Latent Mechanisms of Gradient Force Field Origin in Theory of Electroosmotic Soil Dewatering

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Abstract. The analysis of existing protections, including currently implemented in Russia digital terminals with several digital protections, was made, and it showed their weak points. In addition, the authors proposed a protection that responds to several signs of a transient process with a logical mode of the selection function.

1. Introduction

The analysis of electroosmotic energy and mass transfer by the criterion of specific energy costs for transfer of dispersion medium with allowance for the relaxation of electric and heat and moisture fields in soils is given in this paper. It is established that the processing type corresponds to the characteristic size of the object and the relaxation time of the force gradient field.

The electrokinetic process in the energy aspect is a system of a series of physical, electrophysical, electrochemical, thermodiffusion and diffusion processes. A group of electrophysical and electrochemical processes is characterized by polarization at the molecular and ionic levels and electrolysis, which, when operating at a constant current, inevitably lead to excessive losses. The simplest solution for the removal of polarization, at first glance, is the transition to alternating current, proposed for electrode reactions back in 1948 by Erschler [1]. Later a number of authors confirmed this possibility and explained the effect of alternating current, which removes the "concentration" polarization of the electrolyte. At the same time, some authors point out the possibility of creating electrophoretic (electroosmotic) pressure by an alternating electric field [2], and two mechanisms of directed movement of particles are proposed to explain the phenomenon: dipolar phoresis and aperiodic electrodiffusion.

2. Problem definition

With dipolar diffusion [3], the particle drift is directed to the region of minimum field amplitude, i.e. from the electrode and hence the electroosmotic pressure – to the electrode, of course, taking into account the sign of the charge of dispersed particles.
With aperiodic electrodiffusion, the movement of the particles is explained by the gradient of the electrolyte concentration in the solution, which in its turn is created with an alternating electric field due to the different mobility of ions of different signs. Recently, another mechanism has been discovered for the motion of particles in a liquid - a nonlinear electrofluorio-phorizer - a directed drift of particles in a non-Newtonian liquid caused by a single-phase periodic field. The above mentioned phenomena take place in technological processes related to electrochemistry, but for the purposes of energy and mass transfer are not used as on alternating current the moisture output is low and the heat loss is high.

The use of these phenomena, especially aperiodic electrodiffusion-phoresis, is advisable for electrical measurements, since it makes it possible to reduce the concentration polarization of the electrolyte.

3. Theory
There is an electrotechnological process, in which the reception of voltage supply to the electrodes with unipolar impulses is used, which makes it possible to reduce the costs of electricity and anode material, i.e. reduce the loss of electrolysis. At the same time, there is a decrease in the "water flow", i.e. the electroosmotic transfer of the dispersion medium decreases. To explain the decrease in the dissolution of the metal of the anodes when fed by unipolar impulses, it is possible that the metal ions, torn from its surface during the operating impulse, partially return to the surface during the pause. In other words, the electrokinetic process is also taking place on a pulsating current with a decrease in the dissolution of the metal of the electrodes and, as a result, a decrease in energy costs for electrochemical dissolution.

The technique also knows the principle of the electrochemical system, consisting in the supply of variable asymmetric voltage to the electrodes - it is used when charging electric accumulators. This principle is most often used to increase the efficiency of the charging process achieved by reducing the polarization of electrodes while simultaneously increasing the polarization of the electrolyte achieved by stabilizing the charging current.

When using this principle for the purposes of electroosmosis, obviously, the effects obtained with alternating current should be observed when feeding with unipolar pulses and, in addition, due to the presence of dipole moment in dispersed particles, phenomena of vibration and electrostrictive particle rotation under the action of the variable component of the electric field [4] and fluidization, noted by researchers in the field of colloid chemistry. These phenomena occur during electrophoresis, when the dispersion medium predominates. With the predominance of the dispersed phase, i.e. with electroosmosis, a number of researchers note "orientational ordering of particles" and the formation of "chain structures" [5] under the action of polarization forces. In addition, variable asymmetric feeding should be affected by a decrease in the weakening field of the relaxation of the diffuse layer and, as a consequence, an increase in the yield of water at the same energy costs. In this case, it is expedient to match the relaxation time of the DEL (double electric layer) of the material to be treated and the frequency of the electric field change in order to reduce the dielectric losses [6], the period of oscillations of the electric field strength should not exceed the relaxation time. Any polarization process is characterized by a finite relaxation time, so that at sufficiently high frequencies, when the field period is commensurable with the relaxation time, the phase shift between polarization and field becomes noticeable, which is manifested in dielectric losses [6]. The relaxation time, according to theory, for electrolytic polarization, i.e. for the relaxation of the DEL it lies in the range of 10-2-10-4 s. Experiments have shown that the least relaxation of the DEL affects the frequencies $f = 20-320$ Hz [7]. In addition, the frequency of 20 Hz is considered the lower limit of the operation of aperiodic electrodiffusion. The opinion of some authors [8] about the relaxation time, lying within the limits of 104-108 Hz, does not correspond to the theory and, apparently, is connected with taking into account the sizes of charged particles in the double electrical layer-electrolyte ions (the numbers were obtained analytically). The dimensions of the particles should, in our opinion, be taken for "macroions", i.e. real dispersed particles.
Some researchers have achieved similar results in the field of electrochemical kinetics - the electrodeposition of metals from solutions on an alternating asymmetric current. In this case, it was possible to relate to the mathematical model of energy not only the physical parameters of the atoms of the elements being deposited, but also the parameters of the variable asymmetrical current and to find the resonant frequency for each electrochemical system through calculating the Langmuir frequency:

