

## The impact of the nonlinear effects on thermally stimulated depolarization currents in ion dielectrics

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### ABSTRACT

In this paper, the methods described the calculation of thermally stimulated depolarization currents in materials of the HBC class. In the identification of nonlinear processes of thermally stimulated depolarization, at this stage of the research, as defining criteria the authors consider the calculation of the dielectric initial polarization in the infinite approximation of perturbation theory (at the fundamental frequency fields) and calculation of kinetic coefficients in functions of the polarizing field intensity. Generalized nonlinear expressions for the complex dielectric constant and polarization are formulated, which are performed at the fundamental frequency of the alternating polarizing field. The generalized equations that are nonlinear by the field for kinetic coefficients of the kinetic equation are formulated. The obtained theoretical results are of current interest from the perspective of further development of analytical and computer methods of research and prediction of HBC properties as perspective nonlinear materials for a number of branches of modern industry.

**Keywords:** Nonlinear polarization effect, Polarization of dielectric, Thermally stimulated depolarization, Kinetic theory.

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## 1. Introduction

When studying the electrophysical properties of various semiconducting and dielectric materials with a complex crystal structure (ceramics; layered crystals (mica, crystalline hydrates); perovskites; vermiculites, etc.), the most effective method is dielectric spectroscopy, which is reduced to precision measurements and calculations of the parameters of dielectric loss spectra and thermally stimulated polarization (TSP) and depolarization currents [1-4]. The results of these studies are relevant for modern electric materials science, which constitutes the theoretical basis for the development and search for the most effective methods and schemes for the use of solid-state composite materials (MIS, CPM-structures, etc.) as functional elements of electrical circuits of

various installations and systems (control-and-measuring, electronically-controlled, electronic-computing, diagnostic), operating in real industrial production.

As an object of research, the authors have selected widely used in modern technologies (microelectronics and radio electronics; optoelectronics and laser technology; insulation and cable technology; electrochemical technologies and hydrogen energy, etc.) hydrogen-bonded crystals (HBC), classified as proton semiconductors and dielectrics. The theoretical concepts of the mechanism of thermally stimulated depolarization, at the present time, are based on the phenomenological kinetic theory built on the solution of the system of Fokker-Planck and Poisson equations for a given model of electrodes, in the linear approximation of the perturbation theory in a small parameter [1; 4]. According to M. P. Tonkonogov as a physical relaxation oscillator (the most mobile particle that relaxes the electric field) in the HBC, far from the breakdown, a hydrogen ion (proton) is picked, moving with the activation energy determined in the vicinity of the temperature of the experimental maximum of the thermally stimulated current. Measurements of temperature density spectra of TSP in the work of M.P.

Tonkonogov [1] were carried out at the polarizing field strengths and temperature  $E_0 \approx (10^5 \div 10^6) \frac{B}{M}$  and

temperature  $T = 50-550$  K. From the results of studies carried out in [5-7], it is obvious that expanding the experimental range of variation of field and temperature parameters will deepen the theoretical understanding of the mechanism of thermally stimulated polarization and depolarization, especially in the region of anomalously high nonlinearities. These nonlinearities are exhibited in the range of weak fields (100-1000 kV/m) at ultra-low temperatures (1-10 K) and strong fields (100-1000 kV/m) at ultra-low temperatures (1-10 K).

Dimensionless parameter [6; 8; 9] on the kinetics of bulk-charge polarization and conductivity in the area of abnormally high polarization nonlinearities [4; 5]. Quantum-mechanical nonlinearities associated with proton tunneling transitions will be reflected in the calculation of the generalized diffusion and mobility coefficients, also in an infinite approximation at a small dimensionless parameter, which has the meaning of the ratio of the potential energy in an electric field to the energy of its thermal motion. The developed methodology for calculating the depolarization (TSDC) density spectra is associated with the procedure for optimizing the calculated values of the parameters of relaxers performed by method of comparison function minimization.

In this paper, the methods described in works of V.A. Kalytka [10], will be applied to the calculation of thermally stimulated depolarization currents in materials of the HBC class. Issues related to categorization, practical application and analysis of electrophysical properties of HBC are considered in publications of V.A. Kalytka [10], et al., a comparative analysis of different models of thermally stimulated depolarization currents in HBC was performed from the perspective of comparability of the results of theoretical and experimental studies.

In the identification of nonlinear processes of thermally stimulated depolarization, at this stage of the research, as defining criteria the authors consider the calculation of the dielectric initial polarization in the infinite approximation of perturbation theory (at the fundamental frequency fields) and calculation of kinetic coefficients in functions of the polarizing field intensity.

## 2. Materials and methods

In this paper, the study of polarization processes of a model crystal of the HBC class will be conducted by the methods of quasi-classical kinetic theory [4; 6; 10; 11], using the results of analytical solutions of system of nonlinear equations of the phenomenological proton conductivity model that was previously constructed by methods of perturbation theory and Fourier transform methods [4; 6]. The Fokker-Planck kinetic equation is assumed to be linearized, i.e. it does not contain nonlinear degrees of the sought-for concentration of charge carriers (protons). The electrodes are blocking. The external perturbation is reduced to the effect on the dielectric of a harmonically time-varying uniform electric field:

$$E(t) = E_0 \exp(i\omega t). \quad (1)$$

In order to reduce the bulkiness of mathematical transformations, we will operate on the first approximation on the frequency of the alternating field. Based on the results of the research of [6], we assume the polarization of the crystal in an infinite approximation at a small parameter of the perturbation theory, at the fundamental frequency of the alternating field:

$$P^{(\omega)}(t) = \frac{8aqn_0\gamma}{\pi^2 \left(1 - \frac{8n_0\phi\Lambda_0\gamma}{\pi^2}\right)} \times \sum_{n=1}^{+\infty} \left[ \frac{\sin^2\left(\frac{\pi n}{2}\right)}{n^2 \left(\frac{1}{\tau_n} + i\frac{\omega}{W^{(0)}}\right)} \right] \times \exp(i\omega t). \quad (2)$$

In (2) the complex dimensionless parameter (3):

$$\Xi_0 = \frac{8n_0\phi\Lambda_0\gamma}{\pi^2} \quad (3)$$

is determined by a number of other fundamental parameters of the kinetic theory of proton relaxation (4) [6]:

$$\phi = \frac{aq}{\varepsilon_0\varepsilon_\infty E_0} \quad (4)$$

is a value having the dimension that is inverse of the equilibrium concentration of relaxers (protons)  $n_0$ :

$$\gamma = \frac{\mu_{\text{mob}}^{(i)} a E_0}{D_{\text{diff}}^{(0)}} = \zeta_0 \frac{W^{(i)}}{W^{(0)}} \quad (5)$$

(5) is a small dimensionless parameter of the perturbation theory:

$$D_{\text{diff}}^{(0)} = a^2 W^{(0)}, \quad (6)$$

$$\mu_{\text{mob}}^{(i)} = \frac{q a^2 W^{(i)}}{k_B T} \quad (7)$$

(6), (7) is diffusion and mobility coefficients for protons calculated by the “zero” approximation of the theory of successive approximations [6]. The small dimensionless parameter (8):

$$\zeta_0 = \frac{qE_0 a}{k_B T} \quad (8)$$

has the meaning of the parameter of comparison of potential (in an electric field) energy and energy of proton thermal motion:

$$\Lambda_0 = \sum_{n=1}^{\infty} \frac{\sin^2\left(\frac{\pi n}{2}\right)}{n^2 \left(\frac{1}{\tau_n} + i\frac{\omega}{W^{(0)}}\right)} \quad (9)$$

(9) is a parameter of interaction of relaxation modes, at the fundamental frequency  $\omega$  [6; 11]. The dimensionless relaxation time (10):

$$\tau_n = \frac{\tau_{n,D} \tau_M}{\tau_{n,D} + \tau_M} \quad (10)$$

corresponding to the  $n$ th relaxation mode of the bulk charge density is revealed through the diffusion relaxation time of the  $n$ th mode (11):

$$\tau_{n,D} = \frac{\tau_D}{n^2} \quad (11)$$

and the Maxwell relaxation time (12) [6]:

$$\tau_M = \frac{\varepsilon_0 \varepsilon_\infty W^{(0)}}{q n_0 \mu_{\text{mob}}^{(1)}}, \quad (12)$$

where (13):

$$\tau_D = \left( \frac{d}{\pi a} \right)^2 \quad (13)$$

is determined by the crystal thickness  $d$  and the lattice parameter  $a$ ;  $\varepsilon_\infty$  – is the high-frequency dielectric permittivity;  $q$  – is the proton charge.

