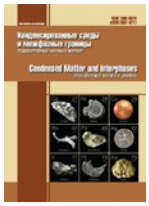

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Electrokinetic regimes of weakly conducting liquids under conditions of oxidation-reduction process

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Abstract

Objectives: The purpose of the work is mathematical modeling of the transport processes and interaction of ions in a weakly conducting liquid placed between two flat metal electrodes under conditions of a redox process.

Problem statement: The main mechanisms described within the proposed physical and mathematical model are the diffusion, electromigration, recombination, and dissociation. The presence of a potential difference between the electrodes causes the electric field generated in the liquid to displace ions resulting from the dissociation of ion pairs. This leads to concentration polarization, i.e. the accumulation of ions near oppositely charged electrodes and the formation of concentration boundary layers. Ions in direct contact with the electrodes are neutralized back into ion pairs, the behavior of which is described by a separate transport equation. Depending on the potential difference applied to the electrodes, two conductivity regimes are observed in the system. At low electric field strengths, the current is maintained due to the neutralization of ions at the electrodes because of rapid dissociation and recombination in the near-electrode regions. In this case, the ions do not diffuse very far from the electrodes. In turn, at high intensities, the electric field energy is sufficient to drive ion migration across the entire interelectrode space. Thus, at low potential differences, current flow is limited by the intensity of recombination and dissociation, while at high potential differences, it is limited by the rate of ion transfer from the one electrode to other. This circumstance is evident in the current-voltage characteristics, which have multiple inflection points in the initial sections. However, as the slow stage of electrical conductivity passes, the current-voltage characteristic becomes linear.

Conclusions: The calculation results allow us to conclude that the varying values of the kinetic coefficients and the electrical conductivity coefficient allows independent adjustment of the regions of the current-voltage characteristics responsible for a particular regime of current flow.

Keywords: Electroconductivity, numerical simulation, diffusion, dissociation, recombination, voltage-current characteristic

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Электрокинетические режимы поведения слабопроводящих жидкостей в условиях окислительно-восстановительного процесса

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Аннотация

Цель статьи: Целью работы является математическое моделирование процессов транспорта и взаимодействия ионов в слабопроводящей жидкости, помещенной между двумя плоскими металлическими электродами, в условиях окислительно-восстановительного процесса.

Постановка задачи: Основными процессами, которые описываются в рамках предлагаемой физико-математической модели, являются диффузия, электромиграция, рекомбинация и диссоциация. Присутствие разности потенциалов на электродах приводит к тому, что формируемое в жидкости электрическое поле смещает ионы, появляющиеся в результате диссоциации ионных пар. Это приводит к концентрационной поляризации, т.е. накоплению ионов у противоположно-заряженных электродов и образованию концентрационных пограничных слоев. Ионы, непосредственно контактирующие с электродами, нейтрализуются обратно в ионные пары, поведение которых описывается отдельным уравнением переноса. В зависимости от приложенной к электродам разности потенциалов в системе наблюдаются два режима электропроводности. При малых напряженностях электрического поля ток поддерживается за счет нейтрализации ионов на электродах вследствие быстрой диссоциации и рекомбинации в приэлектродных областях. Ионы в данном случае не сильно отдаляются от электродов. В свою очередь, при больших напряженностях энергии электрического поля достаточно для того, чтобы организовать миграцию ионов через все межэлектродное пространство. Таким образом, при малых разностях потенциалов прохождение тока лимитируется интенсивностью рекомбинации и диссоциации, в то время как при больших – скоростью переноса ионов от одного электрода к другому. Данное обстоятельство прослеживается в вольтамперных характеристиках, на начальных участках которых имеется множество точек перегиба. Однако при смене медленной стадии электропроводности вольтамперная характеристика принимает линейный характер.

Выводы: Результаты расчетов позволяют сделать вывод, что варьирование значений кинетических коэффициентов и коэффициента электропроводности позволяет независимым образом корректировать участки вольтамперных характеристик, отвечающие за тот или иной режим прохождения тока.

Ключевые слова: электропроводность, численное моделирование, диффузия, диссоциация, рекомбинация, вольтамперная характеристика

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1. Introduction

The physicochemical laws governing the flow of electric current through a liquid dielectric located between two electrodes across which a constant potential difference is maintained have been the subject of active study for many decades [1, 2]. However, a comprehensive description of the electrical conductivity processes in this system cannot currently be provided. Difficulties arising during research, which cannot be explained within the framework of a single theory, are due to a multitude of factors, such as the diversity of near-electrode processes [3–5], complicated kinetics of complex formation [6, 7], the influence of convective heat and mass transfer [8, 9], etc. Despite existing theories describing the phenomenon of electrical conductivity, a multitude of effects, including those leading to inflection points in the current-voltage characteristics, require a more thorough analysis, which typically comes down to taking into account the influence of one or another complicating factor.

