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A calculation of basic thermophysical, gasodynamic and electropower parameters of electric explosion in the gas environment of a metallic conductor

Goal. *Obtainingand analysis of close analyticalrelationships for the engineering calculation of maximal temperature T_m and pressure P_m in a plasma channel, time t_{ex} of explosion of conductor, active resistance R_c and specific conductivity γ_p of plasma channel, thermal energy entered in conductor W_i and dissipated in the channel W_c and high speed of v_{mw} distribution of shock acoustic wave in the plasma products of electric explosion (EE) in gas of conductor under the action of large puls current (LPC).* ***Methodology.*** *Basis of thermophysics, thermodynamics, theoretical and applied electrical engineering, electrophysics based ontechnique of high-voltage and high pulse currents, basis of high-current electronics, theory of explosion and plasma, measuring technique and electromagnetic compatibility.* ***Results*** *. Close formulas are obtained for the analytical calculation of temperature T_m and pressures P_m in a plasma channel, time t_{ex} of explosion of conductor, active resistance R_c and specific conductivity γ_p of plasma channel, thermal energy entered in conductor W_i and dissipated e in the channel W_c speed v_{mw} of shock acoustic wave in «metallic plasma» at EE in gas of conductor, testing action of LPC in the discharge circuit of high-voltage generator of pulse currents (GPC) with the dissipated energy W_0. It isdemonstrated that at EE in atmospheric air of copper conductor of 110 mm length and radiusof 0.1 mm in the discharge circuit of GPC of the microsecond temporal range (I_{mc}≈−190 кА; t_{mc}≈42 μs; ω_c≈26.18·10^3 s^{-1}; W_0≈121.4 кJ) levels of temperature T_m, to time of t_{ex} explosion, pressures P_m and speeds ov_{mw} in the area of his explosion can get numeral values: T_m≈121.6·10^3 K, t_{ex}≈3.32 μs; P_m≈14.19·10^9 Pa and v_{mw}≈4693 m/s. The ways of receipt are formulated in the discharge circuit of PIC of «record» (most) values of temperature T_m, pressures P_m and speeds v_{mw}. It is shown that at EE in atmospheric air of the indicated short thin copper conductor the coefficient of the useful use η_c of electric energy W_0 of capacitor battery of GPC arrives at the numeral value of η_c≈(W_i+W_c)/W_0≈0.326 (32.6 %). Arising up in the plasma channel of discharge, initiated EE in gas of conductor, temperature T_m and pressure P_m, time t_{ex} of explosion of conductor, specific conductivity γ_p of channel, thermal energy W_c and speed v_{mw} of shock acoustic wave dissipated in a channel in «metallic plasma» can be certain experimental by a way on results decoding of oscillograms of discharge current $i_c(t)$ and high-voltage of $u_c(t)$ on conductor in the circuit of GPC. A formula is resulted for the close calculation of critical integral of current J_k at EE in gas of conductor from different metals. Executed on powerful GPC high-current experiments were confirmed by substantive provisions offered approach near the analytical calculation of basic parameters of electro-explosive process for the probed conductor.* ***Originality.*** *Offered the engineeringapproach is scientifically grounded for the analytical calculation of the indicated thermophysical, gasodynamic and electroenergy parameters T_m, P_m, t_{ex}, R_c, γ_p, W_i, W_c and v_{mw} at EE in gas of metallic conductor, connected to the discharge circuit of GPC.* ***Practical value.*** *Application in electrophysics practice of the offered engineering approach for calculation in the ciccuit of GPC of basic parameters of electro-explosive process will allow to facilitate labour of workers of scientific laboratories and promote efficiency of work of technicians and engineers during practical realization by them of different electro-explosive technologies.* References 41, tables 1, figures 2.

Key words: **high pulse current, electric explosion of conductor, temperature, pressure, time and energy of explosion, active resistance and specific conductivity of plasma channel, energy entered in conductor and dissipated in plasma channel, speed of shock wave at the explosion of conductor.**

Надані результати інженерного розрахунку температури T_m і тиску P_m в плазмовому каналі, часу t_{ex} вибуху провідника, активного опору R_c і питомої електропровідності γ_p плазми каналу, теплової енергії, що вводиться в провідник W_i та виділяється в каналі W_c, і швидкості v_{mw} розповсюдження ударної акустичної хвилі в «металевій плазмі», що утворюється при електричному вибуху (ЕВ) в газовому середовищі металевого провідника під дією великого імпульсного струму. Показано, що при ЕВ в атмосферному повітрі короткого тонкого мідного провідника в розрядному колі високовольтного генератора імпульсних струмів (ГІС) мікросекундного часового діапазону рівні температури T_m, тиску P_m і швидкості v_{mw} в зоні його вибуху можуть досягати чисельних значень T_m≈121,6·10^3 К, P_m≈14,19·10^9 Па і v_{mw}≈4693 м/с. Сформульовані електротехнічні шляхи отримання в розрядному колі ГІС з металевим провідником, який вибухає у газовому середовищі, найбільших значень температури T_m, тиску P_m і швидкості v_{mw}. Бібл. 41, табл. 1, рис. 2.

Ключові слова: **великий імпульсний струм, електричний вибух провідника, температура, тиск, час та енергія вибуху, активний опір і питома електропровідність плазмового каналу, енергія, що вводиться в провідник та виділяється в плазмовому каналі, швидкість ударної хвилі при вибуху провідника.**

State and relevance of the problem. Electric explosion (EE) of metal conductors with cross-section S_0 and length l_0 in vacuum, gas and liquid media under the action of high pulse current (HPC) flowing through them of various amplitude-temporal parameters (ATP) has found quite wide practical application both in *scientific* (for example, in the study of the mechanisms of phase transitions of matter [1–5], the phenomena of mass, momentum and energy transfer in extreme conditions, including in the critical modes of nuclear explosions [6, 7], the production of soft X-ray radiation for controlled thermonuclear fusion [8], research of the processes of optical pumping of gas lasers and active media for quantum generators based on metal vapors [9], etc.), as well as *technological* ones (for example, when sputtering thin coatings for microelectronics [10, 11], obtaining highly dispersed conductive powders [12–16], creation fast-acting electric explosive circuit breakers for high-current circuits of high-voltage generators with powerful capacitors and inductive energy storage [17], production of dense high-temperature plasma [18], high-speed power processing and deformation by shock loads of various materials (parts) [19, 20], conducting certification tests of aviation and rocket-space equipment for electromagnetic compatibility and resistance to effects of lightning (first of all, in electrical circuits for introducing current and electromagnetic energy into objects under test) [21, 22], etc.) purposes. When studying the complex process of EE of metal conductors and the practical implementation of electro-explosive technologies, specialists in the course of their work use both more accurate computational numerical methods of studying the phenomenon of EE of metal conductors in gases and liquids [4, 5, 7, 8] and less accurate engineering analytical methods and models for calculating thermophysical, gas-, electric-, and magnetohydrodynamic processes in continuous media during the occurrence of the specified electrophysical phenomenon [9–15, 23–26]. Here, the known calculation methods and the approximate calculation expressions obtained with their help for the analytical study of the indicated phenomenon of EE of a metal conductor have a significant general drawback: they do not allow providing a comprehensive approach to the simultaneous calculation of the main thermophysical, gas-dynamic, and electrical-power parameters of the EE process of a conductor.

