10

# An electrokinetic acoustic repeater located in a constant electric field

© B.P. Sharfarets, S.P. Dmitriev, V.E. Kurochkin

Institute of Analytical Instrument Making, Russian Academy of Sciences,
198095 St. Petersburg, Russia
e-mail: sharb@mail.ru, lavrovas@yandex.ru

Received August 21, 2023
Revised October 10, 2023
Accepted November 17, 2023

It is shown that due to the presence in the electrokinetic acoustoelectric transducer of both electroosmosis and its inverse electrokinetic phenomenon - the flow potential, the possibility of retransmission of the initial external acoustic field occurs in the transducer when a constant electric field (pumping voltage) is applied in the process of acoustic signal reception. Necessary theoretical substantiation of this phenomenon is given. The data of the full-scale experiment confirming the theory are presented, the detailed scheme of the full-scale experiment is given, and the necessary devices involved in it are listed.

**Keywords:** electrokinetic phenomena, electrokinetic repeater, electroacoustic and acoustoelectric conversion, electroosmosis, flow potential, energy pumping. and acoustoelectric conversion, electroosmosis, flow potential, energy pumping.

DOI: 10.61011/JTF.2024.01.56913.100-23

## Introduction

Earlier, the authors considered the theoretical and experimental aspects of the implementation of electroacoustic and acoustic-electric electrokinetic converters (EKCs) based on the use of the phenomenon of electroosmosis and the inverse phenomenon of the flow potential [1,2]. The analysis of the principles of operation of the acoustic-electric EKC results in the conclusion that it is possible to implement an acoustic signal relay mode based on the acoustic-electric EKC. An important role in the process is again played by the application of a constant electric field to the EKC electrodes — pumping voltage.

The theory of the electrokinetic repeater was already briefly outlined for the first time in the express publication [3]. Previously, such use of electrokinetic effects to implement the relay mode was unknown to the authors before this publication.

The theory of the electrokinetic repeater is described in more detail in this paper and details of experimental studies are described in detail as well.

## 1. Physical model of the process in an electrokinetic repeater

Usually, the porous medium in an EKC is a rather complex structure. However, we will assume the simplest model of a porous medium in this paper for simplicity of analysis, namely, representing it as a solid capillary filled with liquid. Such an approximation is justified under very non-rigid constraints on an arbitrary porous structure [4]. The possibility of a relay mode is based on the analysis of the equation of motion in relation to acoustic-electric transformation, when a constant electric field and an external acoustic field $\mathbf{E}_0$ with a pressure field $p_a$ are simultaneously applied to the ends of a capillary filled with liquid. The process is analyzed using the Navier-Stokes equation in the following form:

$$\rho_\Sigma\big(\partial \mathbf{v}_\Sigma/\partial t + (\mathbf{v}_\Sigma\nabla)\mathbf{v}_\Sigma\big) = -\nabla p_\Sigma + \eta\Delta\mathbf{v}_\Sigma + (\xi + \eta/3)\nabla\nabla\mathbf{v}_\Sigma + \rho_{el}\mathbf{E}_0 + \mathbf{F}. \qquad (1)$$

Here $\rho_\Sigma = \rho_0 + \rho$, $\mathbf{v}_\Sigma = \mathbf{v}_0 + \mathbf{v}$, $p_\Sigma = p_0 + p$ — respectively the fields of density, velocity and pressure in the liquid; $\mathbf{E}_0 = \mathrm{const}$ — the intensity vector of the external constant electric field directed along the axis of the capillary; the volumetric force is determined by the expression (see, for example, [2,3] and other articles of the authors)

$$\mathbf{F} = (\rho_e\varepsilon\varepsilon_0\tilde{\zeta}/\eta\sigma)\nabla p(\mathbf{x}, t) \qquad (2)$$

— volumetric external force, the source of which is the flow potential process; $\eta$ and $\xi$ — dynamic and volumetric viscosity, respectively; $\rho_e$ — volumetric electric charge density caused by the presence of a double electric layer in electrokinetic processes; $\varepsilon$ — dielectric constant; $\varepsilon_0$ — electrical constant; $\tilde{\zeta}$ — electrokinetic potential (zeta potential); $\sigma$ — the specific conductivity of the liquid. The index 0 corresponds to an electroosmotic process, the source of which is a constant electric field $\mathbf{E}_0$, values without an index correspond to other processes caused by an external acoustic field, flow potential, as well as fields caused by the pumping process. It should be noted also that the electroosmotic velocity $\mathbf{v}_0$ is equal to zero ($\mathbf{v}_0 = 0$) when the vector of the constant electric field ($\mathbf{E}_0 = 0$) is equal to zero.

