Simulation and experimental investigation of cellular material breakage using the pulsed electric field treatment

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We consider the simplified dielectric breakage model used for simulation of the kinetics of cellular material breakage under the pulsed electric field (PEF) treatment. The model is based on an effective media approximation, which includes equations with the same morphology parameters as in percolation theory. The probability of a whole cell breakage by the pulse with \( t_i \) duration is estimated on the basis of electroporation theory. We account for the bridging effect resulting from the deviations of the local conductivity near the selected cell from the average effective media conductivity. The most important feature of the proposed model is the existence of the “jamming” behaviour occurring sometimes in experimental observations of the biological tissue breakage. The different transitions corresponding to the “jamming” steps are identified. The experimental results are obtained for thin apple slices treated with electric pulses at field strengths \( E = 0.2 - 2.2 \) kV cm\(^{-1}\), pulse durations \( t_i = 10 - 100 \) \( \mu \)s, pulse repetition times \( t = 10 - 100 \) ms and the number of pulses \( N = 1 - 100000 \). The model gives results consistent in general with the experimental observations. We discuss the correlation between the degree of cellular material destruction, field strength, time of PEF treatment and power consumption.

Keywords: Pulsed electric field treatment; Computer simulation; Kinetics of cellular material breakage

Notation

\begin{align*}
C_m & \quad \text{specific capacity of membrane, F m}^{-2} \\
C^* & \quad = C_m(\varepsilon_w/\varepsilon_m)^{-1}/(2\gamma) \\
C & \quad \text{specific heat of cellular material, J kg}^{-1} \text{K}^{-1} \\
d_m & \quad \text{membrane thickness, m} \\
d_c & \quad \text{cell diameter, m} \\
E & \quad \text{electric field strength, kV cm}^{-1} \\
\Delta F^* & \quad = \pi\omega^2/(kT\gamma), \text{reduced critical free energy of pore formation} \\
g & \quad \text{breakage probability for a membrane} \\
j & \quad \text{current density, A m}^{-2} \\
k & \quad \text{Boltzmann constant, 1.38065812x10}^{-23}\text{J K}^{-1} \\
L & \quad = d_cN_z, \text{total width of a sample} \\
m & \quad = d_c/d_m \\
n & \quad \text{number of intact cells neighbouring of a given cell} \\
N & \quad \text{number of pulses} \\
N_b & \quad \text{number of pulses at the moment of the total dielectric breakdown of material} \\
N_m & \quad \text{number of intact cells} \\
N_x, N_y, N_z & \quad \text{dimensions of a lattice} \\
P & \quad \text{degree of biological tissue destruction} \\
P_n & \quad \text{local degree of cell destruction} \\
P_p & \quad \text{critical percolation degree of destruction} \\
r_{m,c,i} & \quad = d_{m,c,c}/(S_m\sigma_{m,c,i}), \text{resistance, Ohm} \\
R & \quad \text{total resistance of a linear chain, Ohm} \\
S_m & \quad \sim d_c^2, \text{cross section area of a cell or a membrane, m}^2
\end{align*}

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I. INTRODUCTION

Pulsed electric field (PEF) treatment is a new and promising nonthermal processing method for heterogeneous cellular materials. PEF methods are based on the effect of cell transformation or rupture under an external electric field, which results in increase of the electric conductivity and permeability of cellular material. This effect known as dielectric breakdown (Zimmermann, Pilwat & Riemann, 1974), or electroplasmolysis (Scheglov, 1983), can be explained generally by electroporation, i.e., electric field induced formation and growth of pores in biological membranes resulting from their polarization. The method of electroporation became very popular because it was found to be an exceptionally practical way of transferring drugs, genetic material (e.g. DNA), or other molecules inside the cells (Chang, Chassy, Saunders & Sowers, 1992). Recently, scientists began to use the PEF methods for treatment of liquid food (fruit juices, milk etc.), as an alternative to high temperature preservation (Barbosa-Canovas, Pothakamury,
III. BACKGROUND THEORY AND SIMULATION MODEL

