

# ELECTRON PROCESSES IN THE PULSE BREAKDOWN OF SOLID DIELECTRICS

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## ABSTRACT.

Physical processes leading to formation and spreading of pulse discharge channels in solid dielectrics were analyzed. It was shown that the mechanism responsible for appearance of the primary discharge channel in the near-electrode region (both at the cathode and the anode) of a dielectric was due to electron-thermal processes. The solid-melt phase transition took place in the dielectric within the primary channel. This mechanism also dominated on subsequent spreading at a subsonic velocity during the cathode discharge. The mechanism responsible for transformation of the primary channel to the main channel during the anode discharge was determined. The spreading rate of the channel always exceeded the sound velocity. Experiments showed that the spreading was accompanied by processes characteristic of the detonation effect. Analyzing specific features of those processes, the corresponding mechanism was identified as electronic detonation. Physical models of the processes were proposed. Relations were calculated from conservation laws in terms of the electric-hydrodynamic approximation. They were used to establish for the first time a mutual quantitative dependence between the voltage pulse parameters, space-time characteristics of the discharge, thermodynamic and electro-physical parameters of the material behind the phase transition front and individual properties of dielectrics.

**Keywords:** detonation, thermodynamic, mechanism, transformation, approximation.

## 1. INTRODUCTION

The physics of electric (electron [1]) breakdown in solid dielectrics passes through a crisis. This statement is supported by the fact that no self-consistent physical models of the breakdown process have been elaborated so far and, correspondingly, scientifically substantiated models describing this process are lacking. In my opinion, this situation can be explained by the following main factors.

1. In recent decades all efforts to derive relations between parameters of condensed dielectrics, breakdown conditions, and the breakdown voltage were made on a unilateral basis considering exclusively the mechanism responsible for deterioration of the electric strength. Therefore it was assumed that other stages of the

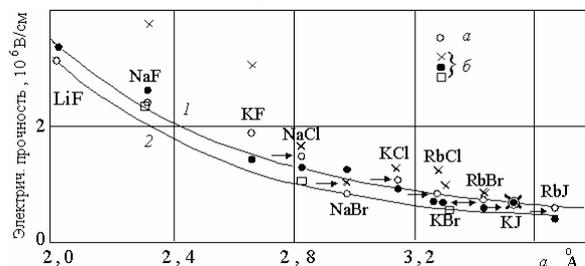
breakdown process did not determine, specifically, the field breakdown intensity.

2. By analogy with gaseous dielectrics, almost the only mechanism responsible for disturbance of the electric strength of condensed dielectrics (especially solid ones) in the case of electric breakdown was considered collision ionization of the valence band. Realization of the said mechanism was not doubted. However, this mechanism was not confirmed experimentally not only for dielectrics, but also for pure wide-band semiconductors [2]. Moreover, it contradicts the band structure of crystalline dielectrics, which have mostly a non-parabolic structure.

An electric discharge in solid dielectrics is closely connected with formation of a channel, which appears when the solid material of a dielectric passes to another state. In other words, an electric discharge may be viewed as corresponding fronts of a phase transition of the I kind that appear and move in the discharge gap. Therefore it is quite possible that this process can be described using the ideas and methods developed for similar effects in the physics of high-density energies.

## II. ELECTRON PROCESSES IN THE SOLID PHASE

In mid-1970s it was found [3] that a superheat instability, which leads to pinching of the electron current,



arises in alkali-haloid crystals (AHC's) at a certain intensity of the field. The fields ( $E_c$ ,  $E_i$ ), where the differential conductivity is negative, were termed the criteria of the superheat instability. It was found that these criteria and so-called criteria of collision ionization were

quantitatively similar and agreed well with experimental data (Fig. 1).

Fig. 1. Experimental values (o) and criteria of collision ionization and superheat instability:  $\times$ ,  $\bullet$ , and  $\square$  stand for collision ionization criteria due to Hippel, Franz, and Frelich-Paranjats; 1 – their graphical representation [1]; 2 – upper boundary of the superheat instability  $E_c$  at  $m^*/m_e = 1$  [3].

The physical meaning of the aforementioned coincidence is obvious. Pinching of the electron current, i.e. the increase in the current density, may be caused by both the local growth of the charge carrier density  $n_e$  and the charge carrier mobility  $\mu_e$  in a dielectric. The latter parameter is known to be the physical essence of the collision ionization criteria, which actually determine just one cause of the current pinching.

