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Numerical evaluation of the efficiency of liquid and air electrokinetic radiators

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Recently, in acoustics, in addition to piezoelectric, magnetostrictive, electrodynamic, electromagnetic, and other converters, electrokinetic converters have become widespread, using various electrokinetic phenomena to convert electrical energy into acoustic (radiators) or acoustic energy into electrical (receivers), or acoustic energy into acoustic (sound repeaters). This field of acoustics is in the process of formation and active development. Many scientific and technical problems related to electrokinetic converters are still under study and practical solution. And, if with electrokinetic converters in the air the task of their creation and application can be considered practically solved, then in a liquid medium (for example, in water) a scientific and practical solution to the problem has not been achieved. The paper considers the comparative efficiency of electroacoustic conversion of an electrokinetic radiator in two media, obtained by modeling on the COMSOL Multiphysics software package: in water and in air. In the course of research, the possibility of modeling the transformation process within the framework of a viscous incompressible fluid model was substantiated, which significantly reduced the complexity of calculations in the modeling process. During modeling, it was possible to get by with a truncated system of electrohydrodynamic equations a closed system of Navier−Stokes equations for an incompressible fluid, which greatly simplified model calculations. The paper presents simulation results that reveal significant advantages of electrokinetic transformation in water compared with electrokinetic transformation in air. In the described simulation, only the losses associated with friction in the liquid were taken into account. In further model studies, it is planned to take into account the losses of electroosmotic electroacoustic transformation associated with heat dissipation. The ongoing research is necessary and useful for the real creation of promising electrokinetic converters operating in both water and air.

Keywords: electrokinetic converters, viscous incompressible fluid.

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Introduction

The studies devoted to improvement of the efficiency of various acoustic transducers occupy a large place in modern theoretical and applied acoustics because of their significant practical importance. Presently there is a wide variety of different ways to convert all kinds of energy into sound energy and the inverse transformations of sound energy into electrical and other types of energy.

Electrokinetic (electrochemical) transformations based on the discovery of electrokinetic phenomena are one of the relatively new ways of conversion of various types of energy into acoustic energy and vice versa [1]. This paper mentions electrokinetic phenomena of electroosmosis — the flow of liquid in capillaries and porous bodies under the impact of an external electric field and the flow potential — the occurrence of an electric potential difference at the ends of a capillary or membrane when liquid flows through them.

The bibliography devoted to the use of electrokinetic phenomena for creating various converters is currently very extensive. We will mention only some of the most significant studies of Russian and foreign scientists (see, for example, [2–15]).

It should be noted that the electrokinetic phenomena of electroosmosis and the flow potential have attracted considerable attention of researchers because of the possibility of their application for designing of radiators and receivers of acoustic vibrations in gaseous and liquid media. This is discussed in sufficient detail in the monographs in Ref. [12,15].

Te invention of Russian scientists S.P.Dmitriev and co-authors also made a significant contribution to the designing of electrokinetic radiators [16]. It was proposed in this study to apply a significant constant pumping voltage to the membranes and capillaries when using electroosmosis in the radiator design, which significantly increased the efficiency of electroacoustic conversion.

The original proposal of the authors of this invention to use standard office paper as a porous structure (membrane) for designing an electrokinetic electroacoustic radiator in relation to the air environment was another specific feature of Ref. [16]. The electrokinetic electroacoustic converter comprised a stack of paper (approximately 20−25 sheets) with a total thickness of 2−2.5 mm, electrodes in the form of two metal grids with a rectangular cell size of approximately 0.5 mm, and an electrical circuit for connecting a DC and AC voltages. A pack of paper, which acts as a porous membrane, was tightly clamped inside the electrodes. The size of the electrodes coincided with the size of a standard sheet of paper, namely 210×297 mm (this design of the electrokinetic converter was later called the converting matrix). The total direct and alternating electric fields were applied from the electrical circuit to the mesh electrodes. The magnitude of the constant electric field could vary from zero to several thousand volts and its maximum value was limited only by the magnitude of the electrical breakdown of the electrokinetic emitter, i.e., the stacks of office paper described above inside the mesh metal electrodes. The value of the alternating voltage at the electrodes of the matrix remained constant.