A. Field Induced on a Cell Membrane in an External Field

We consider at first the case of an individual cell inside the homogeneous medium having a low effective conductivity \( \sigma_e \) placed into an external electric field of strength \( E \). The maximum voltage \( u \) between the internal and external cellular surfaces of membrane (or transmembrane voltage) induced on cell poles by the external field, is equal to (Neumann, Sprafke, & Boldt, 1992):

\[
u = \alpha f d_e E
\]

where \( \alpha \) is the geometry factor equal to 0.75 for the spherical geometry of cell and to 1 for a cell of cubic geometry, and \( f \) depends on the electrical and geometrical properties of the cell (Kotnik, Miklavcic & Slivnik, 1998)

\[
f = \frac{\sigma_e (6m \sigma_e - (12m^2 - 8m^3)(\sigma_m - \sigma_e))}{(\sigma_m + 2\sigma_e)(\sigma_m + \sigma_e/2) - (1 - 2m)^3(\sigma_e - \sigma_m)(\sigma_e - \sigma_m)}
\]

Taking into account the low conductivity of membrane, \( \sigma_m/\sigma_e << 1 \) and expanding Eq. (2) in power of \( \sigma_m/\sigma_e \), we obtain:

\[
f = (1 + \frac{\sigma_m}{2\sigma_e K})/K + O\left(\frac{\sigma_m}{\sigma_e}\right)^2,
\]

where \( K = 1 + \lambda(2 + \sigma_e/\sigma_e)/4 \), and under the usual conditions (standard values of \( d_e, d_m, \sigma_m, \sigma_e \) and \( \sigma_e \) parameters for this problem are collected by Kotnik, Miklavcic and Slivnik (1998)) \( \lambda \sim 10^{-1} - 10^{-2} \ll 1 \) and \( f \sim 1 \). For the purposes of estimation we shall consider further on only the cells of cubic geometry, so we put \( \alpha = 1 \). In this approximation, \( f \) is equal to the normalised transmembrane voltage \( u/d_e E \).

Now we consider a problem of transmembrane voltage \( u \) estimation for a cell inside a biological tissue. In this case, the external media is not homogeneous, so, Eqs. (1) and (2) are inaccurate. They can be used only as approximate estimation by assuming a certain effective value of \( \sigma_e \). This is just the mean field (MF) type of approximation, which does not take local conductivity fluctuations into account. It can be assumed, as a rough approximation, that in an inhomogeneous medium the equation (3) may also be used for determination of the \( u \) values, however, \( f = f(r) \) will depend on the space co-ordinate \( r \) and will vary from cell to cell.

As it follows from Eq. (3), the value of \( f \) gradually increases with the increase of external medium effective conductivity \( \sigma_e \), which depends on the biological tissue destruction degree, \( P \). Here we define the biological tissue destruction degree as:
\[ P = 1 - N_m/N_t. \] (4)

As a more precise estimation of \( \sigma_e \) versus \( P \) dependence, we have used the generalised effective media equation with the same morphology parameters as in percolation theory (McLachlan, 1989):

\[
\frac{\varphi(1 - \Sigma)}{1 + \psi \Sigma} + \frac{\Sigma_o - \Sigma}{\Sigma_o + \psi \Sigma} = 0.
\] (5)

This equation reduces to the well-known Bruggeman’s symmetric equation when \( t = 1 \) (Landauer, 1978). Everywhere throughout this work we use the values of \( t = 2.3, P_p = 0.307 \), which are typical for the 3d simple cubic lattice (Sahimi, 1993). In the general case we obtain the following solution of Eq. (5):

\[
\sigma_e(P) = \sigma_e \left[ \left( \frac{\varphi(\psi - \Sigma_o) + \Sigma_o \psi - 1 + \sqrt{\varphi^2(\psi + \Sigma_o)^2 + 2\varphi[\Sigma_o(\psi + 1)^2 - \psi(\Sigma_o - 1)^2] + (\psi \Sigma_o + 1)^2}}{2\psi(\varphi + 1)} \right)^t. \right.
\] (6)

which can be easily used for the numerical estimation of \( \sigma_e \) versus \( P \) dependency.

From Eq. (6) we can easily obtain \( \sigma_e = \sigma_f = \sigma_c \lambda/(1 + \lambda) \) at \( P = 0 \) and \( \sigma_e = \sigma_c \) at \( P = 1 \).

The example of \( f \) versus \( P \) dependence on the mean field approximation obtained with the help of Eqs. (6) and (7) is presented in Fig. 1 (line 1). At low degrees of the biological tissue destruction, \( P \rightarrow 0 \), the effective conductivity \( \sigma_e \) approximately equals to \( \sigma_e = \sigma_f = \sigma_c \lambda/(1 + \lambda) \). At complete destruction of a biological tissue, \( P \rightarrow 1 \), we have \( \sigma_e \approx \sigma_c \). Thus, we obtain the following limiting relations in MF approximation:

\[
\begin{align*}
 f(P \rightarrow 0) &= 1/(2 + 3\lambda) \approx 1/2, \text{ and} \\
 f(P \rightarrow 1) &= 1/(1 + 3\lambda) \approx 1
\end{align*}
\] (7)

i.e., the value of \( f \) approximately doubles with the biological tissue destruction increase within the range of \( P = 0 \) to \( P = 1 \).