If the superheat instability is assumed the main mechanism operating at the first stage of the electric discharge, it is possible to evaluate the space ( $M_L$ ) and time ( $M_t$ ) instabilities [4]. Neglecting the diffusion, at  $dU/dt \neq 0$  we have

$$M_L \geq \frac{2\varepsilon\varepsilon_0}{\mu_e(M_c)E_c} \frac{dU}{dt}, \quad M_t = \frac{E_c}{2(dU/dt)} M_L. \quad (1)$$

### III. PRIMARY BREAKDOWN CHANNEL

The increase in the local current density during the superheat instability is followed by heating of the phonon subsystem if it has a finite heat capacity. In the limiting case, the solid material of the dielectric melts. So, formation of the primary channel, where a "solid-melt" phase transition takes place thanks to Joule losses, represents a typical electron-thermal process. Formation of this channel in the near-electrode region of dielectrics both at the cathode and the anode has common regular features described by the instabilities (1). Therefore it is probably not by accident that calculated  $M_t$  values and experimental values of the discharge delay time  $t_d$  coincide [5].

A minimum power density necessary for the aforementioned phase transition in AHC's is  $q_0 \geq 10^9 \div 10^{10} \text{ W/m}^2$ .

### IV. THE CATHODE PULSE DISCHARGE CHANNEL

Experiments showed [4] that the cathode discharge channel always spreads at a subsonic velocity:  $V_{cd} < C_0$ . Consequently, the material behind the phase transition front is in the molten state and its thermodynamic parameters are below the critical level. This means, in turn, that the cathode discharge channel spreads through the electron thermal mechanism. The difference between the last mechanism and a similar mechanism of the primary channel formation is not crucial. The thing is that under actual breakdown conditions both the superheat instability and point injection of charge carriers contribute to the local concentration of the current. These two processes can proceed concurrently. The superheat instability is preferred for formation of the primary channel. Oppositely, point injection with a high current density is responsible for the discharge channel spreading.

The last speculation is confirmed by small values of the potential barrier at the dielectric-melt interface. This potential barrier in AHC's equals  $10^{-2} < \Delta < 10^{-1} \text{ eV}$  [4].

From the laws of conservation of mass flux, momentum and energy it follows, as the one-dimensional approximation, that the effective power density at the interface  $\Phi_1$  (Fig. 2) is

$$q_{\text{eff}} = \rho_0 V_{cd} \Delta h_1 + \frac{1}{2} \rho_0 V_{cd} \left( \frac{\rho_0^2}{\rho_1^2} - 1 \right) = \frac{j^e r_0}{\sigma_0}, \quad (2)$$

where  $\Delta h_1$  is the change of the enthalpy, J/kg;  $r_0$  is the radius of a point injector;  $\sigma_0$  is electric conductivity of the solid dielectric near the interface.

The cathode discharge rate can be determined as [4]

$$V_{cd} = C_0 \exp \left[ - \frac{\Delta W(V_{cd})}{kT/V_{cd}} \right], \quad (3)$$

where

$$\Delta W(V_{cd}) = - \frac{\Delta W_{\text{melt}} k T_c \ln(V_{cd}/C_0)}{\Delta W_{\text{melt}} - kc \ln(V_{cd}/C_0)}, \quad (4)$$

$$T(V_{cd}) = - \frac{\Delta W_{\text{melt}} T_c}{\Delta W_{\text{melt}} - ck(\ln V_{cd}/C_0)}. \quad (5)$$

Here  $\Delta W(V_{cd})$  is the change of the enthalpy at a temperature  $T(V_{cd})$  referred to one molecule;  $\Delta W_{\text{melt}}$  is as above for the melt;  $T_c$  is the critical temperature;  $k$  is the Boltzmann constant;  $c = T_c - T_{\text{melt}}$ .

Considering known relations of the theory of injection currents [2], from expressions (2)-(3) it is possible to estimate quantitatively parameters of the material and the discharge depending on the discharge rate for, e.g., NaCl (Table 1).