In theoretical studies of electric current flow through weakly conducting liquids, the so-called electrohydrodynamic approximation is often used. This approach analyzes the effect of a relatively strong electric field on the liquid. This allows for a significant simplification of ion transport equations by eliminating the term responsible for diffusion [10–12]. Despite the technical advantages of this approach, it does not permit for a description of electrical conductivity in the case of weak electric fields, where diffusion flows compete with electromigration flows. Furthermore, such formulations often raise questions about the validity of boundary conditions [13].

In recent years, particular attention has been paid to modeling the electrical conductivity of membranes [14–16]. Unlike studies [10–13], the mathematical formulation here takes into account the diffusion term. In the considered formulations, the weakly conductive membrane system is immersed in an electrolyte solution, which allows for the simplification of the boundary condition on the concentration to a first-order condition. This circumstance allows not only to obtain numerical results with relative ease but also to compare them with experiment.

In [17], when describing the electrical conductivity of a liquid dielectric between flat electrodes, an attempt was made to preserve diffusion and electromigration in the transport equations and simultaneously take into account the possibility of the appearance and destruction of ions in the boundary conditions at the electrodes. However, despite the fact that accounting for near-electrode processes, even in model form, is a very relevant task, the proposed model does not allow us to approach the experimental results, since the coefficients introduced into the boundary conditions [17], responsible for the appearance and destruction of ions, respectively, cannot be associated with a specific process and measured.

It's important to note that none of the aforementioned studies consider the influence of ion pair distribution on electrical conductivity, either within the bulk of the liquid dielectric or in the near-electrode space. In the considered formulations, ion pair concentration is present as a parameter regulating the dissociation intensity in the ion transport equation. The presence of such a parameter forces all of the above formulations to be considered limiting cases of electrical conductivity in a weakly ionized medium, which is not always true.

For example, when analyzing the electrical conductivity of molten benzoic acid, the experiments are performed both with a substance previously maintained under conditions of 100 % humidity and with a pre-dried substance [18]. The results of the studies show that ion pairs in the molten benzoic acid are present in the form of complexes of its molecules and water molecules. Thus, by adjusting the conditions of benzoic acid storage, it is possible to greatly influence the number of ion pairs and, accordingly, the degree of ionization under given electrical conductivity conditions. The study of the properties of this particular substance is of great importance, since molten benzoic acid is used to protonate a lithium niobate crystal in the manufacturing of integrated optical circuits. The presence of impurities in the melt greatly affects the properties of the waveguides obtained during the technological process. In particular, the presence of lithium benzoate impurity, formed from the products of the proton exchange reaction [19, 20], can reduce the intensity of crystal hydrogenation [21]. Moreover, as shown in [19, 20], an integral effect accompanying proton exchange is the formation of an ionic boundary layer near the crystal, the characteristics of which can also influence the final product and are determined by the electrokinetic properties of the melt. According to earlier experiments [21], an external electric field generated near the protonated crystal surface can significantly alter the characteristics of the resulting waveguide. In order to model the proton exchange process taking this field into account, it is necessary to have a detailed understanding of the specific phenomena observed in liquid dielectrics through which an electric current is passed.

In this regard, a mathematical model is proposed and, with its help, the influence of the distribution of ion pairs on the process of electrical conductivity of a weakly conducting medium placed between two electrodes is described in this paper.

2. Problem statement

Let us consider a weakly conducting liquid as a melt similar in molecular kinetics to molten

benzoic acid with a small admixture of water, enclosed between two flat metal electrodes across which a constant potential difference is maintained. Since the electrodes are assumed to be flat, it is sufficient to consider a one-dimensional problem in which the origin of the x-axis coincides with the location of the positive electrode. The negative electrode is located at a point with coordinate h. In the bulk of the melt, positive hydronium and negative benzoate ions are constantly formed due to dissociation [18]. The presence of an electric field causes ions to migrate toward the oppositely charged electrodes. Diffusion, electromigration, and mutual transformations of ions are described using the following equations [10]:

$$\frac{\partial n_{\pm}}{\partial t} = D_{\pm} n_{\pm}'' \pm k_{\pm}\left(n_{\pm}'\varphi' + n_{\pm}\varphi''\right) - \\ -k_R n_+ n_- + 2k_D \frac{I_1(z)}{z} n_0, \quad (1)$$

where $n_{\pm}(x,t)$, and $n_0(x,t)$ – distributions of the concentration of positive and negative ions, as well as ion pairs, $\varphi(x,t)$ – electric potential field, $D_{\pm}$ и $k_{\pm}$ – diffusion and mobility coefficients of the corresponding ions, k_R and k_D – recombination and dissociation coefficients:

$$k_R = \frac{e\left(k_+ + k_-\right)}{\varepsilon_0 \varepsilon}, \; k_D = \frac{3e\left(k_+ + k_-\right)}{4\pi\varepsilon_0 \varepsilon a^3} \exp\left(\frac{-2L_b}{a}\right),$$

$I_1(z)$ – modified Bessel function of the first kind, $z = L_b/L_e$:

$$L_b = \frac{e^2}{2\pi\varepsilon_0 \varepsilon kT}, \; L_e = \sqrt{\frac{e}{4\pi\varepsilon_0 \varepsilon \left|\varphi'\right|}}.$$

The mobility of ions was determined using the Einstein relation:

$$k_{\pm} = \frac{eD_{\pm}}{k_B T}.$$

Parameters e, ε_0, ε, k_B, T и a – elementary charge, electric constant, permittivity, Boltzmann constant, temperature, and the characteristic distance between ions in an ion pair. Primes denote derivatives with respect to the coordinate.