In addition, when establishing the necessary modes of operation of the high-voltage pulse technology (HPT) used in electro-explosive technologies and predicting the effects of the electrophysical effects created by EE of conductors on the processed materials, parts and objects, the engineering and technical personnel needs simplified and convenient in practical application approximate analytical relationships for the calculated assessment of the discharge of powerful capacitive energy storage devices of HPT in the EE of conductors and the plasma channel initiated by it: the maximum levels of temperature T_m, pressure P_m, time t_{ex} of the explosion, active resistance R_c and specific electrical conductivity γ_p of the plasma channel, energy W_i introduced into conductor, and energy W_c released in the plasma channel and the speed v_{mw} of the shock wave in the plasma products of the discharge channel in the gas (liquid). In this regard, obtaining approximate analytical ratios for the engineering complex calculation of the specified parameters T_m, P_m, t_{ex}, R_c, γ_p, W_i, W_c and v_{mw}, characteristic of EE of metallic conductors, is an actual applied scientific and technical problem in the world.

The goal of the paper is to obtain and analyze approximate analytical relationships for the engineering complex calculation of the maximum values of temperature T_m and pressure P_m in the plasma channel, time t_{ex} of the conductor explosion, active resistance R_c and specific electrical conductivity γ_p of the plasma channel, energy W_i introduced into the conductor, and thermal energy W_c released in the plasma channel and the maximum velocity v_{mw} of propagation of the shock acoustic wave in plasma products of EE in the conductor gas under the influence of HPC.

1. Problem deinition. Consider a thin metallic conductor of cylindrical shape located in a gaseous environment under normal atmospheric conditions, along which in its longitudinal direction from a high-voltage pulsed energy source (for example, from a powerful low-inductance capacitor battery) a HPC flows with ATP sufficient to reach in the conductive structure of the conductor with length l_0 and radius r_0 with cross-section $S_0=\pi r_0^2$ the numerical value of the current integral J_k, which is critical for the conductor under study. By the current integral J_k we will understand the well-known integral involving the square of the current density, which is determined by the expression accepted in the works [3, 24, 27] in time t: $J_k = \int_0^{t_{ex}} \delta_k^2(t)dt$, where $\delta_k(t)$ is the critical pulse current density in the conductor that causes sublimation of the metal and overheating of his steam; t_{ex} is the time of onset of EE and the beginning of the spatial spread of the sublimated metal of the conductor and its vapor.

Let us dwell on the use of low-impedance generators of pulse currents (GPC) for EE of the investigated conductor, whose ATP of the discharge current $i_c(t)$ changes in time t according to the law of a decaying sinusoid [9, 10, 19]. We believe that the pulse current density $\delta_k(t)$ is characterized by an almost uniform distribution over the cross-section S_0 of the accepted thin conductor, because for it the thickness of the current skin layer can significantly exceed its radius r_0. We assume that in the pre-explosion state of the sublimated body of a thin conductor, its maximum values of temperature T_m and pressure P_m are uniformly distributed over the cross section of the formed dense «metal plasma» [9, 10], which is located before its high-speed expansion (flight) within the critical section $S_{0c}>S_0$ [20]. We believe that the specified «metal plasma» of the conductor is, in the first approximation, a superheated metal vapor, which refers to highly unsaturated vapors (real gases) with temperature T_m much higher than its boiling point at temperature T_b and high pressure P_m. In this connection, the gas laws known in classical physics can be applied to the «metal plasma» formed after the sublimation of the metal with its highly superheated vapor and their subsequent high-speed expansion (expansion at EE) in the surrounding gas in the considered approximation [28]. We believe that the maximum temperature T_m in the indicated equilibrium «metal plasma», for which the electron temperature practically does not differ from the temperature of its ions and atoms, is determined by the electron temperature, which depends on the amplitude of the longitudinal heat flux density g_m in the cross-section S_0 of the conductor. In the analyzed case, g_m will be determined by the amplitude δ_{mc} of the current density in the conductor and the near-electrode voltage drop U_e in the edge zones of the sublimated body of the conductor [24]. The gas surrounding the investigated conductor with the initial temperature T_a of its material, as well as the «metallic plasma» formed during the EE of its strongly overheated body, are taken as ideal gas environments that correspond to the classical concept of «ideal gas» [10, 28].

Taking into account the normal atmospheric conditions before the EE of the conductor under study, one can use the following basic characteristics of the surrounding source gas medium for the conductor [28]: the gas pressure is $P_a\approx1.013\cdot10^5$ Pa; absolute gas temperature is $T_a\approx273.15$ K; the molar volume of the gas is $V_{Ma}\approx22.41\cdot10^{-3}$ m^3/mol. Taking into account the rapid explosive nature of the thermophysical and gas-dynamic processes occurring during EE of the metal of the conductor (when their duration in time t is up to 0.5 ms

[10]), and the insignificant removal of heat from the EE zone to the radial expansion of the «metal plasma» of the conductor under study [9] we will limit ourselves to the consideration of the flow in the conditions of almost complete thermal insulation of the conductor of the adiabatic process in the local zone around the exploding conductor, with the HPC flowing along it, in which case heat exchange processes between the conductor under study and the gas will not occur in the volume of EE occupied by the cylindrical zone, which surrounds it.

It is necessary, under the assumed assumptions, to obtain calculated relations for estimating the temperature T_m and pressure P_m in the plasma, the time t_{ex} of the conductor explosion, the active resistance R_c and the specific electrical conductivity γ_p of the plasma channel, the energy W_i introduced into the conductor, and the energy W_c released in plasma channel, and the velocity v_{mw} of shock wave propagation in the plasma products of EE of the conductor metal in the gas medium under the influence of HPC.

2. Approximate calculation of the maximum temperature *T*$_m$ in the plasma channel of the discharge at the gas EE of the conductor. For the engineering calculation of the maximum temperature T_m in the «metal plasma» at EE in the gas environment of the investigated metal conductor with a cross-section S_0 under the action of HPC flowing through it, the following thermophysical relationship can be used [24]:

$$T_m \approx \left[\pi\sigma_c^{-1} U_e (2J_k S_0^{-1} \,|\, I_{mc} \,|\, \omega_c)^{1/3}\right]^{1/4}, \qquad (1)$$

where σ_c=5.67·10^{-8} W·(m^2·K^4)$^{-1}$ is the Stefan-Boltzmann constant [28]; U_e is the near-electrode voltage drop in the edge zones of the sublimated conductor, which numerically does not exceed 10 V for base metals used in HPC technology [29]; I_{mc} is the first amplitude of the discharge current $i_c(t)$ in the electrical circuit of the HPC generator, which changes in time t with the circular frequency ω_c and is determined by the electrical parameters of the discharge circuit of the generator; J_k is the critical value of the current integral for a conductor metal with cross-section S_0 [27].

Calculation estimation based on (1) of the value of the highest temperature T_m in the «metal plasma» at EE in air of a short thin copper conductor ($l_0 \approx$ 110 mm; $r_0 \approx$ 0.1 mm; $S_0 \approx$ 3.14·10^{-8} m^2; $U_e \approx$ 10 V [29]; $J_k \approx$ 1.95·10^{17} A^2·s·m^{-4} [27]) under the influence of HPC of the microsecond time range ($I_{mc}\approx-$190 kA; $\omega_c\approx$26.18·10^3 s^{-1}), experimentally obtained in the conditions of a high-voltage electrophysical laboratory using a GPC with capacitance of $C_0\approx$333 μF and electric energy $W_0\approx$121.4 kJ stored in its powerful capacitor battery (at its charging voltage $U_{c0}\approx-$27 kV) [30] shows that the temperature in this case, it will be approximately equal to $T_m \approx$121.6·10^3 K. It should be noted that verification by the authors of this temperature by other methods (for example, with the help of appropriate experimental devices) is currently impossible in the conditions of a high-voltage electrophysical laboratory. Let us point out that in [18] at EE in a vacuum of a short thin lithium conductor ($l_0 \approx$ 10 mm; $r_0 \approx$ 63.5 μm; $S_0\approx$1.27·10^{-8} m^2; $J_k\approx$0.61·10^{17} A^2·s·m^{-4} [31]; $U_e\approx$5 V [29]), which is connected in the discharge circuit of a high-voltage GPC ($I_{mc}\approx-$45 kA; $\omega_c\approx$1.25·10^6 s^{-1}) with nominal electrical energy $W_0\approx$100 kJ, which is stored in its capacitor bank, the maximum temperature $T_m \approx$113.5·10^3 K was experimentally recorded in the plasma products of EE of this conductor with GPC of the microsecond time range with high frequency of oscillation. The use of (1) to estimate the temperature level T_m in the test case specified in [18] indicates that the numerical value of the temperature will be equal to $T_m \approx$122.4·10^3 K. As we can see, the approximate results of the numerical calculation by (1) of the maximum temperature T_m in the «metal plasma» during EE of the specified lithium conductor indicate that the calculated data indicated above agree well with the experimental data that were given in [18] and obtained by other EE research methods.