The acoustic process in a capillary is described in terms of a compressible liquid in a linearized form by the equation ([1–3])

$$\rho_0\left(\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v}_0\nabla)\mathbf{v} + (\mathbf{v}\nabla)\mathbf{v}_0\right) = -\nabla p + \eta\Delta\mathbf{v} + \left(\xi + \frac{\eta}{3}\right)\nabla\nabla\mathbf{v} + \mathbf{F}, \quad (3)$$

with the continuity equation for a compressible fluid $\frac{\partial\rho}{\partial t} + \rho_0\nabla\mathbf{v} = 0$.

The equation (3) is linear with respect to the acoustic fields $\mathbf{v}$ and $p$, which, after representing them as sums

$$\mathbf{v} = \mathbf{v}' + \mathbf{v}_a, \quad p = p' + p_a, \quad (4)$$

where $(\mathbf{v}_a, p_a)$ — the acoustic field in the capillary caused by an external acoustic field without pumping, adheres to the following equation:

$$\rho_0\frac{\partial \mathbf{v}_a}{\partial t} = -\nabla p_a + \eta\nabla\mathbf{v}_a + (\xi + \eta/3)\nabla\nabla\mathbf{v}_a + \mathbf{F}_a, \quad (5)$$

and $(\mathbf{v}', p')$ — the acoustic field obtained inside the capillary due to the application of a stationary field $\mathbf{E}_0$ adheres to the following equation (this is evidenced by the presence in it of an electroosmotic velocity other than zero $\mathbf{v}_0$)

$$\rho_0\left(\frac{\partial \mathbf{v}'}{\partial t} + (\mathbf{v}_0\nabla)\mathbf{v}' + (\mathbf{v}_0\nabla)\mathbf{v}_a + (\mathbf{v}'\nabla)\mathbf{v}_0 + (\mathbf{v}_a\nabla)\mathbf{v}_0\right) = -\nabla p' + \eta\nabla\mathbf{v}' + (\xi + \eta/3)\nabla\nabla\mathbf{v}' + \mathbf{F}'. \quad (6)$$

In the inertial term of equation (5), the term $(\mathbf{v}_0\nabla)\mathbf{v}_a + (\mathbf{v}_a\nabla)\mathbf{v}_0$ disappears because, as noted above, the electroosmotic velocity $(\mathbf{v}_0 = 0)$ is equal to zero when the vector of the constant electric field $(\mathbf{E}_0 = 0)$ is equal to zero.

The sum of the equations (5) and (6) leads, as can be seen, to the original equation (3). The system of equations (5), (6) is obviously unrelated, while first it is necessary to find the field $(\mathbf{v}_a, p_a)$ from (5), and then, find the field $(\mathbf{v}', p')$ by solving the equation (6), and then the general field (4) $(\mathbf{v}, p)$ should be determined.

According to (2) and the second equation (4) in (5), (6):

$$\mathbf{F} = (\rho_e\varepsilon\varepsilon_0\tilde{\xi}/\eta\sigma)\big(\nabla p_a(\mathbf{x}, t) + \nabla p'(\mathbf{x}, t)\big) = \mathbf{F}_a + \mathbf{F}'. \quad (7)$$

$\mathbf{F}$ is interpreted as the Coulomb force $\mathbf{F} = \rho_e\mathbf{E}$ in expression (7), where $\mathbf{E} = \mathbf{E}_a + \mathbf{E}'$ — the intensity vectors of some variable electric fields (see [3])

$$\mathbf{E}_a = (\varepsilon\varepsilon_0\tilde{\xi}/\eta\sigma)\nabla p_a, \quad \mathbf{E}' = (\varepsilon\varepsilon_0\tilde{\xi}/\eta\sigma)\nabla p'. \quad (8)$$

Equations (5) and (6) are re-arranged in the equivalent form taking into account (7) and (8).