Inhomogeneity in the distribution of ion concentrations, associated with differences in mobility coefficients, leads to the formation of a complex electric field distribution between the electrodes. This field is described using Poisson's equation:

$$\varepsilon_0 \varepsilon \varphi'' = e\left(n_+ - n_-\right). \quad (2)$$

The combination of equations (1) – (2) allows for the automatic inclusion of the effect of concentration overpotential [8] in the problem formulation, which is associated with the increase in ion concentrations in the near-electrode boundary layers. From an electrochemical perspective, the presence of concentration polarization leads to a change in the electrode potential (concentration overpotential), the magnitude of which can be estimated using the thermodynamic relationships derived in [3, 8]. In our mathematical model, an effect analogous to overpotential arises due to the corresponding relationship between the electrostatic and transport equations.

In contrast to earlier works devoted to modeling the electrical conductivity process, the distribution of ion pairs is also non-uniform and obeys a separate transport equation inextricably linked to the distribution of ions:

$$\frac{\partial n_0}{\partial t} = D_0 n_0'' + k_R n_+ n_- - 2k_D \frac{I_1(z)}{z} n_0, \quad (3)$$

where D_0 – the diffusion coefficient of ion pairs, calculated according to [23] for the case when the absolute value of the ions charge of different signs is the same and equal to e:

$$D_0 = \frac{2D_+ D_-}{D_+ + D_-}.$$

At the initial moment, the ion concentrations were zero, and the melt contained only ion pairs with a concentration of $\bar{n}_0$. To simplify the calculations, the electric potential distribution was also specified at this time moment:

$$n_{\pm}\left(t=0\right) = 0, \; n_0\left(t=0\right) = \bar{n}_0, \; \varphi\left(t=0\right) = \varphi_0\left(1 - \frac{x}{h}\right).$$

A constant potential difference φ_0 is maintained across the electrodes such that the electric field strength vector is directed along the x-axis. Furthermore, the problem under consideration models a redox process, i.e. the ions, reaching the oppositely charged electrode, are neutralized (Fig. 1). For simplicity, we will assume that both the benzoate and the hydronium ions are converted into the original ion pair upon

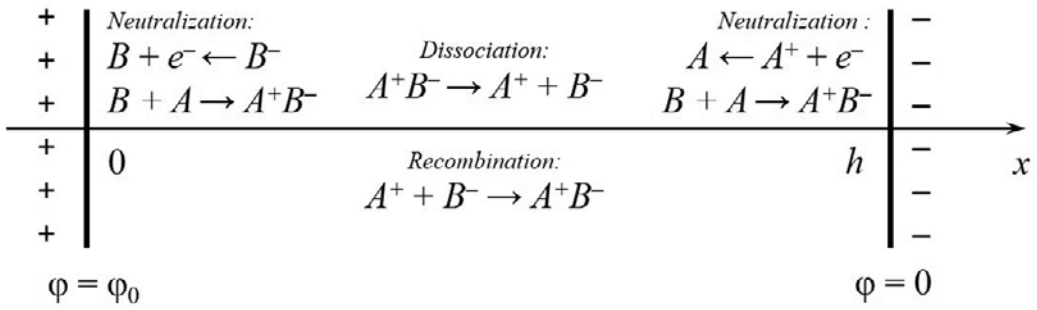

Fig. 1. System of coordinate and schematic representation of reactions

contact with the oppositely charged electrode through intermediate chemical reactions that are not considered explicitly. In response to neutralization, a flux of ion pairs appears from the electrodes into the melt. At electrodes with the same sign as the ions, the flux of the latter must be zero. Thus, the boundary conditions for the system of equations (1) – (3) are written as follows:

$$\begin{aligned} x=0:\quad & -D_+n_+' - k_+n_+\varphi' = 0,\\ & -D_n_' + k_n_\varphi' = \frac{\sigma\varphi'}{e},\\ & D_0n_0' = \frac{\sigma\varphi'}{2e},\quad \varphi=\varphi_0, \end{aligned} \tag{4}$$

$$\begin{aligned} x=h:\quad & -D_+n_+' - k_+n_+\varphi' = -\frac{\sigma\varphi'}{e},\\ & -D_n_' + k_n_\varphi' = 0,\\ & D_0n_0' = -\frac{\sigma\varphi'}{2e},\quad \varphi=0. \end{aligned} \tag{5}$$

These boundary conditions involve the value σ, which represents the electrical conductivity of the melt. Boundary conditions (4)–(5) assume that there is no electrodeposition or electrodissolution of the substance on the electrodes, i.e. the process considered in the mathematical model can be called oxidation-reduction [9].