\[ \omega = \sqrt{\frac{4\pi n_1 z^2 e^2}{M_1}}, \]  

where \( M_1 \) - mass of a charged particle,
\( n_1 \) - density of ions,
\( z \) - ion charge,
\( e \) - electron charge.

The frequency calculated for this formula refers to the kHz range, but experimental results have been obtained confirming the presence of a resonance at a low frequency, which suggests that the vibrations are performed not by ions, but by whole associates or "macroions" - dispersed particles whose mass is much larger than the mass ion, and the charge is still equal. Thus, the use of variable asymmetric current should give a reduction in energy costs for the same work of electroosmosis and electrophoresis in comparison with DC power supply and even more so on alternating sinusoidal.

In the practice of dewatering, in the construction industry [8], there are often situations when the needle filter permeates several layers of soil at once. It was noted [10] that in some cases, the successful drying of the overlying layer with a low filtration coefficient is achieved if this soil is underlain by a soil of greater permeability, allowing groundwater to be evacuated. It affects not only the filtration properties of soils, but also colloid-dispersed, i.e. difference of potentials of moisture transfer.

At the same time, if an electric field is applied to this system, the flow of the vector of electrical induction will be distributed unevenly in the volume, and the lines of force of the electric field will be concentrated in that part of the volume where the dielectric constant of the disperse phase is higher - the effect of the "dielectric lens", which will be equivalent to increasing the strength of the electric field for this layer. If, at the same time, the "lens" underlying layer possesses even better electrokinetic properties - less specific energy costs, the effect of reducing of energy costs will increase. It is also advisable to use a hydrostatic head, which allows displacement of moisture into the underlying layer, i.e. to place a layer with better electrokinetic characteristics below the drained one. In connection with the foregoing, we cannot agree with the methodology of Professor A.V. Netushila [9], which assumes averaging of the coefficient of electroosmosis over the cross section of a dispersed material perpendicular to the vector of electrical induction (as geometric mean), without taking into account the thickening of the electric field strength lines and moisture transfer between the layers.

In the process of operation of installations for electroosmotic dehydration of wet dispersed materials, the researchers observed "heating and drying of the soil adjacent to the anodes" [10]. Dehumidification of the material in the pre-anode region under the influence of electroosmosis leads to a significant increase in the resistivity of the material and to an increase in the voltage drop in the region adjacent to the anode. Increasing the voltage drop, in turn, leads to an increase in heating and further drying out of the material. Thus, near the anode, a progressively increasing process of overheating and drying of the material, which limits the possibilities of the electroosmotic installation, can occur.

4. Experimental results
Hence, it can be concluded that the specific energy costs increase as the pre-anode zone drains. Switching the positive pole of the source from one anode to the other located on the line connecting the maximally remote anode to the cathode should ensure the best possible mode of operation for each anode, since switching can be made before the emergence of the drained zone, thereby sharply reducing heat.
losses in the near-anode zone. In this case, it is expedient to additionally carry out the measurement of the electric current through the material, and connect the anodes to the electric power source in series in the direction of the electric field. One should disconnect the first anode from the positive pole of the power source and connect the subsequent one taking into account the measured value of the electric current. The setting of the current relay must be such that the specific energy costs will be at an acceptable level from the economic point of view.

In this regard, it follows that the established practice of using multi-electrode systems is inefficient, since it involves simultaneous inclusion of all anodes located in the volume of dehydrated material.

It is obvious that with electrophoresis and fore-emf, this phenomenon is not observed in connection with a good heat dissipation through a dispersion medium-water.

With electroosmotic dehydration of soils, the theory of continuum mechanics for a finite volume is applicable. From the theory of continuum mechanics for a finite volume, it follows that electroosmosis is a diffusion process, with the first component (the dispersion medium - moisture) moving in one direction relative to the original volume, the second (the dispersed phase - the solid dielectric) in the other. Consequently, when studying the motion of multicomponent mixtures, it is necessary to unite the laws of continuum mechanics with the laws of physics and chemistry for quantities-the change in the mass of the component of the mixture per unit time per unit volume due to electroosmosis with a perforated cathode and the diffusion flux vector, which in the language of mathematics will appear in the form systems of equations for a processed material as a continuous medium:

\[
\begin{align*}
\frac{\partial \rho_i}{\partial t} + \text{div}(\rho_i V) &= \chi_i - \text{div} I_i \\
I_i &= \rho_i \left(V_i - V\right)
\end{align*}
\]

where \(V_i - V\) - the velocity of the i-th component with respect to the medium as a whole;
\(\rho_i\) - density of the i-th component.