In fact, the change in \( f \) with increasing biological tissue destruction degree \( (P) \) is impossible to describe within the frames of such simplified approach, because of substantial local fluctuations of the external medium conductivity existing in the real inhomogeneous biological tissues. Such fluctuations are especially high near the punctured cells, where the local values of conductivity can exceed the effective average value \( \sigma_e \) by some orders of magnitude. The MF approximation works especially poor at low degrees of biological tissue destruction, \( P \rightarrow 0 \), when the local conductivity fluctuations are high. In order to demonstrate the complex behaviour of \( f \) versus \( P \) dependence in a real biological tissue, we have considered the oversimplified linear chains (LC) approximation as a simulation of a real tissue structure. The tissue is simulated by linear chains consisting of \( N_t \) cells of a cubic-like geometry (\( \alpha = 1 \)). The total resistance of such linear chain consisting of serially connected membrane resistances \( (r_m = d_m/(\sigma_m S_m)) \) and intercellular fluid resistances \( (r_c = d_c/(\sigma_c S_c)) \) can be estimated using the following relation:

\[ R = (N_t r_c + N_m r_m). \] (8)

The density of current running through such linear chain is equal to:

\[ j = U/(RS_m) = U/(N_td_c/\sigma_c + N_m d_m/\sigma_m) = \sigma_c U/(N_t d_c) = \sigma_c E, \] (9)

where

\[ \sigma_c = \lambda \sigma_c/(\lambda + 1 - P), \] (10)

is an effective chain conductivity, and \( E = U/L = U/(N_t d_c) \).

The percolation point is observed in LC-approximation at \( P = P_p = 1 \), and it can be easily shown, that the more general Eq. (6) reduces to the Eq. (10) in the case of \( t = 1 \).

The voltage drop at a single membrane is equal to:

\[ u = jS_m r_m = j d_m/\sigma_m = d_c E \sigma_c/(\lambda \sigma_c), \] (11)

or we obtain for \( f = u/d_c E \) (at \( \alpha = 1 \)):

\[ f = \sigma_c(P)/\lambda \sigma_c. \] (12)

The example of \( f \) versus \( P \) dependence for the linear chain approximation obtained with the help of Eqs. (6) and (12) is presented in the Fig. 1 (line 2).
We obtain from Eqs. (6) and (12) in LC approximation with account for \( \lambda \ll 1 \):

\[
\begin{align*}
    f(P \to 0) &= 1/(1 + \lambda) \approx 1, \quad \text{and} \\
    f(P \to 1) &= 1/\lambda \gg 1
\end{align*}
\]

i.e. in this case the value of \( f \) can considerably increase in the course of biological tissue destruction, and it is in contradiction with the conclusion, which follows from Eq. (3) on the basis of MF approximation.

Moreover, MF approximation gives us \( f(P \to 1) \approx 1 \), but in LF approximation we have \( f(P \to 0) = 1/(1 + \lambda) \approx 1 \). How can we clear this contradiction? MF approximation is good only at large values of \( P \to 1 \), when all the cells of tissue are destroyed and the media is practically homogeneous. On the other side, LC approximation works well only at small values of \( P \to 0 \). In this latter case we can neglect any bridging effects, which are very important in the middle of the range of \( P \) values. The bridging effect results from the deviations of local conductivity near the selected cell from the average effective conductivity of the whole media. Analysing the parallel electrical circuits in the near-neighbours environments of a given cell, we can easily approximate the averaged local cell resistance \( r_n \) as

\[
r_n \approx 1/((1 - P_n)/r_i + P_n/r_c).
\]  

For the cells arranged in the sites of a simple cubic lattice we have \( P_n = (1 - n/6) \), where \( n \) is the discrete number of intact cells neighbouring a given cell. Then the voltage drop at a single membrane equals to:

\[
u = j r_m S_m r_i = \frac{d_e E \sigma_e}{\lambda \sigma_e (1 + P_n/\lambda)},
\]

and we obtain the following generalised equation for estimation of the local value \( f_n = u/d_e E \)

\[
f_n(P, P_n) = \sigma_e(\lambda + P_n) \sigma_c
\]  

where in the general case the value of \( \sigma_e \) at given \( P \) may be determined from Eq. (3).