$$\rho_0\frac{\partial \mathbf{v}_a}{\partial t} = -\nabla p_a + \eta\nabla\mathbf{v}_a + (\xi + \eta/3)\nabla\nabla\mathbf{v}_a + \rho_e\mathbf{F}_a, \quad (9)$$

$$\rho_0\big(\partial\mathbf{v}'/\partial t + (\mathbf{v}_0\nabla)\mathbf{v}' + (\mathbf{v}'\nabla)\mathbf{v}_0\big) = -\nabla p' + \eta\nabla\mathbf{v}' + (\xi + \eta/3)\nabla\nabla\mathbf{v}' - \rho_0\big[(\mathbf{v}_0\nabla)\mathbf{v}_a + (\mathbf{v}_a\nabla)\mathbf{v}_0\big] + \rho_e\mathbf{E}'. \quad (10)$$

The volumetric source in the right side (9) is caused by the pressure $p_a$ of the external acoustic field in equation (9) describing the acoustic field $(\mathbf{v}_a, p_a)$ in the capillary caused by an external acoustic field without pumping (at $\mathbf{E}_0 = 0$). The following should be noted here: the analysis of the equation (9) shows that even without pumping $(\mathbf{E}_0 = 0)$, the acoustic field $(\mathbf{v}_a, p_a)$ is different from zero, and therefore $\nabla p_a \neq 0$, which in turn creates a potential difference at the ends of the capillary (a flow potential arises), which ultimately as a result, it creates an alternating electroosmotic flow, i.e. there is a retransmission effect. However, this process is uncontrollable, and with a weak acoustic field, the relay effect may be insignificant.

Field $(\mathbf{v}', p')$ in (10) — the acoustic field obtained inside the capillary due to the application of a stationary field $\mathbf{E}_0$ (the presence of a volumetric source on the right in (10) $-\rho_0[(\mathbf{v}_0\nabla)\mathbf{v}_a + (\mathbf{v}_a\nabla)\mathbf{v}_0]$ is attributable to the nonlinearity of the problem (1) with the velocity vector of the electroosmotic flow $\mathbf{v}_0$), i.e. due to pumping. We study equation to consider the electrokinetic repeater (10).

We assume that the capillary axis is oriented along the axis $Oz$. [3] shows that under the assumption of a thin double layer $\kappa_a \gg 1$ ($a$ —capillary radius; $\kappa = 1/\lambda_D$; $\lambda_D$ — Debye length or thickness of the double layer), the electroosmotic velocity is written as

$$\mathbf{v}_0 = (0, 0, U_{eo}), \quad U_{eo} = E_0\frac{\varepsilon\varepsilon_0}{\eta}\tilde{\xi} = \text{const}.$$

Therefore, $\mathbf{v}_0(0, 0, U_{eo})$. The following equalities take place in the Cartesian and cylindrical coordinate systems with $\mathbf{v}_0 = \text{const}$ according to [3,5].

$$(\mathbf{v}_0\nabla)\mathbf{v}' = U_{eo}\partial\mathbf{v}'/\partial z = E_0(\varepsilon\varepsilon_0/\eta)\tilde{\xi}\partial\mathbf{v}'/\partial z,$$

$$(\mathbf{v}_0\nabla)\mathbf{v}_a = U_{eo}\partial\mathbf{v}_a/\partial z = E_0(\varepsilon\varepsilon_0/\eta)\partial\mathbf{v}_a/\partial z. \quad (11)$$

Let's re-arrange (10) taking into account equalities (8), (11), as well as the obvious identity $\nabla\mathbf{v}_0 \equiv 0$

$$\rho_0(\partial\mathbf{v}'/\partial z) = -\nabla p' + \eta\Delta\mathbf{v}' + (\xi + \eta/3)\nabla\nabla\mathbf{v}' - \rho_0 U_{eo}\partial(\mathbf{v}_a + \mathbf{v}')/\partial z + \rho_e(\varepsilon\varepsilon_0\tilde{\xi}/\eta\sigma)\nabla p'.$$

Assuming the process to be potential $\mathbf{v}' = \nabla\Phi'$, $\mathbf{v}_a = \nabla\Phi_a$, the last equation can be written in the scalar form

$$\rho_0\partial\Phi'/\partial z = -p' + (\xi + 4\eta/3)\Delta\Phi' - \rho_0 U_{eo}\partial(\Phi_a + \Phi')/\partial z + \rho_e(\varepsilon\varepsilon_0\tilde{\xi}/\eta\sigma)p'. \quad (12)$$

