NUMERICAL SIMULATION OF GAS-DYNAMIC STAGE OF SPARK DISCHARGE IN OXYGEN

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A numerical model of gas-dynamic stage of spark discharge in oxygen that takes into consideration transient processes in an electric circuit and a change in the composition of gas-discharge atmosphere has been presented. The components of *e*, *O*, O_+, O_{++} were considered for the conductive channel of a spark. The plasma ionization was neglected in the region beyond the conductive channel and the consideration was given to the components of O_2, *O*. The results of the distribution of thermodynamic parameters, spark channel resistance, radiation losses, and those of expenditure of discharge energy for dissociation and ionization have been given.

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INTRODUCTION

The spark discharge development is accompanied by many elementary processes that arise in gas-dynamic environment and are interconnected with different types of atom and molecule excitations, molecule dissociation, and atom and molecule ionization. These processes are superimposed by the processes of chemical transformations, transient processes in a discharge circuit, gas-dynamic expansion of a spark channel, heat transfer processes, diffusion, radiation, near-electrode processes, etc. Each process has its own specific time required for the establishment of equilibrium state. For some processes this time differs by orders of magnitude. Some processes related, for example, to the radiation in non-equilibrium plasma and to the formation of spatial near –cathode charge require additional studies.

The above aspects cause difficulties in the creation of generalized numerical model describing the entire set of processes that occur in the spark discharge.

Due to the fact that the spark discharge has a broad practical application numerical models that allow for the description of individual stages of spark discharge have been created. The gas-dynamic stage of spark discharge is of practical interest, because this stage is accompanied by the shock wave formation, which produces a mechanical effect on the environment surrounding the gas discharge channel.

In practical application, the spark shock action is used, for example, by electrical and hydraulic punching systems, by vibratory cleaning and detonation initiation systems, etc [1]. With regard to these problems it is very important to obtain a high factor of conversion of the total electric energy into the shock wave energy. The studies of this process and the definition of possible ways of an increase of electric discharge efficiency with regard to shock effect-related problems require the use of numerical models describing the gas-dynamic stage of spark discharge taking into consideration transient processes that arise in the electric circuit.

Numerical models of gas-dynamic stage of spark discharge channel and the results of experimental research of this discharge stage are described, for example, in [2 - 15].

In S.I. Drabkina's model the system of differential equations of gas dynamics is solved using prescribed boundary conditions [2]. Model versions with instantaneous and gradual deposition of energy in the discharge channel have been given. For the model version that takes into account a gradual energy deposition and which is more close to the real spark discharge the shock wave front radius and its derivative parameters, in particular shock wave-front velocity and wave front pressure presented as a function of the amount of energy inputted in the spark channel at the current instant of time are used as boundary conditions.

Therefore this model can be used for the case when the dependence of the amount of energy inputted in the spark channel on time is defined using the results of experimental research. This hampers the analysis of processes if discharge conditions are changed.

In the S.I. Braginsky model [3] processes occurring at the stage of gas-dynamic spark expansion are described by the discharge current curve. Such formulation of a problem allowed us to study the influence produced by discharge circuit parameters that define the discharge current curve on the distribution field of thermodynamic parameters of gas discharge environment at different instants of time that arise during the gas-dynamic channel expansion.

In [3] problem was solved using a self-similar approximation, which is applied for the definite relationship of a current rise *i* as a function of time *t*, which is expressed as $i \sim t^{3/4}$.This relationship describes in the rough only the first quarter-period of oscillatory decaying discharge that arises at the capacitor discharge in a spark gap.

The papers [4, 5] give numerical models taking into consideration transient processes in electric circuit. Proceeding from these descriptions we can state that a change in the discharge environment composition caused by dissociation and ionization processes was not taken into account by models.

A relatively detailed description of processes arising at the gas-dynamic stage of spark channel expansion is given by the numerical model presented in [6]. This model describes the behavior of discharge processes with regard to the chemical nonequilibrium environment taking into consideration magnetic pressure forces, diffusion, radiation losses and heat conductivity. For the computation of heat conductivity the model took account of only molecular and electron components of the heat conductivity. The neglect of radiant heat conductivity results in overrated thermodynamic parameters of the environment that are reached in the discharge channel [7].