Further, the theoretical studies and model experiments conducted with the participation of the authors of this paper revealed the physical causes of a significant increase of the efficiency of the conversion process due to the presence of a constant pumping voltage, not only in the radiation mode (see, for example, [17,18]), but also in the mode of receiving of acoustic vibrations (see, for example, [19]), and in the acoustic vibration repeater mode (see, for example, [20]).

It should be noted that the transformation matrix described above with minor modifications was used in all cases of practical use of electrokinetic transformations in air conditions, both in the case of electroacoustic transformation (electrokinetic radiator), and in the case of acousto-electric transformation (electrokinetic receiver), as well as in the case of electrokinetic repeater in the works of [17–20] and in other publications with the participation of the authors of this paper.

It should be noted here that experiments were conducted only in air in Ref. [17–20] and in numerous other studies with the participation of the authors of these studies devoted to the study and creation of electrokinetic transducers (radiators, receivers and repeaters of acoustic vibrations). These experiments revealed significant advantages of electrokinetic converters in comparison with existing equivalents using other physical principles of transformations. For example, the experiments with an air electrokinetic microphone in Ref. [21] showed that it was possible to experimentally obtain a microphone sensitivity by using the pumping voltage for an electrokinetic microphone that is almost twice as high as the sensitivity of a carbon microphone which has the highest sensitivity among air microphones (its sensitivity is about 1000mV/Pa), whereas the sensitivity of the electrokinetic microphone in experiments with the application of pumping voltage was about 2000 mV/Pa.

The authors did not conduct such experiments with liquid electrokinetic converters with a converting matrix of the type described above replacing paper with some porous matrix, for example, quartz structure due to their great complexity. All this leads to the need, even before solving technical problems, to conduct a study of the functioning of liquid converters in comparison with their air counterparts using numerical model experiments with computer software systems.

It is known that the theories of electrokinetic converters for gas and liquid are almost identical in the hydrodynamic aspect because of small differences in the corresponding system of hydrodynamic equations in these media. The main differences between converters in gas and liquid are the significantly higher electrical conductivity in liquid compared to the electrical conductivity in gas. This leads to the fact that mathematical modeling in a gas can only take into account viscous losses, while in a liquid, thermal losses can significantly exceed viscous losses. Therefore, it is also necessary to take into account the equation of thermal conductivity in a liquid, in addition to the system of equations of hydrodynamics.

In addition, air converters are quite technically simple for implementation. Everything is different in the case of liquid converters, which is attributable to significant impact of electrical processes in the working fluid, where the membrane with electrodes is placed, and to which an electric voltage with an amplitude of significant magnitude should be applied. The technical problems arising in this regard have not been fully studied, however, it seems necessary, given the great applied importance of creating effective electrokinetic liquid radiators (and later not only radiators, but also receivers, as well as repeaters of sound vibrations), to forecast the expected efficiency of liquid electrokinetic radiators compared to with air equivalents in conditions of neglect of heat losses. Such a forecast will be made in this paper.

In connection with the above, it seems feasible to use the COMSOL Multiphysics computing package to build a mathematical model forecast of the expected efficiency of liquid electrokinetic converters in comparison with their air counterparts in conditions of neglect of thermal losses. The results of such forecasting may prove to be in great demand in further studies and suggest ways to increase the efficiency of electrokinetic converters. Such a comparative forecast will be made in this paper for air and liquid electrokinetic radiators.

1. Problem statement

The purpose of this work, due to the great practical importance of liquid radiators, is to preliminarily (before solving difficult technical issues related to field experiments in the case of liquid electrokinetic radiators) identify, using mathematical model experiments, the capabilities and probable advantages of liquid electroacoustic electrokinetic radiators in comparison with atmospheric analogues in terms of the efficiency of electroacoustic conversion.