Table 1 [4]

Parameter	Meas. unit	Discharge velocity, $V_{cd}$ (U), m/s		
		$7.5 \cdot 10^2$	$1.4 \cdot 10^3$	$2.5 \cdot 10^3$
$U_0$	$10^3 \text{ V}$	25	47	130
$i$	$10^{-3} \text{ A}$	$\sim 0.1$	$\sim 1.0$	$\sim 10$
$T$	$10^3 \text{ K}$	1.47	1.84	1.98
$\Delta h$	$10^6 \text{ J/kg}$	1.65	2.13	2.68
$\rho_1$	$10^3 \text{ kg/m}^3$	1.35	1.18	0.95
$q$	$10^{12} \text{ W/m}^2$	3.48	13.5	85.7
$r_0$	$10^{-7} \text{ m}$	0.5	1.55	4.0
$r$	$10^{-6} \text{ m}$	47.4	65	108
$U(r)$	$10^3 \text{ W}$	0.55	2.0	8.3
$E$	$10^7 \text{ V/m}$	0.65	1.75	4.3
$j$	$10^{10} \text{ A/m}^2$	1.27	1.33	2.9
$\sigma$	$10^2 \text{ Ohm}^{-1} \text{ m}^{-1}$	5.89	4.26	2.52

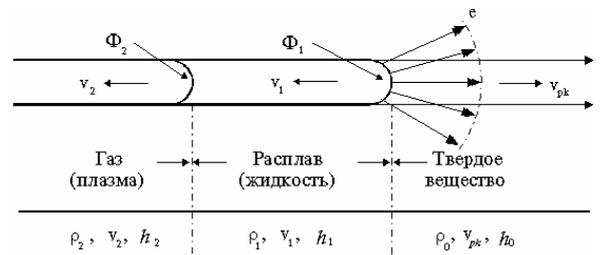


Fig. 2. One-dimensional model of the cathode discharge channel

### V. THE ANODE PULSE DISCHARGE CHANNEL

As was emphasized in the foregoing, the electron-thermal mechanism is also responsible for formation of the primary channel at the anode. A subsonic spreading velocity of this channel determines the shape of the channel, which is a capillary with fused smooth walls. Later the mechanism is altered. The channel spreads at a supersonic velocity  $V_{ad}$ . This is accompanied by an intensive decomposition of the solid material near the channel (Fig. 3).

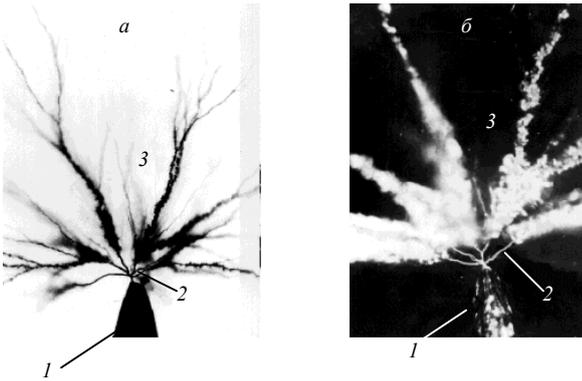


Fig. 3. Channels of an incomplete pulse discharge in acrylic glass in transmission (a) and reflected (b) light: 1 – pointed anode; 2 – region of primary channels; 3 – region of main channels.

The physical origin of this transition is considered elsewhere [6]. It is due to an exponential development of an instability of the interface between the melt and the solid electrolyte if the latter possesses a "frozen" positive charge.

Some effects accompany spreading of the main discharge channel from the anode. They are very significant for elaborating the corresponding physical models of the process. Thus, from the moment the channel glows at  $U_0$  and  $(Du/dt)_0$ , the velocity  $V_{ad}$  remains unchanged and is independent of any changes in the voltage pulse parameters with time. The glow velocity and the phase transition front speed coincide until a maximum speed  $V_{ad} > 1000$  km/s (Fig. 4).

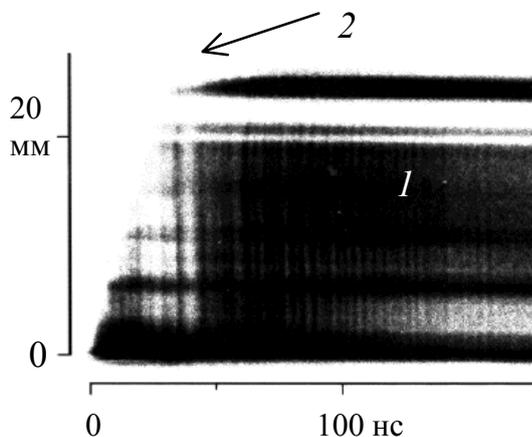


Fig. 4. Chronogram of intrinsic glow of the anode discharge channel in KCl (1) and channel plasma (2)

Plasma in the discharge channel has two regions with different thermodynamic parameters. Parameters of the plasma immediately behind the phase transition front are much superior to those of the rest channel plasma. As a result, they issue at different speeds from the channel mouth to air (Fig. 5). Finally, the phase transition front produces an oblique shock wave, which is quite natural if one considers a supersonic speed  $V_{ad}$ .