Figure 2 shows the example of local conductivity \( f_n \) versus \( P \) dependencies obtained at various \( n \) with the help of Eqs. (6) and (13). We see that the local behaviour of \( f_n(P, P_n) \) function can be rather complex and it can reflect the local conductivity changes near the chosen cell. We have shown with the dashed curve the imaginary fluctuations of \( f_n \) with \( P \) increase and successive breakdown of neighbouring cells. We understand that this approach proposed for estimation of the \( f_n(P, P_n) \) behaviour is very simplified. Particularly, here we overestimate the importance of the lattice contribution to the \( f_n(P, P_n) \) behaviour due to the discreteness of this problem, and in the case of continuum more smooth behaviour of \( f_n(P, P_n) \) can be observed for the continual parameter \( P_n \).

The behaviour of the averaged value \( \langle f(P) \rangle = \langle f_n(P, P_n) \rangle \) (here \( \langle \ldots \rangle \) implies averaging over all the cells of a system) will depend on the spatial distribution of broken cells in such system. Let us consider as an example, the \( f(P) \) behaviour for the model of random sequential occupation (RSO) of the lattice sites with the broken cells. This problem is very complex and has no exact solution. Here, the Monte Carlo simulation is a rather simple and useful method allowing to get the \( f(P) \) function for the given type of cell distribution in the system. We have considered the cells located in the sites of a simple cubic lattice with the following dimensions: 100x100x100. The simulation consisted of successive random choice of an intact cell, its further destruction and averaging of the calculated \( f \)-values over the whole lattice. We used the periodical boundary conditions along all the \( x \), \( y \) and \( z \) directions in order to reduce the influence of boundaries. The results were averaged over 10 different initial configurations. The example of \( f \) versus \( P \) dependence obtained as described above is presented in the Fig. 3 (line 3). The dashed line 4 corresponds to \( f \) dispersion \( (\Delta f) \) and characterises fluctuations of \( f \) in the system. We see that on increase of the destruction degree \( (P) \) the values of \( f \) first decrease, then pass through a minimum and increase again. The point of minimum \( f(P) \) approximately corresponds to the maximal fluctuations of the local values \( f_n \) in a system, i.e., to the maximum of \( \Delta f \). The important positive feature of this method of \( f(P) \) estimation is as follows: we get \( f \approx 1 \) in both limit cases of \( P \to 0 \) and \( P \to 1 \), i.e., we remove here the contradiction between MF and LC approximations.

**B. Probability of a Single Cell Destruction**

The average lifetime of a membrane in the external electric field can be estimated with the help of the following equation (Weaver & Chismadzhev, 1996):

\[
\tau(T, u) = \tau_\infty \exp(\Delta F^*/(1 + u^2 C^*)),
\]  

where \( \Delta F^* \) is the free energy change associated with the transition of the membrane from its normal state to the broken state.
Lebedeva (1987) has presented the following estimates for the general lipid membranes: \( \tau_\infty \equiv 0.37 \times 10^{-6} \) s, \( \omega \approx 1.69 \times 10^{-11} \) N, \( \gamma \approx 2 \times 10^{-3} \) N m \(^{-2}\), \( C_m \approx 3.5 \times 10^{-3} \) F m \(^{-2}\) at \( T = 298 \) K.

Then the breakage probability for a membrane (as a whole cell) during the impact period of an impulse with duration of \( t_i \) may be estimated as

\[
g = 1 - \exp(-t_i/\tau(T,u)).
\] (18)

Taking Eq. (17) into account, we can rewrite Eq. (18) in the following convenient dimensionless form

\[
g(u^*) = 1 - \exp\left(-\ln 2/\exp\left(\left(1 - (1 - u^2)/(a\Delta u ln 2/u_o)\right)^{-1} - 1\right)\right),
\]

where \( u^* = u/u_o, u_o = \sqrt{(\Delta F^*/a - 1)/C^2}, \Delta u = u_o((1 - a/\Delta F^*)a ln 2)^{-1}, a = \ln(t_i/(\tau_\infty ln 2)), \) and \( du \geq du_c = 1/(a ln 2) \).