The purpose of this paper is to provide a numerical modeling of the gas-dynamic stage of spark discharge in oxygen taking into consideration a change in the composition of gas-discharge environment and transient processes arising in electric circuit.

NUMERICAL MODEL DESCRIPTION

Gas-dynamic spark channel expansion has a cylindrical symmetry. In the case of one-dimensional formulation of a problem in the range of $0 < r < L_*$, where L_* is a size of the simulation area the system of gas-dynamic equations (mass storage, pulse and energy continuity) was solved for gas mixture as follows

$$\frac{\partial \vec{a}}{\partial t} + \frac{1}{r}\frac{\partial (r\vec{b})}{\partial r} = \frac{1}{r}\vec{f}, \qquad (1)$$

where column vectors have equal values:

$$\vec{a} = \begin{pmatrix} \rho \\ \rho u \\ \rho\varepsilon + \dfrac{\rho u^2}{2} \end{pmatrix}, \quad \vec{b} = \begin{pmatrix} \rho u \\ p + \rho u^2 \\ u(\rho\varepsilon + \dfrac{\rho u^2}{2} + p) + k_T \dfrac{dT}{dr} \end{pmatrix},$$

$$\vec{f} = \begin{pmatrix} 0 \\ p \\ r\cdot(\sigma E^2 - Q_{rad}) \end{pmatrix}$$

ρ is the gas density, u is the velocity, p is the pressure, ε is the internal gas energy, k_T is the heat transfer coefficient, E is the electric field in the discharge channel column, σ is the plasma conductivity in a channel, Q_{rad} is radiation discharge energy losses, r is the radius coordinate, T is the temperature.

To consider processes that occur in a spark discharge conductive channel proceeding from the current thermodynamic state the region was defined in which plasma is highly ionized following the mechanism of thermal ionization. In the conductive channel components e, O, O_+, O_{++} have been considered. In the calculated region outside the conductive channel plasma ionization has been neglected. In this field the components O_2, O have been considered. The energy deposition in a discharge channel was defined by the parameters of electric circuit. The diffusion process was not taken into account.

The problem was solved numerically splitting the rated area of L_* into rated cells.

To calculate the Joule heat deposited into the discharge channel we are supposed to know the current values of electric field E in the discharge channel column and plasma conductivity distribution σ in the plasma channel. It was assumed that only a longitudinal component of the electric field is present in the discharge channel and the field is uniformly distributed across the channel cross-section.

The conductivity distribution in a gas-discharge channel was considered proceeding from the channel-based problem formulation. The highly ionized region was defined from the condition of tenfold exceed of the frequency of Coulomb collisions in comparison with that of elastic collision of electrons with a neutral plasma component (O atoms) as follows:

$$N \cdot \sigma_{tr} \le \frac{n_e \cdot \sigma_{\tilde{N}ol}}{10}. \qquad (2)$$

Where σ_{tr} is the transport cross – section of elastic collisions of electrons with a neutral plasma component, – N is the neutral plasma component density; n_e is an electron number density, σ_{Col} is the Coulomb collision cross-section.

Complete dissociation of molecular oxygen occurs at a temperature higher than 5000 K. Therefore the additional condition for the conductivity calculation relevance in the rated region was a condition of

$$T > 5000 \text{ K}. \qquad (3)$$

Taking into consideration the above only elastic electron collisions with oxygen atoms were taken into account in the expression (2) while estimating electron collisions with oxygen atoms. The dependence of transport cross-sections of elastic electron collisions with oxygen atoms on the electron temperature is taken from [16].

Due to the fact that the fulfillment of a condition (2) was verified with regard to the region with single plasma ionization the cross section of Coulomb collision was calculated using the expression [8]

$$\sigma_{Col} = \frac{2.87\cdot 10^{-14}\ln\Lambda}{T_e^2}[\text{cm}^2], \qquad (4)$$

where $\ln\Lambda$ is the Coulomb logarithm, T_e is the electron temperature in [eV].

In the model the electron temperature was equal to the temperature of heavy plasma component $T_e = T$.

It was assumed for the model that plasma in a discharge channel is quasi neutral with the ionization degree not exceeding a double one.

$$n_e = n_+ + 2n_{++}, \qquad (5)$$

where n_e is an electron density; n_+ is the single ionization atom density; n_{++} is the double ionization atom density. An electron attachment process was neglected in the model.