We will simplify the problem by keeping only the equations of hydrodynamics from the entire system of electrohydrodynamic equations (see, for example, Navier–Stokes momentum conservation equation and continuity equation [22]), which describe the considered process. The equation of conservation of energy (thermal conductivity) and other equations of electrohydrodynamics are omitted to simplify the already cumbersome numerical calculations. Their impact on the processes in electrokinetic converters will be discussed in the following papers of the authors. Thus, only the system of hydrodynamic Navier–Stokes equations is studied in this paper of the entire set of equations of the electrohydrodynamics system of equations (i.e., only viscous liquid losses are taken into account), while heat losses in the liquid are not taken into account.

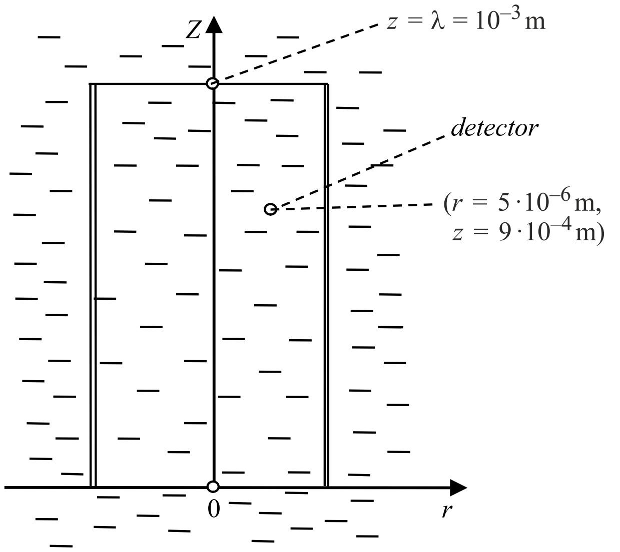
2. Model experiments. Model selection

The COMSOL Multiphysics software package was used as a medium for conducting model experiments in water or in the air. The following physical model of electrokinetic radiators was implemented (see Figure). A cylindrical glass capillary also filled with the surrounding liquid with the ends open to the environment was placed in an infinite three-dimensional space filled with liquid (water or air). The capillary modeled the pores of the membrane (a porous medium). The validity of such a model describing a porous medium of a general kind follows from Ref. [6] under fairly unhindered conditions [6]:

A) the thickness of the double layer λ_D in the membrane is quite small, and the radii of curvature of the inner surface of the membrane pores are greater than a certain value, significantly exceeding the thickness of the double layer in the membrane;

B) the minimum linear pore size in the membrane significantly exceeds the thickness of the double layer λ_D.

The order of values for the thickness of the double layer $\lambda_D \simeq 19\,\text{nm}$ is provided below in sec. 4, Remark 2. The following dimensions of the cylindrical capillary were selected to meet conditions A and B: length $l = 10^{-3}\,\text{m}$, inner radius of the capillary $r_0 = 10^{-5} \gg 19 \times 10^{-9}\,\text{m}$. This implies the validity of modeling a porous structure of a general type with a cylindrical capillary of the specified dimensions.



A capillary in an infinite liquid.

The total voltage was applied to the ends of the capillary

$$u = U_0 + u_1(t). \tag{1}$$

Here U_0 — constant voltage (pumping voltage). The time variable t voltage $u_1(t)$ was determined by the expression

$$u_1(t) = u_1 \sin(2\pi f)t. \tag{2}$$

We considered a single value of the amplitude of the alternating voltage $u_1 = 600\,\text{V}$ in this paper. The oscillation frequency was $f = 1000\,\text{Hz}$. The pumping voltage U_0 in (1) had the following discrete values in turn: 0, 1000, 2000, 3000, 5000, 8000 and 10 000 V.

The acoustic field was calculated inside the capillary at a point (detector) with coordinates $r = 0.5 \cdot 10^{-5}\,\text{m}$, $z = 9 \cdot 10^{-4}\,\text{m}$. The origin of coordinates corresponded to the point ($r = 0$, $z = 0$) located at one of the ends of the capillary (see figure).