We see that \( g(u^*) \) is a kind of probability transition function and \( u = u_o \) corresponds to the midpoint, where \( g(u) = 1/2 \) and \( du \) is the width of this function. We can estimate the following actual values for the general lipid membranes using the experimental data of Lebedeva (1987): \( u_o \approx 0.92 \) V, \( \Delta u \approx 0.41, a \approx 3.66 \) and \( \Delta u_c \approx 0.394 \) (at \( t_i = 10 \) \( \mu \)s) and \( u_o \approx 0.71 \) V, \( \Delta u \approx 0.26, a \approx 5.97 \) and \( \Delta u_c \approx 0.242 \) (at \( t_i = 100 \) \( \mu \)s).

C. Description of the Simulation Model

To achieve the best performance, we have used here a hybrid of MF and cellular automaton strategies in order to reduce the computational complexity. First we construct an array of destroyed cells located in the sites of a simple cubic lattice. The system has the \( N_x \times N_y \times N_z \) dimension and periodical boundary conditions are applied in all directions (Fig. 3). We use \( N_x = N_y = 10 \) and \( N_z = 1000 \) in our simulation. The external electric field of the E strength is applied along the \( z \)-axis and the total sample width is \( L = d_z N_z \). The site with intact cell is marked as occupied. We consider the idealised square pulse sequence with the pulse duration \( t_i \), and the pulse repetition time \( \Delta t \).

The simulation procedure is done at each time step according to the following scheme:

a) choose of the next occupied site within a lattice using the linear search procedure;

b) determination of the number of occupied sites \( n \) among all of its six near-neighbours, determination of \( P_n \), and calculation of the transmembrane voltage \( u \) at a given cell with the help of Eqs. (1), (6) and (16);

c) calculation of the probability of a given cell destruction using Eq. (19);

d) reiteration of the step (a) until all the occupied lattice sites appear to be tested.

The total destruction degree \( P \) and values of \( \sigma_c \) and \( < f_n(P,P_n) > \) are calculated after each pulse. These time steps run until \( P \) reaches its asymptotic value. This model is a simple cellular automaton for the purposes of simulation of the heterogeneous material breakage kinetics. Indeed, at the step (b) we test the near-neighbour interior of a given cell and then we calculate the probability of destruction.

The elevation of the temperature after each pulse was estimated with account to the Joule heating of material. The ohmic temperature increase \( \Delta T(t_i) \) after each pulse of \( t_i \) duration was calculated using the following equation

\[
\Delta T(t_i) = \frac{d\Delta T}{dN} = \frac{E^2 \sigma_c t_i}{C \rho}.
\] (20)

We use in all calculations: \( d_c = 10^{-5} \) m, \( d_m = 10^{-8} \) m, \( \sigma_c = 0.1 - 1 \) S m \(^{-1}\), \( \sigma_m = 10^{-4} - 10^{-6} \) S m \(^{-1}\), \( t_i = 10 - 100 \) \( \mu \)s and putting \( C = 3.93 \) kJ kg \(^{-1}\)K \(^{-1}\) and \( \rho = 0.81 \times 10^3 \) kg m \(^{-3}\), which values are characteristic for apples at 25°C (Losano, Urbicain & Rotstein, 1979).

III. MATERIALS AND METHODS

A. Materials

Freshly harvested apples of Golden Delicious variety were selected for investigation and stored at 4°C until required. In all the cases \( W \) was within 80-85%. We estimated the cell destruction degree as a ratio of effective conductivities measured before and after pulsed electric field treatment. The specific conductivities of samples, both initial (before treatment) and final (after the full treatment at highest voltages) were within \( \sigma_b = 0.004 - 0.008 \) S m \(^{-1}\) and \( \sigma_a = 0.1 - 0.2 \) S m \(^{-1}\), respectively. The specific conductivity of the apple juice extracted from the sample apples was within \( \sigma_j = 0.1 - 0.3 \) S m \(^{-1}\).
Thin slices (6 ± 0.2 mm thickness and 45 ± 0.5 mm diameter) were cut from an apple pap. The conductivity was measured with LCR Meter HP 4284A (Hewlett Packard) for the thin apple slice samples and with Conductimetre HI8820N (Hanna Instruments, Portugal) for the apple juice samples at frequency 50Hz (this frequency was selected as an optimal in order to remove the influence of the polarising effects on electrodes and inside the samples). Figure 4 is a schematic representation of the experimental pulsed electric field treatment set-up. The temperature was recorded by the thermocouple THERMOCOAX type 2 (AB 25 NN, ±0.1°C). High voltage pulse generator, 1500V-15A (Service Electronique UTC, France) allowed to vary \( t_i \) within the interval of 10 – 1000 µs (to precision ±2 µs), \( \Delta t \) within the interval of 1 – 100 ms (to precision ±0.1ms) and \( N \) within the interval of 1 – 100000. All the experiments were repeated, at least, five times. Pulse protocols and all the output data (current, voltage, impedance, and temperature) were controlled with the data logger via Windows 95 software.