The kinetic coefficients are calculated in the approximations  $l=0$ ,  $l=1$ , at a small parameter (14):

$$\zeta(\mathbf{x}; t) = \left| \frac{qE(\mathbf{x}; t)a}{2k_B T} \right| < 1, \quad (14)$$

with regard to both thermally activated (classical) and tunneled (quantum) proton transitions through the parabolic potential barrier (15)-(18) [11]:

$$W^{(0)}(T) = \frac{v_0}{2} \left( \exp(-X) + \langle D^{(0)} \rangle \right), \quad (15)$$

$$\langle D^{(0)} \rangle = \frac{\exp(-\Lambda) - \exp(-X)}{1 - \frac{\Lambda}{X}}, \quad (16)$$

$$W^{(1)}(T) = \frac{v_0}{2} \left( \exp(-X) + \langle D^{(1)} \rangle \right), \quad (17)$$

$$\langle D^{(1)} \rangle = \frac{\frac{\Lambda}{X} \exp(-\Lambda) - \exp(-X)}{1 - \frac{\Lambda}{X}}, \quad (18)$$

where:

$$X = \frac{U_0}{k_B T}, \quad \Lambda = \frac{\pi \delta_0 \sqrt{mU_0}}{\hbar \sqrt{2}}, \quad (19)$$

$m$  – is the mass of the proton;  $U_0$  – is the height of the potential barrier (the hydrogen-bonded proton activation energy);  $\delta_0$  – is the width of the potential barrier;  $\nu_0$  – is the linear frequency of the self-oscillations of the proton in the potential well [11]. Noticing that:

$$\tau_M = \frac{1}{\theta}, \tag{20}$$

where:

$$\theta = \phi \gamma n_0 \tag{21}$$

and taking

$$\Xi_0 = \frac{8 \Lambda_0}{\pi^2 \tau_M}, \tag{22}$$

and then moving on to dimensional relaxation time:

$$T_M = \frac{\tau_M}{W^{(0)}}, \tag{23}$$

because of:

$$\Xi_0 = \frac{8 \Lambda_0}{\pi^2 T_M W^{(0)}}, \tag{24}$$

and given equality:

$$T_n = \frac{\tau_n}{W^{(0)}}, \tag{25}$$

we rewrite (2) as:

$$P^{(\omega)}(t) = \varepsilon_0 \varepsilon_\infty E(t) \times \frac{\Gamma^{(\omega)}}{1 - \Gamma^{(\omega)}}. \tag{26}$$

In (15)-(16) the complex function is introduced:

$$\Gamma^{(\omega)} = \frac{8}{\pi^2 \tau_M} \sum_{n=1}^{\infty} \left[ \frac{\sin^2\left(\frac{\pi n}{2}\right)}{n^2 \left(\frac{1}{\tau_n} + i \frac{\omega}{W^{(0)}}\right)} \right] = \frac{8}{\pi^2 T_M} \sum_{n=1}^{\infty} \left[ \frac{\sin^2\left(\frac{\pi n}{2}\right)}{n^2 \left(\frac{1}{T_n} + i \omega\right)} \right] \tag{27}$$

Take (26) as

$$\Gamma^{(\omega)} = \Gamma_1^{(\omega)} - i \Gamma_2^{(\omega)} \tag{28}$$

and denote (29)-(30):

$$\Gamma_1^{(\omega)}(\mathbf{T}) = \frac{8}{\pi^2} \sum_{n=1}^{\infty} \left[ \frac{\tau_n \sin^2\left(\frac{\pi n}{2}\right)}{n^2(1 + \omega^2 \tau_n^2)} \right] = \frac{4}{\pi^2} \sum_{n=1}^{\infty} \left[ \frac{T_n (1 - (-1)^n)}{n^2(1 + \omega^2 T_n^2)} \right], \quad (29)$$

$$\Gamma_2^{(\omega)}(\mathbf{T}) = \frac{8}{\pi^2} \sum_{n=1}^{\infty} \left[ \frac{\omega \tau_n^2 \sin^2\left(\frac{\pi n}{2}\right)}{n^2(1 + \omega^2 \tau_n^2)} \right] = \frac{4}{\pi^2} \sum_{n=1}^{\infty} \left[ \frac{\omega T_n^2 (1 - (-1)^n)}{n^2(1 + \omega^2 T_n^2)} \right]. \quad (30)$$

Presenting the polarization of the dielectric in the general form (31):

$$\mathbf{P}^{(\omega)}(\mathbf{t}) = \varepsilon_0 (\hat{\varepsilon}^{(\omega)} - \varepsilon_\infty) \cdot \mathbf{E}(\mathbf{t}) \quad (31)$$

according to (26), we write the complex dielectric constant (32):

$$\hat{\varepsilon}^{(\omega)} = \varepsilon_\infty \times \frac{1}{1 - \Gamma^{(\omega)}}, \quad (32)$$

Combining (31) and (32) we have (33):

$$\mathbf{P}^{(\omega)}(\mathbf{t}) = \varepsilon_0 \varepsilon_\infty \left( \frac{1}{1 - \Gamma^{(\omega)}} - 1 \right) \cdot \mathbf{E}(\mathbf{t}), \quad (33)$$

Equations (32), (33) are the most generalized at the fundamental frequency of the alternating field and can be further used in detailed studies of the properties and behavior of the spectra of complex dielectric constant in a wide range of field frequencies and temperatures [10]. At a certain level, this issue has already been solved in the study of V.A. Kalytka [6], which describes a scheme for calculating the polarization up to the second odd harmonic multiple of , constructs approximate equations for polarization on an arbitrary frequency harmonic of  $r$  multiplicity. However, components of complex dielectric constant were not explicitly calculated in the above work [6], which is the subject of a separate theoretical study based on rather cumbersome mathematical transformations, the result of which is relevant for areas of abnormally high polarization nonlinearities (ultra-low temperatures and strong electric fields) [4; 6; 11].

Now we proceed to the calculation of dielectric constant (32) and polarization (33) in a static uniform electric field. Then, noticing that  $\Gamma_2^{(\omega=0)}(\mathbf{T}) = 0$ ,

$$\Gamma_1^{(\omega=0)}(\mathbf{T}) = \frac{4}{\pi^2} \sum_{n=1}^{\infty} \left[ \frac{T_n (1 - (-1)^n)}{n^2} \right] \quad (34)$$

and, owing to (35):

$$\frac{T_n}{T_M} = \frac{T_{n,D}}{T_{n,D} + T_M}, \quad (35)$$

where:

$$T_{n,D} = \frac{T_D}{n^2}, \tag{36}$$

$$T_D = \left( \frac{d}{\pi a} \right)^2 [W^{(0)}]^{-1}, \tag{37}$$

when:

$$\frac{T_n}{T_M} = \frac{\frac{T_D}{n^2}}{n^2 + \frac{T_D}{T_M}}, \tag{38}$$

write:

$$\hat{\epsilon}^{(\omega=0)} = \epsilon_S(\mathbf{T}) = \epsilon_\infty \times \frac{1}{1 - \Gamma^{(\omega=0)}} = \frac{\epsilon_\infty}{1 - \frac{4T_D}{\pi^2 T_M} \sum_{n=1}^{\infty} \frac{(1 - (-1)^n)}{n^2 \left( n^2 + \frac{T_D}{T_M} \right)}}. \tag{39}$$

On the basis of equality (40):

$$\sum_{n=1}^{\infty} \frac{(1 - (-1)^n)}{n^2 \left( n^2 + \frac{T_D}{T_M} \right)} = \frac{\pi^2}{4} \frac{1}{\frac{T_D}{T_M}} \left( 1 - \frac{\text{th} \left( \frac{\pi}{2} \sqrt{\frac{T_D}{T_M}} \right)}{\frac{\pi}{2} \sqrt{\frac{T_D}{T_M}}} \right), \tag{40}$$

from (39) and (33) we obtain static equations:

$$\epsilon_S(\mathbf{T}) = \epsilon_\infty x_{D,M} \cdot \text{cth}(x_{D,M}), \tag{41}$$

$$\mathbf{P}_S = \epsilon_0 \epsilon_\infty (x_{D,M} \cdot \text{cth}(x_{D,M}) - 1) \cdot \mathbf{E}_0, \tag{42}$$

where:

$$x_{D,M} = \frac{\pi}{2} \sqrt{\eta(\mathbf{T})}, \tag{43}$$

$$\eta(\mathbf{T}) = \frac{T_D(\mathbf{T})}{T_M(\mathbf{T})} = \frac{d^2 n_0 q^2}{\pi^2 \epsilon_0 \epsilon_\infty k_B T} \cdot \frac{W^{(1)}(\mathbf{T})}{W^{(0)}(\mathbf{T})}. \tag{44}$$

From the identity (45):

$$\frac{T_D}{T_M} = \left( \frac{d}{r_D} \right)^2 \tag{45}$$

we compute the Debye's shielding radius (46):

$$r_D(T) = d \sqrt{\frac{T_M}{T_D}}, \quad (46)$$

or (47):

$$r_D(T) = \pi \sqrt{\frac{\varepsilon_0 \varepsilon_\infty \cdot D_{\text{dif}}^{(0)}(T)}{q n_0 \cdot \mu_{\text{mob}}^{(i)}(T)}}. \quad (47)$$

Then, in the relaxation of the mixed type ( $T_M \approx T_D$ ) we have (48):

$$r_D(T) = \frac{\pi}{q} \sqrt{\frac{\varepsilon_0 \varepsilon_\infty k_B T}{n_0}} \cdot \frac{\sqrt{\exp\left(-\frac{U_0}{k_B T}\right) + \langle D^{(0)} \rangle}}{\sqrt{\exp\left(-\frac{U_0}{k_B T}\right) + \langle D^{(i)} \rangle}} \quad (48)$$

In the area of diffusion relaxation, taking  $T_D \ll T_M$ , when (49):

$$x_{D,M} = \frac{\pi d}{2 r_D} \ll 1, \quad (49)$$

due to an approximate equation (50):

$$\text{cth}(x_{D,M}) \approx \frac{1}{x_{D,M}} + \frac{x_{D,M}}{3}, \quad (50)$$

from (41), (42) we obtain the approximated equations (51)-(52):

$$\varepsilon_S(T) \approx \varepsilon_\infty \left( 1 + \frac{\pi^2 d^2}{12 r_D^2} \right), \quad (51)$$

$$P_S \approx \frac{\varepsilon_0 \varepsilon_\infty \pi^2 d^2}{12 r_D^2}. \quad (52)$$

Here, in the numerical evaluation of temperature effects on the Debye's shielding radius  $r_D(T)$ , the equation (48) is used, in which, at the microscopic level, both thermally activated and tunneling proton transitions are taken into account. At the same time, at the macroscopic level, the type of proton relaxation, due to the large values of the Maxwell relaxation time (owing to small concentrations of protons), is taken as diffusion one. In the case of an infinitesimal ratio of (53):

$$\eta(T) = \frac{T_D(T)}{T_M(T)} \ll 1, \quad (53)$$

when (54):



$$x_{D,M} = \frac{\pi d}{2r_D} \rightarrow 0, \quad (54)$$

according to the limit (55):

$$\lim_{x \rightarrow 0} [x \cdot \text{cth}(x)] = \lim_{x \rightarrow 0} \left[ \frac{1}{\frac{\text{th}(x)}{x}} \right] = 1, \quad (55)$$

the dielectric constant tends to high-frequency permeability and the polarization tends to zero. In the area  $T_M \ll T_D$  when (56):

$$\eta(T) = \frac{T_D(T)}{T_M(T)} \gg 1, \quad (56)$$

$$x_{D,M} = \frac{\pi d}{2r_D} \gg 1 \quad (57)$$

according to (58):

$$\lim_{x \rightarrow \infty} [\text{cth}(x)] = \lim_{x \rightarrow \infty} \left[ \frac{1}{\text{th}(x)} \right] = 1 \quad (58)$$

and (59):

$$x \cdot \text{cth}(x) \approx x, \quad (59)$$

we have approximately (60), (61):

$$\varepsilon_s(T) \rightarrow \frac{\pi d \varepsilon_\infty}{2r_D} \gg 1, \quad (60)$$

$$P_S \approx \frac{\varepsilon_0 \varepsilon_\infty \pi d}{r_D}, \quad (61)$$

in the case. It is obvious that the Maxwell relaxation caused by high proton concentrations provides abnormally small values of the Debye shielding radius  $r_D \ll d$ . At the same time, as in the case of diffusion-relaxation polarization, both the classical and quantum mechanism of proton transfers through the potential barrier is equally taken into account.