The formulated problem was solved in dimensionless variables. The coordinate, time, concentration, and electric potential were normalized to h, h^2/D_+, $\bar{n}_0$ and φ_0. After the nondimensionalization procedure, the boundary value problem and initial conditions can be written in following form:

$$\begin{aligned} &\frac{\partial n_\pm}{\partial t} =\\ &= A_\pm n_\pm'' \pm B_\pm\left(n_\pm'\varphi' + n_\pm\varphi''\right) - Cn_+n_- + 2D\frac{I_1(z)}{z}n_0, \end{aligned} \tag{6}$$

$$\frac{\partial n_0}{\partial t} = A_0n_0'' + Cn_+n_- - 2D\frac{I_1(z)}{z}n_0, \tag{7}$$

$$\varphi'' = E\left(n_+ - n_-\right), \tag{8}$$

$$\begin{aligned} x=0:\quad & -A_+n_+' - B_+n_+\varphi' = 0,\\ & -A_n_' + B_\varphi' = \bar{\sigma}\varphi',\\ & A_0n_0' = \frac{\bar{\sigma}\varphi'}{2},\quad \varphi=1, \end{aligned} \tag{9}$$

$$\begin{aligned} x=1:\quad & -A_+n_+' - B_+\varphi' = -\bar{\sigma}\varphi',\\ & -A_n_' + B_\varphi' = 0,\\ & A_0n_0' = -\frac{\bar{\sigma}\varphi'}{2},\quad \varphi=0, \end{aligned} \tag{10}$$

$$A_\pm = \frac{D_\pm}{D_+},\quad A_0 = \frac{D_0}{D_+},\quad B_\pm = \frac{k_\pm\varphi_0}{D_+},\quad C = \frac{k_R\bar{n}_0h^2}{D_+},$$

$$D = \frac{k_Dh^2}{D_+},\quad E = \frac{e\bar{n}_0h^2}{\varepsilon_0\varepsilon\varphi_0},\quad \bar{\sigma} = \frac{\sigma\varphi_0}{e\bar{n}_0D_+},$$

$$n_\pm\left(t=0\right)=0,\quad n_0\left(t=0\right)=1,\quad \varphi\left(t=0\right)=1-x.$$

3. Solution technic

The formulated problem was solved numerically in the Comsol Multiphysics mathematical package using the MUMPS (MUltifrontal Massively Parallel Sparse Direct Solver) computational algorithm. The presence of terms responsible for the recombination and the dissociation in equations (6) and (7) requires a relatively large number of elements per computational domain. Moreover, to resolve the boundary layers forming at the electrode surfaces, it is necessary to refine the computational grid at the boundaries of the computational domain. Therefore, during the solution, a non-uniform grid symmetrical with respect to the center of the computational domain was generated with refinement near the points x = 0 and x = 1. The total working number of grid elements was 120000.

During the solution, cases with different values of electrical conductivity and parameters determining the kinetics of negative ions were simulated, which made it possible to obtain a family of current-voltage characteristics and thereby expand the scope of application of the results to a variety of substances. It should be noted that, for simplicity, the value of electrical conductivity was taken to be significantly lower than that obtained in the experiment [18], which, however, does not change the essence of the obtained results. The characteristic values that were taken by electrical conductivity, the diffusion coefficient of negative ions, and the potential difference: $\sigma = 5 \cdot 10^{-13} \ldots 2 \cdot 10^{-12}$ S/m, $D_- = 5 \cdot 10^{-10} \ldots 2 \cdot 10^{-9}$ m^2/s, $\varphi_0 = 0 \ldots 8000$ V. The remaining parameters retained their values: $h = 0.01$ m, $D_+ = 0.5 \cdot 10^{-8}$ m^2/s, $\varepsilon = 10$, $T = 300$ K, $a = 5 \cdot 10^{-10}$ m, $\bar{n}_0 = 10^{17}$ m^{-3}.

4. Results and discussion

Regardless of the values of the control parameters $A_\pm$, A_0, $B_\pm$, C, D, E, $\bar{\sigma}$, the calculations always lead to a steady-state regime ($\partial/\partial t = 0$), characterized by the accumulation of negative and positive ions, respectively, near the positive and negative electrodes. Depending on the value of the potential difference φ_0 applied to the electrodes, the distributions of all calculated quantities undergo significant changes. Thus, at small φ_0 (Fig. 2a) ions are present with identical concentrations throughout the melt, with the exception of the near-electrode regions. Near the electrodes, however, thin boundary layers form,