IV. RESULTS AND DISCUSSION

Figure 4 presents the experimental curves of relative conductivity \( \sigma_a/\sigma_b \) versus number of pulses \( N \) for different values of the electric field strength \( E \) with \( t_i = 100 \) µs and \( \Delta t = 10 \) ms. We have obtained practically similar results for \( \sigma_a/\sigma_b \) vs \( N \) dependencies at different values of \( \Delta t \) within the interval of 1 – 100ms. Hence, pulse repetition time does not influence our data and we have used \( \Delta t = 10 \) ms in all the experiments. We have observed similar results for \( \sigma_a/\sigma_b \) versus \( N t_i \) (equivalent time of electrical treatment) on \( t_i \) variation. The kinetics of temperature evolution \( \Delta T \) against \( N \) is presented in Fig. 5.

We can conclude out of the data obtained that there exist, at least, two different stages of the material breakdown evolution. We have divided these stages conditionally by a horizontal dashed line in the Fig. 3. At the first stage, the sequential and the correlated breakdowns of cells develop in the system. The time of the first stage changes drastically with \( E \) increase. At low values of \( E \) we observe a very slow evolution of the material breakdown. The second stage of material breakdown (over the horizontal dashed line) flows more rapidly until terminated by an abrupt total dielectric breakdown of the material. At this moment we observe the overflow value of the out-of-limit current (15A) and stop the further treatment of material. We observe for each \( E \) a certain value of \( N_b \), which corresponds to the number of pulses at the moment of the total dielectric breakdown of material. Figure 5 presents \( N_b \) versus \( E \) (electric field strength) dependence.

The insert in Fig. 4 shows that practically in all the cases we observe approximately linear \( T \) versus \( N \) dependencies. Some deviation from this linear behaviour can be seen only for small \( E \) values (\( E = 0.2 \) kV cm\(^{-1} \)) and at large \( N > 10^4 \); we can explain it by the heat exchange with the outside media. The slopes of the near-linear \( T \) versus \( N \) curves correspond to the mean values of \( \Delta T(t_i) = d\Delta T/dN \) averaged over the total interval of \( N \). They are shown in Fig. 3 for the different values of \( E \). Here the solid line corresponds to the square-law \( \Delta T(t_i) \) versus \( E \) increase in accordance with relation

\[
\Delta T(t_i) = a + bE + cE^2,
\]

which is consistent with Eq. (20). Here \( a = 1.116x10^{-4}, \ b = -1.118x10^{-5}, \ c = 4.946x10^{-8} \) are the values obtained from root mean square treatment of the experimental data for the interval \( E < 1 \) kV cm\(^{-1} \). At large values of field strength, \( E > 1 \) kV cm\(^{-1} \), we observed a considerable deviation from the parabolic law of Eq. (20) in the \( d\Delta T/dN \) versus \( E \) dependency. The reasons of such deviation are still unclear.

The computer simulation results for the breakage degree \( (P) \) versus number of pulses \( (N) \) and effective conductivity \( (\sigma_e) \) versus number of pulses \( (N) \) dependencies at the different values of \( E, \lambda = 0.1 \) and \( \lambda = 0.01 \) are presented at Fig. 6.a.b. We observe the obvious step-like behaviour of these \( P(N) \) and \( \sigma_e(N) \) curves describing the breakage kinetics. This behaviour reflects the “jamming” effects present in the systems under investigation and has a pure geometric origin.

The “jamming” problem is very important and occurs in a number of situations, such as irreversible surface deposition of extended objects, random sequential adsorption (RSA problem), polymer physics problem or car-parking problem (J. W. Evans, 1993; Nielaba, Privman & Wang, 1993). The basic characteristic of this problem is the “ jamming” coverage that depends on the type of the lattice and system dimensionality. In the case of deposition of the definite size particles the “jamming” limit is reached when it is impossible to place any further objects without overlapping the deposited before. The “jamming” effects in the dielectric breakdown problem have the following origin: when a cell gets punctured, there appear the bridging effects, which cause the abrupt fall of destruction probability for cells surrounding the punctured one. In the frame of our model, this bridging effect results from deviations of...
the local conductivity near the selected cell \(n\) (see, Eq. (14)) against the average effective conductivity of the whole media \(\sigma_e\).