Regarding the effect that microscopic mechanism of proton transitions in the potential relief has on the Debye shielding radius, it is easy to see from (48) that in the temperature area (zone) of classical transitions, at temperatures much higher than the critical (62) [10]:

$$T_{cr,mov} = \frac{\hbar \sqrt{2U_0}}{\pi \delta_0 k_B \sqrt{m}} \quad (62)$$

when (63), (64):

$$T \gg T_{cr,mov}, \tag{63}$$

$$\frac{\Lambda}{X} \gg 1 \tag{64}$$

and (65):

$$W^{(l)}(T) \rightarrow W_{therm}^{(l)}(T) = \frac{v_0}{2} \exp(-X), \tag{65}$$

we obtain an equation (66):

$$r_D(T) \approx \frac{\pi}{q} \sqrt{\frac{\epsilon_0 \epsilon_\infty k_B T}{n_0}} \tag{66}$$

that is consistent with the representations of the classical statistical theory and, near the temperature of absolute zero  $r_D(T) \rightarrow 0$ .

In the temperature area of quantum transitions, at temperatures below the critical ones, when  $T < T_{cr,mov}$ ,  $\frac{\Lambda}{X} < 1$  and (67):

$$W^{(l)}(T) \rightarrow W_{tunnel}^{(l)}(T) = \frac{v_0}{2} \langle D^{(l)} \rangle, \tag{67}$$

from (68):

$$r_D(T) = \frac{\pi}{q} \sqrt{\frac{\epsilon_0 \epsilon_\infty k_B T}{n_0}} \cdot \frac{\sqrt{\langle D^{(0)} \rangle}}{\sqrt{\langle D^{(l)} \rangle}}. \tag{68}$$

In the case of  $T \ll T_{cr,mov}$ ,  $\frac{\Lambda}{X} \ll 1$ , when (69):

$$\langle D^{(l)} \rangle \approx \frac{\left(\frac{\Lambda}{X}\right)^l \exp(-\Lambda)}{1 - \frac{\Lambda}{X}}, \tag{69}$$

we obtain the limit equation (70):

$$r_D(T) \approx \frac{\pi}{q} \sqrt{\frac{\epsilon_0 \epsilon_\infty k_B T}{n_0}} \cdot \sqrt{\frac{X}{\Lambda}} = \frac{\pi}{q} \sqrt{\frac{\epsilon_0 \epsilon_\infty \hbar \sqrt{2U_0}}{n_0 \pi \delta_0 \sqrt{m}}}. \tag{70}$$

The identity (71):

$$\frac{X}{\Lambda} = \frac{\hbar \sqrt{2U_0}}{\pi k_B T \delta_0 \sqrt{m}} \tag{71}$$

was used here. It is easy to see that, taking into account the quantum effects reflected in the expression (72):

$$\langle \mathbf{D}^{(l)} \rangle \approx \left( \frac{\Lambda}{\mathbf{X}} \right)^l \langle \mathbf{D}^{(0)} \rangle, \quad (72)$$

where

$$\langle \mathbf{D}^{(0)} \rangle \approx \left( 1 - \frac{\Lambda}{\mathbf{X}} \right)^{-1} \times \exp(-\Lambda), \quad (73)$$

in contrast to the classical theory, causes a non-zero value of the Debye shielding radius near the temperature of absolute zero. In this case, assuming  $\frac{\Lambda}{\mathbf{X}} \rightarrow 0$ ,  $\langle \mathbf{D}^{(0)} \rangle \rightarrow \exp(-\Lambda)$ :

$$\langle \mathbf{D}^{(l)} \rangle \approx \frac{\Lambda}{\mathbf{X}} \langle \mathbf{D}^{(0)} \rangle, \quad (74)$$

we obtain the same result as above:

$$r_D(0) \rightarrow \frac{\pi}{q} \sqrt{\frac{\varepsilon_0 \varepsilon_\infty \hbar \sqrt{2U_0}}{n_0 \pi \delta_0 \sqrt{m}}}. \quad (75)$$

### 3. Results and discussion

A detailed analysis of the effects of various external factors (variation of the amplitude of the electromotive force (EMF) of the voltage source; alloying; calcination; negative currents) makes it possible to reveal the physical nature of each type of relaxation oscillators (charged structural defects), activated near temperatures corresponding to the experimental maximum density of the TSP  $-J_{depol,exp}(T)$ , or dielectric loss tangent  $-tg_{exp}(T)$ . Of greatest theoretical and practical interest are the anomalously high nonlinearities exhibited during the polarization of ionic dielectrics in the region of strong electric fields (10-1000 MV/m) [5-7; 11], when, as a result activation of two or more types of relaxation oscillators, against the background of sufficiently high conduction currents, the amplitude of the high-temperature (500-1500 K) current density maximum begins to depend significantly on the intensity of the polarizing field [2; 9].

An important issue is the study of the processes of charge accumulation and relaxation in nanoscale surface plastic deformations (low-temperature electret effect) in the development of fuel cells for hydrogen energy [12-15] in the field of space technology and for electrochemical technology [16-21].

Mathematical modeling of the quantum transfer of protons in systems from thin potential barriers with potential wells containing quantum-well energy levels is relevant in the development of physical principles and schemes of operation of resonant tunneling diodes (RTD) and quantum field effect transistors (FETs) based on proton semiconductors and dielectrics, for microelectronics, radio electronics and quantum electronics [22-28].

Anomalously high transparency of potential barriers of the transverse voltage pattern [29], against the background of sufficiently high frequencies of proton vibrations in transverse potential wells (around  $10^{13} \text{ c}^{-1}$ ) [2-4; 6; 9], make it possible to use the effects of the nanoscale state of the HBC [29] and some other quantum size effects to create ultrafast digital or microwave devices with operating frequencies of more than 1 THz [24; 30-32]. Devices of this type include optical interferometers, interference filters, monochromators, thin-film systems such as resonant tunneling diodes, triodes, etc. [33-36]. The main directions of further studies of the kinetics of low-temperature proton relaxation in crystals with hydrogen bonds (HBC) will be reduced to the construction and development of schemes for analytical solutions of quantum-mechanical kinetic equations, taking into account the effect of proton-phonon interactions on proton-relaxation polarization and conductivity.

At the same time, the methods of the semiclassical kinetic theory of space-charge polarization and depolarization are effective from the point of view of comparative estimates of the effects of various kinds of quantum nonlinearities on the spectra of depolarization currents and on the values of the characteristic parameters of relaxers. It is obvious that the dynamics of interactions in the systems "electron and phonons in a dielectric" and "protons and phonons in a dielectric" [37-39], is not absolutely identical, even if this dielectric is a HBC, due to a number of differences in the conditions of motion of the major charge carriers and in the specifics of their interaction with phonons. The same applies to the mathematical apparatus describing these models [40-58]. In fact, vibrations of a proton, in a certain range of field and temperature parameters (close to breakdown), themselves can generate phonons that affect conduction electrons. In this case, far from breakdown, when the effects of proton relaxation dominate in the dielectric, and electrons are distributed deep in the valence band, the proton already becomes a light mobile particle, and the vibrations of more massive sedentary anions generate phonons for protons and the proton-phonon interaction is activated [59-75]. All these issues can be investigated only in combination with the results of preliminary detailed theoretical studies of the effects of the tunneling motion of protons on the theoretical spectra of the complex permittivity (CDP), polarization and depolarization currents in the HBC, within the framework of the nonlinear quasi-classical kinetic theory, taking into account the transparency of the potential barrier so far only in as a term in the kinetic coefficients of the Fokker-Planck equation, which also determines the scientific significance of the studies carried out in this paper [76-95].

Note that due to the similarity of the diffusion mechanisms of high-temperature proton conductivity in HBC [4; 6; 10] and ionic conductivity in YSZ crystals [96-100], constructed in [4-6] equations of diffusion transfer of protons in an electric field, after some model upgrades, can be used in the mathematical description of the kinetics of transfer of oxygen ions during the polarization of dielectrics such as zirconium dioxide [101-123].

In the study of Yu.M. Annenkov experimentally, in samples of corundum-zirconium ceramics, or CZC ( $ZrO_2 - Y_2O_3 - n(Al_2O_3)$ ), at a frequency of an alternating field of 1 kHz, at the point  $T = 1250$  K, anomalously high dielectric constants  $\epsilon = 5 \cdot 10^6$  were found, due to, according to the authors (Annenkov et al., 2005), structural rearrangement of the oxygen sublattice in the CZC, near the critical temperature (quasi-ferroelectric effect) [124]. The equations of high-temperature (550 – 1500) space-charge polarization of the HBC – nonlinear equations of the Fokker – Planck type [4; 6], can also be applied to the CZC, when describing the mechanism of relaxation motion (transfer) oxygen ions and, accordingly, to the study of the spectra  $\epsilon(T)$ , near the phase transition temperature, which is important when constructing theoretical methods for predicting the nonlinear electrophysical properties of high-temperature ionic superconductors [125-146].

