the results, the experiments were carried out in series. The number of experiments in a series characterized by the fixed conditions depended on the spread of the registered HECE parameters. The minimum value chosen was five. Based on the samples acquired, we calculated the estimates of averages:

$$\bar{x} = \sum_{k=1}^n \frac{x_k}{n} \quad (5) \quad \bar{\mu}$$

At a controlled two-pulse input of electrical energy into the HECE channel, it is necessary to determine the initial distribution of energy, between the first and second pulses, ensuring the maximum specific energy efficiency of exothermal transformation μ . By using the proposed procedure for determining μ , we studied the effect of the ratio of the energies of the second and first pulses W_2/W_1 on the efficiency of the release of the WEM potential chemical energy.

Experimental studies were conducted in a 1 m³ technological tank filled with water, with a fixed exothermal composition containing 40% of the aluminum powder in an aqueous solution of the oxidizer whose application effectiveness was justified in [4]. To introduce WEM into a plasma channel zone, it was previously placed in dielectric capsules, the ends of which hosted current conductive electrodes made from copper. Next, such a capsule with WEM was installed in the water intra-electrode gap. The length l of the capsule, corresponding to the length of a discharge gap, was determined from the condition for ensuring the initial intensity of an electric field necessary for the formation of the channel through conductivity. For the selected type of WEM, $E_{cr} \geq 10^6$ V/m, $l = 3 \times 10^{-2}$ m [4]. The total energy of a two-circuit PCG W_τ varied from 400 J to 750 J. A change in the modes of controlled energy input was provided by varying the energies W_1 and W_2 by changing the initial voltages U_1, U_2 on energy drives and by changing the capacitance C_1 and C_2 . The magnitude of the energy ratio W_2/W_1 varied from 2.0 to 23.0. The natural inductiveness of each contour L_1 and L_2 was determined based on short-circuiting experiments and did not change in the course of the study: $L_1 = 6.8 \times 10^{-6}$ Gn and $L_2 = 3.54 \times 10^{-6}$ Gn.

To compare the results of experimental studies under different modes of electrical energy input as regards the efficiency of chemical energy conversion, the magnitude of specific energy efficiency μ was normalized to the value of μ_0 at a single-pulse energy input and is represented by a relative magnitude:

$$\bar{\mu} = \mu / \mu_0, \quad (6)$$

where μ_0 is the efficiency of combustion of WEM unit mass in a discharge channel at the conventional single-pulse energy input, J/kg; μ is the efficiency of combustion of WEM unit mass in a discharge channel during HECE with a controlled two-pulse energy input, J/kg.

The results of experimental studies are shown in Fig. 2 in the form of dependences

$$\bar{\mu} = f\left(\frac{W_2}{W_1}\right),$$

built on the basis of experimental data (indicated by points) for three values of energy W_τ . It also shows their approximation by a third-degree polynomial dependence, performed using a standard function – the trend line in the Microsoft Excel software (marked in the Fig.2 by solid lines).

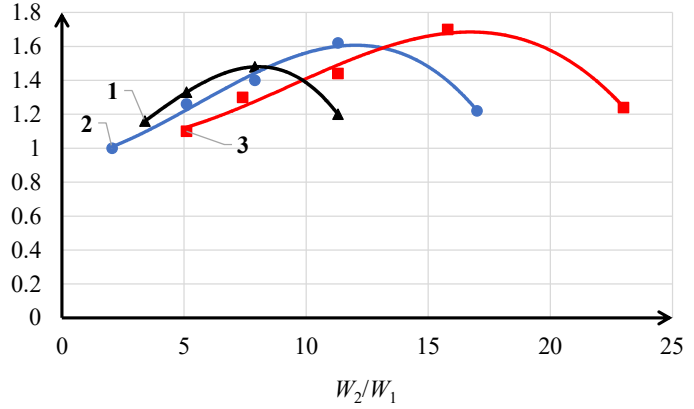


Fig. 2. Dependence of specific energy efficiency $\bar{\mu}$ on the ratio of energy in the second and first pulses W_2/W_1 at different values of the full introduced electrical energy W_τ : 1 – 400 J, 2 – 550 J, 3 – 750 J

The dependences

$$\bar{\mu} = f\left(\frac{W_2}{W_1}\right)$$

(Fig. 2) show that the magnitude of the energy ratio W_2/W_1 has a significant impact on the effectiveness of the exothermic chemical reaction under controlled energy input. The dependences

$$\bar{\mu} = f\left(\frac{W_2}{W_1}\right)$$

have, for each value W_τ , the maxima that shift upwards as full energy increases. The limitation of the growth in $\bar{\mu}$ with a further increase in the ratio W_2/W_1 is explained by that the energy of the first pulse should provide the conditions for the ignition of WEM, that is, each composition and volume of WEM is characterized by a minimum value of W_1 , the further reduction of which is unacceptable.