3. Mathematical model in a numerical experiment

When studying the behavior of a liquid or gas when they move under the impact of forces of different nature, systems of various interconnected equations are usually used. For example, if the motion of a liquid is associated with electric forces, then an additional system of electrohydrodynamic equations is involved. Such systems of heterogeneous equations are characterized by the need for their joint solution because of the connectivity of their physical fields. It is usually impossible to solve such systems analytically because of the complexity of the interrelated equations of the system, the non-trivial geometry of the boundary conditions considered in the problem, etc. Therefore, as a rule, such problems have to be solved numerically using specialized computing packages, in particular the COMSOL Multiphysics package, a software system for finite element analysis, solution and modeling for various physical and engineering applications, especially for related multiphysical phenomena.

Mathematical models of varying complexity can be selected from the toolkit of the package. The main task of the subject specialist is to choose a compromise set of mathematical models based on the criterion „price–quality“, i.e. choosing the least complex mathematical model with acceptable accuracy of the resulting solution.

A mathematical model of a viscous compressible fluid is usually used in acoustic processes (which is the process under consideration). Such a model is very laborious for numerical calculations. The possibility of substitution, under certain conditions, of the model of a viscous compressible fluid with a model of a viscous incompressible fluid was used in this paper for numerical simulation of electrokinetic radiators. The results of Ref. [23] were taken into account for obtaining the following estimates.

The first condition for steady motion of a liquid for such a simplification has the following form [23]:

$$|v| \ll c, \tag{3}$$

this means that the flow velocity of the liquid v should be much less for small variations in the density of the medium than the velocity of sound in a liquid c.

The second condition, but already with unsteady motion of the liquid, is such that if the following condition is fulfilled [23]:

$$\tau \gg \frac{l}{c}, \tag{4}$$

the derivative of the density of the liquid ρ with respect to time $\frac{\partial \rho}{\partial t}$ can be neglected (considering that the density ρ is time-invariant).

Here τ and l are constants with the order of magnitude of the time interval (τ) and the distance (l) at which the velocity of the liquid noticeably changes. The period of harmonic vibrations of the liquid $\tau = T = 1/f$ is taken as τ in (4), where T is the period of vibrations, and f is their frequency. The following inequality is obtained by substituting the last expression in (4)

$$f \ll \frac{c}{l}. \tag{5}$$

Let us consider the restrictions (3) and (5) for air and for water. The velocities of sound in air and in water are $c_{air} \approx 340$ m/s and $c_{water} \approx 1500$ m/s, respectively. The thickness of the membrane in which the electroosmosis process is carried out is $l = 10^{-3}$ m. Then, we obtain estimates of the oscillation frequency for air and water, respectively

$$f_{air} \ll \frac{c_{air}}{l} = \frac{340}{10^{-3}} = 340\,\text{kHz}, \tag{6}$$

$$f_{water} \ll \frac{c_{water}}{l} = \frac{1500}{10^{-3}} = 1500\,\text{kHz}. \tag{7}$$

As can be seen from the expressions (6) and (7), the restriction (5) begins in the deep ultrasonic range, and remains valid at frequencies of about $f \leq 50$ kHz for air and $f \leq 200$ kHz for water.

Next, let's check the restriction (3) for both considered environments. The amplitude of the vibrational velocity of particles reaches only 1 m/s at the pain threshold according to the data provided in Ref. [24], in case of impact of strong sound in the air. Therefore, the condition (3) is obviously fulfilled for air: $1 \ll 340$.

Since the authors were unable to find the appropriate values for the limiting values of acoustic flow velocities in water, we obtain the value for them from the arguments given below.