We obtain expression $\partial p'/\partial t = -\rho_0 c^2\Delta\Phi'$ via scalar potential for pressure $p'$ from the continuity equation and the liquid barotropy condition. The equation (12) is transformed as follows in the harmonic case with the time factor $e^{-\omega t}$, after expressing the pressure amplitude $p'$ through the potential amplitude $\Phi'$ in the form $p' = (\rho_0 c^2/i\omega)\Delta\Phi'$

$$-\rho_0 i\omega\Phi' = -(\rho_0 c^2/i\omega)\Delta\Phi' + (\xi + 4\eta/3)\Delta\Phi' - \rho_0 U_{eo}\frac{\partial(\Phi_a + \Phi')}{\partial z} + \left(\frac{\rho_e\varepsilon\varepsilon_0\tilde{\xi}\rho_0 c^2}{\eta\sigma i\omega}\right)\Delta\Phi'.$$

After elementary transformations, this equation takes the form of an inhomogeneous Helmholtz equation

$$\Delta\Phi' + k^2\Phi' = U_{eo}\big(k^2/(i\omega)\big)\partial(\Phi_a + \Phi')/\partial z, \qquad (13)$$

where $k$ — the corresponding wave number determined from the ratio

$$k = k_0/\big(1 - \rho_e(\varepsilon\varepsilon_0\tilde{\xi})/\eta\sigma - i\omega/(\rho_0 c^2)(\xi + 4\eta/3)\big)^{1/2},$$

and $k_0 = \omega/c$ — the wave number for a nonviscous homogeneous liquid; $c$ — velocity sound in the liquid. Equation (13) is re-arranged in the following form

$$\Delta\Phi' + k^2\Phi' = U_{eo}(k^2/i\omega)(\nu_{za} + \nu_z'),$$

where $\nu_{za}$ and $\nu_z'$ — $z$ are the components of the velocities and, respectively. Let's re-arranged the last expression taking into account the value of the electroosmotic velocity $U_{eo}$:

$$\Delta\Phi' + k^2\Phi' = E_0\big(\varepsilon\varepsilon_0\tilde{\xi}k^2/(\eta i\omega)\big)(\nu_{za} + \nu_z'). \qquad (14)$$

It can be seen from (14) that the potential $\Phi'$ of the relay flow velocity $\mathbf{v}'$ is directly proportional to the amplitude $E_0$ of the electric field strength of the pump $\mathbf{E}_0$ and the amplitude $z$-components of the velocity $\mathbf{v}_a$ caused by an external acoustic field $(p_a, \mathbf{v}_a)$. There is no relay mode caused by pumping if there is no pumping field $E_0 = 0$ : $p' = 0$, $\mathbf{v}' = 0$. In addition, the impact of other process parameters can be seen from (14), in particular, that the relay effect is inversely proportional to the magnitude of the cyclic frequency $\omega$. The remaining features of the behavior of the solution (14) are described by the authors earlier.

It should be noted also that the relay process caused by pumping is controlled by varying the parameters observed in the right side of the expression (14).

Concluding the theoretical section, we would like to note that electrokinetic topics are of great scientific and practical interest in the research community, in particular, we note the recently published fundamental monograph [6], which contains extensive theoretical and applied material about the latest achievements related to electrokinetic problems. A lot of useful information can be found about the subject under consideration in the long-standing and insufficiently known monograph [7]. Related issues are covered, for example, in [8–13] and a number of other papers.

## 2. Full-scale experiment

2.5 mm thick pack of A4 office paper was used as a porous structure used as a repeater in the experiments described below conducted in the air environment. The bundle of paper inside the electrodes was compressed along the perimeter by metal spring clips, thereby forming a porous single through structure (matrix), similar to those described in [1,2].

### 2.1. Measuring instruments

The following instruments and elements were used in the measuring circuit.

I. Acoustic system (speaker): speakers 2.0 Oklick OK-164 with a power of 30 W. Two speakers reproduce sound in the range of 35–20,000 z with a signal-to-noise ratio of 65 . One speaker was used in these experiments.

II. Digital two-channel signal generator FY3200S: sinusoidal signal frequency setting range — 0,Hz–24,MHz; sinusoidal signal frequency setting accuracy $\pm 5 \cdot 10^{-6}$ Hz; adjustable output signal amplitude $\leq 20$ V.