Analysis of the results obtained has shown that at different values of the total introduced electrical energy W_τ and different ratios of energies in the W_2/W_1 pulses, the thermal energy of the exothermal transformation of WEM increases within the range of 1.2 to 1.7 times. This increases the total energy of HECE without increasing the capacity of capacitor banks, but only by increasing the contribution of the energy released as a result of the exothermal reaction of WEM oxidation. Thus, the results of evaluation studies have shown that by changing the ratio between the magnitudes of electrical energy in pulses and, at constant capacity values, by changing the ratio between the magnitudes of charging voltages of sequentially supplied discharge pulses, it is possible to purposefully control the efficiency of WEM exothermic transformations.

The full VGC energy W_b , required to carry out the preset technological operations, is determined based on technological tests. The maximum energy of the exothermal transformation ΔW_{ch} is determined by the amount and composition of WEM. By using the dependences

$$\bar{\mu} = f\left(\frac{W_2}{W_1}\right),$$

derived in the course of our study, as well as the values of W_t and ΔW_{ch} , it is possible to determine the initial conditions for a control algorithm for a discharge-pulse installation, ensuring maximum exothermic efficiency energy conversion, from the following ratios:

$$W_\tau = \frac{W_t - \Delta W_{ch}}{\eta_t}; \quad W_\tau = W_1 + W_2; \quad W_{1,2} = \frac{C_{1,2} U_{1,2}^2}{2}. \quad (7)$$

After determining the ratios of energies W_2/W_1 , acceptable to ensure effective exothermic conversion, the initial conditions set are the voltages on capacitors U_1, U_2 , determined from ratios (7).

The next step in the synthesis of the control system is to construct an algorithm to send a signal that would enable a second discharge circuit in order to increase the time of the exothermic reaction under a self-sustaining mode. The second discharge circuit should be enabled at the moment when the pressure in the discharge channel reaches the maximum allowable value for the WEM used. In this case, it is important to use a reliable information signal when indirectly assessing the pressure in the discharge channel.

5. Studying the relationship between the HECE electrodynamic and hydrodynamic characteristics to determine information signals

Discharge-pulse installations are stochastic control objects [12], so the synthesis of control systems employs methods for averaging an information signal using different filters [16]. That makes it possible to improve the efficiency of a discharge-pulse treatment, on average, without providing maximum efficiency at each discharge, which, in the case of HECE, leads to significant losses of electricity and expensive exothermal mixtures.

Our study has shown a significant correlation between the effectiveness of exothermic energy conversion at a multi-pulse energy input into the HECE discharge channel on the time of subsequent pulses. In order to ensure fuller combustion of WEM and the maximum efficiency of exothermal energy conversion, it is necessary to send another discharge pulse at the moment when the pressure in the discharge channel reaches the minimum boundary value, required for the self-sustaining exothermal reaction $P_{\min}=23$ MPa. However, pressure in the discharge channel has a significant statistical variance and is not operationally defined; therefore, it cannot be used as an information signal to the control system. Given this, research is needed to determine the information signals that serve an indirect assessment of pressure in the discharge channel. Since the electrodynamic and hydrodynamic processes during HECE are stochastic, it is necessary to operate with the probabilistic indicators of random magnitudes that characterize these processes. These include the breakdown voltage $U(t)$, discharge current $I(t)$, electrical power $N(t)$, and pressure in a compression wave $P(t)$. There are a series of studies showing that these characteristics are subject to the normal distribution law [12]. In order to establish a link between the electrodynamic $U(t), I(t), N(t)$ and hydrodynamic $P(t)$ characteristics

of HECE, their correlation analysis was carried out. Since the magnitudes under study are distributed normally, the Pearson linear correlation coefficient r was used in the correlation analysis to assess the linear link, as well as the determination coefficient $R=r^2$ that characterizes the link density [17]. Correlational analysis was conducted for various combinations of the electrodynamic $U(t), I(t), N(t)$ and hydrodynamic $P(t)$ quantities. The results of r and R computation are given in Table 1.