Let us determine the value of the limiting oscillatory velocity in water using the following consideration. Let's assume that there is an acoustic pressure in water with an amplitude p_{water} equal to the amplitude of the pressure in air p_{air} and equal to p_0:

$$p_{water} = p_{air} = p.$$

The amplitude of the oscillatory velocity in water v_{water} will be equal to $v_{water} = \frac{p_{water}}{z_{water}}$ at pressure p_0. We find the following after a simple chain of identical transformations

$$\begin{aligned} v_{water} &= \frac{p_0}{z_{water}} = \frac{p_{water}}{z_{water}} = \frac{p_{air}}{z_{water}} \\ &= \frac{z_{air}p_{air}}{z_{air}z_{water}} = \frac{z_{air}p_{air}}{z_{water}z_{air}} = \frac{z_{air}}{z_{water}} v_{air}. \end{aligned} \tag{8}$$

Here, $z = p/v$ denotes the specific acoustic resistance of the corresponding medium, equal to the ratio of pressure amplitudes and oscillatory velocity.

Let us find the ratio z_{air}/z_{water} by substituting the corresponding values that are generally available ($z_{air} \approx 417$ Pa s/m, $z_{water} \approx 150 \cdot 10^4$ Pa s/m). Finally we obtain

$$\frac{z_{air}}{z_{water}} \approx \frac{417}{150 \cdot 10^4} = 2.78 \cdot 10^{-4}.$$

Thus, we obtain from (8) that the oscillatory velocity of water is about the fourth order of magnitude smaller than the oscillatory velocity in air with the same amplitude of pressure in water and in air.

Hence the restriction (3) for the oscillatory velocity in air and in water, with the accepted parameters, model experiments are performed with a large margin, and the (5) is valid for air up to frequencies $f \leq 50$ kHz and for water up to frequencies $f \leq 200$ kHz.

4. The equations of motion of an incompressible fluid

We present below the system of Navier–Stokes equations for incompressible fluid since the assumptions about the incompressibility of the liquid are fulfilled [23]. The equation of motion has the form

$$\rho \left[\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v}\nabla)\mathbf{v} \right] = -\nabla p + \eta \Delta \mathbf{v} + \mathbf{F}. \tag{9}$$

The continuity equation also reduces to the form corresponding to an incompressible fluid [23]:

$$\nabla \cdot \mathbf{v} = 0. \tag{10}$$

It is necessary to add the boundary condition for liquid adhesion to the inner lateral surface of the capillary to equations (9) and (10), i.e. the velocity of the liquid on this surface is equal to zero $v\big|_{r=r_0} = 0$.

The system of equations (9), (10) consists of four equations (three scalar equations included in the vector equation (9) and the scalar equation (10)) and is closed for calculating the three components of the velocity field $\mathbf{v} = (v_x, v_y, v_z)$ and the scalar pressure field p. Here

$\rho = \text{const}$ — density of an incompressible medium; η — dynamic viscosity coefficient of the medium (for simplification, we take it constant $\eta = \text{const}$); $\mathbf{F} = \rho_e \mathbf{E}$ — volumetric force; $\mathbf{E} = (0, 0, E)$ — the intensity of the external electric field, $E = E_0 + E_1(t)$, where the magnitude of the amplitude of the vector of constant electric field strength E_0 corresponds to a constant voltage U_0, and the variable magnitude of the electric field strength $E_1(t)$ corresponds to the alternating voltage $u_1(t)$; ρ_e — the density of electric charge in a liquid (electric charge per unit volume of liquid).

Remark 1

It should be noted that the problem is modelled in the COMSOL Multiphysics package using a homogeneous equation of motion (9): the force $\mathbf{F} = \rho_e \mathbf{E}$ is assumed to be zero. An „electroosmotic" boundary condition equivalent to the force $\mathbf{F}$ is introduced at the same time, which consists in the fact that instead of the standard condition for liquid adhesion at the lateral boundary of the capillary $\mathbf{v}\big|_{r=r_0} = 0$, the condition is assumed that the liquid layer adjacent to the lateral boundary has a velocity equal to the electroosmotic velocity

$$\mathrm{v}_z\big|_{r=r_0} = U_{eo} = \frac{\varepsilon\varepsilon_0\xi}{\eta}E = \frac{\varepsilon\varepsilon_0\xi}{\eta}\big(E_0 + E_1(t)\big). \qquad (11)$$

The following notation is introduced in (11): U_{eo} — electroosmotic velocity; ε and ε_0 — the relative permittivity of the medium and the electrical constant, respectively; ξ — the zeta potential. The validity of such a boundary condition on the inner lateral surface of the capillary will be shown below, however, one more remark should be made for this.