It is interesting to note the fact that during our experimental study [30] of EE in atmospheric air of a thin round copper conductor ($l_0\approx$110 mm; $r_0\approx$0.1 mm), it reached the amplitude of the critical pulse current density δ_{mk}, which is calculated by the following approximate expression:

$$\delta_{mk} \approx (2J_k S_0^{-1} \,|\, I_{mc} \,|\, \omega_c)^{1/3}. \qquad (2)$$

From (2) at $I_{mc}\approx-$190·10^3 A and $\omega_c\approx$26.18·10^3 s^{-1} [30] for the considered thin copper conductor ($l_0 \approx$ 110 mm; $r_0 \approx$ 0.1 mm; $S_0 \approx$ 3.14·10^{-8} m^2; $J_k \approx$ 1.95·10^{17} A^2·s·m^{-4} [27]) we find that the amplitude of the critical density δ_{mk} of the sinusoidal current in it will take a numerical value of about $\delta_{mk} \approx$3.95·10^{11} A/m^2. According to the data of the magnetohydrodynamic calculation of EE from [32, 33], this level of current density δ_{mk} will correspond to the high-temperature mode of flow of EE of the conductor.

Calculation data obtained in [32] on the basis of numerical magnetohydrodynamic modeling of the electroexplosive process for metal in vacuum (water) indicate that at high-temperature EE of an aluminum conductor ($r_0\approx$0.1 mm; $S_0\approx$3.14·10^{-2} mm^2; $\delta_{mk}\approx$10^{12} A/m^2) regardless of the properties of the environment in which its explosion occurs, the temperature of the «metallic plasma» formed from it reaches a level of up to 8 eV, which corresponds to an absolute temperature of 92.8·10^3 K [27]. The calculated estimation according to the proposed formula (1) for the maximum temperature T_m of the created plasma in the air discharge channel of a powerful high-voltage GPC ($I_{mc} \approx -$190 kA; $\omega_c\approx$26.18·10^3 s^{-1}) at EE of the specified aluminum conductor ($U_e\approx$8 V [29]; $J_k\approx$0.82·10^{17} A^2·s·m^{-4} [31]) shows that in this case $T_m\approx$107,1·10^3 K. This calculated level of the temperature T_m of the «metal plasma» from that specified in [32] ($T_m \approx$92.8·10^3 K) differs by almost 13 %. Of course, such a comparison is not entirely correct (here, the initial data for EE were taken by us from different studies). It should not be forgotten that there are very few relevant research results for T_m in the field of EE of conductors. Despite this, for the case under consideration, we can say that formula (1) for T_m works.

It follows from (1) that in order to achieve «record» (highest) levels of absolute temperature T_m in the local zone of EE in a gas environment (vacuum) during the explosion under study, it is necessary to use extremely thin conductors with the maximum possible value of the critical current integral J_k for them, as well as to use «fast» GPC generators, which are capable of forming on the exploding conductor the maximum possible amplitudes I_{mc} of the first half-waves of the GPC discharge current of nanosecond duration.

Let us point out that experimental numerical values of the critical current integral J_k were given in [27] only for aluminum and copper conductors. Of undoubted practical interest are the calculated data for the current integral J_k for other conductive materials used in HPT and HPC technology for EE of thin metals, when the critical density δ_k of current $i_c(t)$ in them is at least 10^{11} A/m^2.

3. Approximate calculation of the critical current integral J_k at the gas EE of the conductor. Calculation of the numerical value of the critical current integral J_k at EE in the gas of the thin conductor under study can be performed according to the formula [31]:

$$J_k \approx \gamma_{cb} N_0 W_f , \tag{3}$$

where γ_{cb} is the specific electrical conductivity of the conductor metal at its boiling temperature T_b (during its sublimation) $(\Omega\cdot\text{m})^{-1}$; N_0 is the concentration (density) of atoms (positive ions) in the crystal lattice of the metal of the conductor before the action of HPC on it (m^{-3}); W_f is the thermodynamic work of the release of free electrons from the metal of the conductor before the flow of HPC begins (J).

Equation (3) is based on the results of a theoretical study by the authors of the phenomenon of anomalous thermoelectronic emission of free electrons from the material of the conductor, which during EE is destroyed and loses its metallic conductivity under the action of HPC in the high-current discharge circuit of a powerful high-voltage GPC [31].

Let us point out that the value of γ_{cb} for the main conductor materials can be determined according to the experimentally obtained empirical relations for them given in [34]. The numerical value of the initial concentration (density) of atoms N_0 in the electrically explosive solid metal of the conductor under study with its initial density d_c can be found using the following formula [28]:

$$N_0 = d_c (M_{a0} \cdot 1{,}6606 \cdot 10^{-27})^{-1} , \tag{4}$$

where M_{a0} is the atomic mass of the metal of the conductor of the density d_c.

The value of the thermodynamic work of output W_f of free electrons from the metal in (3) can be found from [35], where experimental emission data for most metals used in experimental physics, high-current HPT, and HPC technology were given.

Table 1 summarizes the numerical values of the parameters γ_{cb}, N_0, W_f and J_k determined according to (3), (4) taking into account [28, 34–36] for a number of metals used in the study of EE of thin conductors in gaseous media and in the circuits of electrotechnical devices of electroexplosive technologies [9, 10, 20]. From the data in Table 1, it can be seen that the approximate calculated value of the critical current integral J_k for a thin copper conductor ($J_k \approx 1.71\cdot10^{17}$ A^2·s·m^{-4}) obtained under the accepted assumptions and normal atmospheric conditions according to (3) is approximately 12 % less than its corresponding experimental value in air ($J_k \approx 1.95\cdot10^{17}$ A^2·s·m^{-4}) at room temperature ($T_a \approx 293.15$ K) [27]. One of the reasons for this may be that the calculated relation (3) does not take into account the influence on the specified thermophysical parameters γ_{cb}, N_0 and W_f of the rapid overheating of the sublimated metal of the conductor (its vapor), which accompanies the high-temperature EE mode in the gas of the conductor placed in the circuit of a powerful high-voltage GPC.