Table 1

Results of correlation analysis

Combination of examined quantities	r	R
$P - I$	0.8602	0.7399
$P - U$	0.9458	0.8945
$P - N$	0.9679	0.9368

The resulting determination coefficients R between the electrodynamic and hydrodynamic characteristics confirm the existence of a dense enough link between them despite the stochasticity of these processes. Thus, the operationally determined electrodynamic characteristics $U(t), I(t), N(t)=U(t) I(t)$ could be used as information signals indirectly determining pressure in a discharge channel. The densest information link is observed between $P(t)$ and $N(t)$. The dependence between $P(t)$ and $N(t)$, experimentally established in advance for a particular process, could be stored in a control system database and used in the implementation of the control algorithm for a discharge-pulse installation. Alternatively, it can be promptly computed based on expressions (8), (9) suggested in [1]:

$$\frac{1}{\gamma - 1} \cdot \frac{d(P \cdot \pi \cdot a^2)}{dt} + P \cdot \frac{d(\pi \cdot a^2)}{dt} = \frac{N}{l}, \quad (8)$$

$$P = \frac{\rho}{2 \cdot \pi} \cdot \frac{d^2(\pi \cdot a^2)}{dt^2} \cdot \ln\left(\frac{l}{a}\right) - \frac{\rho}{8 \cdot \pi \cdot (\pi \cdot a^2)} \cdot \left(\frac{d(\pi \cdot a^2)}{dt}\right)^2, \quad (9)$$

where P is the pressure in a discharge channel, a is the radius of a discharge channel, l is the length of a discharge gap, γ is the effective adiabatic indicator, ρ is the density of an environment, $N(t)=U(t) I(t)$.

Using $N(t)=U(t) \cdot I(t)$ as an information signal makes it possible to derive a pressure assessment in the discharge channel $P(t)$ with a sufficient degree of accuracy for the timely delivery of the control signal.

6. Construction of a control algorithm for a multi-contour discharge-pulse installation that implements HECE

In the existing two-circuit PCGs [14], obtaining pressure waves of the required shape in a condensed medium implies that the next circuit is enabled in the preset time t_{set} relative to the beginning of the discharge of the preceding circuit. The high voltage discharge in a liquid is stochastic,

and the amount of pressure has a relatively large variance. Therefore, it is not possible to determine exactly a time point when the current pressure value in a discharge channel of the first pulse reaches the limit P_{min} . It is also impossible to determine in advance the required time interval t_{set} from the first pulse to the second pulse at the time when the pressure in the discharge channel reaches the value of P_{min} . Pressure during the pre-set time t_{set} may decrease, given the process stochasticity, to less than the maximum allowable value P_{min} over a period that is less than the preset $t < t_{set}$ (Fig. 3).

In this case, the exothermic reaction would stop until the second pulse is sent. There would be a loss of thermal energy of the exothermal transformation of WEM due to the premature extinction of the exothermal reaction and the lack of complete combustion of the mixture. In addition, the electrical energy of the second pulse would be wasted unproductively, the supply of which would not reach the goal of increasing the time of the exothermal reaction and fuller combustion of WEM. This leads to significant losses not only of energy but also exothermal mixtures.

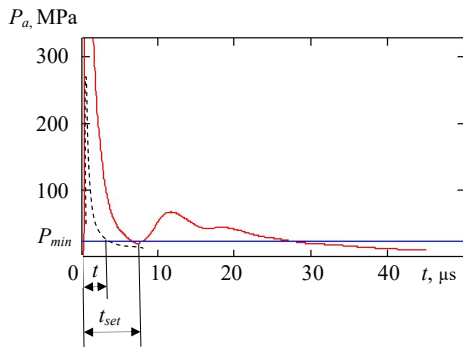


Fig. 3. Pressure in the plasma discharge channel $P_a(t)$ at a two-pulse input of electric energy

In order to ensure the efficient conversion of energy at each discharge, a discharge-pulse installation control algorithm is supplemented with an operation to operatively determine the time to send the second discharge pulse, depending on the pressure of the current implementation of the first impulse. The information signals used for the indirect assessment of pressure in a discharge channel are the electrodynamic characteristics of the discharge $N(t) = U(t) \cdot I(t)$, the correlation analysis of which had shown their dense informational link to the pressure in a discharge channel $P(t)$. Timely delivery of the second pulse at $P(t) = P_{min}$ in each HECE implementation would help avoid the extinction of the exothermal reaction at an accidental reduction of pressure to the limit minimum value between the delivery of the first and second discharge pulses. This would prolong the duration of exothermic reaction under a self-sustaining mode until the complete combustion of the exothermal mixture in each HECE implementation. This would help avoid losses and increase the amount of the released total HECE energy without increasing the cost of electricity.