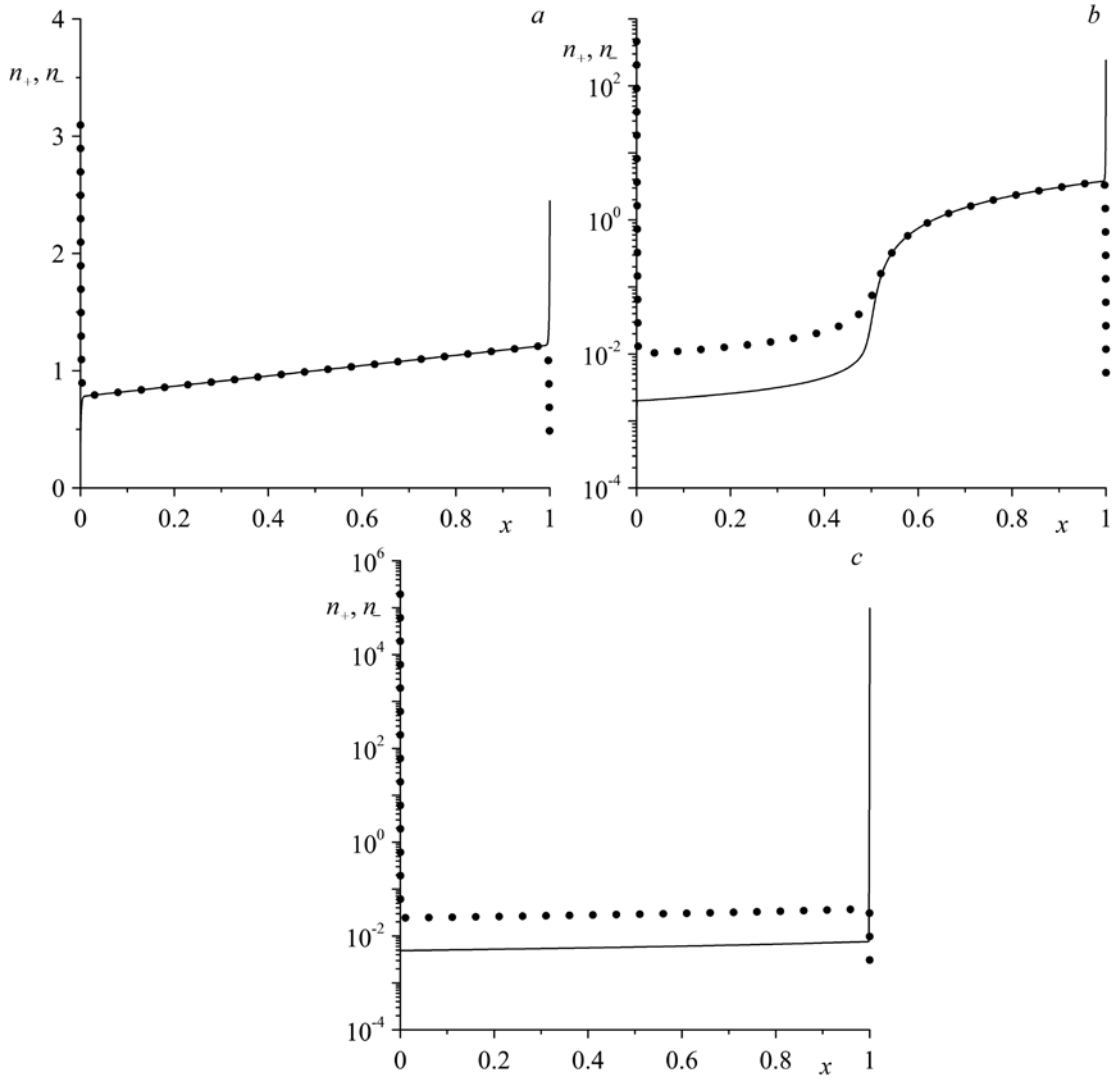

Fig. 2. Distributions of positive (solid lines) and negative (dots) ions in dependence on applied potential difference for $D_- = 5 \cdot 10^{-10}$ m^2/s, $\sigma = 5 \cdot 10^{-13}$ S/m: *a* – $\varphi_0 = 0.2$ V, *b* – $\varphi_0 = 100$ V, *c* – $\varphi_0 = 1000$ V

in which the concentration difference increases sharply. This also leads to a sharp jump in the electric field (Fig. 3a). The flow of electric current in this situation is ensured primarily by dissociation and recombination in the near-electrode regions.

Increasing φ_0 distorts the profiles (Fig. 2b). Gradually, on the positive electrode side, a region emerges in the melt volume where the ions have a non-zero concentration difference. The electric field strength in this region is significantly greater than in the region where the ions are of equal concentrations (Fig. 3a). Due to the increased field strength, the ion electromigration becomes more intense. However, the field energy is still insufficient to generate a through ion current from one electrode to the other. At a certain distance from the positive electrode, the probability of recombination of migrating ions increases significantly, and their concentrations equalize. Thus, the region of equal concentrations acts as a stagnation region, where transport processes slow down.