Table 1
Numerical values of parameters γ_{cb}, N_0, W_f, J_k [27, 31, 34, 35]

Metal	Parameter values				
	γ_{cb}, 10^6 $(\Omega\cdot\text{m})^{-1}$ (by [34])	N_0, 10^{28} m^{-3} (by (4))	W_f, 10^{-19} J (by [35])	J_k, 10^{17} A^2· s·m^{-4} (by (3))	J_k, 10^{17} A^2· s·m^{-4} (by [27])
Copper	2,87	8,43	7,05	1,71	1,95
Aluminum	1,99	6,05	6,81	0,82	1,09
Nickel	0,97	9,10	7,21	0,63	–
Molybdenum	0,65	6,40	6,89	0,28	–
Tungsten	0,50	6,26	7,27	0,23	–

On the other hand, the experimental methods of quantitative determination of the value of the integral J_k are also not without shortcomings and the errors introduced by them in the determination of J_k [32]. The parameters N_0 and W_f in (3) clearly do not depend on the value of γ_{cb}. Therefore, the calculated data of Table 1 for γ_{cb} and J_k clearly demonstrate to us that the smaller the value of the specific electrical conductivity γ_{cb} (the greater the specific electrical resistance of the conductor material) used for EE in the metal in the gas, the smaller the value of the critical current integral J_k necessary for the occurrence of this electrophysical phenomenon will be and accordingly, based on the numerical magnetohydrodynamic model of EE in vacuum (water) of a thin aluminum conductor investigated in [32], the integral of the specific action $h(t)$ of the GPC pulse discharge current with its density $\delta_k(t)$ in this conductor. This, taking into account the theoretical results of works [5, 32], indicates the possibility of using formula (3) for the integral J_k.

4. Approximate calculation of the time t_{ex} of thermal explosion of theconductor in the gas. The calculation estimation of the time t_{ex} of EE in the gas of the investigated metal conductor, which corresponds to the moment of its maximum resistance and peak-like increase in the electric voltage $u_c(t)$, can be carried out according to the expression [30]:

$$t_{ex} \approx 4\left[(2J_k S_0^2)/(\omega_c^2\, |I_{mc}|^2)\right]^{1/3}/3 . \tag{5}$$

From (5) for a thin round copper conductor ($l_0 \approx 110$ mm; $r_0 \approx 0.1$ mm; $S_0 \approx 3.14\cdot10^{-8}$ m^2; $J_k \approx 1.95\cdot10^{17}$ A^2·s·m^{-4} [27]) with the HPC parameters used by us in the discharge circuit of a powerful GPC ($I_{mc} \approx -190$ kA; $\omega_c \approx 26.18\cdot10^3$ s^{-1}), we obtain that $t_{ex} \approx 3.32$ μs. Based on (5), for a given conductor material (a given numerical value of the critical integral J_k), to decrease (increase) the t_{ex} parameter, it is necessary to: decrease (increase) the section S_0 of the conductor and increase (decrease) the circular frequency ω_c of oscillations and the first amplitude I_{mc} of the discharge current in the GPC circuit.

5. Approximate calculation of the maximum pressure P_m in the plasma channel of the discharge at the gas EE of the conductor. Using the well-known equation of state of an ideal gas [28], taking into account the accepted assumptions in a rough approximation that does not take into account the pressure of electrons, for the maximum pressure P_m in the cylindrical zone of the «metal plasma» at EE in the gas environment of a thin metal conductor, we have:

$$P_m \approx \rho_p R_m M_p^{-1} T_m\,, \qquad (6)$$

where R_m =8.314 J/(mol·K) is the universal gas constant [28]; M_p is the molar mass (in kg/mol) of superheated metal vapor with density ρ_p, which occurs before its radial expansion within the critical section $S_{0c}\approx 10S_0$ of the sublimated body of the conductor under study with the initial density d_c of its solid metal.

For the case under consideration, $\rho_p\approx 0.1d_c$ [20, 23]. Then, taking into account (1) and (6), for the pressure amplitude P_m in the plasma cylindrical channel, which is initiated by EE in the conductor gas, in the final form we obtain the following approximate calculation ratio:

$$P_m \approx 0{,}1 d_c R_m M_p^{-1}\left[\pi\sigma_c^{-1} U_e (2J_k S_0^{-1}\,|\,I_{mc}\,|\,\omega_c)^{1/3}\right]^{1/4}. \qquad (7)$$

Note that expression (7) corresponds to the approximate calculation model of EE of a metal conductor in gas under conditions where the «metal plasma» within the section of the conductor S_{0c} can be considered as an ideal gas.

From (7) at EE in a gas (for example, in air) of a thin copper conductor ($S_0\approx 3.14\cdot 10^{-8}$ m^2; $d_c\approx 8920$ kg/m^3 [28]; $M_p\approx 63.55\cdot 10^{-3}$ kg/mol [28]; R_m=8.314 J/(mol·K) [28]; $U_e\approx 10$ V [29]; $J_k\approx 1.95\cdot 10^{17}$ A^2·s·m^{-4} [27]), connected in a high-current discharge circuit of the indicated high-voltage GPC ($I_{mc}\approx -190$ kA; $\omega_c\approx 26.18\cdot 10^3$ s^{-1} [30]), we find that the maximum gas-dynamic pressure P_m arising in the local zone of its explosion in the «metal plasma» will be equal to $P_m\approx 14.19\cdot 10^9$ Pa (up to $14\cdot 10^4$ atm [28]). This calculated result for P_m indicates that with EE in the gas environment of thin metal conductors, gas-dynamic pressure of large values can arise in their cross-section S_0. It can be seen from (6), (7) that the pressure value P_m is directly proportional to the temperature level T_m, which is reached in the EE zone of the conductor, and practically does not depend on the parameters of the gas environment in which the EE of the investigated metal conductor takes place. In this regard, in order to achieve «record» (highest) levels of maximum pressure P_m in «metal plasma» at EE in the gas of a thin metal conductor, it is necessary to ensure that the maximum temperature T_m of this plasma is obtained in the zone of this explosion. For this, it is necessary to use the smallest cross-sections S_0 of short metal conductors, as well as «fast» HPC generators, which reproduce in GPC circuits the largest amplitudes I_{mc} and circular frequencies ω_c of their discharge current $i_c(t)$.

6. Approximate calculation of the sublimation energy W_s of the metal at the gas EE of the conductor. The sublimation energy W_s of the conductor substance will be equal to the sum of the energies of its heating Q_{h1} from the initial temperature T_a to the melting temperature T_w, heating Q_{h2} from the melting temperature T_w to the boiling temperature T_b, melting Q_f and vaporization Q_v [28]. For the heating energy Q_{h1}, the formula will be valid:

$$Q_{h1} \approx c_h m_c (T_w - T_a)\,, \qquad (8)$$

where c_h is the specific heat capacity (at constant volume) of the material of the investigated metal conductor of the initial mass m_c=$l_0S_0d_c$ [28].

We have the following expression for the heating energy Q_{h2}:

$$Q_{h2} \approx c_h m_c (T_b - T_w)\,. \qquad (9)$$

For the heat of melting of the metal of the conductor Q_f, the following relation will be valid [28]:

$$Q_f = q_f m_c\,, \qquad (10)$$

where q_f is the the specific heat of melting of the material of the cylindrical conductor with its initial absolute temperature $T_a\approx 273.15$ K and the mass m_c=$l_0S_0d_c$.

For the heat of vaporization Q_v of the metal of the conductor under study, the expression can be written [28]:

$$Q_v = q_v m_c\,, \qquad (11)$$

where q_v is the specific heat of vaporization of the material of a cylindrical conductor of the mass m_c=$l_0S_0d_c$ at its initial absolute temperature $T_a\approx 273.15$ K.