The discharge-pulse installation for the implementation of the controlled high-voltage electrochemical explosion (HECE) is shown in Fig. 4.

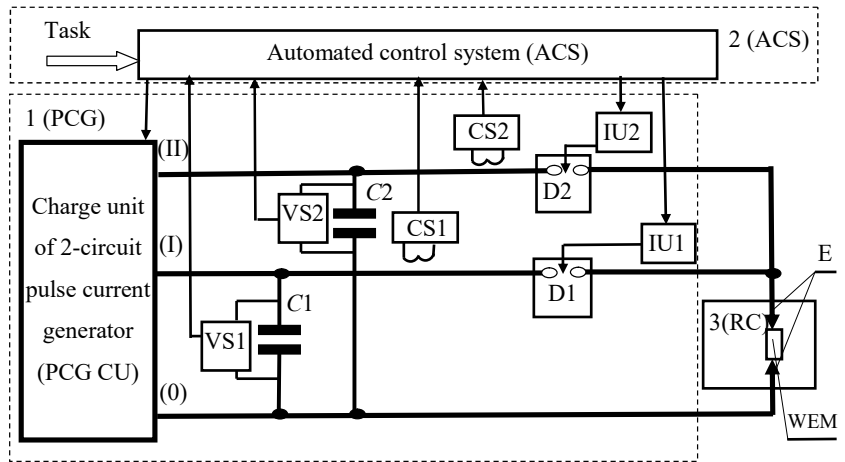


Fig. 4. Structural diagram of a discharge-pulse installation for implementing the controlled HECE

The installation includes a two-circuit pulse current generator 1 (PCG), automated control system 2 (ACS), and reaction chamber 3 (RC). The two-circuit pulse current generator includes a charging unit (PCG CU) with two terminals (I–0), (II–0) and two discharge contours connected to electrodes E located in the reaction chamber RC. The discharge circuits include, connected in parallel to the PCG CU terminals, capacitive energy drives (C1) and (C2) with parallelly-connected voltage sensors (VS1), (VS2). The high-voltage dischargers (D1) and (D2) are controlled by ignition units (IU 1), (IU 2). The current sensors (CS1) and (CS2) are inductively connected to discharge circuits. In the reaction chamber, in the liquid environment between two opposite electrodes, there is a water-filled exothermal mixture (WEM) of the selected mass and composition. The automated control system (ACS) receives information signals from voltage sensors (VS1,2) and current sensors (CS1,2); control signals are sent to the charging unit (PCG CU) and ignition units (IU1,2) of the dischargers (D1,2). The automated software control system implements a discharge-pulse installation control algorithm (Fig. 5).

The task to the control system comes from a database that stores the results of pre-conducted experimental studies and calculations that determine the necessary energies of the first and second discharge pulses W_1, W_2 providing the maximum efficiency of the release of WEM chemical energy. The magnitude of a pressure value limit in the discharge channel P_{min} , necessary to maintain the progress of the exothermal reaction under a self-sustaining mode in the aqueous solution of the oxidizer, is determined by the composition and mass of the exothermal mixture chosen based on the assigned technological regime. Next, one computes the magnitudes of charging voltages U_1, U_2 on the first and second capacitive energy storage units needed to provide the energy of the discharge pulses W_1 and W_2 . The derived values (U_1, U_2 , and P_{min}) are set by software as the initial conditions for the algorithm of the automated control system for the current implementation of HECE. Next, a signal is received from the automated control system to enable the charging unit of the pulse current generator in order to

charge the capacitive energy storage units (C_1, C_2). In the process of charging, the current values of voltages $U_1(t), U_2(t)$ on capacitive storage units are measured by voltage sensors (VS1, VS2). Information signals from the sensors are sent to the automated control system where the current voltage values $U_1(t), U_2(t)$ are compared to the preset values U_1, U_2 . The moment the voltages on the capacitors reach the specified values, the automated control system sends a signal to enable the ignition unit (IU1), which triggers a high-voltage discharger (D1) of the first discharge circuit and the electrodes receive the first discharge pulse. The process of a high-voltage electrochemical explosion of the exothermal mixture in the reaction chamber begins.