In the RSA problem, the cell puncture is equivalent to the lattice site occupation, thus, occupation of definite site results in abrupt fall of the occupation probability for sites neighbouring the punctured one. The dielectric breakdown problem in such formulation is very similar to the RSA problem, except for successive "jamming" limits, which correspond to the site occupation with one, two, and et-cetera near-neighbours. We have carried out the Monte-Carlo simulation for the random sequential occupation of sites in the simple cubic lattice with \(j\) neighbour punctured cells in order to find the "jamming" limits \(P(j)\). We have obtained the following values for the lattice of 200x200x200 dimension by averaging the calculation results over the 10 different initial configurations: \(P(0) = 0.305047 \ldots, P(1) = 0.42026 \ldots, P(2) = 0.49368 \ldots, P(3) = 0.544401 \ldots, P(4) = 0.59321 \ldots, P(5) = 0.64347 \ldots, \) and \(P(6) = 1\).

The "jamming" effects in the dielectric breakdown problem result in existence of the saturation regimes in the breakdown kinetics. The first "jamming" step is clearly observed in the Fig. 5 for the small values of \(E/u_o < 1\) at \(P = P(0) \approx 0.3\). The next "jamming" steps are less pronounced and can be clearly observed only at small values of \(\Delta u\). The initial increase on the \(P\) versus \(N\) curves corresponds to the breakdown development without any near-neighbours bridging effects. At large values of \(E/u_o > 1.5\) we observe the jump on the next "jamming" steps \((P(1), P(2))\) with the subsequent saturation regime.

We have observed the similar saturation regimes in experimental observations of the kinetics of dielectric breakage in thin apple slices (see Fig. 4), particularly, at small values of \(E < 0.5\) kV cm\(^{-1}\). The step-like behaviour is not so pronounced in experimental results as in computer simulation data presented in the Fig. 5; this difference results from the simulation model restrictions and, partially, from the lattice nature.

Figure 6 presents the curves of the calculated breakage degree \(P\) versus relative ohmic temperature increase \(\Delta T(\degree C)\) at different values of the electric strength \(E\) for \(\lambda = 0.1\) and \(\lambda = 0.01\). These calculations were done using Eq. (24). These data allow us to understand the correlation existing between the achieved breakdown degree and the power consumption, which is proportional to \(\Delta T\).

When the electric strength (\(E\)) values are low, the high destruction degree (\(P\)) can be achieved only on account of high power consumption and, correspondingly, with high overheating of the surrounding medium. However, the weakness of the electric field treatment is the possibility of a "jamming" regime, when the increase in power consumption fails to result in \(P\) increase, and poor control over the course of process. As far as it is difficult to choose precisely the required electric treatment mode for the given field strength values, here the transition to the mode of the overflowing out-of-limit current value occurs readily. In this case we stop the further treatment of a material and actually don’t achieve the high values of \(P\).

Figure 7 presents the curves of the number of pulses in the total breakdown point \((N_b)\) versus reduced electric strength \((E/u_o)\) for different values of \(\Delta u/u_o\) and \(\lambda\). We see that the character of \(N_b\) vs \(E\) curves depends on the values of \(\Delta u/u_o\) and \(\lambda\). The \(N_b\) increases with decrease of \(\Delta u/u_o\) at given \(E\) value. Unfortunately, we are unable to make more strict comparison between theoretical and experimental data, as far as we have no precise data for \(u_o\), \(\Delta u\) and \(\lambda\) parameters present in computer model. However, the general character of calculated \(N_b\) vs \(E\) dependencies (Fig. 4) correlates with experimental data presented in Fig. 5.