From (8)–(11) for the analyzed short thin cylindrical copper conductor ($l_0\approx 110$ mm; $r_0\approx 0.1$ mm; $S_0\approx 3.14\cdot 10^{-8}$ m^2; $d_c\approx 8920$ kg/m^3; $m_c\approx 0.308\cdot 10^{-4}$ kg; $T_a\approx 273.15$ K; $T_w\approx 1356.15$ K; $T_b\approx 2863.15$ K; $c_h\approx 385$ J/(kg·K); $q_f\approx 2.05\cdot 10^5$ J/kg; $q_v\approx 4.79\cdot 10^6$ J/kg [28]), later used when we conducted high-current experiments ($I_{mc}\approx -190$ kA; $\omega_c\approx 26.18\cdot 10^3$ s^{-1} [30]) on a powerful high-voltage GPC according to its air EE, we find that $W_s\approx (Q_{h1}+Q_{h2}+Q_f+Q_v)\approx 197.4$ J. Note that according to experimental data from [9, 37], the specific sublimation energy q_s for copper is numerically equal to approximately $q_s\approx 4.68\cdot 10^{10}$ J/m^3. In this regard, the refined value of the sublimation energy W_s for the thin copper conductor ($V_0\approx l_0S_0\approx 34.5\cdot 10^{-10}$ m^3) will be equal to about $W_s\approx 161.5$ J. It can be seen that the calculated and experimental values for the sublimation energy W_s of the indicated copper conductor under study ($l_0\approx 110$ mm; $r_0\approx 0.1$ mm) differ from each other with an error of no more than 18 %. Therefore, we can say that the calculated estimation of the sublimation energy W_s of the copper conductor metal is valid.

7. Approximate calculation of the overheating energy W_{sh} of the sublimated metal at the gas EV of the conductor. The energy of strong overheating W_{sh} of the metal vapor in the discharge plasma channel, which was formed from the sublimated one by discharge current $i_c(t)$, which flows through the conductor in the GPC circuit, its metal and is part of the «metal plasma» of this cylindrical channel, can be estimated by the following expression:

$$W_{sh} \approx (T_m - T_b) c_{vs} m_c\,, \qquad (12)$$

where c_{vs} is the specific heat capacity (at constant volume) of the metal vapor of the sublimated body of the conductor with mass equal to the initial mass m_c=$l_0S_0d_c$ of the metal conductor exploding in a gas environment.

From (12) taking into account the accepted assumptions for the investigated thin copper cylindrical conductor ($l_0\approx 110$ mm; $r_0\approx 0.1$ mm; $S_0\approx 3.14\cdot 10^{-8}$ m^2;

d_c≈8920 kg/m^3; m_c≈0.308·10^{-4} kg; T_b≈2863.15 K; c_{vs}≈0.385·10^3 J/(kg·K) [28]; J_k≈1.95·10^{17} A^2·s·m^{-4} [27]; U_e≈10 V [29]) at high-current discharge on the conductor of a powerful high-voltage GPC (I_{mc}≈−190 kA; ω_c≈26.18·10^3 s^{-1}; T_m≈121.6·10^3 K [30]), which explodes electrically in air, we obtain that the sought overheating energy W_{sh} will take a numerical value of about W_{sh} ≈1407.9 J. As can be seen, the calculated value of the overheating energy W_{sh} of the sublimated conductor metal and, accordingly, the metal vapor formed from it, is approximately seven times greater than the calculated sublimation energy W_s≈197 .4 J of copper conductor metal: W_{sh}/W_s≈7.1. According to the theoretical data from [32], obtained on the basis of a complex numerical magnetohydrodynamic model of EE of the metal with current, this indicator for high-temperature EE (T_m≈92.8·10^3 K; δ_{mk}≈10^{12} A/m^2) in vacuum (water) of thin aluminum of the conductor is also approximately W_{sh}/W_s≈7 (without taking into account the energy released during EE, which is introduced into the metal structure of this conductor). In this regard, the approximate results of the estimated energy W_{sh} given by us are valid.

8. Approximate calculation of the energy of the thermal explosion W_{ex} in the gas of the superheated vapor of the metal conductor. Taking into account the accepted assumptions, in the approximate calculation of the energy of the thermal explosion W_{ex} in the gas medium of the highly superheated metal vapor of the metal conductor under study, we use the formulas known in thermodynamics for the work done by the gas during its adiabatic expansion [28]. Using the mode of adiabatic expansion of a highly superheated metal vapor with a gas-dynamic pressure P_m of a sublimated body of a metal conductor with mass of m_c≈$l_0S_0d_c$, in the considered approximation for the work W_{ex} produced by this vapor and, accordingly, the thermal energy released in the surrounding gas by the «metal plasma» that rapidly expands around the conductor in a gaseous medium, the following gas-dynamic relation can be written [28]:

$$W_{ex} \approx l_0 S_0 d_c R_m (M_a + M_p)^{-1} (T_m - T_{ap})(\beta_p - 1)^{-1}, \quad (13)$$

where M_a, M_p are, respectively, the molar mass (in kg/mol) of the initial gas around the conductor (T_a ≈273.15 K) and the metal vapor formed in this gas from its sublimated metal; β_p is the adiabatic index for «metal plasma» in the EE zone; T_{ap} is the temperature that is established in the EE zone of the conductor after the expansion of its highly superheated metal vapor in the gas.

In the general case T_{ap}≠T_a for further calculation estimations according to (13) of the largest values of the thermal explosion energy W_{ex} at EE of a metallic conductor in a gas (for example, in air), we limit ourselves to the particular thermophysical case when T_{ap}≈T_a.

It can be seen from (13) that the thermal explosion energy W_{ex} of the highly overheated metal of the conductor is determined mainly by the mass m_c=$l_0S_0d_c$ of the exploding conductor and the maximum temperature T_m according to (1) in the formed plasma channel of the high-current GPC discharge. As for the adiabatic index β_p for «metallic plasma», taking into account the fact that at EE in the gas of a metallic conductor, this plasma usually contains diatomic gases by its composition (for example, nitrogen N_2, hydrogen H_2 and oxygen O_2, which are part of air), in the first approximation for it in the case of the presence of diatomic gases in the gaseous medium around the conductor, it is possible to take the numerical value of the adiabatic index β_p, which is about β_p≈1.4 [28]. Then from (13) for EE in atmospheric air (T_a≈273.15 K; β_p≈1.4; M_a≈28.97·10^{-3} kg/mol [28]) of the copper conductor (l_0≈110 mm; r_0≈0.1 mm; S_0≈3.14·10^{-8} m^2; d_c≈8920 kg/m^3; m_c≈0.308·10^{-4} kg; J_k≈1.95·10^{17} A^2·s·m^{-4} [27]; U_e≈10 V [29]; M_p≈63.55·10^{-3} kg/mol [28]) in the high-current discharge circuit of a powerful high-voltage GPC (I_{mc} ≈ −190 kA; ω_c ≈ 26.18·10^3 s^{-1} [30]) for R_m = 8.314 J/(mol·K) [28] and T_m≈121,6·10^3 K, we obtain that in this electrophysical case the value of the thermal explosion energy W_{ex} of the conductor under study will be numerically equal to approximately W_{ex}≈838.8 J.