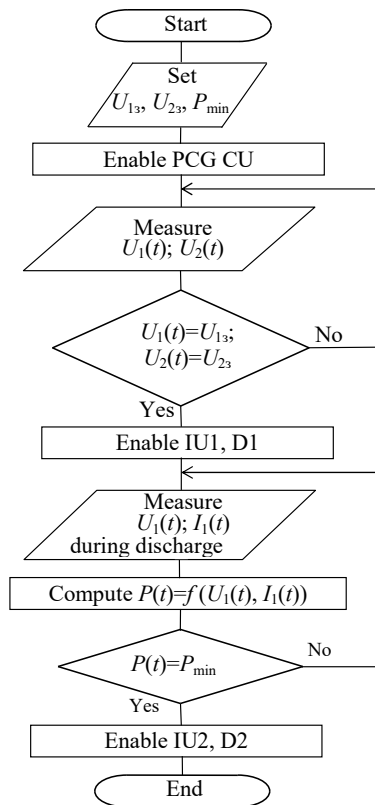


Fig. 5. Automated control system algorithm operation

In the process of implementing the first discharge pulse, voltage $U_1(t)$ is measured by a voltage sensor (VS1), discharge current $I_1(t)$ is measured by a current sensor (CS1), which is inductively connected to the first discharge circuit. The values of voltage $U_1(t)$ and discharge current $I_1(t)$ are sent to the control system. The software in the control system computes the current pressure value in the discharge channel of the first high-voltage pulse $P(t)$. One could also use a pre-compiled database to determine pressure based on electric characteristics. The current pressure value in the discharge channel $P(t)$ is compared to the set threshold minimum value P_{min} , required to maintain the exothermic reaction under a self-sustaining mode. When the current pressure value reaches the limit value $P(t)=P_{min}$, a signal is sent from the automated control system to enable the ignition unit (IU2). The high-voltage discharger (D2) is triggered and the discharge of the second discharge circuit begins. The electrodes receive a second discharge pulse, which increases the pressure in the reaction chamber and ensures further

exothermic reaction under a self-sustaining mode until the exothermal mixture burns completely.

The proposed algorithm to control a discharge-pulse installation would avoid the extinction of the exothermal reaction in case of an accidental, given the stochasticity of the process, reduction of pressure to the limit minimum value between the first and second discharge pulses. That would prolong the duration of its progress under a self-sustaining mode in each implementation until the exothermal mixture is completely burned. This could decrease the loss of electrical and chemical energy at each implementation of a high-voltage electrochemical explosion and increase the amount of the total energy released by HECE, without increasing the amount of electricity introduced; in addition, the loss of expensive exothermal mixtures would be prevented.

7. Discussion of results of synthesizing a control system for a discharge-pulse installation when implementing the electrochemical explosive technological regimes

In the design of a discharge-pulse installation control system that implements a high-voltage electrochemical explosion, it is important to define the initial conditions in order to set a task for control software for a particular technological mode. These include the choice of necessary energies and voltages of each discharge at a multi-pulse energy input into a discharge channel, ensuring maximum efficiency of the WEM exothermal transformations. Our experimental studies have established the dependences of relative specific energy efficiency on the ratio of energies of discharge pulses

$$\bar{\mu} = f\left(\frac{W_2}{W_1}\right)$$

for the range of energies from 400 J to 750 J, which are shown in Fig. 2. The resulting dependences demonstrate a maximum corresponding to the maximum chemical energy conversion efficiency during HECE. By using these dependences, the optimal ratio of energies in pulses W_2/W_1 is determined. At known values of energies W_t and ΔW_{ch} set by the requirements of the technology and the type of WEM, the ratios (7) are used to determine the initial conditions for the control algorithm of a discharge-pulse installation in the form of voltages on capacitors U_1, U_2 .

The range of energies in experimental studies was chosen based on the requirements of the oversized destruction technology. Under other discharge-pulse technologies, one may change the energy range, which would require additional research to determine the initial conditions for the control algorithm.