The ionization in the discharge channel was calculated using the Saha equation with regard to the single and double ionization of gas with components of e, O, O_+, O_{++}. The electron density n_e and plasma temperature in rated cells were defined by solving the equation system:

$$\frac{n_e n_{O+}}{N_O} = \frac{g_{O+}}{g_O} A\cdot T^{\frac{3}{2}}\exp(-\frac{eI_{O+}}{kT}); \qquad (6)$$

$$\frac{n_e n_{O++}}{n_{O+}} = \frac{g_{O++}}{g_{O+}} A\cdot T^{\frac{3}{2}}\exp(-\frac{eI_{O++}}{kT}); \qquad (7)$$

$$\varepsilon = \frac{3}{2}(N_O + n_{O+} + n_{O++} + n_e)kT + n_{O+}eI_{O+} + n_{O++}eI_{O++} + (N_O + n_{O+} + n_{O++})I_O/2; \qquad (8)$$

$$n_e = n_{O+} + 2n_{O++};\qquad(9)$$

$$\rho_O = (N_O + n_{O+} + n_{O++})Z_O m_{a.i.m},\qquad(10)$$

where A = $6{,}06\cdot10^{-21}$ cm^{-3}·eV$^{-3/2}$; g_i are statistical weights of relevant components; I_O is an oxygen molecule dissociation energy; I_{O+}, I_{O++} is an potential of single and double ionization of oxygen atom; Z_O is a atomic number of oxygen; $m_{a.i.m.}$ = $1{,}66\cdot10^{-27}$ kg; ρ_O is an atomic oxygen density, n_i is a density of relevant components; e is electron charge.

Statistical weights g_i and ionization energy of I_i components accepted for computations using the Saha equation were taken from [17]. The plasma conductivity was calculated using the equation [3]

$$\sigma(Z,T) = \frac{96{,}994\cdot K_\sigma(Z)\cdot T_e^{\frac{3}{2}}}{\ln\Lambda}\ [\text{Ohm}^{-1}\cdot\text{cm}^{-1}],\qquad(11)$$

where $K_\sigma(Z)$ is the non-dimensional coefficient; Z is the average ion charge; lnΛ is the Coulomb logarithm calculated using the expression [3]

$$\ln\Lambda = \ln\left(\frac{1{,}55\cdot10^{10}\cdot T_e^{\frac{3}{2}}}{Z\sqrt{n_e[cm^{-3}]}}\right).\qquad(12)$$

According to [3], $K_\sigma(Z{=}1) = 1{,}95$; $K_\sigma(Z{=}2) = 1{,}135$.

In the region of strongly ionized plasma (conductive channel) gas pressure p was calculated using the expression of

$$p = (N + n_e + n_+ + n_{++})kT,\qquad(13)$$

where k is the Boltzman constant.

Resistance R_{sp} of a discharge channel for the current time point was defined by the integration of current conductivity values σ in rated cells using the expression of

$$R_{sp} = l_{sp} \Big/ \int_0^{r_{ch}} 2\pi r\sigma dr,\qquad(14)$$

where l_{sp} is a discharge gap length (channel); r_{ch} is a conductive channel radius.

The current value of electric field E in conductive channel was calculated using the expression

$$E = R_{sp} i / l_{sp}.\qquad(15)$$

This paper describes the simulation of gas-dynamic expansion of a spark discharge, where the capacitor served as a pulse source of discharge energy. The transient process in the involved electrical circuit was calculated using the equation of

$$L\frac{di}{dt} + [R_c + R_{sp}(t)]\cdot i + \frac{1}{C}\int_0^t idt = 0,\qquad(16)$$

where C is the capacitor capacitance, R_c is the equivalent active resistance of discharge circuit; L is the equivalent inductance of discharge circuit.

The conductive channel expansion results both from thermal expansion and from the heating of gas layers adjacent to the channel due to the heat conductivity. Results of the research obtained by S.I. Braginsky, N.G. Basov, B.L. Borovych, et al [3, 18], showed that the thermal wave speed can reach gas-dynamic speed of channel expansion. In the model the heat conductivity coefficient was calculated using the expression of

$$k_T = k_{el} + k_{rad},\qquad(17)$$

where k_{el} is a coefficient of electronic heat conductivity; k_{rad} is a coefficient of radiant heat conductivity.