9. Approximate indicators of the process of introducing energy W_i into the structure of the conductor at its gas EE. As is known, the peculiarities of the process of rapid introduction of thermal energy W_i into the crystalline structure of the metal conductor will determine all the thermophysical and thermodynamic characteristics of its next EE both in vacuum and in gas and liquid media [5, 9, 10, 20, 32]. In the studied case of the engineering approach to the gas EE of a thin metal conductor in the high-current discharge circuit of a powerful high-voltage GPC, this process includes the stages of its sublimation, severe overheating, and thermal explosion of the metal vapor of the conductor. For a brief description of these stages above, in sections 2 and 4–8, the corresponding approximate calculation formulas (1) and (5)–(13) were given for determining the maximum temperature T_m of the plasma, the time t_{ex} of the thermal explosion, the maximum pressure P_m, the sublimation energy W_s, the overheating energy W_{sh} and the thermal explosion energy W_{ex} at EE in the accepted gas environment (T_a≈273.15 K; P_a≈1.013·10^5 Pa [28]) of the considered metal conductor. With respect to a short thin copper cylindrical conductor ((l_0≈110 mm; r_0≈0.1 mm; S_0≈3.14·10^{-8} m^2; d_c≈8920 kg/m^3; m_c≈0.308·10^{-4} kg; J_k≈1.95·10^{17} A^2·s·m^{-4} [27]), placed in the high-current discharge circuit of a powerful high-voltage GPC (I_{mc}≈−190 kA; ω_c≈26.18·10^3 s^{-1}; U_{c0}≈−27 kV [30]), it was established by calculation that the thermal energy W_i ≈ (W_s + W_{sh} + W_{ex}) injected into the metal of the conductor in the microsecond time range is numerically about W_i ≈ 2.44 kJ (with a powerful GPC stored in a capacitor battery with capacitance of C_0≈333 μF electrical energy is about W_0≈121.4 kJ [30]). It can be seen that the thermal energy W_i does not exceed 2 % of the electrical energy W_0 of the GPC battery. Such an electrophysical approach to the calculated determination of the energy W_i introduced into the metal structure of the conductor is in full agreement with the first law of classical thermodynamics [28].

10. Approximate calculation of the active resistance R_c of the plasma channel of the discharge at the gas EE of the conductor. After the considered conductor loses its metallic conductivity, which is characterized at the boiling temperature T_b by the specific electrical conductivity γ_{cb} (see Table 1) [34], strong overheating of the metal vapor, the appearance of radial spread (from the moment of time t_{ex}) of the sublimated metal vapor of the thin conductor [4, 5, 7, 32] and the formation in the local zone of its EE in the gas of a high-temperature «metal plasma» [31], which forms a cylindrical plasma channel of a gas discharge [29], the main part of the stored in the GPC capacitor battery of its electrical energy is «switched on» in the electrophysical process energy W_0. This part of the energy W_0 will be dissipated on the active resistances of the electric circuit of the high-voltage GPC: R_c for the formed plasma cylindrical discharge channel of length l_c and R_k for the current-carrying elements of the GPC discharge circuit [19, 20]. Analytical determination of R_c faces serious technical difficulties. Therefore, later, when calculating R_c numerically, we will limit ourselves to the results of our own experimental studies [37], performed on a low-impedance powerful high-voltage GPC (R_k≈50 mΩ [21]) with a discharge decaying sinusoidal current $i_c(t)$, which was used (see the following section 14) during the experimental study of EE in the atmospheric air of a thin cylindrical conductor (l_0≈110 mm; r_0≈0.1 mm).

In [36, 37], experimentally when using in the discharge circuit of a powerful GPC a decaying sinusoidal current $i_c(t)$ of microsecond duration, the first amplitude of which Imc varied within ±(30–220) kA, the validity of Braginsky formula for the maximum radius r_{mc} of the plasma channel of a spark discharge in atmospheric air initiated by EE of a copper conductor was confirmed [38]:

$$r_{mc} \approx 0{,}093 \cdot |I_{mc}|^{1/3} \cdot t_{mc}^{1/2}, \qquad (14)$$

where t_{mc} is the time (s) corresponding to the first amplitude I_{mc} (A) of the discharge decaying sinusoidal current $i_c(t)$ in the capacitor battery circuit of the high-voltage GPC.

When (14) is valid for the air channel of a spark discharge and the specified conditions of change in a cylindrical plasma channel with length l_c≈l_0 of the ATP of the discharge current $i_c(t)$ of a powerful high-voltage GPC [37], it was established that the minimum running active resistance $R_{c0}=R_c/l_c$ of a high-current plasma of the spark discharge channel in atmospheric air when it is initiated by the exploding thin copper conductor (l_0 ≈ 50 mm; r_0 ≈ 0.1 mm) is numerically R_{c0}≈(0.167±0.005) Ω/m. Knowing R_{c0}, the minimum value of the active resistance R_c of the plasma discharge channel in atmospheric air, formed by the GPC capacitor battery, which is discharged on a thin, exploding metal conductor of length l_0≈l_c, can be found from the relationship: R_c≈$R_{c0}l_c$. At l_c≈110 mm for the minimum active resistance $R_c<R_k$ formed in the high-current discharge circuit of the GPC (I_{mc}≈−190 kA; ω_c≈$26.18\cdot10^3$ s^{-1} [30]) of the plasma discharge channel that initiates EE in air of the short thin round copper conductor (l_0≈110 mm; r_0≈0.1 mm), we get the following numerical value for R_c: R_c≈18.37 mΩ.

11. Approximate calculation of the specific electrical conductivity γ_p of the plasma channel of the discharge at the gas EE of the conductor. From the classical electrical engineering formula for R_c of a conductor with radius r_{mc}, taking into account (14) and the minimum linear active resistance R_{c0} of initiated EE in the gas of the conductor of the plasma cylindrical discharge channel in the GPC electric circuit, we obtain the formula for the engineering estimation of the maximum specific electrical conductivity γ_p of its plasma:

$$\gamma_p \approx 36{,}8(R_{c0} \cdot |I_{mc}|^{2/3} \cdot t_{mc})^{-1}. \qquad (15)$$

From (15) at the studied EE in atmospheric air (T_a≈273.15 K; P_a≈$1.013\cdot10^5$ Pa [28]) of a thin copper conductor (l_0≈110 mm; r_0≈0.1 mm), which is connected in a high-current discharge GPC high-voltage capacitor bank circuit (I_{mc}≈$-190\cdot10^3$ A; t_{mc}≈$42\cdot10^{-6}$ s; ω_c≈$26.18\cdot10^3$ s^{-1}; U_{c0}≈−27 kV [30]) for R_{c0}≈0.167 Ω/m the specific electrical conductivity γ_p of the plasma cylindrical channel with length l_c≈110 mm, which occurs in this case, turns out to be numerically equal to γ_p≈1587.6 (Ω·m)$^{-1}$. This calculated value of γ_p is in good agreement with the corresponding experimental data of γp for «metallic plasma» given in [9, 10, 37].

12. Approximate calculation of the energy W_c released in the plasma channel of the discharge at the gas EE of the conductor. At EE in the gaseous medium of the metal conductor of length l_0 under consideration, through it and the cylindrical channel of length l_c≈l_0 formed by this explosion with «metal plasma» in the high-current GPC circuit of the capacitive type, a discharge decaying sinusoidal current $i_c(t)$ flows, which is described in time t by the following dependence [6, 36]:

$$i_c(t) = \pm k_c I_{mc} \cdot \exp(-\delta_c t) \cdot \sin(\omega_c t), \qquad (16)$$

where δ_c, ω_c are, respectively, the attenuation coefficient and the circular frequency of oscillations of the discharge current of the powerful GPC; k_c = $[\exp(-\delta_c/\omega_c \mathrm{arcctg}\,\delta_c/\omega_c)\cdot\sin(\mathrm{arcctg}\,\delta_c/\omega_c)]^{-1}$ is the dimensionless normalizing coefficient.