This class of materials also includes magnesium-doped ceramic crystals of the copper (I) chromite type with hopping hole conductivity [147-149].

Studies of the mechanism of proton relaxation in thermally stimulated depolarization in HBC should be conducted on the basis of the kinetic equation describing the transfer of protons in the field of destructive electret charge accumulated in the dielectric volume for the period of polarization during the time of the order of relaxation time. The value of the polarization relaxation time, as established from the solutions of the nonlinear Fokker-Planck equation, is a discrete value calculated separately for each number  $n$  of the relaxation mode. The temperature of the crystal is assumed to be constant and equal to the polarization  $T_{pol}$ . In this case, the ratio

$\frac{T_D(T_{pol})}{T_M(T_{pol})}$  determines the mechanism of formation of the volume-charge distribution in the space between the capacitor plates at the field strength  $E_{pol}$  and the type of temperature dependence of the Debye shielding radius of the charge  $r_D(T_{pol})$ .

Thus, the study of relaxation time spectra  $T_n(T_{pol})$  is an important component of the polarization problem and ultimately determines the asymptotics of polarization established in the dielectric during the polarization time  $t_{pol}$ . Then, the calculation of the initial polarization of the dielectric, according to the traditional scheme of measuring the thermally stimulated depolarization current, will be conducted at the temperature  $T_{pol}$  and intensity of a uniform static polarizing field  $E_{pol}$ . In this case, the initial polarization of the experimental sample (76):

$$P_{depol}(0) = \varepsilon_0 \varepsilon_\infty (x_{D,M}(T_{pol})) \cdot \text{cth}(x_{D,M}(T_{pol})) - 1) \cdot E_{pol} \quad (76)$$

Here (77):

$$x_{D,M}(T_{pol}) = \frac{\pi}{2} \sqrt{\eta_{pol}} \quad (77)$$

where (78):

$$\eta_{pol} = \frac{T_D(T_{pol})}{T_M(T_{pol})} = \frac{d^2 n_0 q^2}{\pi^2 \varepsilon_0 \varepsilon_\infty k_B T_{pol}} \cdot \frac{W^{(1)}(T_{pol})}{W^{(0)}(T_{pol})} \quad (78)$$

The kinetic equation for the process of thermally stimulated depolarization describes the processes of relaxation motion of charge carriers (protons) in the absence of an external electric field  $E(t) = 0$ , when the linear heating of the crystal (79):

$$T(t) = T_0 + ct \quad (79)$$

where  $c = \text{const}$ ,  $T_0$  – is the initial depolarization temperature, causes the destruction of the polarized state  $P_{depol}(0)$ , and the current polarization of the dielectric in the process of thermally stimulated depolarization, as a function of time  $P_{depol}(t)$ , should asymptotically tend to zero  $\lim_{t \rightarrow \infty} (P_{depol}(t)) = 0$ .

The structure of the kinetic equation of proton-relaxation depolarization [5; 6] depends, firstly, on a number of properties of the physical model, under given conditions of the process (laws of temperature change and the intensity of the external electric field in time, the type of electrodes, the effect of strains and mechanical stresses on polarization processes, etc.) and, secondly, on the pre-predicted degree of accuracy of the final analytical solutions.

In this regard, within the phenomenological model of proton conductivity and relaxation in HBC [4-6; 10; 11], two main variants of the choice of this kinetic equation are possible:

1) on the basis of the quasi-classical Fokker-Planck equation for depolarization, with kinetic coefficients (15)-(18) being functions of temperature. In this case, the initial distribution of the bulk charge will be determined by the sum of the distributions of the hetero-charge (associated with the distribution of protons along the dielectric thickness) and homo-charge (associated with the injection of charges from the near-surface area of the electrodes deep into the crystal) [2];

2) on the basis of a general kinetic equation based on the model of a double symmetric potential well perturbed by a uniform electric field  $E(t)$  [9]. In depolarization, the field strength is assumed to be zero. The effect of spatially inhomogeneous homo-charge distribution is not taken into account.

Since in this paper the factor determining the degree of rigor of the mathematical model is, in continuation of the linear kinetic theory [2; 3; 9], the focus on the effects of the interaction of relaxation modes  $n$  on the initial polarization (76) inherent in parameter (27), then, to describe the kinetics of depolarization, we choose the second version of the kinetic equation (80) [9]:

$$\frac{d(\Delta n)}{dt} + 2\Omega(t) \cdot \Delta n = \frac{1}{3} n_0 \cdot \Xi(t) \quad (80)$$

Next, we present the average velocity of the probability of proton transitions between potential wells (81):

$$\Omega(t) = \frac{W^{(-)}(t) + W^{(+)}(t)}{2} = \frac{D_{diff}(t)}{a^2} \quad (81)$$

and the excess velocity of the probability of diffusion transport of protons across the field (82) [11]:

$$\Xi(t) = W^{(-)}(t) - W^{(+)}(t) = \frac{v_{mob}(t)}{a}, \quad (82)$$

taking into account (15)-(18), as:

$$\Omega(t) = \frac{v_0}{2} \left\{ \text{ch}(\zeta(t)) \cdot \exp(-X) + \frac{\text{ch}(\eta(t)) \cdot \exp(-\Lambda) - \text{ch}(\zeta(t)) \cdot \exp(-X)}{1 - \frac{\Lambda}{X}} \right\}, \quad (83)$$

$$\Xi(t) = v_0 \left\{ \text{sh}(\zeta(t)) \cdot \exp(-X) + \frac{\text{sh}(\eta(t)) \cdot \exp(-\Lambda) - \text{sh}(\zeta(t)) \cdot \exp(-X)}{1 - \frac{\Lambda}{X}} \right\}. \quad (84)$$

Here (85), (86) [6]:

$$\zeta(t) = \frac{|\Delta U(t)|}{k_B T} \approx \frac{qE(t)a}{2k_B T}, \quad (85)$$

$$\eta(t) = \Lambda \frac{|\Delta U(t)|}{U_0} \approx \frac{qE(t)\Lambda a}{2k_B T U_0}. \quad (86)$$

Also we should note the ratio (87):

Obviously, at the critical temperature  $T_{cr,mov}$ , the equation (88):

$$\zeta(t) = \eta(t) \quad (88)$$

is performed. In the case of  $E(t) = 0$ , assuming  $\Omega(t) = W^{(0)}(t)$ ,  $\Xi(t) = 0$ , rewriting (80) as (89):

$$\frac{\partial(\Delta n)}{\partial t} + 2W^{(0)}(t) \cdot \Delta n = 0 \quad (89)$$

and introducing the coordinate averaged polarization (90):

$$P_{depol}(t) = \frac{q}{d} \int_0^d \Delta n(x,t) dx, \quad (90)$$

we formulate a differential equation (91):

$$\frac{dP_{depol}(t)}{dt} + 2W^{(0)}(t) \cdot P_{depol}(t) = 0, \quad (91)$$

solved with regard to the initial condition (76). Then (92):

$$P_{depol}(t) = P_{depol}(0) \cdot \exp\left(-2 \int_0^t W^{(0)}(t) dt\right). \quad (92)$$

Calculation of the current density of the thermally stimulated depolarization (93):

$$J_{depol}(t) = -\frac{\partial P_{depol}(t)}{\partial t}, \quad (93)$$

taking into account (94):

$$c = \frac{dT(t)}{dt}, \quad (94)$$

finally gives (95):

$$J_{depol}(T) = 2P_{depol}(0) \cdot W^{(0)}(T) \cdot \exp\left(-\frac{2}{c} \int_{T_0}^T W^{(0)}(T) dT\right) dT. \quad (95)$$

Equation (95) formally coincides with the Bucci-Riva formula known from thermal depolarization analysis [9], however, the obtained result contains a number of fundamental model differences and additions. First, the kinetic coefficients  $W^{(0)}(T)$  are calculated as a function of temperature, taking into account the tunnel transitions of relaxers (protons) through the parabolic potential barrier and, secondly, the initial polarization is quite complex in structure and informative function, reflecting the influence of nonlinear polarization effects (interaction of relaxation modes; nonlinear bulk-charge polarization of mixed type; electret effect, etc.) on the kinetics of depolarization. At the same time, the expression (76) works in a sufficiently wide theoretical range of field parameters (100 kV/m-1000 MV/m) and temperatures (0-1500 K) and allows to reveal at the theoretical level the polarization nonlinearities occurring in the area of ultra-low temperatures (1-10 K) and strong fields (100-1000 MV/m). The phenomenological Bucci-Riva formula, according to the results of numerical calculations, is limited to the experimental range of variation of the macroscopic parameters of the process [150]

$E_{pol} \approx (10^5 \div 10^6) \frac{V}{m}$ ,  $T_{pol} \approx (70 \div 450) K$ . Studies of the integral (96):

$$B(T) = \int_{T_0}^T W^{(0)}(T) dT \quad (96)$$

are conducted by numerical methods [151]. A condition  $T_0 \leq T_{pol}$  is imposed on the initial depolarization temperature. As a rule, when measuring the temperature spectra of TSDC density, experimental values  $T_0$  are taken near the nitrogen temperature (50-70 K), and the polarization temperature is set within  $T_{pol} \approx$

$(300 \div 350) K$ . The rate of linear heating of the crystal  $c \approx (0,1 \div 1) \frac{K}{s}$ .