A further increase in φ_0 makes the electric field energy between the electrodes sufficient to generate a through current, i.e., ion migration across the entire interelectrode space from one electrode to the other. The region of unequal concentrations occupies the entire interelectrode space (Fig. 2c). In other words, at large potential differences, we can speak of spatial charge separation throughout the entire volume. The electric potential distribution tends toward linearity throughout the melt volume. It can also be noted that the gradual displacement of the stagnation region leads to a significantly higher degree of melt ionization (Fig. 3b).

Changes occurring in the melt with increasing potential difference across the electrodes also lead to nonlinearity in the current-voltage characteristic. The resulting specific current flowing between the electrodes was calculated using the following dimensional expression:

$$i = \int_0^h \left(j_+ - j_-\right) dx =$$

$$= \int_0^h \left(-D_+ n_+' - k_+ n_+ \varphi' + D_n_-' - k_n_\varphi'\right) dx,$$

where $j_\pm$ – current densities corresponding to certain types of ions.

The initial section of the current-voltage characteristics, corresponding to the presence of a stagnation region in the interelectrode space, exhibits a nonlinear increase in current. Calculations show that ion kinetics determines the current values in this section. For example, an increase in the diffusion coefficient of negative ions and, consequently, an increase in their mobility, as well as the diffusion coefficient of ion pairs, dissociation, and recombination, initiates an increased rate of growth of the specific current (Fig. 4a).

In turn, the disappearance of the stagnation region leads to the current-voltage characteristics

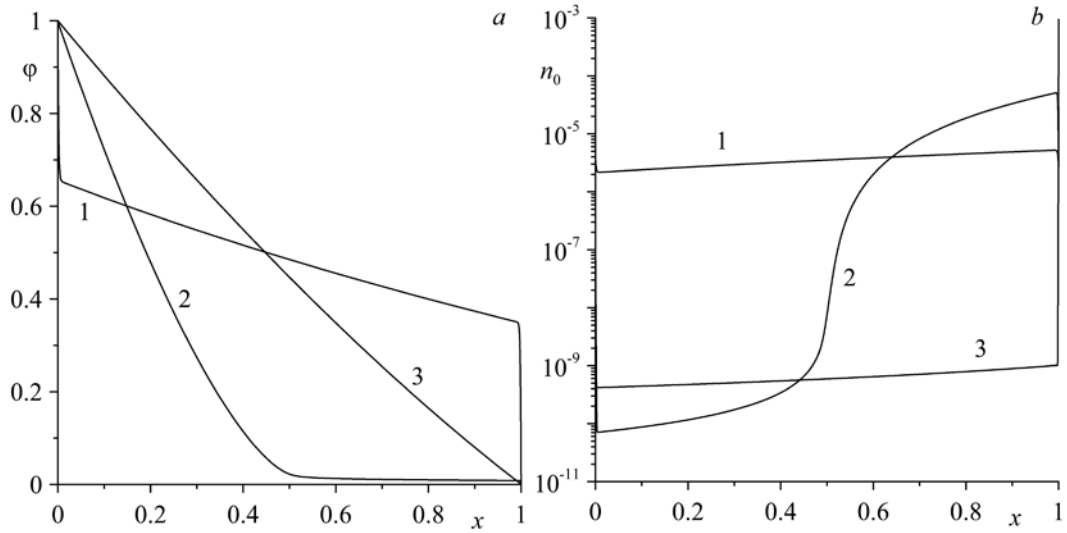

Fig. 3. Distributions of electric potential (a) and ion pairs (b) in dependence on applied potential difference for $D_- = 5 \cdot 10^{-10}$ m²/s, $\sigma = 5 \cdot 10^{-13}$ S/m: *a* – $\varphi_0 = 0.2$ V, *b* – $\varphi_0 = 100$ V, *c* – $\varphi_0 = 1000$ V