On the active resistance R_c of the plasma cylindrical channel of the spark discharge of length l_c≈l_0, initiated by EE in the gaseous medium of a thin metal conductor of length l_0, in the accepted high-current circuit of the high-voltage GPC of the capacitor type with pulsed sinusoidal current $i_c(t)$ according to (16), thermal energy W_c will be released, which is calculated according to the following electrotechnical formula:

$$W_c \approx l_0 R_{c0} k_c^2 I_{mc}^2 \int_0^{\infty} e^{-2\delta_c t} \sin^2(\omega_c t)\, dt. \qquad (17)$$

After integration in (17) for the thermal energy W_c released in the plasma discharge channel formed in the GPC circuit due to EE in the metal conductor gas, we obtain finally:

$$W_c \approx l_0 R_{c0} k_c^2 I_{mc}^2 \delta_c^{-1} [1 + (\delta_c / \omega_c)^2]^{-1} / 4. \qquad (18)$$

According to (18), at EE in the atmospheric air of the short copper conductor (l_0≈110 mm; r_0≈0.1 mm) and the plasma channel of the spark discharge initiated by it (l_c≈l_0≈110 mm; R_{c0}≈0.167 Ω/m [37]) in the high-current circuit of a powerful high-voltage GPC (I_{mc}≈−190 kA; δ_c≈$14.39\cdot10^3$ s^{-1}; ω_c≈$26.18\cdot10^3$ s^{-1}; k_c≈2.05 [30]) in the indicated channel with «metallic plasma» thermal energy W_c will release, numerically equal to W_c≈37.2 kJ. This energy W_c in sum with the thermal energy W_i≈2.44 kJ introduced into the investigated explosive copper conductor (l_0≈110 mm; r_0≈0.1 mm) is approximately (W_c + W_i) ≈ 39.6 kJ. Then the ratio of the sum of thermal energies ($W_c + W_i$) to the electrical energy W_0≈121.4 kJ [30] stored in the GPC capacitor battery will be numerically equal to $(W_i + W_c)/W_0$≈0.326. Therefore, it can be said that in the considered electric circuit with the use of a powerful high-voltage GPC of the capacitor type (C_0≈333 μF; U_{c0}≈−27 kV; W_0≈121.4 kJ [30]) for the practical implementation of the EE process in the atmospheric air of the short copper conductor (l_0≈110 mm; r_0≈0.1 mm) the efficiency $\eta_c \approx (W_i + W_c)/W_0$ of the electrical energy of the GPC capacitor bank is numerically η_c≈0.326 (32.6 %). This indicator η_c turned out to be smaller than the similar indicator η_c ≈ 57.1 %, typical for the use of the same powerful high-voltage GPC when forming a similar copper conductor of a plasma channel of an underwater discharge in its discharge circuit based on EE in technical water [39]. The reason for this is the greater value of the active resistance $R_c \approx R_{c0} l_c$ of the underwater plasma discharge channel compared to the gas discharge channel [20, 39]. It follows from (1) and (18) that both the temperature T_m of the plasma channel and the energy W_c released in it can be determined from the oscillogram of the discharge current $i_c(t)$ of the GPC at EE in the conductor gas.

13. Approximate calculation of the maximum velocity v_{mw} of the shock acoustic wave at the gas EE of the conductor. In the analyzed electrophysical case, the expression for the maximum velocity v_{mw} of propagation of theshock acoustic wave in plasma products formed from EE in the gas medium of the investigated metal conductor can be represented in the following form [28, 40]:

$$v_{mw} \approx 0{,}5(\beta_p + 1)\left[\beta_p R_m T_m / (M_a + M_p)\right]^{1/2}. \qquad (19)$$

When obtaining (19), we used the known relationship between the shock wave velocity v_{mw} and the velocity of expansion v_{ex} of a highly overheated metal vapour of a conductor behind the shock wave front [27, 40]: $v_{mw} \approx 0{,}5(\beta_p+1)v_{ex}$. In the studied case, it is assumed that the velocity v_{ex} corresponds to the velocity of a sound wave in a dense «metal plasma» formed at the initial stage of EE in the gas of a metal conductor [10, 28]. It can be seen that the value of v_{mw} is directly proportional to the level of the temperature indicator $T_m^{1/2}$.

From (19) at EE in air with normal atmospheric conditions (T_a≈273.15 K; β_p≈1.4; $M_a \approx 28.97 \cdot 10^{-3}$ kg/mol; R_m = 8.314 J/(mol·K) [28]) of the short copper conductor (l_0 ≈ 110 mm; r_0 ≈ 0.1 mm; $S_0 \approx 3.14 \cdot 10^{-8}$ m^2; $J_k \approx 1.95 \cdot 10^{17}$ A^2·s·m^{-4} [27]; $M_p \approx 63.55 \cdot 10^{-3}$ kg/mol [28]), connected in the high-current discharge circuit of a high-voltage GPC (I_{mc}≈−190 kA; $\omega_c \approx 26.18 \cdot 10^3$ s^{-1}; $T_m \approx 121.6 \cdot 10^3$ K), it turns out that the velocity of the shock acoustic wave v_{mw} acquires a numerical value of approximately v_{mw}≈4693 m/s. This estimated calculated value of the velocity v_{mw} of the gas-dynamic shock wave at EE in the atmospheric air of a thin copper conductor corresponds to the velocity as a shock wave from the EE of a copper wire with radius of 75 μm with HPC propagating in distilled water at speed of approximately $4.3 \cdot 10^3$ m/s (at thus, the pressure amplitude in the water near the exploding wire reaches the level of $6.5 \cdot 10^9$ Pa or $6.42 \cdot 10^4$ atm) [8], as well as the detonation wave in «slow» solid explosive explosives [41]. In this regard, the EE phenomenon in gas environments of thin metal conductors can be used in electrodetonators when detonating ammunition with both conventional and nuclear explosives [40, 41].

14. Results of experiments for air EE of the thin cylindrical conductor. To verify some of the calculation results obtained above for EE in the gaseous medium of thin metal conductors, corresponding experiments were performed for EE in the atmospheric air of the thin copper conductor (l_0 ≈ 110 mm; r_0 ≈ 0.1 mm; $S_0 \approx 3.14 \cdot 10^{-8}$ m^2). Here, a low-impedance high-voltage GPC with a powerful capacitor battery was used as a source of electrical energy, characterized by the following nominal electrical parameters [22, 30]: C_0≈333 μF; U_{c0}≈±50 kV; W_0≈416 kJ.

Figures 1, 2 show the combined in time t oscillograms of the discharge decaying sinusoidal current $i_c(t)$ of the indicated GPC (curve 1; I_{mc}≈−190 kA; $\delta_c \approx 14.39 \cdot 10^3$ s^{-1}; $\omega_c \approx 26.18 \cdot 10^3$ s^{-1}; t_{mc}≈42 μs; k_c≈2.05) and pulsed peak-like voltage $u_c(t)$ (curve 2; $u_{mc}(t_{ex})$≈−28.17 kV; t_{ex}≈3.2 μs [30]) at air EE of the short thin copper conductor (l_0≈110 mm; r_0≈0.1 mm) in a high-current discharge circuit of a powerful high-voltage GPC (U_{c0}≈−27kV; W_0≈121.4 kJ) at a horizontal scale of 5 and 50 μs/division.