The analytical equation (95) enables to construct theoretical spectra of the density of the thermally stimulated depolarization current  $J_{depol,th}(T)$  and, on this basis, by minimizing the comparison function of the theory with the experiment (97) [7]:

$$\Psi(\vec{\zeta}_{max}) = \left[ T_{max,th}^{[J_{depol,th}(T;\vec{\zeta})]} - T_{max,exp}^{[J_{depol,exp}(T;\vec{\zeta}_0)]} \right]^2 \rightarrow \min, \quad (97)$$

by programmable computer enumeration of the theoretical values of the characteristic parameters (98):

$$\vec{\zeta} = \{U_{0,th}, v_{0,th}, n_{0,th}, a_{th}, \delta_{0,th}\}, \quad (98)$$

in the vicinity (on the set of continuum) temperature of the experimental maximum  $T_{max,exp}$ , to determine the optimized against the experimental values (99):

$$\vec{\zeta}_0 = \{U_{0,exp}; v_{0,exp}; n_{0,exp}; \delta_{0,exp}\}, \quad (99)$$

the theoretical values of these parameters for the temperature  $T_{max,th}$ , as a vector (100):

$$\vec{\zeta}_{max;opt} = \left\{ U_{0,th,max;opt}; v_{0,th,max;opt}; n_{0,th,max;opt}; \delta_{0,th,max;opt} \right\} \quad (100)$$

#### 4. Conclusions

Generalized nonlinear expressions for the complex dielectric constant (32) and polarization (33) are formulated, which are performed at the fundamental frequency of the alternating polarizing field. In the case of a stationary homogeneous electric field, the formulas (32), (33) are reduced to the analytical dependences (41), (42), more illustrative and convenient for comparison with the experiment, in comparison with the results of the linear kinetic theory.

From the solution of the general quzasi-classical kinetic equation (91), an expression for the current density of thermally stimulated depolarization (95) is formulated, with regard to the nonlinear polarization effects due to the interaction of relaxation modes of the bulk charge density, which is reflected in (76). The generalized equations that are nonlinear by the field for kinetic coefficients (83), (84) of kinetic equation (80) are formulated. A significant impact of quantum effects on the kinetic coefficients (83), (84) at temperatures much lower than the critical temperature (in the area of nonlinear quantum diffusion polarization) is established.

The proposed scheme of numerical calculation of the characteristic parameters of the relaxers limited to the study of current density of thermally stimulated depolarization (91) by minimization of theory and experiment comparison function (97), by computer enumeration of parameters of relaxers at a set of points of the continuum in the vicinity of the temperature of each mono-relaxational maximum of TSDC density.

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#### References

- [1] M. P. Tonkonogov, "Dielectric spectroscopy of hydrogen-bonded crystals, and proton relaxation", *Uspekhi Fizicheskikh Nauk*, vol. 168, no. 1, pp. 29-54, 1998.
- [2] M. P. Tonkonogov, Zh. T. Ismailov, V. M. Timokhin, K. K. Fazylov, V. A. Kalytka and Z. K. Baymukhanov, "Nonlinear theory of spectra of thermally stimulated current in complex hydrogen-bonded crystals", *Izvestiya Vysshykh Uchebnykh Zavedeniy, Fizika*, vol. 10, pp. 76-84, 2002.
- [3] M. P. Tonkonogov, T. A. Kuketaev, K. K. Fazylov and V. A. Kalytka, "Quantum effects in thermodepolarization in complex hydrogen-bonded crystals", *Izvestiya Vysshykh Uchebnykh Zavedeniy, Fizika*, vol. 6, pp. 8-15, 2004.
- [4] V. A. Kalytka and M. V. Korovkin, "Dispersion relations for proton relaxation in solid dielectrics", *Russian Physics Journal*, vol. 59, no. 12, pp. 2151- 2161, 2017.



- 
- [5] V. A. Kalytka, "Mathematical description of nonlinear relaxation polarization in hydrogen-bonded dielectrics", *Vestnik Samarskogo Universiteta, series "Estestvennonauchnaya"*, vol. 23, no. 3, pp. 71-83, 2017.
- [6] V. A. Kalytka, "Nonlinear kinetic phenomena in solid-state dielectrics", *Vestnik Moskovskogo Gosudarstvennogo Oblastnogo Universiteta, series "Fizika-Matematika"*, vol. 2, pp. 61-75, 2018a.
- [7] V. A. Kalytka, "Development of scheme of numerical computation of parameters of nonlinear electrophysical processes by method of comparison function minimization", *Prostranstvo, Vremia i Fundamentalnye Vzaimodeystviya*, vol. 3, no. 24, pp. 68-77, 2018b.
- [8] A. K. Demin, *The method of increasing of SOFC efficiency*, Paris: MCI, 1992.
- [9] V. A. Kalytka and M. V. Korovkin, *Proton conductivity*. Germany: LAP LAMBERT Academic Publishing, 2015.
- [10] V. A. Kalytka, M. V. Korovkin, A. D. Mekhtiev and A. V. Yurchenko, "Non-linear polarizing effects in dielectrics with hydrogen bonds", *Russian Physics Journal*, vol. 61, no. 4, pp. 757-769, 2018.
- [11] V. A. Kalytka, A. V. Bashirov, A. V. Taranov, G. G. Tatkeyeva, Y. G. Neshina and Y. A. Sidorina, "Methods of theoretical researches the properties of electrotechnical materials class of dielectrics with hydrogen bonds", *Journal of Computational and Theoretical Nanoscience*, vol. 16, no. 7, pp. 2799-2804, 2019.
- [12] N. V. Korovin, *Electrochemical power industry*, Moscow: Energoatomizdat, 1991.
- [13] U. G. Bossel and L. Dubal, *Facts and Figures: An international energy agency SOFC task report*, Berne: Swiss Federal Office of Energy, 1992.
- [14] N. I. Timofeeva and A. K. Demin, *Modelling of SOFC operation in variable regime*, Gottingen: Druckerei J. Kinzel, 1994.
- [15] S. F. Palguev, *High-temperature proton solid-state electrolytes*, Ekaterinburg: UrO RAN, 1998.
- [16] A. B. Yaroslavtsev, "Proton conductivity of inorganic hydrates", *Uspekhi Fizicheskikh Nauk*, vol. 63, no. 5, pp. 429-435, 1994.
- [17] R. Glöckner, A. Neiman, Y. Larring and T. Norby, "Protons in perovskite" *Solid State Ionics*, vol. 125, pp. 369-376, 1999.
- [18] T. S. Zyubina, G. V. Shilov, Yu. A. Dobrovolskiy, L. S. Leonova and A. M. Mebel, "Modelling of proton transport in ortho-periodic and ortho-telluric acid and theirs salts", *Elektrokimiya*, vol. 39, no. 4, pp. 414-424, 2003.
- [19] I. E. Animitsina, "High-temperature proton conductors with structural disorder of oxygen sublattice", *Elektrokimiya*, vol. 45, no. 6, pp. 712-721, 2009.
- [20] A. B. Yaroslavtsev, "The main directions of development and research of solid electrolytes", *Uspekhi Fizicheskikh Nauk*, vol. 85, no. 11, pp. 1255-1276, 2016.
- [21] R. Reijers and W. Haije, *Literature review on high temperature proton conducting materials: Electrolyte for fuel cell or mixed conducting membrane for H<sub>2</sub> separation*, Petten: ECN Research Centre, 2008.
- [22] A. P. Silin, "Semiconducting superlattice", *Uspekhi Fizicheskikh Nauk*, vol. 147, no. 3, pp. 485-521, 1985.
- [23] E. R. Brown, C. D. Parker and T. C. L. G. Sollner, "Effect of quasi-bound state lifetime on the oscillation power of resonant-tunneling diodes" *Applied Physics Letters*, vol. 54, pp. 934-936, 1989.
- [24] E. R. Brown, *Resonant tunneling in high-speed double-barrier diodes. Hot electrons in semiconductor hetero-structures*, Boston: Academic Press, 1991.
- [25] A. A. Abrikosov, "Resonant tunneling in high-temperature superconductors", *Uspekhi Fizicheskikh Nauk*, vol. 168, pp. 6, 683-695, 1998.
- [26] J. P. Mattia, A. L. McWhorter, R. J. Aggarwal, F. Rana, E. R. Brown and P. Maki, "Comparison of a rate-equation model with experiment for the resonant tunneling diode in scattering-dominated regime", *Applied Physics Letters*, vol. 84, no. 2, pp. 1140-1148, 1998.
- [27] V. G. Popov, "Current instability in resonant-tunneling diodes", *Uspekhi Sovremennoy Radioelektroniki*, vol. 6, pp. 23-38, 2010.
- [28] D. A. Usanov and A. V. Skripal, *Physical foundations of nanoelectronics*, Saratov: Saratov State University, 2013.
- [29] Yu. M. Annenkov, V. A. Kalytka and M. V. Korovkin, "Quantum effects under migratory polarization in nanometer layers of proton semiconductors and dielectrics at ultralow temperatures", *Russian Physics Journal*, vol. 58, no. 1, pp. 35-41, 2015.
- [30] F. Capasso, *Physics of quantum electron devices*, Berlin: Springer, 1990.
-