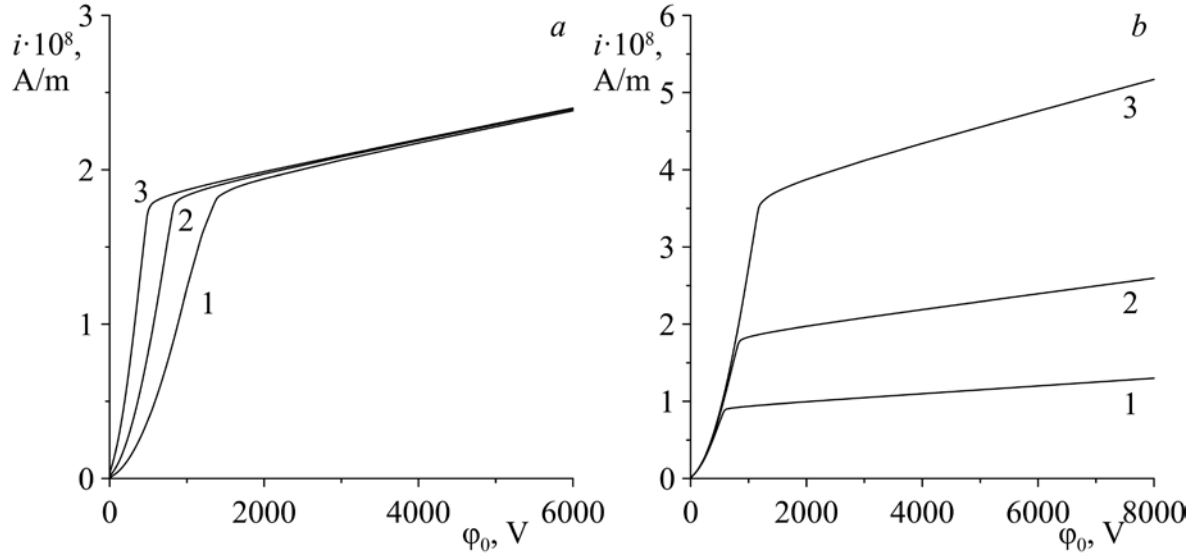

Fig. 4. Dimensional voltage-current characteristics for different kinetic coefficients and electroconductivity: *a*) 1 – $D_- = 5 \cdot 10^{-10}$ m²/s, 2 – $D_- = 10^{-9}$ m²/s, 3 – $D_- = 2 \cdot 10^{-9}$ m²/s, $\sigma = 10^{-12}$ S/m; *b*) 1 – $\sigma = 5 \cdot 10^{-13}$ S/m, 2 – $\sigma = 10^{-12}$ S/m, 3 – $\sigma = 2 \cdot 10^{-12}$ S/m, $D_- = 5 \cdot 10^{-10}$ m²/s

becoming linear. The slope of the linear region is determined by the electrical conductivity σ (Fig. 4b). Interestingly, the changes in ion kinetics have no effect on the slope of the linear interval, while changes in electrical conductivity primarily control its slope. Thus, by adjusting these parameters, one can independently influence the flow regimes of electric current in weakly conductive liquids.

The obtained results allow us to clearly determine the moment during which the factor limiting the flow of electric current changes [3, 8]. Thus, at small φ_0, when the current flow is associated only with the near-electrode boundary layers, the current strength is determined precisely by the dissociation and recombination of ions and ion pairs, and diffusion phenomena do not make a noticeable contribution to the current. As it is known, the resistance of electrolytes in the case of small potential differences is determined mainly by near-electrode processes. Thus, dissociation and recombination in the presented model are responsible for that part of the chemical overpotential that is determined by the properties of the liquid. Potential consideration of processes occurring directly in the electrodes (the idea is proposed in [8]) can correct the initial sections of the current-voltage characteristics, but will not qualitatively change the results. The curves shown in Fig. 3a can thus be interpreted as a comparison of the current-voltage characteristics of three substances whose kinetics are different, but the interaction with the electrodes is the same.

In turn, when a through current appears between the electrodes, the resistance associated with the effect of chemical overpotential becomes negligible compared to that associated with concentration overpotential. Within the proposed model, the quantitative characteristic of concentration overpotential is electrical conductivity. Thus, Fig. 4b compares the current-voltage characteristics of three substances whose dissociation-recombination properties and interaction with electrodes are identical, but whose ability to conduct electric current differs. The results presented in Fig. 4a and 4b allow us to characterize the various mechanisms responsible for current flow in the system under consideration.

5. Conclusion

Calculations have shown that two regimes of electric current flow through a weakly conductive medium can be distinguished, in which the current strength is limited by various factors. At low potential differences, the ion kinetics is decisive, while at high potential differences, the

electrical conductivity of the liquid's volume takes place. Varying the values of kinetic coefficients or electrical conductivity allows for independent adjustment of sections of the system's current-voltage characteristics. While kinetic coefficient values primarily determine near-electrode processes and, accordingly, the initial sections of the current-voltage characteristics, electrical conductivity controls the intensity of the through-current between the electrodes and the linear section of the characteristics.

Authors' declared contributions

Petukhov M. I. – development of the mathematical model, calculations, writing the text, discussion of the results. Demin V. A. – development of the mathematical model, discussion of the results.

References

1. Kim S. J., Wang Y.-C., Lee J. H., Jang H., Han J. Concentration polarization and nonlinear electrokinetic flow near a nanofluidic channel. *Physical Review Letters*. 2007;99: 044501. https://doi.org/10.1103/physrevlett.99.044501

2. Ganchenko G. S., Shelistov V. S., Olberg I. I., Morshneva I. V., Demekhin E. A. A study of electroconvection during uniform flow of an electrolyte solution through an ion-selective region. *Colloid Journal*. 2025;87: 454–461. https://doi.org/10.1134/s1061933x25600551