Statistical analysis of the HECE electrodynamic and hydrodynamic characteristics has confirmed significant stochasticity of processes in exothermal transformations under a mode of explosive combustion. The stochasticity of the processes does not make it possible to use the averaged values of information signals in the control system of a high-voltage electrochemical explosion. Ensuring the necessary technological regimes requires maintaining the preset pressure values in a discharge channel at each HECE implementation. Since pressure in a discharge channel has a significant statistical variance and is not operationally defined, it cannot be used as an information signal to the control system. In order to determine information signals, a correlation analysis was

performed on the relationship between current pressure in the discharge channel $P(t)$ and the discharge electrical characteristics; the results are given in Table 1. The resulting values for the correlation coefficients $r \geq 0.86$ have confirmed the possibility of using $U_1(t)$, $I_1(t)$, $N(t)$ as information signals for the discharge-pulse installation control system.

When applying analytical expressions (8), (9) to quickly determine the pressure in a discharge channel, it is necessary to ensure the hardware implementation of the proposed control algorithm to ensure sufficient performance speed of the system.

The constructed control algorithm for a discharge-pulse installation aimed at the implementation of a high-voltage electrochemical explosion (Fig. 5) avoids the extinction of the exothermal reaction at an accidental, given the process stochasticity, reduction in pressure to the low limit value. The algorithm implements operative control over electric characteristics in the discharge process, indirectly determining the pressure in a discharge channel, which is compared to the minimum allowable value. Achieving the minimum allowable pressure value is a signal to enable the next discharge contour of PCG, which ensures that the pressure is maintained at the required level for the exothermic reaction to proceed under a self-sustaining mode. Using the proposed control algorithm provides an increase in the duration of the exothermal reaction under a self-sustaining mode until the exothermal mixture is completely burned at each HECE implementation. This reduces the non-productive loss of the exothermal mixture, chemical and electrical energy at each implementation of a high-voltage electrochemical explosion, and increases the amount of total energy released, without increasing electricity costs. At the same time, technological requirements are fulfilled for the implementation of the predefined technological modes of operation of discharge-pulse installations at minimal energy costs.

Further improvement of control over discharge-pulse technologies involving a high-voltage electrochemical explosion implies the construction of an inverse model of HECE. Using an inverse model in control would make it possible, by using software, based on the required characteristics of technological influences, to determine the necessary parameters and operational modes of pulse current generators, in order to maintain them in the current implementations of HECE.

8. Conclusions

1. Based on the studies of a high-voltage electrochemical explosion as a control object, a significant influence of the

controlled input of electric energy into the discharge channel on the efficiency of exothermic energy conversion has been revealed. The dependence of the specific energy efficiency of the potential chemical energy of the exothermic mixture on the distribution of the total input electric energy among successive discharge pulses has been derived. This makes it possible, in line with the rules that we proposed, to determine the initial conditions of the control algorithm for the regime of a high-voltage electrochemical explosion during the discharge, which ensure the maximum efficiency of exothermic transformations.

2. Studies of the electrodynamic and hydrodynamic characteristics of a high-voltage electrochemical explosion and their statistical analysis have shown significant stochasticity of the processes during exothermic transformations under an explosive combustion mode. The stochasticity of the processes explains the ineffectiveness of using control systems that regulate only the initial conditions of an electrochemical explosion. The necessity of current control in the process of exothermic transformations has been justified in order to prevent a decrease in pressure in the discharge channel below the permissible value that maintains the exothermic reaction of explosive combustion. Correlation analysis of the relationship between the current pressure in the discharge channel and the electrical parameters of the discharge, characterizing the mode of input of electric energy, has shown the presence of a fairly dense informational relationship between them, despite the stochasticity of the processes. Thus, as information signals in the control system, indirectly determining the pressure in the discharge channel, the operationally determined electrical characteristics of the discharge can be used.

3. An algorithm has been developed to control a discharge-pulse installation that implements a high-voltage electrochemical explosion, which avoids the extinction of the exothermal reaction in case of an accidental, due to the process stochasticity, reduction in pressure to the extremely low value. Using the proposed control algorithm would prolong the duration of the exothermal reaction under a self-sustaining mode at each HECE implementation until the exothermal mixture is completely burned. This reduces the non-productive loss of the exothermal mixture, chemical and electrical energy at each implementation of a high-voltage electrochemical explosion, and increases the amount of total energy released, without increasing electricity costs.

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