- [31] E. Ozbay, D. M. Bloom and S. K. Diamond, Resonant tunneling in semiconductors: Physics and Applications. New York: Plenum Press, 1991.
- [32] A. S. Tager, "Dimensional quantum effects in submicronic semiconducting structures and prospect of their use in microwave electronics", *Elektronnaya Tekhnika, series 1 "Elektronika SVCh"*, vol. 9, no. 403, pp. 21-34, 1987.
- [33] L. V. Iogansen, "On the possibility of resonant transfer of electrons in crystals through barrier system", *ZhETF*, vol. 45, pp. 207-218, 1963.
- [34] L. V. Iogansen, "On resonant tunneling of electrons in crystals", *ZhETF*, vol. 47, no. 1, pp. 270-277, 1964.
- [35] L. V. Iogansen, "Thin-film electron interferometer", *UFN*, vol. 86, pp. 175-179, 1965.
- [36] A. S. Tager, "Dimensional quantum effects in submicronic semiconducting structures and prospect of their use in microwave electronics (Part 2: Resonant tunneling diodes and transistors)", *Elektronnaya Tekhnika, series 1 "Elektronika SVCh"*, vol. 2, no. 406, pp. 17-33, 1988.
- [37] V. I. Fistul, Tunneling diodes, Moscow: IL, 1961.
- [38] N. A. Belova, V. P. Bonch-Bruevich, P. E. Zilderman, A. N. Kovalev, P. S. Serebrennikov and N. E. Skvortsova, Tunneling diodes (Physical basics of the work), Moscow: Nauka, 1966.
- [39] V. E. Andreev, Generators of harmonic oscillation on tunneling diodes, Moscow: Energiya, 1972.
- [40] R. Tsu and L. Esaki, "Tunneling in a finite superlattice", *Applied Physics Letters*, vol. 22, no. 11, pp. 562-564, 1973.
- [41] L. Chang, L. Esaki and R. Tsu, "Resonant tunneling in semiconductors double barrier", *Applied Physics Letters*, vol. 24, no. 12, pp. 593-595, 1974.
- [42] T. C. Sollner, W. D. Goodhue, P. E. Tannenwald, S. D. Parker and D. D. Peck, "Resonant tunneling through quantum wells at frequencies up to 2.5 THz", *Applied Physics Letters*, vol. 43, no. 6, pp. 588-590, 1983.
- [43] T. C. Sollner, P. E. Tannenwald, D. D. Peck and W. D. Goodhue, "Quantum well oscillators", *Applied Physics Letters*, vol. 45, no. 12, pp. 1319-1321, 1984.
- [44] A. R. Bonnefoi, R. T. Collins, T. C. McGill, R. D. Burnham and F. A. Ponce, "Resonance tunneling in Ga As/Al As heterostructures grown by metalloorganic chemical vapor deposition", *Applied Physics Letters*, vol. 46, no. 3, pp. 285-287, 1985.
- [45] T. J. Shewchuk, P. C. Chapin, P. D. Coleman, W. Kopp, R. Fischer and H. Morkoc, "Resonant tunneling oscillations in a GaAs-AlxGa1-x As heterostructure at room temperature", *Applied Physics Letters*, vol. 46, no. 5, pp. 508-510, 1985.
- [46] Yu. I. Dahnovsky, V. D. Krevchik, V. Ya. Krivnov, M. B. Semenov and K. Yamamoto, Transfer processes in low-dimensional systems, Tokyo: UT Research Institute Press, 2005.
- [47] V. Ch. Zhukovskiy, O. N. Gorshkov, V. D. Krevchik, M. B. Semenov, E. V. Groznaya, D. O. Filatov and D. A. Antonov, "Controlled dissipative tunneling in external electric field", *Vestnik Moskovskogo Universiteta, series 3 "Fizika-Astronomiya"*, vol. 5, pp. 475-479, 2009a.
- [48] A. Grodecka, P. Machnikowski and J. Forstner, "Phonon-assisted tunneling between singlet states in two-electron quantum dot molecules", *Physical Review*, vol. 78, article number 085302, 2008.
- [49] Y. Imry, Introduction to mesoscopic physics, Oxford: Oxford University Press, 2008.
- [50] Yu. Bomze, H. Mebrahtu, I. Borzenets, A. Makarovski and G. Finkelstein, "Resonant tunneling in a dissipative environment" *Physical Review*, vol. 79, article number 241402(R), 2009.
- [51] P. A. Borodin, A. A. Bukharaev, D. O. Filatov, D. A. Vorontsov and M. A. Lapshina, "Combined STM/AFM visualization of the local density of states in the InAs/GaAs quantum dots", *Journal of Surface Investigations: X-ray, Synchrotron, and Neutron Techniques*, vol. 3, no. 5, pp. 721-724, 2009.
- [52] L. G. G. V. Dias da Silva and E. Dagotto, "Phonon-assisted tunneling and two-channel Kondo physics in molecular junctions", *Physical Review*, vol. 79, article number 155302, 2009.
- [53] V. Ch. Zhukovskiy, Yu. I. Dakhnovskiy, V. D. Krevchik, M. B. Semenov, V. G. Mayorov, E. I. Kudriashov, Ye. V. Shcherbakova and K. Yamamoto, "Study of controlled dissipative tunneling in the systems of interacting quantum molecules", *Vestnik Moskovskogo Universiteta, series 3 "Fizika-Astronomiya"*, vol. 2, pp. 10-14, 2007.
- [54] V. Ch. Zhukovskiy, Yu. I. Dakhnovskiy, O. N. Gorshkov, V. D. Krevchik, M. B. Semenov, Yu. G. Smirnov, E. V. Chuprunov, V. A. Rudin, N. Yu. Skibitskaya, P. V. Krevchik, D. O. Filatov, D. A. Antonov, M. A. Lapshina, K. Yamamoto and M. E. Shenina, "Observed two-dimensional tunnel

- bifurcation in external electric field", *Vestnik Moskovskogo Universiteta, series 3 "Fizika-Astronomiya"*, vol. 5, pp. 3-8, 2009b.
- [55] D. K. Ferry, S. M. Goodnick and J. Bird, *Transport in Nanostructures*, Cambridge: Cambridge University Press, 2009.
- [56] A. Venkatesan, K. J. Lulla, V. J. Patton, A. D. Armour, C. J. Mellor and J. R. Owers-Bradley, "Dissipation due to tunneling two-level systems in gold nanomechanical resonators", *Physical Review*, vol. 81, no. 7, article number 073410, 2010.
- [57] A. J. Leggett, *Controlled dissipative tunneling. Tunnel transport in low-scale systems*, Moscow: Fizmatlit, 2011.
- [58] D. Filatov, V. Shengurov, N. Nurgazizov, P. Borodin and A. Bukharaev, *Tunneling atomic force microscopy of self-assembled*, Croatia: InTech, 2012.
- [59] M. Kuprikov, L. N. Rabinskiy, "Cross-polar routes as a factor that changed the geometric layout of long-haul aircrafts flying over long distances," *Journal of Mechanical Engineering Research and Developments*, vol. 41, no. 4, pp. 53-57, 2018.
- [60] M. Y. Kuprikov, N. M. Kuprikov, L. N. Rabinskiy, "The dependence of the appearance of the aircraft on the conditions of the arctic basing," *INCAS Bulletin*, vol. 11, pp. 115-123, 2019.
- [61] O. V. Egorova, Y. K. Kyaw, "Solution of inverse non-stationary boundary value problems of diffraction of plane pressure wave on convex surfaces based on analytical solution," *Journal of Applied Engineering Science*, vol. 18, no. 4, pp. 676-680, 2020.
- [62] A. G. Getmanov, L. N. Rabinskiy, "Assessment of durability of coatings in difficult stress conditions," *Periodico Tche Quimica*, vol. 16, no. 33, pp. 490-497, 2019.
- [63] V. A. Zagovorchev, O. V. Tushavina, "The use of jet penetrators for movement in the lunar soil," *INCAS Bulletin*, vol. 11, pp. 121-130, 2019.
- [64] V. A. Zagovorchev, O. V. Tushavina, "Selection of temperature and power parameters for multi-modular lunar jet penetrator," *INCAS Bulletin*, vol. 11, pp. 231-241, 2019.
- [65] S. Vakhneev, E. Starovoitov, "Damping of circular composite viscoelastic plate vibration under neutron irradiation," *Journal of Applied Engineering Science*, vol. 18, no. 4, pp. 699-704, 2020.
- [66] Y. Sun, M. Y. Kuprikov, E. L. Kuznetsova, "Effect of Flight range on the dimension of the main aircraft," *INCAS Bulletin*, vol. 12, pp. 201-209, 2020.
- [67] Y. Li, A. M. Arutiunian, E. L. Kuznetsova, G. V. Fedotenkov, "Method for solving plane unsteady contact problems for rigid stamp and elastic half-space with a cavity of arbitrary geometry and location," *INCAS Bulletin*, vol. 12, pp. 99-113, 2020.
- [68] E. L. Kuznetsova, G. V. Fedotenkov, E. I. Starovoitov, "Methods of diagnostic of pipe mechanical damage using functional analysis, neural networks and method of finite elements," *INCAS Bulletin*, vol. 12, pp. 79-90, 2020.
- [69] D. A. Kozorez, E. A. Dolgova, A. V. Korneenkova, A. V. Rumakina, M. Sha, "Higher education institutions educational process digitalization in the context of the necessity to provide a model for students' choice of training areas and academic specialties," *International Journal of Criminology and Sociology*, vol. 9, pp. 3033-3039, 2020.
- [70] R. R. Anamova, L. V. Bykov, D. A. Kozorez, "Algorithm for designing professional retraining programs based on a competency approach," *Education Sciences*, vol. 10, no. 8, pp. 1-9, 2020.
- [71] E. V. Akimov, D. A. Kozorez, D. M. Kruzhhkov, "Navigation solution concept and its practical approach development for lunar missions," *Russian Engineering Research*, vol. 40, no. 7, pp. 605-607, 2020.
- [72] R. R. Anamova, L. V. Bykov, D. A. Kozorez, "Aircraft industry staff retraining as a part of vocational education in the Russian Federation," *TEM Journal*, vol. 8, no. 3, pp. 978-983, 2019.
- [73] M. N. Krasil'shchikov, D. A. Kozorez, K. I. Sypalo, O. F. Samarin, V. Y. Savost'yanov, "High accuracy positioning of phase center of multifunction airborne radar antenna," *Gyroscopy and Navigation*, vol. 4, no. 3, pp. 164-173, 2013.
- [74] A. E. Sorokin, S. V. Novikov, "Formation of the national economy of russia in the context of state support of innovation actions," *Espacios*, vol. 40, no. 38, pp. 1-9, 2019.
- [75] N. S. Kudryavtseva, A. E. Sorokin, "Comparative reliability assessment and costing of life support systems for extended interplanetary missions," *Aviakosmicheskaya i Ekologicheskaya Meditsina*, vol. 54, no. 2, pp. 30-37, 2020.
- [76] E. E. Galkina, A. E. Sorokin, "Quality management and sustainable economic development," *Russian Engineering Research*, vol. 40, no. 7, pp. 577-578, 2020.