3. Antropov L. I. *Theoretical electrochemistry*. Moscow: Vysshaya Shkola Publ.; 1975. 568 p. (in Russ.)

4. Newman J., Balsara N. P. *Electrochemical systems*. Wiley; 2021. 608 p.

5. Gamburg Yu. D., Polyakov N. A. Studies of Electrocrystallization processes performed at the laboratory of the structure of surface layers of Frumkin institute of Physical Chemistry and Electrochemistry. *Russian Journal of Physical Chemistry A*. 2020;94(3): 477–484. https://doi.org/10.1134/s0036024420030103

6. Zhakin A. I. Ionic conductivity and complexation in liquid dielectrics. *Physics-Uspekhi*. 2003;173(1): 51–68. https://doi.org/10.1070/PU2003v046n01ABEH001141

7. Zhakin A. I. Kinetics of aggregation in non-polar liquid dielectrics. *Electronic Processing of Materials*. 2015;51(4): 49–60. (In Russ.). URL: https://cyberleninka.ru/article/n/kinetika-agregirovaniya-v-nepolyarnyh-zhidkih-dielektrikah/viewer

8. Levich V. G. *Physicochemical hydrodynamics*. Prentice Hall; 1962. 700 p.

9. Ostroumov G. A. *Interaction of electric and hydrodynamic fields*. Moscow: Nauka Publ.; 1979. 322 p. (in Russ.)

10. Pontiga F., Castellanos A. Physical mechanisms of instability in a liquid layer subjected to an electric field and a thermal gradient. *Physics of Fluids*. 1994;6: 1684–1701. https://doi.org/10.1063/1.868231

11. Smorodin B. L., Kartavykh N. N. Periodic and chaotic oscillations in a low conducting liquid in an alternating electric field. *Microgravity Science and Technology*. 2020;32: 423–434. https://doi.org/10.1007/s12217-020-09779-y

12. Nekrasov O., Smorodin B. The electroconvective flows of a weakly conducting liquid in the external DC and AC electric fields. *Microgravity Science and Technology*. 2022;34: 75. https://doi.org/10.1007/s12217-022-10002-3

13. Ilin V. A., Zadorozhny N. I. Stability of a poorly conductive liquid subjected to unipolar autonomous charge injection in an electric field. *Bulletin of Perm University. Physics*. 2022;4: 27–33. https://doi.org/10.17072/1994-3598-2022-4-27-33

14. Melnikov S. Ion transport and process of water dissociation in electromembrane system with bipolar membrane: modelling of symmetrical case. *Membranes*. 2022;13: 47. https://doi.org/10.3390/membranes13010047

15. Ganchenko N., Repina M., Ganchenko G., Demekhin E. Thermodiffusion in electrolyte between electric membranes under external electric field. *Microgravity Science and Technology*. 2020;32: 1199–1210. https://doi.org/10.1007/s12217-020-09842-8

16. Zhang P., Wan Z., Wei P., Wang P., Liu W. Controlling electroconvective flow via circular geometry. *Physics of Fluids*. 2025;37: 052020. https://doi.org/10.1063/5.0265294

17. Bloshchitsyn V. V., Stishkov Y. K., Shaposhnikov A. M. Modelling of multicomponent dielectric liquids with low conductivity using MATLAB. *Vestnik of Saint Petersburg University*. 2008;10(3): 114–120. (in Russ.) URL: https://cyberleninka.ru/article/n/modelirovanie-protsessov-ionnoy-provodimosti-mnogokomponentnyh-slaboprovodyaschih-sred-v-matlab-114/viewer

18. Kichigin V. I., Petukhov I. V., Kornilitsyn A. R., Mushinsky S. S. The effect of the moisture content in benzoic acid on the electrical conductivity of its melts. *Condensed Matter and Interphases*. 2022;24(3): 315–320. https://doi.org/10.17308/kcmf.2022.24/9853

19. Demin V. A., Petukhov M. I., Ponomarev R. S., Kuneva M. Dynamics of the proton exchange process in benzoic acid interacting with lithium niobate crystals. *Langmuir*. 2023;39: 10855–10862. https://doi.org/10.1021/acs.langmuir.3c00957

20. Petukhov M. I., Usatov M. V. The ionic boundary layer relaxation in the problem of proton exchange. *Bulletin of Perm University. Physics*. 2024;1: 16–23. https://doi.org/10.17072/1994-3598-2024-1-16-23

21. Pitt C. W., Burbie G., Wan T. Electric-field-assisted proton-exchanged optical waveguides in lithium niobate. *Electronic Letters*. 1987;23(19): 987–989. https://doi.org/10.1049/el:19870693

22. Kichigin V. I., Petukhov I. V., Mushinsky S. S., ... Volyntsev A. B. Structure and properties of proton exchange waveguides on Z cut of lithium niobate crystal fabricated in molten benzoic acid with the addition of lithium benzoate. In: *International Conference and Seminar of Young Specialists on Micro/Nanotechnologies and Electron Devices*. 2012; 238–241. https://doi.org/10.1109/edm.2012.6310225

23. Erdey-Gruz T. *Transport phenomena in aqueous solutions*. Budapest: Academia, 1974. 586 p.

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