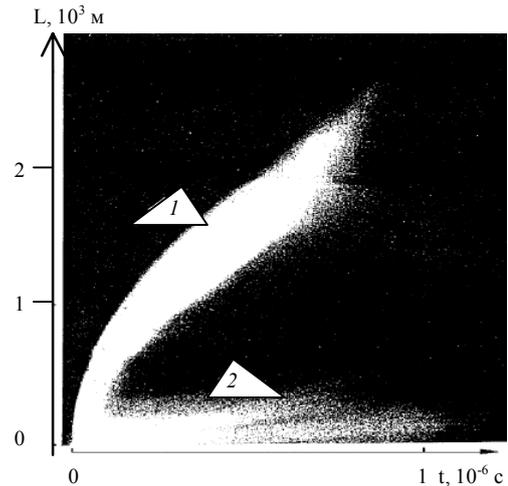


Fig. 5. Chronogram (slit scan) of issuing channel plasma of a nanosecond anode discharge in KCl: 1 – plasma at the head of the discharge channel ( $V_{nl} \leq 30$  km/s); 2 – channel plasma.

All these features are characteristic of detonation in a wide sense of this term. A most general formulation of this phenomenon can be found in [7]. The detonation process is characterized [10] as "appearance and existence of a stationary complex 'shock wave + energy generation zone' ". Let it be recalled that today other forms of detonation, e.g., light and thermonuclear detonations [8], are considered in addition to the widely known detonation of explosives. The concept of detonation is also used to describe spreading of a discharge channel in air [9] or after breakdown of thin-film M-D-M structures [10].

Considering specific features of the spreading mechanism of anode discharge channels, it was called "electronic detonation". Indeed, a shock wave is formed initially when its speed exceeds the supersonic velocity and the melt-dielectric interface is highly unstable.

The shock wave acts upon the solid electrolyte and, as a result, the forbidden band  $E_{fb}$  narrows to values providing appearance of conduction electrons with a required velocity [11]. In turn, this process is accompanied by generation of an energy  $Q_{ed}$  behind the phase transition front (in the energy generation zone), which supports further propagation of the shock wave. The process becomes a quasi-stationary one [4].

The detonation approximation can be used to estimate main parameters of the material in the energy generation zone for the whole range of the electronic detonation rate  $D_{ed}$ :

$$\left. \begin{aligned} P &= \rho_0 D_{ed}^2 / (n+1) = 2\rho_0(n-1)Q_{ed}, \\ Q_{ed} &= D_{ed}^2 / 2(n^2-1) \\ H &= \frac{P}{\rho_1} \frac{n}{n-1}, \quad U = \frac{P}{\rho_0} \frac{1}{n-1}, \quad \delta = \frac{\rho_1}{\rho_0} \end{aligned} \right\} \quad (6)$$

Here  $Q_{ed}$ ,  $H$  and  $U$  denote the specific energy, the enthalpy and the internal energy in the energy generation zone respectively, J/kg.

The relation between the velocity  $V_{ad}$  and the rate  $D_{ed}$  is established by measuring [12] initial velocities at which plasma issues to air. It was found [4] that at  $6 \leq V_{ad} \leq 1100$  km/s the rate  $D_{ed}$  in KCl changes in the limits  $6 \leq D_{ed} \leq 26$  km/s. This fact confirms occurrence of oblique shock waves when  $D_{ed} = V_{ad} \sin \alpha$ . The angle  $\alpha$  is larger than the Mach angle for all  $V_{ad}$  values [12]. The polytropic index  $n$  in (6) is found from experimental shock adiabats of solid dielectrics.

The analysis of velocities  $V_{ad}$  showed that when solid dielectrics are broken down, the plateau of square pulses has some voltage interval  $\Delta U_1$  where  $V_{ad}$  changes abruptly. In AHC's this changes takes place at  $100 \leq U \leq 150$  kV (Fig. 6).