- [77] V. V. Bodryshev, L. G. Nartova, L. N. Rabinskiy, "Digital interpretation of gas dynamics problems as a means of optimizing fundamental general engineering education," *Asia Life Sciences*, vol. 2, pp. 759-774, 2019.
- [78] V. V. Bodryshev, A. A. Larin, L. N. Rabinsky, "Flaw detection method for radomes in weakly anechoic conditions," *TEM Journal*, vol. 9, no. 1, pp. 169-176, 2020.
- [79] V. V. Bodryshev, N. P. Korzhov, L. N. Rabinskiy, "Grapho-analytical analysis of video frames of supersonic flow around two solid revolutions using the digital image processing method," *TEM Journal*, vol. 9, no. 2, pp. 449-459, 2020.
- [80] V. S. Terentieva, A. N. Astapov, "Conceptual protection model for especially heat-proof materials in hypersonic oxidizing gas flows," *Russian Journal of Non-Ferrous Metals*, vol. 59, no. 6, pp. 709-718, 2018.
- [81] V. S. Terentieva, A. N. Astapov, L. N. Rabinskiy, "State in the field of heat-resistant coatings for heat-proof nickel alloys and steels," *Periodico Tche Quimica*, vol. 16, no. 33, pp. 561-572, 2019.
- [82] V. A. Pogodin, A. N. Astapov, L. N. Rabinskiy, "CCCM specific surface estimation in process of low-temperature oxidation," *Periodico Tche Quimica*, vol. 17, no. 34, pp. 793-802, 2020.
- [83] V. A. Pogodin, L. N. Rabinskii, S. A. Sitnikov, "3D printing of components for the gas-discharge chamber of electric rocket engines," *Russian Engineering Research*, vol. 39, no. 9, pp. 797-799, 2019.
- [84] N. S. Severina, "Software Complex for solving the different tasks of physical gas dynamics," *Periodico Tche Quimica*, vol. 16, no. 32, pp. 424-436, 2019.
- [85] A. V. Babaytsev, L. N. Rabinskiy, K. T. Aung, "Investigation of the contact zone of a cylindrical shell located between two parallel rigid plates with a gap," *INCAS Bulletin*, vol. 12, pp. 43-52, 2020.
- [86] A. V. Babaytsev, L. N. Rabinskiy, "Design calculation technique for thick-walled composite constructions operating under high-speed loading," *Periodico Tche Quimica*, vol. 16, no. 33, pp. 480-489, 2019.
- [87] A. V. Babaytsev, Y. K. Kyaw, S. N. Vakhneev, T. Zin Hein, "Study of the influence of spherical inclusions on mechanical characteristics," *Periodico Tche Quimica*, vol. 17, no. 35, pp. 654-662, 2020.
- [88] A. V. Babaytsev, A. A. Zotov, "Designing and calculation of extruded sections of an inhomogeneous composition," *Russian Metallurgy (Metally)*, vol. 2019, no. 13, pp. 1452-1455, 2019.
- [89] A. V. Babaytsev, A. A. Orekhov, L. N. Rabinskiy, "Properties and microstructure of als<sub>10</sub>mg samples obtained by selective laser melting," *Nanoscience and Technology*, vol. 11, no. 3, pp. 213-222, 2020.
- [90] V. V. Bodryshev, A. V. Babaytsev, L. N. Rabinskiy, "Investigation of processes of deformation of plastic materials with the help of digital image processing," *Periodico Tche Quimica*, vol. 16, no. 33, pp. 865-876, 2019.
- [91] V. A. Korolenko, Y. Li, V. N. Dobryanskiy, Y. O. Solyaev, "Experimental studies and modelling of fracture toughness of the epoxy samples with eccentric cracks," *Journal of Applied Engineering Science*, vol. 18, no. 4, pp. 719-723, 2020.
- [92] M. Sha, O. A. Prokudin, Y. O. Solyaev, S. N. Vakhneev, "Dependence of glare destruction mechanisms on the elongation of samples in tests to three-point flexural," *Periodico Tche Quimica*, vol. 17, no. 35, pp. 549-558, 2020.
- [93] A. Babaytsev, V. Dobryanskiy, Y. Solyaev, "Optimization of thermal protection panels subjected to intense heating and mechanical loading," *Lobachevskii Journal of Mathematics*, vol. 40, no. 7, pp. 887-895, 2019.
- [94] S. A. Lurie, P. A. Belov, Y. O. Solyaev, E. C. Aifantis, "On one class of applied gradient models with simplified boundary problems," *Materials Physics and Mechanics*, vol. 32, no. 3, pp. 353-369, 2017.
- [95] Yu. G. Evtushenko, V. I. Zubov, S. A. Lurie, Yu. O. Solyaev, "Identification of kinetic parameters of the model of interphase layer growth in a fibrous composite," *Composites: Mechanics, Computations, Applications*, vol. 7, no. 3, pp. 175-187, 2016.
- [96] J. F. Ziegler, J. P. Biersack and M. D. Ziegler, SRIM – The stopping and range of ions in matter, Chester: SRIM Co., 2012.
- [97] I. V. Khromushin and T. I. Aksenova, "Effect of low-energy argon ions on YSZ conducting properties", *Vestnik NYaTs RK*, vol. 1, pp. 55-61, 2017a.
- [98] I. V. Khromushin and T. I. Aksenova, Effect of argon and oxygen ion irradiation on the conducting properties of yttrium-stabilized zirconium dioxide (YSZ), Almaty: National Nuclear Center Publishing House, 2017b.

- [99] I. V. Khromushin, T. I. Aksenova and Yu. M. Baykov, "Regularities of oxygen and water thermal desorption from barium cerate doped by neodymium, samarium, and gadolinium", *Russian Journal of Electrochemistry*, vol. 53, no. 6, pp. 647-650, 2017.
- [100] A. A. Skvortsov, S. M. Zuev, M. V. Koryachko, "Contact melting of aluminum-silicon structures under conditions of thermal shock," *Key Engineering Materials*, vol. 771, pp. 118-123, 2018.
- [101] V. I. Ivin, V. V. Ryndin, "Unsteady flow in branched ducts of inlet pipes of internal combustion engines," *Izv Vyssh Uchebn Zaved Mashinostr*, vol. 9, pp. 100-105, 1976.
- [102] V. V. Ryndin, "Mathematical modeling of the process of filling an engine through an inlet manifold," *Izvestia vyssih ucebnykh zavedenij. Masinostroenie*, vol. 2, pp. 71-75, 1980.
- [103] O. Zh. Rabat, D. Absametov, M. M. Kunelbayev, E. L. Hasanov, D. V. Mykhalevskiy, R. N. Abdrashitova, Y.I. Salnikova, "Performance calculation of solar water heating unit at a petrol filling station," *Periodico Tche Quimica*, vol. 15, no. 30, pp. 589-598, 2018.
- [104] N. Zaurbekov, A. Aidosov, N. Zaurbekova, G. Aidosov, G. Zaurbekova, I. Zaurbekov, "Emission spread from mass and energy exchange in the atmospheric surface layer: Two-dimensional simulation," *Energy Sources, Part A: Recovery, Utilization and Environmental Effects*, vol. 40, no. 23, pp. 2832-2841, 2018.
- [105] K. Imanbayev, B. Sinchev, S. Sibanbayeva, A. Mukhanova, A. Nurgulzhanova, N. Zaurbekov, N. Zaurbekova, N. V. Korolyova, L. Baibolova, "Analysis and mathematical modeling of big data processing," *Peer-to-Peer Networking and Applications*, vol. 1, pp. 1-10, 2020.
- [106] I. V. Cherunova, S. S. Tashpulatov, S. V. Kurenova, "Treated textile electrostatic properties study," *Materials Science Forum*, vol. 992, pp. 439-444, 2020.
- [107] S. S. Tashpulatov, I. V. Cherunova, M. K. Rasulova, D. D. Inogamdjanov, M. Yu. Umarova, A. D. Daminov, U.R. Uzakova, S. G. Jurayeva, "Development of the calculation method of polymer compound mass to be applied onto the textile garment pieces," *IOP Conference Series: Materials Science and Engineering*, vol. 459, no. 1, 012067, 2018.
- [108] L. N. Nutfullaeva, A. F. Plekhanov, I. G. Shin, S. S. H. Tashpulatov, I. V. Cherunova, S. H. N. Nutfullaeva, E. A. Bogomolov, "Research of conditions of formation package and ensure the safety of the pillows from composite nonwoven fibers materials," *Izvestiya Vysshikh Uchebnykh Zavedenii, Seriya Teknologiya Tekstil'noi Promyshlennosti*, vol. 380, no. 2, pp. 95-101, 2019.
- [109] I. Cherunova, S. Tashpulatov, S. Kolesnik, "Automation of deformed fibrous materials thermal characteristics accounting process in garments production," *2018 International Russian Automation Conference, RusAutoCon 2018*, vol. 1, 8501795, 2018.
- [110] I. Cherunova, S. Tashpulatov, A. Merkulova, "Development of automation algorithm for step of designing technology of static electricity protection clothing," *2018 International Russian Automation Conference, RusAutoCon 2018*, vol. 1, 8501821, 2018.
- [111] I. Cherunova, S. Tashpulatov, Y. Davydova, "Geometric conditions of mathematical modeling of human heat exchange processes with the environment for CAD systems creating heat-shielding clothing," *IOP Conference Series: Materials Science and Engineering*, vol. 680, no. 1, 012039, 2019.
- [112] G. A. Ganiyeva, B. R. Ryskulova, S. Sh. Tashpulatov, "Ergonomic studies of dynamic compliance of parameters within the man-special clothing system for workers of the oil industry," *Izvestiya Vysshikh Uchebnykh Zavedenii, Seriya Teknologiya Tekstil'noi Promyshlennosti*, vol. 2015, no. 3, pp. 151-154, 2015.
- [113] G. A. Ganiyeva, B. R. Ryskulova, S. S. Tashpulatov, "Selection of special clothes design parameters on the basis of optimisation of dynamic conformance parameters," *International Journal of Applied Engineering Research*, vol. 10, no. 19, pp. 40603-40606, 2015.
- [114] A. Baibatsha, "Geotectonics and geodynamics of paleozoic structures from the perspective of plume tectonics: A case of Kazakhstan," *International Journal of GEOMATE*, vol. 17, no. 71, pp. 194-202, 2020.
- [115] A. B. Baibatsha, A. Muszyński, T. K. Shaiyakhmet, G. S. Shakirova, "3D modeling for estimation of engineering-geological conditions of operating mineral deposits," *News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences*, vol. 4, no. 442, pp. 19-27, 2020.
- [116] A. Mustafin, "Coupling-induced oscillations in two intrinsically quiescent populations," *Communications in Nonlinear Science and Numerical Simulation*, vol. 29, no. 1-3, pp. 391-399, 2015.
- [117] A. Kantarbayeva, A. Mustafin, "A biologically inspired fluid model of the cyclic service system," *Mathematical Modelling and Analysis*, vol. 25, no. 4, pp. 505-521, 2020.