The heat transfer by the radiation in the region of conductive channel, where gas temperature exceeds 10000 K, was considered in approximation of radiant heat conductivity ([7], c. 74; [19], c. 133). The coefficient k_{rad} of radiant heat conductivity was calculated using the expression of

$$k_{rad} = \frac{16}{3}\sigma_{SB}T^3 l_R,\qquad(18)$$

where σ_{SB} is the Stephan-Boltzman constant; T is a gas temperature in [K]; l_R is the Rosseland mean in [m], accepted in the problem as being equal to [18]

$$l_R = 6{,}8\cdot10^{-10}\frac{T_e^{\frac{4}{3}}}{[10^{-3}\rho]^{\frac{7}{4}}},\qquad(19)$$

where ρ in [kg/m^3].

The radiation discharge energy losses taking into consideration the cylindrical symmetry of the problem were calculated using the expression of

$$Q_{rad} = 2\sigma_{SB}T^4 / l_R.\qquad(20)$$

According to the work, ([8], c. 218) the electron heat conductivity was calculated using the expression of

$$k_{el} = 2{,}65\frac{T_e^{\frac{5}{2}}}{\ln\Lambda}\ [\text{W/(m·K)}].\qquad(21)$$

The dissociation process of molecular oxygen was calculated by reaction: O + O ↔ O_2, where reaction rate coefficients were taken from [20]. The forward rate coefficient was calculated using the expression of k_f = $1{,}2\cdot10^{17}T^{-1}$ [cm^3·mole^{-1}·s^{-1}]. The reverse rate coefficient was calculated from the forward rate and the equilibrium constant.

Specific heat capacity at constant pressure C^0_p, standard-state molar enthalpy H^0 and standard-state molar entropy S^0 of kth component (O_2, O) as a function of a temperature T in the range of 300 to 5000 K were calculated as in [20].

At a temperature of $T > 5000$ K exceeding the limits of approximation curves the expressions of

$$C^0_{pk}(T) = C^0_{pk}(5000).\qquad(22)$$

$$H^0_k(T) = H^0_k(5000) + C^0_{pk}(5000)\cdot(T - 5000),\qquad(23)$$

$$S^0_k(T) = S^0_k(5000) + C^0_{pk}(5000)\cdot\ln\left(\frac{T}{5000}\right)\qquad(24)$$

were used. The superscript ^{o} refers to standard-state.

The energy of the unit of mixture volume U_0 was prescribed by the expression of

$$\rho\varepsilon = \sum_k y_k U^0_k,\qquad(25)$$

where y_k is the molecular concentration of the k-th component of mixture, U_k^0 is The internal energy of 1 mole of the k-th component.

A mixture pressure in the cells outside the conductive channel was calculated using the sum of partial pressures of mixture components as

$$p = RT\sum_k y_k,\qquad(26)$$

where R is the gas constant.

Initial conditions assume the absence of gas-dynamic disturbances in the entire computational area. In the computations given below at p_0 = 1,013·10^5 Pa, T_0 = 300 K, the rated area was filled with molecular oxygen.

The gradients of thermodynamic gas parameters are assumed to be absent for the discharge channel axis in a cylindrical symmetry. The computational area size was prescribed in the manner of preventing disturbance from reaching the right boundary.

The numerical model did not take into account the initial stage of spark discharge, which is related to the formation of conducting region in a narrow spark channel. If the conducting region is not included into initial conditions the energy is not deposited in the computational cells by the prescribed source. Therefore, in order to create the initial conductivity in the model during the time of t = 10^{-8} s the energy was deposited in a simulated region with the radius of r_0 = 0,05 mm at a constant specific power of W = 7·10^{15} W/m^3. The energy inputted into a simulated channel was within 2,8 mJ, which is several orders less than the total energy stored in the capacitor in the problem considered below. The variation of the power within W = (5…10)·10^{15} W/m^3, time t = 10^{-10}…10^{-8} s, and the radius r_0 = 0,05…0,1 mm did not change calculated results starting from the time point exceeding $t > 5\cdot10^{-8}$ s.