III. Digital noise meter DT-805: lower measurement limit 30 dB; upper measurement limit 130 dB; measurement duration 125 ms; measurement error 1.5 dB; frequency range 31.5 Hz–8 kHz; resolution 0.1 dB. The DT-805 noise meter is a calibrated spectrum analyzer operating in the frequency range indicated above and consisting of a line of bandpass filters that allow recording the level of the analyzed signal depending on frequency (frequency spectrum of the analyzed signal).

IV. Repeater matrix (described above).

V. Constant voltage generator (developed by the authors).

### 2.2. Description of experiments

The following experiments were conducted to verify the above theory. Sound speaker I emitting harmonic sound vibrations with a frequency of 1 Hz was used as the source of sound. 1 kHz frequency was chosen for the reasons that this frequency is used for measuring the sensitivity of receiving devices (and a repeater implies reception of a signal and its re-emission). The vibrations received by the speaker were generated by the sound signal generator II. The following experiments were carried out sequentially. The signal levels of the spectroanalyzer (noise meter) provided below are specifically related to the frequency 1 kHz.

1. A laboratory noise meter III was installed at some distance in the wave zone relative to the speaker I in the first experiment. There was a free space between the speaker and the sound meter. The sound level meter recorded a sound level of 61 dB at a frequency of 1 kHz after activation of the sound field. The distance between the speaker and the noise meter remained constant in this and subsequent experiments. Scheme of the experiment is presented in Fig. 1.

2. Repeater matrix IV was installed between the sound level meter and the speaker on the same line with the previous geometric configuration of the sound level meter and the speaker. At the same time, no pumping was applied to the matrix. The sound level meter recorded sound pressure of 56.5 dB at with a frequency of 1 kHz. Fig. 2 shows the design of the experiment.

3. At this stage, the conditions of the experiment 2 were used but with the difference that the pumping voltage from 0 to 1320 V was smoothly applied to the repeater matrix from

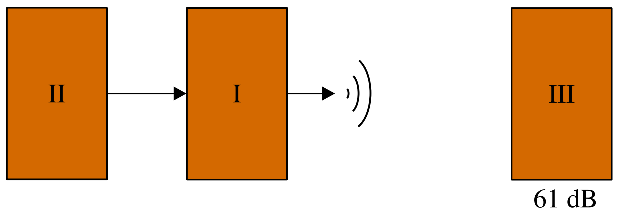


**Figure 1.** Scheme of the experiment № 1 to determine the pressure level on the sound meter III at a fixed distance between the sound meter and the speaker I and a fixed level of the speaker radiation. There are no obstacles between the speaker and the noise meter.

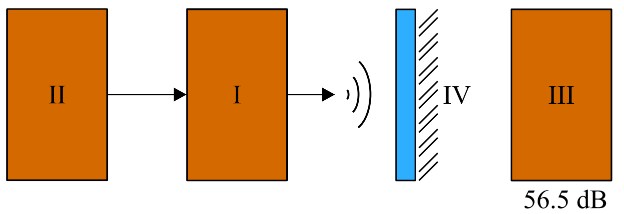


**Figure 2.** The design of the experiment № 2 for determining the level of pressure on the sound meter III with a fixed distance between the sound meter and the speaker I and a fixed level of the speaker radiation. Matrix III is located between the speaker and the noise meter in the non-pumping mode.

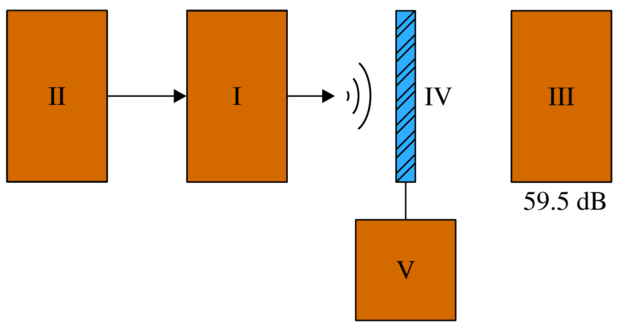


**Figure 3.** The design of the experiment № 3 to determine the pressure level on the sound meter III at a fixed distance between the sound meter and the speaker I and a fixed level of the speaker radiation. Matrix III is located between the speaker and the sound level meter in the pump mode.

a constant voltage generator V. The sound meter recorded a smooth increase of the sound pressure level from 56.5 to 59.5 dB at a frequency of 1 kHz with an increase of pumping rate on the repeater. The sound pressure level in the rest of the spectrum of the sound signal recorded by the sound meter also slightly increased. However, the magnitude of the change of the noise component level was not specially measured due to the high signal-to-noise ratio, wherein the signal was a discrete component of the useful signal 1 kHz, and the rest of the spectrum of the audio signal was a noise. Fig. 3 shows the design of the experiment.