- [118] D. V. Topchiy, A. S. Bolotova, "The monolithic buildings complex renovation's organizational and technological model creation," *IOP Conference Series: Materials Science and Engineering*, vol. 913, no. 4, 042016, 2020.
- [119] D. Topchiy, A. Bolotova, "Systematization of factors affecting the organizational processes in the conversion of buildings," *IOP Conference Series: Materials Science and Engineering*, vol. 753, no. 3, 032042, 2020.
- [120] D. Topchiy, A. Bolotova, "Assessment and inspection of the technical condition of monolithic reinforced structures in transportation infrastructure facilities," *Journal of Physics: Conference Series*, vol. 1425, no. 1, 012005, 2020.
- [121] A. Tokarskiy, D. Topchiy, "State construction supervision during repurposing project implementation in the urban areas," *IOP Conference Series: Materials Science and Engineering*, vol. 698, no. 6, 066061, 2019.
- [122] D. Topchiy, A. Bolotova, "Studying specific features of the monolithic construction technology based on systemic analysis," *IOP Conference Series: Materials Science and Engineering*, vol. 603, no. 5, 052004, 2019.
- [123] V. Klimina, A. Yurgaitis, D. Topchiy, "Unified classification of defects detected by the technical examination," *E3S Web of Conferences*, vol. 110, 01086, 2019.
- [124] Yu. M. Annenkov, A. S. Ivashutenko, I. V. Vlasov and A.V. Kabyshev, "Electric properties of corundum zirconia ceramics", *Izvestiya Tomskogo Politekhnikheskogo Universiteta*, vol. 308, no. 7, pp. 35-38, 2005.
- [125] D. V. Topchy, "Formation of organizational and technological systems for renovation of production facilities located on the territory of megacities," *International Journal of Civil Engineering and Technology*, vol. 9, no. 8, pp. 1452-1457, 2018.
- [126] N. I. Kobasko, N. M. Fialko, N. O. Meranova, "Numerical determination of the duration of the nucleate-boiling phase in the course of steel-plate hardening," *Heat Transfer. Soviet Research*, vol. 16, no. 2, pp. 130-135, 1984.
- [127] N. M. Fialko, V. G. Prokopov, N. O. Meranova, Yu. S. Borisov, V. N. Korzhik, G. P. Sherenkovskaya, "Single particle-substrate thermal interaction during gas-thermal coatings fabrication," *Fizika i Khimiya Obrabotki Materialov*, vol. 1, pp. 70-78, 1994.
- [128] D. G. Blinov, V. G. Prokopov, Yu. V. Sherenkovskii, N. M. Fialko, V. L. Yurchuk, "Simulation of natural convection problems based on low-dimensional model," *International Communications in Heat and Mass Transfer*, vol. 29, no. 6, pp. 741-747, 2002.
- [129] A., Zvorykina, S. Gupta, W. Peiman, I. Pioro, N. Fialko, "Current status and future applications of supercritical pressures in power engineering," *International Conference on Nuclear Engineering, Proceedings, ICONE*, vol. 5, no. 1, pp. 285-300, 2012.
- [130] R. Dinzhos, E. Lysenkov, N. Fialko, "Simulation of thermal conductivity of polymer composites based on poly (methyl methacrylate) with different types of fillers," *Eastern-European Journal of Enterprise Technologies*, vol. 6, no. 11, pp. 21-24, 2015.
- [131] A. Zvorykin, N. Fialko, S. Julii, S. Aleshko, N. Meranova, M. Hanzha, I. Bashkir, S. Stryzheus, A. Voitenko, I. Pioro, "CFD study on specifics of flow and heat transfer in vertical bare tubes cooled with water at supercritical pressures," *International Conference on Nuclear Engineering, Proceedings, ICONE*, vol. 9, pp. 1-13, 2017.
- [132] N. M. Fialko, R. O. Navrodska, S. I. Shevchuk, G. O. Gnedash, "The environmental reliability of gas-fired boiler units by applying modern heat-recovery technologies," *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, vol. 2020, no. 2, pp. 96-100, 2020.
- [133] N. M. Fialko, R. O. Navrodska, G. O. Gnedash, G. O. Presich, S. I. Shevchuk, "Study of heat-recovery systems of or heating and moisturing combustion air of boiler units," *Science and Innovation*, vol. 16, no. 3, pp. 43-49, 2020.
- [134] A. Vlasyuk, V. Zhukovskyy, N. Zhukovska, H. Rajab, "One-dimensional modeling of contaminant migration in unsaturated porous media with dispersed catalyst particles," in *Proceedings – 2nd International Conference on Mathematics and Computers in Science and Engineering, MACISE 2020*, Madrid, Spain, pp. 197-201, 2020.
- [135] V. Z. Kutsova, M. A. Kovzel, A. V. Grebeneva, I. V. Ratnikova, O. A. Velichko, "The influence of alloying elements on structure formation, phase composition and properties of chromium-manganese iron in the cast state," *Metallurgical and Mining Industry*, vol. 7, no. 9, pp. 1090-1095, 2015.

- [136] A. M. Nesterenko, V. Z. Kutsova, M. A. Kovzel, "Investigation of crystal structure of Me<sub>7</sub>C<sub>3</sub>-type carbides," *Metallofizika i Noveishie Tekhnologii*, vol. 25, no. 1, pp. 99-106, 2003.
- [137] S. A. Montayev, N. S. Montayeva, A. B. Shinguzhiyeva, K. Zhanabaevichdosov, M. Zhanaidarovichryskaliyev, "Possibility of producing sintered fine porous granulated ceramic filler using ash of thermal power stations in combination with clay rocks," *International Journal of Mechanical and Production Engineering Research and Development*, vol. 9, no. 4, pp. 1087-1096, 2019.
- [138] S. Kukharets, G. Golub, O. Skydan, Y. Yarosh, M. Kukharets, "Justification of air flow speed in the oxidation area of a gasifier in case of straw pellets using," *INMATEH – Agricultural Engineering*, vol. 60, no. 1, pp. 37-44, 2020.
- [139] G. Golub, S. Kukharets, O. Skydan, Y. Yarosh, V. Chuba, V. Golub, "The optimization of the gasifier recovery zone height when working on straw pellets," *International Journal of Renewable Energy Research*, vol. 10, no. 2, pp. 529-536, 2020.
- [140] G. A. Golub, O. V. Skydan, S. M. Kukharets, O. A. Marus, "Substantiation of motion parameters of the substrate particles in the rotating digesters," *INMATEH – Agricultural Engineering*, vol. 57, no. 1, pp. 179-186, 2019.
- [141] S. Z. Mirzaev, I. Iwanowski, M. Zaitdinov, U. Kaatze, "Critical dynamics and kinetics of elementary reactions of 2,6-dimethylpyridine-water," *Chemical Physics Letters*, vol. 431, no. 4-6, pp. 308-312, 2006.
- [142] S. Z. Mirzaev, U. Kaatze, "Scaling function of critical binary mixtures: Nitrobenzene-n-hexane data revisited," *Chemical Physics*, vol. 393, no. 1, pp. 129-134, 2012.
- [143] E. L. Kuznetsova, A. V. Makarenko, "Mathematic simulation of energy-efficient power supply sources for mechatronic modules of promising mobile objects," *Periodico Tche Quimica*, vol. 15, no 1, pp. 330-338, 2018.
- [144] Y. K. Kyaw, E. L. Kuznetsova, A. V. Makarenko, "Complex mathematical modelling of mechatronic modules of promising mobile objects," *INCAS Bulletin*, vol. 12, pp. 91-98, 2020.
- [145] N. Khripach, L. Lezhnev, A. Tatarnikov, R. Stukolkin, A. Skvortsov, "Turbo-generators in energy recovery systems," *International Journal of Mechanical Engineering and Technology*, vol. 9, no. 6, pp. 1009-1018. 2018.
- [146] M. Kuprikov, L. N. Rabinskiy, "Influence of infrastructure constraints on the geometrical layout of a long-haul aircraft," *Journal of Mechanical Engineering Research and Developments*, vol. 41, no. 4, pp. 40-45, 2018.
- [147] V. G. Kytin, V. A. Kulbachinskiy, D. Yu. Kondratieva, A. V. Pavlikov, A. N. Grigoriev, A. S. Mankevich and I. E. Korsakov, "Hopping hole transfer in magnesium-doped ceramic samples", *Uchenye Zapiski Fizicheskogo Fakulteta Moskovskogo Universiteta*, vol. 1, article number 1810501, 2018.
- [148] M. Kuprikov, L. N. Rabinskiy, "Vertical take-off and landing aircrafts: myth or reality of modern aviation," *Journal of Mechanical Engineering Research and Developments*, vol. 41, no. 4, pp. 46-52, 2018.
- [149] A. Lapidus, D. Topchiy, "Construction supervision at the facilities renovation," *E3S Web of Conferences*, vol. 91, 08044, 2019.
- [150] E. R. Brown, J. R. Söderström, C. D. Parker, L. J. Mahoney, K. M. Molvar and T. C. McGill, "Oscillations up to 712 GHz in In-As/AlSb resonant-tunneling diodes", *Applied Physics Letters*, vol. 58, no. 20, pp. 2291-2293, 1991.
- [151] F. V. Kumartseva, V. D. Krevchik, M. B. Semenov, D. O. Filatov, A. V. Shorokhov, A. A. Bukharaeve and K. Yamamoto, "Phonon assisted resonant tunnelling and its phonons control", *Pisma v ZhETF*, vol. 104, no. 6, pp. 406-412, 2016.