Remark 2

The ratio of the Debye length (radius) ratio λ_D characterizing the thickness of the diffuse mobile layer in the double layer of the electroosmotic process, to the radius of the capillary has a great impact on electroosmotic processes: λ_D/r_0. The velocity of the liquid in the capillary has a reciprocating character in case of small values of this ratio $\lambda_D/r_0 \leq 0.01$, i.e. it is practically constant throughout the entire cross-section of the capillary along its entire length [25].

It was found in Ref. [25] by considering the boundary value problem (9), (10) in a circular capillary under boundary conditions $\mathrm{v}_z(r_0) = 0$; $\frac{\partial \mathrm{v}_z}{\partial r}\big|_{r=0} = 0$ that the structure of the electroosmotic velocity in the capillary has a piston (one-dimensional) character $\mathbf{v} = \big(0, 0, \mathrm{v}_z(r)\big)$, and the following expression is obtained for the longitudinal velocity v_z in a cylindrical capillary:

$$\mathrm{v}_z(r) = \left[1 - \frac{I_0(r/\lambda_D)}{I_0(r_0/\lambda_D)}\right]U_{eo}.$$

It follows from this expression for $\lambda_D \ll r_0$ (see [25]). Here I_0 is a modified zero-order Bessel (imaginary argument) function. In our case, $\lambda_D \simeq 19 \cdot 10^{-9}$ m, $r_0 = 10^{-5}$ m, therefore, $\lambda_D/r_0 = 1.9 \cdot 10^{-3} \ll 1$. This allows making a conclusion that the boundary condition (11) is valid.

This applies to both the constant component of the electroosmotic velocity caused by the constant pumping voltage U_0 and the variable harmonic component of the electroosmotic velocity caused by the alternating voltage $u_1(t)$. This fact will be confirmed below by the results of model experiments using the COMSOL Multiphysics package.

5. Model experiment

The model experiment was conducted using the COMSOL Multiphysics software package. An incompressible viscous fluid model was used as a hydrodynamic model (9), (10). Water and air (generally liquid) were used as the medium in the experiments. A cylindrical capillary with open ends filled with the surrounding liquid was placed in the limitless liquid. Capillary dimensions: length — $l = 1 \cdot 10^{-3}$ m, radius — $r_0 = 1 \cdot 10^{-5}$ m, the ends of the capillary axis had coordinates $(r, z)_{\text{lower}} = (0, 0)$ m and $(r, z)_{\text{upper}} = (0, 10^{-3})$ m. An electrical voltage was applied to the ends of the capillary (1), (2). As noted above, the amplitude of the constant pumping voltage U_0 had alternating values of 0; 1000; 2000; 3000; 5000; 8000; 10 000 V. The amplitude of the alternating voltage remained unchanged in all experiments $u_1 = 600$ V. The oscillation frequency also remained constant in all model experiments: $f = 1000$ Hz.

Remark 3

The boundary condition (11) is an important parameter for solving boundary value problem $(9)-(11)$ when modeling fields in a capillary. The greatest uncertainty in (11) is caused by setting the value of the ξ-potential in liquid and in air. The value of the ξ-potential in the liquid reaches the value of $\xi_{water} = 100$ mV and more according to [25]. As for the value of the ξ-potential in the air, it was difficult for the authors to determine it because there is no such information in the published articles. Communication with leading experts on this issue did not help either. As a result, it was decided to accept the value of the zeta potential for air also equal to $\xi_{air} = 100$ mV.

The fields of acoustic pressure and vibrational velocity inside the capillary were calculated using the COMSOL Multiphysics package at various points (detectors) according to the system of equations $(9)-(11)$.