The gas-dynamic equation system (1) was calculated using the S.K. Godunov scheme [21] modified up to the second order of space accuracy.

Hydrodynamic, chemical, heat transfer processes in spark channel and transient process that occur in electrical circuit are considered in this model. Therefore the time step was prescribed by the smallest step of maximum values of permissible steps defined by each of four processes involved.

The model application is restricted by the condition of considerable prevalence of gas-dynamic pressure over the magnetic one. In the considered problem this condition is defined by the expression of

$$\frac{10^{-7}\mu i^2}{16\pi^2 r_{ch}^{\ 2}\cdot p} \prec\prec 1, \qquad (27)$$

where μ is the relative magnetic permeability of the environment (for oxygen $\mu \approx 1$).

In the case of low discharge currents and long duration of the current increase plasma conductivity support conditions will disappear and the discharge current is terminated. Therefore, a lower limit of the model application was differed through the calculation.

NUMERICAL MODELING RESULTS

The testing of numerical model was conducted by way of comparison of calculated and experimental results. The data on spark channel evolution are given in details in papers written by I.S. Abramson and N.M. Gegechkori with regard to the capacitor discharge at a rating of C = 0,25 μF, the initial voltage of capacitor charge of U_0 = 15 kV, discharge circuit inductance of L = 2 μH in the air environment of atmospheric pressure [10, 13]. It was assumed that in oxygen environment quantitative deviations in the development of spark channel will be within one order. The papers [10, 13] give no data on the active impedance of discharge circuit, however taking into consideration the level of development of electronic devices during the fulfillment of that work the active circuit resistance, which is actually defined by the internal capacitor resistance, could be approximately equal to R_{cp} = 5 mOhm. Taking into consideration the presence of connecting wires it was assumed for calculations that R_c = 10 mOhm. The length of a discharge gap was prescribed to be equal to l_{ch} = 5 mm.

The results of comparison of calculated values of electric field E in the spark channel column with experimental data in [13] showed (Fig. 1) that calculated values are within the limits between the experimental values of discharge gap voltage reduced to the gap length and an electric field E in the spark channel column. It should be noted that the authors of the paper [13] noted the incompleteness of the technique used for the determination of the values of electric field E in the spark channel column.

In the calculated results the electric field at similar time points was lower by 100 ± 10 V/cm in comparison with experimental values of the field in the discharge gap reduced to the gap length.

One can assume that total values of the drop of cathode and anode potentials obtained in [13] are set too high.

In calculations the separation of conductive channel from shock wave front (Fig. 2) takes place according to the results of experimental research [10].

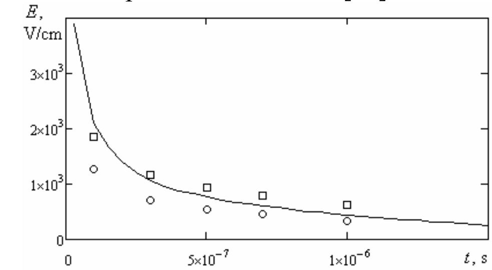

Fig. 1. Time variation of electric field E in the spark channel column: solid line corresponds to the calculated curve; □ is for experimental voltage values of a discharge gap; ○ is for experimental values of electric field E in the spark channel column

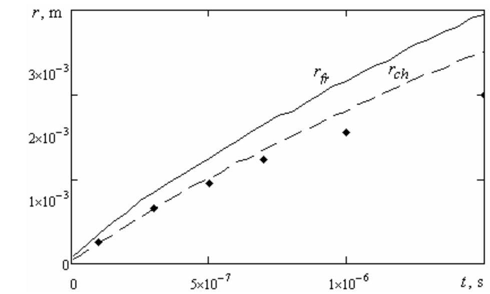

Fig. 2. Time variation of radius: r_{fr} is a radius of shock wave front and r_{ch} is a radius of conductive channel. Rhombs show experimental values of the radius of a conductive channel

A comparison of experimental values for the radius of conductive channel with the calculated curve shows that the calculated expansion speed of the channel exceeds the experimentally measured speed.

At the time point of 1.5 μs a deviation of the calculated radius r_{ch} from the experimentally measured was equal to 30%. This difference can be caused by that the coefficient of radiant heat conductivity adopted for air in this problem differs from an actual value of this coefficient for oxygen.