V. CONCLUSION

The simplified dielectric breakage model based on effective media approximation is proposed. This approximation includes equations with the same morphology parameters as in percolation theory. The normalised transmembrane voltage \(f = u/d_mE\) versus media breakage degree \(P\) dependence is obtained; this dependence is useful for estimating the transmembrane voltage and of the cell breakdown probability under the PEF treatment of cellular material. The most important feature of the proposed model is the existence of the "jamming" behaviour occurring in experimental observations of the biological tissue breakage. The different transitions corresponding to the different "jamming" steps are identified. The experimental study has yielded information about the material destruction degree and temperature elevation versus the time of PEF treatment at different values of field strength \(E\) in the interval of \(0.2 - 2.2\) kV cm\(^{-1}\). The proposed simulation model gives results consistent with the general trends observed in experimental breakage kinetics. The electric treatment is the most efficient at high values of the electric field strength \(E\). However the efficiency of such electric treatment is limited by manifestations of the "jamming" effect, as well as by the processes of electric treatment upset. Reduction of \(E\) values allows controlling the treatment process more precisely and prevents from uncontrolled breakdown but it is accompanied with increase of electric power consumption.
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FIG. 1. Normalised transmembrane voltage $f = u/d_e E$ versus media destruction degree $P$ dependencies calculated for the MF approximation using Eqs. (2), (6) (curve 1), for the LC approximation using Eqs. (1), (2) (curve 2) and for the RSO model using results of simulation (curve 3). The dashed curve 4 corresponds to $f$ dispersion $\Delta f$ in RSO model. The calculations were performed at $t = 2.3$, $P_p = 0.307$, $d_e = 10^{-5}$ m, $d_m = 10^{-8}$ m, $\sigma_e = 1$ S m$^{-1}$, $\sigma_m = 10^{-5}$ S m$^{-1}$, and $\lambda = 0.01$. 

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FIG. 2. Normalised transmembrane voltage $u/d_c E$ versus media destruction degree $P$ at various $n$ (the number of intact cells neighbouring a given cell). The dashed line corresponds to the example of $u/d_c E$ behaviour with increase of the number of destroyed near-neighbours in the course of the media breakage. The calculations were performed at $t = 2.3$, $P_p = 0.307$, $d_c = 10^{-5}$ m, $d_m = 10^{-8}$ m, $\sigma_c = 1$ S m$^{-1}$, $\sigma_m = 10^{-5}$ S m$^{-1}$, and $\lambda = 0.01$ for cells arranged in the sites of a simple cubic lattice.

FIG. 3. The model of the cellular material structure used in the computer simulation.

FIG. 4. Schematic representation of the experimental set-up used in the study of pulsed electric field treatment of the apple slices.

FIG. 5. Relative conductivity $\sigma_a/\sigma_b$ versus number of pulses $N$ at different values of the electric field strength $E$, $t_i = 100$ µs and $\Delta t = 10$ ms for thin apple slices at 25°C.

FIG. 6. Relative ohmic temperature increase $\Delta T(\degree C)$ versus number of pulses $N$ at different values of the electric field strength $E$, $t_i = 100$ µs and $\Delta t = 10$ ms for thin apple slices at 25°C. Insert shows the same data for small $N$ values in linear co-ordinates $T$ vs $N$.

FIG. 7. Dependencies of the number of pulses in the total breakdown point $N_b$ and of the mean ohmic temperature increase $\Delta T(t_i)$ after each pulse of $t_i$ duration against the electric strength $E$ at $t_i = 100$ µs and $\Delta t = 10$ ms for thin apple slices at 25°C.

FIG. 8. Calculated breakage degree $P$, effective conductivity $\sigma_e$ versus number of pulses $N$ dependencies (a,b) and breakage degree $P$ versus relative ohmic temperature increase $\Delta T(\degree C)$ dependencies (c) at different values of electric field strength $E$ for $\lambda = 0.1$ and $\lambda = 0.01$. The calculation are performed at $t = 2.3$, $P_p = 0.307$, $\Delta u = 0.35$, $u_o = 1$, $t_i = 100$ µs, $d_c = 10^{-5}$ m, $d_m = 10^{-8}$ m, $\sigma_c = 1$ S m$^{-1}$, $\sigma_m = 10^{-5}$ S m$^{-1}$ ( $\lambda = 0.01$), and $\sigma_e = 0.5$ S m$^{-1}$, $\sigma_m = 5\times10^{-5}$ S m$^{-1}$ ( $\lambda = 0.1$).

FIG. 9. Calculated number of pulses in total breakdown point $N_b$ versus reduced electric strength $E/u_o$ for different values of $\Delta u/u_o$ and $\lambda$. The calculation are performed at $t = 2.3$, $P_p = 0.307$, $\Delta u = 0.35$, $u_o = 1$, $t_i = 100$ µs, $d_c = 10^{-5}$ m, $d_m = 10^{-8}$ m, $\sigma_c = 1$ S m$^{-1}$, $\sigma_m = 10^{-5}$ S m$^{-1}$ ( $\lambda = 0.01$), and $\sigma_e = 0.5$ S m$^{-1}$, $\sigma_m = 5\times10^{-5}$ S m$^{-1}$ ( $\lambda = 0.1$).
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