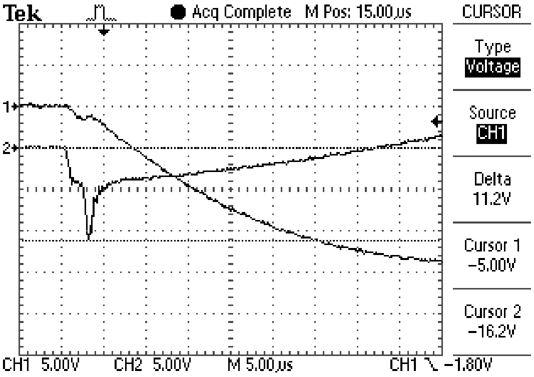

Fig. 1. Combined oscillograms of current $i_c(t)$ (curve of channel 1) and voltage $u_c(t)$ (curve of channel 2) in the high-current circuit of a powerful high-voltage GPC at EE in atmospheric air of the thin copper conductor (l_0=110 mm; r_0=0.1 mm; t_{ex}≈3.2 μs [30]) (vertical scale for current – 50 kA/division; vertical scale for voltage – 12.6 kV/division; horizontal scale – 5 μs/division)

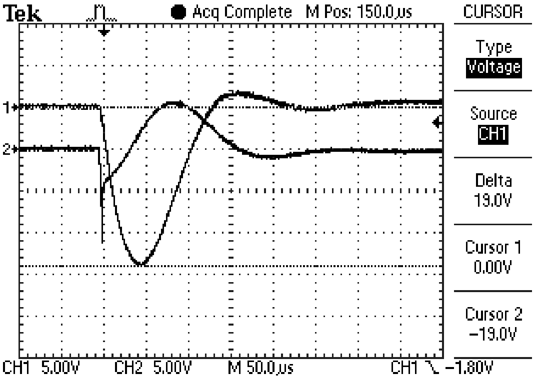

Fig. 2. The same as in Fig. 1 combined oscillograms of the discharge current $i_c(t)$ (curve of channel 1; I_{mc}≈−190 kA; $\delta_c \approx 14.39 \cdot 10^3$ s^{-1}; $\omega_c \approx 26.18 \cdot 10^3$ s^{-1}; $T_c \approx 2\pi/\omega_c \approx 240$ μs [30]) and voltage $u_c(t)$ (curve of channel 2) in the high-current circuit of a powerful high-voltage GPC at EE in the atmospheric air of the thin copper conductor (l_0=110 mm; r_0=0.1 mm; t_{ex}≈3.2 μs) but with horizontal scale – 50 μs/division

When conducting experimental studies of air EE of the specified thin copper conductor, the coaxial measuring shunt of the ShK-300 type, the capacitive voltage divider of the EPN-100 type, and the Tektronix TDS 1012 digital oscilloscope [30] were used, which passed the state metrological inspection.

From the oscillograms of the discharge current $i_c(t)$ (curve 1) and the voltage $u_c(t)$ on the exploding copper conductor (curve 2), it should be noted that in this case the experimental time t_{ex} of the thermal explosion of the conductor in question, which occurs at the front of the first half-wave of the discharge current $i_c(t)$, is approximately t_{ex}≈3.2 μs (when its value is t_{ex}≈3.32 μs calculated by (5)).

It can be seen that for the t_{ex} parameter, the discrepancy between its calculated and experimental values does not exceed 4 %. These data indicate the efficiency and reliability of the applied calculation approach to the determination of the t_{ex} parameter when describing the electrophysical process of EE in the gas environment of the round thin metal conductor.

In addition, given according to Fig. 1, 2 experimental data for the ATP of the discharge current $i_c(t)$ together with the experimental results from [36, 37] for the electrophysical parameters R_{c0} and r_{mc} indirectly indicate the validity of the calculated estimations according to (1), (7), (14), (15) and (18), respectively, of the parameters T_m, P_m, R_c, γ_p and W_c at the EE in atmospheric air of the copper conductor (l_0≈110 mm; r_0≈0.1 mm) connected in the electric circuit of a powerful high-voltage GPC.

Conclusions.

1. The proposed electrophysical approach to the analytical complex calculation of the main parameters of the EE in the gas medium of a thin metal conductor allows to determine with engineering accuracy such thermophysical, gas-dynamic and electrical parameters of a given explosion as: the maximum temperature T_m and the pressure P_m in the plasma channel, the time t_{ex} of the explosion of the conductor, the active resistance R_c and the specific electrical conductivity γ_p of the plasma channel, the thermal energy W_i introduced into the conductor and the thermal energy W_c released in the channel, and the maximum velocity v_{mw} of the propagation of the shock acoustic wave in the «metal plasma» from EE in the gas of a thin metal conductor under electrothermal action of the HPC.

2. It was found that at the EE in the atmospheric air of the thin copper conductor (l_0≈110 mm; r_0≈0.1 mm), which is connected in the discharge circuit of a capacitor battery of a powerful high-voltage GPC of the microsecond time range (I_{mc}≈−190 kA; δ_c≈$14.39\cdot10^3$ s^{-1}; ω_c≈$26.18\cdot10^3$ s^{-1}; t_{mc}≈42 μs; U_{c0}≈−27 kV; W_0≈121.4 kJ), the specified parameters of the electroexplosive process in its circuit take the following approximate numerical values: T_m≈$121.6\cdot10^3$ K; P_m≈$14.19\cdot10^9$ Pa; t_{ex}≈3.32 μs; R_c ≈ 18.37 mΩ; γ_p ≈ 1587.6 $(\Omega\cdot m)^{-1}$; W_i ≈ 2.44 kJ; W_c ≈ 37.2 kJ; v_{mw} ≈ 4693 m/s.

3. As part of the further development of the engineering approach to the analytical complex calculation of the above-listed main parameters of the electro-explosive process in the discharge circuit of the GPC, the relationship (3) is given for the approximate calculation of the values of the critical current integral J_k at the EE in the gaseous medium of thin metal conductors with the most widely used in the field of experimental physics HPT and electro-explosive technologies with conductive materials (see Table 1).

4. It is shown that such parameters of the electric explosion process as the maximum temperature T_m and the highest pressure P_m in the plasma channel, the time t_{ex} of the conductor explosion, the specific electrical conductivity γ_p of the plasma channel, the thermal energy W_i introduced into the metal conductor, and the thermal energy W_c released in the channel, do not depend on the properties of the gas in which the EE of the investigated metal conductor takes place.

5. At the EE in the gas environment of a thin metal conductor connected in the discharge circuit of a powerful high-voltage GPC, the temperature T_m and the pressure P_m, the time t_{ex} of the conductor explosion, the specific electrical conductivity γ_p of the plasma channel, the thermal energy W_c released in the channel, and the velocity v_{mw} of the wave in the explosion zone, occurring in the discharge plasma channel, can be determined by (1), (5), (7), (15), (18) and (19) on the basis of deciphering the oscillograms of the discharge current $i_c(t)$ and voltage $u_c(t)$ in the electrical circuit of the GPC.

6. The thermal energy W_i≈2.44 kJ, which is introduced into the investigated short thin copper conductor (l_0≈110 mm; r_0≈0.1 mm), which is connected in the high-current discharge circuit of the indicated powerful high-voltage GPC, at its EE in atmospheric air, does not exceeds 2 % of the electrical energy W_0≈121.4 kJ stored in the capacitor bank of this GPC.

7. In the analyzed electrical circuit of the practical implementation of the phenomenon of high-temperature EE in the atmospheric air of the studied short thin copper conductor (l_0≈110 mm; r_0≈0.1 mm), the thermal energy released in the plasma channel W_c≈37.2 kJ together with the energy introduced into the conductor W_i ≈2.44 kJ, ensures the achievement of the efficiency η_c of the electrical energy of the capacitor bank of the powerful high-voltage GPC W_0≈121.4 kJ, which is numerically equal to approximately η_c≈0.326 (32.6 %).

8. The high-current experiments performed with the help of a powerful high-voltage GPC confirmed the main provisions of the proposed engineering approach to the analytical complex calculation of the specified parameters of the electro-explosive process in a gaseous medium with normal atmospheric conditions and showed that the difference between the calculated according to (5) and the experimental data for the explosion time t_{ex} of the copper conductor (l_0≈110 mm; r_0≈0.1 mm) does not exceed 4 %.

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