The table below shows the ratios of the values of the characteristic parameters of pressure fields and oscillatory velocity in water and air at the point (detector) $(r, z) = (5 \cdot 10^{-6}, 9 \cdot 10^{-4})$ m inside the capillary at $r = r_0/2$ depending on different values of the pumping voltage at a constant amplitude of alternating voltage

The ratio of the values of characteristic parameters in case of electroosmotic electroacoustic transformation in water and air (sound emission)

Pumping voltage, U_0, V	Pressure in the air, p_{air}, Pa	Pressure in water, p_{water}, Pa	Oscillatory velocity in the air, v_{air}, m/s	Oscillatory velocity in water, v_{water}, m/s	Ratio amplitudes of pressures in water and in air, P_{water}/P_{air}	Ratio of amplitudes of oscillatory velocities in water and in air, v_{water}/v_{air}	Ratio of intensities of sound in water and in air, $(pv)_{water}/(pv)_{air}$
0	0.011	7.5	0.02	0.0035	750	0.175	131.3
1000	0.012	45.75	0.02	0.004	3812	0.2	762.5
2000	0.0175	77.55	0.02	0.004	4431	0.2	886.3
3000	0.0265	100.9	0.02	0.0039	3807	0.195	742.5
5000	0.044	133	0.019	0.0037	3022	0.195	588.6
8000	0.070	162.75	0.019	0.0034	2325	0.18	416
10 000	0.085	176.05	0.019	0.0033	2071	0.174	359.7

from (2) $u_1 = 600$ V. (The values characterizing the parameters of the variable component of the liquid flow in the capillary, namely the amplitudes of acoustic pressure and the amplitude of the oscillatory velocity in the capillary for water and air, respectively, are listed in the table)

6. Discussion and interpretation of the results of the model experiment

6.1. Verification of the validity of Remark 2

The model experiments primarily verified the validity of Remark 2 on the constancy of amplitudes of pressure and field velocity (p, v) in the capillary cross-section. The field parameters (p, v) were calculated for this purpose at the pumping voltage $U_0 = 1000$ V, at the following points of the capillary cross-section with coordinates (r, z): $(1 \cdot 10^{-6},\ 9 \cdot 10^{-4})$, $(5 \cdot 10^{-6},\ 9 \cdot 10^{-4})$ and $(9 \cdot 10^{-6},\ 9 \cdot 10^{-4})$ m, i.e. almost at the axis of the capillary, at half its radius and at the lateral surface of the capillary. The calculation results of the corresponding fields $(p,\ \mathrm{v})$ turned out to be identical.

6.2. Effect of pumping voltage

The table shows that the pressure amplitudes in both media are directly proportional to the amplitude of the pumping voltage U_0, while the amplitudes of the oscillatory velocity practically do not dependent on U_0. Physically, these facts can be explained as follows. An increase of the pumping voltage U_0 causes a directly proportional increase of the amplitude P of the acoustic pressure field $p(r,\ z,\ t)$ due to the nonlinearity of the problem (9), (10) as was shown in [17,18]. The amplitude of the oscillatory velocity V in the capillary is determined by the sum of two components: the component depending on the amplitude of the acoustic pressure P (which, in turn, depends on the variable amplitude of pumping through the wave resistance of the medium), and the magnitude of the amplitude of the alternating pumping voltage $U_1(t)$ related to the electric field $E_1(t)$ (see (11)). The analysis shows that the contribution associated with the change of acoustic pressure is 2−3 orders of magnitude less than the contribution of the value of the alternating pump voltage associated with the value of the electric potential $E_1(t)$ in (11). Thus, the amplitude of the oscillatory velocity in the capillary is determined practically only by the alternating pumping voltage, which remained constant during the experiment under consideration, which indicates the electroosmotic nature of the origin of the oscillatory velocity in the capillary in these experiments.