The calculated speed D of shock wave front deviated from experimental values by not more than 25% (Fig. 3)

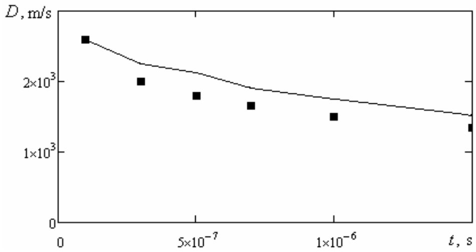

Fig. 3. The calculated (solid line) and experimental (squares) speed of shock wave propagation

The following distributions of thermodynamic parameters at different time points (Fig. 4) have been obtained.

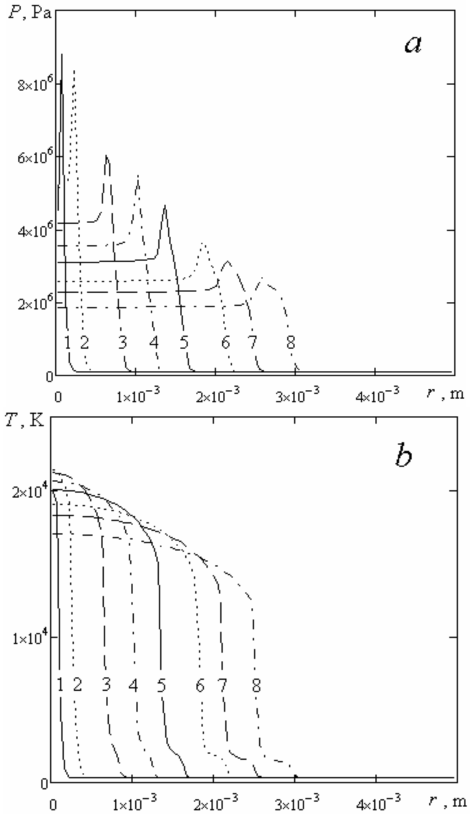

Fig. 4. Time variation of thermodynamic parameters (a – pressure; b – temperature) at the following time points: 1 – $3\cdot10^{-8}$ s; 2 – 10^{-7} s; 3 – $3\cdot10^{-7}$ s; 4 – $5\cdot10^{-7}$ s; 5 – $7\cdot10^{-7}$ s; 6 – 10^{-6} s; 7 – $1.2\cdot10^{-6}$ s; 8 – $1.5\cdot10^{-6}$ s

For the calculated time period the plasma temperature in conductive channel was equal to T_e = 1.5…2 eV. The shock wave front starts moving away from the conductive channel at time $t > (3…5)\cdot10^{-7}$ s.

The gas heating between the shock wave front and conductive channel occurs due to the adiabatic compression of the environment.

Time variation of the conductive channel resistance is shown on Fig. 5.

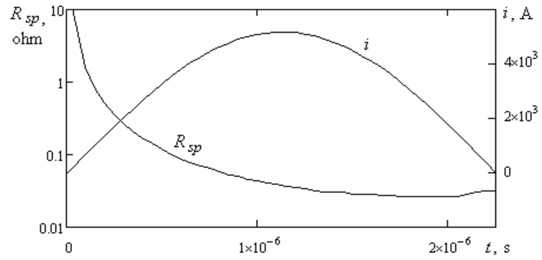

Fig. 5. Time variations of discharge channel resistance R_{sp} and current i

The results obtained for spark resistance allow us to work out requirements for the external circuit resistance at which the preferred release of energy in a spark is provided. In the calculated version the active impedance of external circuit should be within 10…30 mOhm to fulfill the condition of high efficiency factor of energy release in the spark gap.

Time variation of fractions of energy deposited in spark channel is shown (Fig. 6).