Therefore, the signal level on the noise meter increased by 3 dB in the harmonic audio signal relay mode with a frequency of 1 kHz in case of pumping from 0 to 1320 V (experiment 3) compared with the relay mode without pumping (experiment 2, pumping 0 V). The decrease of the harmonic signal on the noise meter in experiments 2 and 3 without pumping compared to experiment 1 is explained by the geometric shielding of the speaker emitted sound field by the repeater matrix.

## Conclusion

It was theoretically shown and experimentally confirmed by this study the effect of retransmission of the initial acoustic signal can be obtained in case of implementation of the acoustic-electric converter in the presence of pumping due to the presence of two reverse electrokinetic phenomena in the EKC such as electroosmosis and flow potential.

This is possible due to the simultaneous presence of two reverse electrokinetic processes in the converter under consideration:

— a flow potential effect occurs in a porous structure under the impact of an external acoustic field (the occurrence of an electric potential difference $U_{\mathrm{FP}}$ on the electrodes of a porous structure);

— the potential difference $U_{\mathrm{FP}}$ caused by the flow potential due to the presence of an electroosmosis phenomenon in the same system causes the appearance of an acoustic field $(p_{\mathrm{FP}}, v_{\mathrm{FP}})$ similar to the initial external acoustic field $(p_0, v_0)$;

— due to the nonlinearity of the hydrodynamic system in the process of the described transformations, the field $(p_{\mathrm{FP}}, v_{\mathrm{FP}})$ is repeatedly amplified by the presence of a constant potential difference $U_0$ on the electrodes of the converter.

### Funding

The work was carried out in the IAP RAS within the framework of the state task 122032300337-4 of the Ministry of Science and Higher Education.

### Conflict of interest

The authors declare that they have no conflict of interest.

## References

[1] B.P. Sharfarets, V.E. Kurochkin, V.A. Sergeev, Yu.V. Gulyaev. Acoust. Phys., **66**, 431 (2020). DOI: 10.1134/S1063771020030057

[2] B.P. Sharfarets, S.P. Dmitriev, V.E. Kurochkin, V.A. Sergeev. Acoust. Phys., **68**, 521 (2022). DOI: 10.1134/S1063771022050104

[3] B.P. Sharfarets V.E. Kurochkin, S.P. Dmitriev, F.F. Legusha. Tech. Phys. Lett., **48** (6), 21 (2022). DOI: 10.21883/TPL.2022.06.53459.18971

[4] S.S. Dukhin. B.V. Deryagin, *Elektroforez* (Nauka, M., 1976) (in Russian).

[5] A.N. Guz. *Introduction to the dynamics of a compressible viscous fluid* (LAP Lambert Publ., Saarbrucken, 2017 (in Russian).
[6] A.S. Dukhin, P.J. Goetz. *Characterization of Liquids, Nano- and Microparticulates, and Porous Bodies using Ultrasound*. 3 eds (Elsevier, Amsterdam-Boston-London-New-York, 2018)
[7] M.S. Kasimzade, R.F. Khalilov, A.N. Balashov. *Electrokineticheskie preobrazovateli informatsii* (Energiya, M., 1973) (in Russian).
[8] R.J. Hunter. *Zeta potential in Colloid Science. Principles and Applications* (Academic Press, London,1981)
[9] J. Lyklema. *Fundamentals of Interface and Colloid Science* (Academic Press, San Diego, 2001), v. 2.
[10] D.A. Friedrichsberg. *Kurs kolloidnoj khimii* (Lan, St. Petersburg, M., Krasnodar, 2010), 4th ed., corrected and amended (in Russian).
[11] E.D. Shchukin, A.V. Pertsov, E.A. Amelina. *Kolloidalnaya khimiya* (Higher School, Moscow, 2004) (in Russian).
[12] J. Newman. *Elektrokhimicheskie sistemy* (Mir, M., 1977) (in Russian).
[13] O.N. Grigorov, Z.P. Kozmina, A.V. Markovich, D.A. Friedrichsberg. *Elektrokineticheskie svojstva kapillyarnykh sistem* (Publishing House of the USSR Academy of Sciences, M.-L, 1956), p. 113–124 (in Russian).

*Translated by A.Akhtyamov*