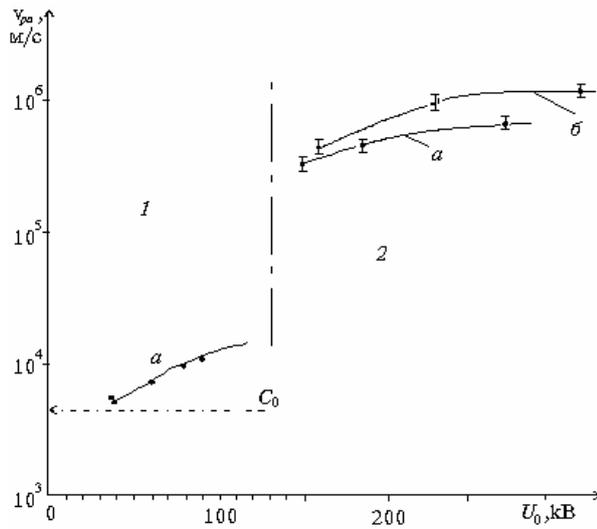


Fig. 6. Spreading velocity of the anode discharge channel after NaCl (a) and KCl (b) are punctured with microsecond (1) and nanosecond (2) square pulses of voltage.  $C_s$  is the sound velocity.

The analysis of equations of the energy balance during electronic detonation showed that this effect is connected with substitution of the mechanism responsible for generation of the energy  $Q_{ed}$ . Given a relatively low rate  $D_{ed} < 10$  km/s, the pressure in the energy generation zone (Fig. 7)

$$P_1 = \rho_0 D_{ed}^1 (1 - \delta^{-1}) - \frac{\varepsilon \varepsilon_0}{2} \left[ 2E_0^2 - \left( \frac{j}{\sigma_1} \right)^2 \right] \quad (7)$$

and the specific energy

$$Q_{ed} \cong \frac{D_{ed}}{\rho_0} \left( \frac{j^2 l_1}{\sigma_1} \right) \quad (8)$$

depend on the extent  $l_1$  of the energy generation zone, the current density  $j$ , and electroconductivity  $\sigma_1$ . Values of  $Q_{ed}$  determined using hydrodynamic (6) and electric-hydrodynamic (8) models were compared. Experimental data on the dependence  $\sigma_1(P_1)$  confirm the possibility that a Joule energy sufficient for upkeeping a shock wave is produced [13].

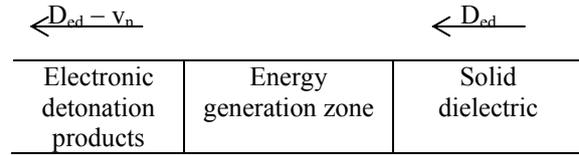


Fig. 7. Conditions of flow in a one-dimensional electronic detonation wave in a moving system of coordinates at  $D_{ed} < 10$  km/s.

If the rate  $D_{ed}$  and, correspondingly, the plasma pressure and temperature, increases further, electroconductivity of the plasma is improved. In this case the Joule energy is insufficient for the electronic detonation process. The mechanism responsible for generation of the energy  $Q_{ed}$  is altered and, consequently, a number of phenomenological values of the channel formation process change [14].

If  $D_{ed} > 15$  km/s and, correspondingly,  $V_{ad} > > 500$  km/s, the lifetime ( $z \geq 1$ ) of the strongly ionized material becomes comparable with the natural oscillation frequency of the lattice. Therefore dense non-ideal plasma immediately behind the shock wave front may be in the state of a physical cluster [15].

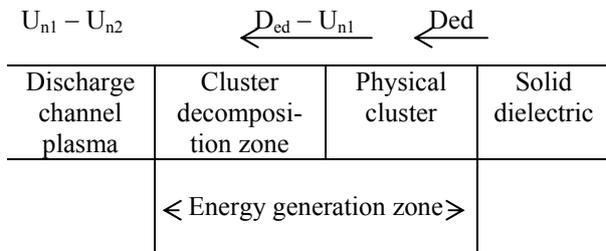


Fig. 8. Conditions of flow of a one-dimensional electronic detonation wave in a moving system of coordinates at  $D_{ed} > 15$  km/s.

The energy generation zone has a more complex structure (Fig. 8) and the specific energy  $Q_{ed}$  becomes

$$Q_{ed} = \frac{l_0 E_0 j}{2\rho_0 D_{ed}} + U_T, \quad (9)$$

where  $l_0$  is the extent of the region of the solid dielectric with the field  $E_0$  and  $U_T$  is the thermal component of the cluster energy [15]. It is not improbable that the energy produced at the end of the energy generation zone during decomposition of the physical cluster can change the character of the electronic detonation and transfer it to the group of "overcompressed" detonation [16].