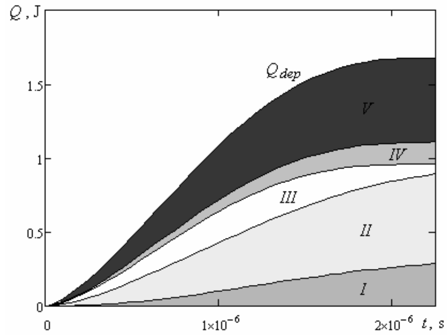

Fig. 6. Time variation of fractions of an energy inputted in spark channel Q_{dep}: I) radiated energy; II) energy consumed by dissociation process; III) energy consumed by ionization process; IV) energy of gas flow; V) heat energy

During the first quarter of the period of oscillatory decaying discharge the spark released just about 1.5 J of energy out of 28 J stored in the capacitor. This makes up about 5% of the total energy. By the time point of $t = 1.5\cdot10^{-6}$ s the discharge channel radiated 0.18 J of energy, which makes up 12 % of deposited energy. An increase in the amount of radiation energy is caused by an increase in volume and a rise in plasma temperature in conductive channel.

Efficiency of conversion of the deposited energy into the one of mass flow was calculated (Fig. 7). It explained the experimental fact that power spark discharge has a low efficiency of shock wave generation in gas when the capacitor served as a pulse source of discharge energy.

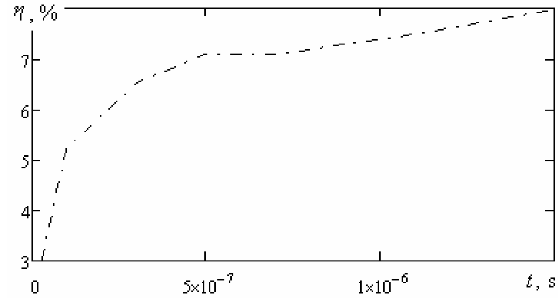

Fig. 7. Efficiency of conversion of the deposited energy into the energy of mass flow

For example, by the time point of $t = 1.5 \cdot 10^{-6}$ s the energy of mass flow was equal to 0.12 J, which makes up 0.4% of total energy.

CONCLUSIONS

The proposed numerical model for a gas-dynamic stage of spark discharge in oxygen allows us to take into account transient processes in electric circuit and a change in the composition of gas discharge environment.

The authenticity of numerical model was confirmed by the satisfactory agreement of calculated and experimental results. Thus, the calculated values of electric field for the capacitor discharge with the rated value of C = 0.25 μF, initial capacitor charge voltage of U_0 = 15 kV, discharge circuit inductance of L = 2 μH in the oxygen of atmospheric pressure are within the limits between the experimental values of discharge gap voltage reduced to the gap length and the values of electric field E in the spark channel column for the air discharge. The difference between the calculated radius of conductive channel and the experimentally measured value was equal up to 30%, and that of the speed of shock wave front was equal up to 25%.

This model can be used for the estimation of the parameters of shock waves generated by spark discharges, for the determination of the distribution of radiation dissociation and ionization losses of discharge energy in case of change of discharge circuit parameters.

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МАТЕМАТИЧЕСКОЕ МОДЕЛИРОВАНИЕ ГАЗОДИНАМИЧЕСКОЙ СТАДИИ РАЗВИТИЯ ИСКРОВОГО РАЗРЯДА В КИСЛОРОДЕ

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Представлена математическая модель газодинамической стадии развития искрового разряда в кислороде, учитывающая переходные процессы в электрической цепи и изменение состава газоразрядной среды. В области токопроводящего канала рассматривались компоненты e, O, O_+, O_{++}. В области вне токопроводящего канала ионизацией плазмы пренебрегалось, и рассматривались компоненты O_2, O. Представлены результаты распределения термодинамических параметров, сопротивления искрового канала, потерь на излучение, затрат энергии разряда на ионизацию.

МАТЕМАТИЧНЕ МОДЕЛЮВАННЯ ГАЗОДИНАМІЧНОЇ СТАДІЇ РОЗВИТКУ ІСКРОВОГО РОЗРЯДУ В КИСНІ

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Представлено математичну модель газодинамічної стадії розвитку іскрового розряду в кисні, що враховує перехідні процеси в електричному ланцюзі і зміну складу газорозрядного середовища. В області струмопровідного каналу розглядалися компоненти e, O, O_+, O_{++}. В області поза струмопровідного каналу іонізацією плазми нехтували, і розглядалися компоненти O_2, O. Представлено результати розподілу термодинамічних параметрів, опору іскрового каналу, втрат на випромінювання, витрат енергії розряду на іонізацію.