6.3. About the impact of the assumption $\xi_{air} = 100$ mV

The table shows that the ratio of pressure amplitudes in water and air reaches about 4,500, and the corresponding ratio of sound field intensities — about 900. Therefore, even if we assume that the value of the zeta potential of the air will reach the values of $\xi_{air} = 300{-}500$ mV (which is very unlikely), then, as the analysis shows, in this case the efficiency of the liquid electrokinetic radiator will significantly exceed the efficiency of the air equivalent.

6.4. About the effect of the magnitude of the zeta potential ξ, the thickness of the diffuse layer in the double electric layer λ and the radius of the capillary r_0 and their ratio on the electrokinetic transformation

These matters are discussed in detail in the specialized literature, for example, in Ref. [10,12,13,15,25, etc.]. We will not discuss this in detail here, but only the results of a numerical experiment performed within the framework of the described physical model at the pump voltage $U_0 = 2000$ V. At the same time, the magnitude of the zeta potential ξ varied, taking the values 100, 10, and 1 mV sequentially. The ratio of pressure amplitudes in water and air at the considered point of the capillary was calculated with other unchanged physical and geometric parameters discussed above. As a result, the following results were obtained. The ratio of pressure amplitudes in water and air was 4431 times (see table) at $\xi = 100\,\text{mV}$, this ratio was 6267 times at $\xi = 10\,\text{mV}$, and finally, the ratio was 6423 times at $\xi = 1\,\text{mV}$. This fact, apparently, requires a separate study.

Conclusion

The paper draws attention to the practical significance of such important phenomena for science and technology as electrokinetic phenomena. A brief history of the discovery of electrokinetic phenomena and their use in various fields of science and technology is given. The current state of the issue is presented in relation to the creation of one of the types of electrokinetic converters — an electrokinetic radiator. It is noted that the authors had previously managed to create a theoretically unified theory of such radiators for air and liquid conditions. At the same time, it is noted that it is not yet possible to implement in practice an electrokinetic radiator as effective as an air one due to the large technical difficulties associated with electrical processes in liquids. As a result, the task is to conduct preliminary model studies of the comparative effectiveness of air and liquid radiators in order to determine the feasibility of designing and creating an electrokinetic liquid radiator. The comparative efficiency of electroacoustic conversion of an electrokinetic radiator in water and in air is considered using numerical simulation using the COMSOL Multiphysics software package. The porous structure was modeled by a cylindrical capillary. The validity of choosing such a physical model of a porous structure is justified in this paper. In addition, the paper considered only losses related to the viscosity of the medium, and did not take into account heat losses, which will be considered in the next studies of the authors. The possibility of performing calculations with the „lightweight" hydrodynamic model — model of a viscous incompressible fluid was revealed in the process of setting and solving the problem. This approach has made it possible to significantly reduce the computational costs of conducting model experiments with virtually no loss of accuracy of the calculations performed. The results of numerical simulation with a zeta potential equal to 100 MV showed the following very encouraging results: at the same electrical potentials under the conditions of the same physical models, the pressure emitted by the electrokinetic converter in water turned out to be in the range from 750 to 4431 times higher than the pressure in air for different pumping voltages; the ratio of sound intensities in water and air pressure ranges from 131.3 to 866.3 times for different pumping voltages. The results obtained will certainly prove to be very useful in the final practical phase of designing liquid electrokinetic radiators.

It seems extremely necessary to continue the study in the near future in terms of further consideration of the features of the described electrokinetic electroacoustic transformations, namely heat losses in converter models, as well as other important technical and applied features of the considered transformation due to the great scientific and practical significance of the described topic.

The same comparative analysis should be conducted in the future for the receiving mode of electrokinetic converters. In addition, the same comparative analysis should be carried out for the acoustic vibration relay mode due to the possibility of creating electrokinetic repeaters discovered by the authors.

All this combined will make it possible, after completing these studies, to make decisions on choosing the optimal ways for further scientific study for creating efficient, competitive electrokinetic converters.

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Conflict of interest

The authors declare that they have no conflict of interest.

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