Calculated parameters of the material in the energy generation zone during the anode discharge in KCl are given in Table 2.

Table 2 [4]

U, kV	$V_{ad}, 10^4$ , m/s	$D_{cd}, 10^4$ , m/s	$r_0, 10^6$ , m	$n$ , $\text{Ohm}^{-1}\text{m}^{-1}$
50	6.0	5.5	0.5	2.5
120	180	10.0	2.0	102
140	250	13.0	5.0	103
175	490	16.9	7.5	$5.13 \cdot 10^6$
220	890	20.0	9.0	$1.1 \cdot 10^6$
315	1.15	26.0	12.9	$2.1 \cdot 10^6$

U, kV	Q, $10^6$ , J/kg	j, $10^{10}$ , A/m <sup>2</sup>	i, A	
			calc.	exp.
50	1.0	0.23	$1.8 \cdot 10^{-3}$	$\sim 10^{-3}$
120	8.5	2.6	0.32	–
140	12.3	8.0	6.3	–
175	50.0	22.4	19.7	–
220	75.0	33	42.0	60,0
315	125.0	51.8	135	–

In the interval  $5.5 \leq V_{ad} \leq 1150$  km/s the power density in KCl changes between  $10^{14} \leq q_0 \leq 3 \cdot 10^{16}$  W/m<sup>2</sup>.

## VI. CONCLUSION

The proposed approach to description of pulse electric breakdown of solid dielectrics is based on the study into physical processes that take place during formation and spreading of discharge channels. This approach seems to show much promise. It allows determining for the first time the mutual quantitative relation between parameters of voltage and current pulses (U, dU/dt, j), thermodynamic and energy parameters of materials in the phase transition zone (P, T,  $\Delta h$ ,  $Q_{eff}$ , q,  $\sigma$ ), and individual properties of dielectrics ( $\rho_0$ ,  $\epsilon$ , K,  $E_G$ ). However, further development of the proposed approach calls for a variety of special theoretical and experimental studies, most of which are listed in [4].

## REFERENCES

- [1] W. Franz. Dielektrischer Durchschlag. *Handbuch der Physik*, **17**, p. 155-263, (1956).
- [2] M.A. Lampert, P. Marc. Current Injection in Solid, N.-Y., (1970).
- [3] Yu.N. Vershinin, Yu.A. Zotov. *Phys. Sol. St.* **17**, 3, 526 (1975).
- [4] Yu.N. Vershinin. Electron-Thermal and Detonation Processes upon Electric Breakdown of Solid Dielectrics, Ekaterinburg, p. 273 (2000). (in Russian)
- [5] A.A. Vorobiev, G.A. Vorobiev. Electric Breakdown and Decomposition of Solid Dielectrics, Moscow, p. 224 (1966). (in Russian)
- [6] D.S. Iljichev. p. 214 in [4].
- [7] A.I. Prohorov, V.I. Konov, I. Ursu, I.I. Mihailescu. Interaction of laser radiation with metals, Edit. Acad., Bucuresti; M.: Nauka, p.537. (1988).

- [8] Y.P. Raizer. Laser Spark and Spreading of Discharges, Moscow, p. 308 (1974). (in Russian)
- [9] A.F. Dyakov, Yu.K. Bobrov. *Proc. JCPJG XXIII*, Toulouse, (1997).
- [10] E.G. Kostsov. *Proc. Conf. Physics of Dielectrics, Baku*, p. 21 (1982).
- [11] Yu.N. Vershinin. *Buttl. Soc. Cat.* **XII**, 2, p. 533 (1991).
- [12] F.A. Baum, K.P. Stanyukovich, B.I. Shekhter. Physics of Explosion, Moscow, p. 800 (1959). (in Russian)
- [13] Yu.N. Vershinin. *Dokl. Akad. Nauk*, **347**, 5, 1, p. 279 (1996). (in Russian)
- [14] Yu.N. Vershinin, D.S. Iljichev. *Dokl. Akad. Nauk* (to be published). (in Russian)
- [15] B.F. Fortov, I.T. Yakubov. Physics of Non-Ideal Plasma, Chernogolovka, p. 263 (1984). (in Russian)
- [16] Ya.B. Zeldovich, A.S. Kompaneyets. Theory of Detonation, Moscow, p. 273 (1955) (in Russian)