Consequently, the phenomenon of electrokinetics cannot be considered in isolation from the mechanics of a continuous medium, especially when working with closed volumes of processed materials, since it follows by the theory that the mass of each of the components in local volumes is subject to change, electrokinetic (electroosmosis coefficient), electrical (electrical conductivity) and electric power (specific energy consumption for moisture release) characteristics of materials. It should be noted that the theory of a continuous medium takes into account the motion of all components relative to the original volume at the same time - the superposition principle, which was not taken into account in previous works on electrokinetics, in view of the fact that processes were considered in unlimited volumes that take place only when the soils are dehydrated [9, 10]. When the dispersed materials are dehydrated with electroosmosis in closed volumes, a continuous change in the physicochemical characteristics of the material takes place, which is expressed in an increase in the electrical resistivity of the material in the pre-anode zone and in a decrease in the cathode. As is known, there is a stable interdependence between the electrical resistivity and the energy costs. In practice, dehydration of the pre-anode zone leads to a loss of electrical conductivity of the near-anodic zone, an increase in specific energy costs and, ultimately, a cessation of the dehydration process until satisfactory characteristics of the processed materials are obtained. The greatest impact on the growth of energy consumption in the process of electroosmotic dehydration in a closed volume is provided by the accelerated drainage of the near-anode zone and a jump in heat losses at the increased electric resistivity of the near-anode zone, the relationship between the electrical resistance and moisture of the material is obvious and experimentally proved.

Moreover, the sharply identified drained pre-anode zone is small - its thickness is usually within 0.05-0.1 m, but it is sufficient to interrupt the electric circuit. At the same time, the bulk of the supply voltage
falls to the drained near-anode zone, which has a large electrical resistivity, and a small part - for the rest of the material, and the field strength in the material is insufficient to break loosely bound water and the process of electroosmosis does not proceed. Electric energy is consumed only for heating the drained near-anode zone. In order to move the loosely bound water, it is necessary to again create the electric field strength in the dehydrated mass above the threshold. This can be achieved in several ways: using behind the anode effect, switching the power supply from the anode to the anode - "running pulse", a short-time power source operation mode.

Behind the anode effect, the anodes are spaced at a certain distance from the vessel wall and, due to this, to the dried pre-anode zone from behind the anode zone under the influence of the humidity gradient [10], i.e. forces of diffusion, the moisture moves, which reduces the electrical resistance of the pre-anode zone, and consequently, losses and it increases the overall efficiency of the process.

However, the operating time of behind the anode effect is due to the reserve of the liquid phase in behind the anode zone, the increase of which may cause the liquid from behind the anode zone to stop moving to the anode, since the diffusion forces caused by the humidity gradient at the large zone will be less than the forces due to the thermal- which increases with increasing temperature of the material located around the anode and directed in behind the anode zone to meet the diffusion forces. The above mentioned factors do not allow one to significantly reduce energy costs for dewatering of wet dispersed materials and lower their moisture content.

The short-time operation mode at the two electrodes should also provide lower energy costs due to the humidification of the pre-anode zone during the pause by diffusion - the moisture gradient and thereby reducing the total energy costs.

The reason for this assumption can be that the short-time operation mode is used in a number of electrochemical processes with the achievement of energy savings: in the electroassembly of saline soils, with the clarification of sewage. In the works listed, the effect is achieved by using the relaxation of the double electric layer of the dispersed phase. It is assumed that with a rational combination of the DEL relaxation of the dispersed phase and the relaxation of the moisture content in the gap between the electrodes, a positive effect can be achieved. The analysis of existing classifications of dispersed materials in technological processes made it possible to conclude that the modern classification of disperse systems and technologies is incomplete because of dialectical incompleteness, since there is a unidirectional study of phenomena toward the microlevel. The energy analysis of the processes of energy and mass transfer in heteroporous, heterogeneous materials allows us to conclude that during the transfer it is impossible to single out one physical phenomenon: electroosmosis, electrophoresis, fore-emf, osmo-emf, moisture conductivity, polarization of electrodes, polarization of the dielectric of the dispersed phase, electrolyte polarization, electrolysis, electrical heating, thermal conductivity, osmosis, iontophoresis, etc.; all (or almost all) processes go simultaneously in the system, but at different levels of the system hierarchy (micro-, meso- and macrolevel) as a result, some of the processes participate in the energy and mass transfer as driving, and some create losses, and their participation in the energy balance in that or the other side depends on both the nature and composition of the dispersed phase, and the dispersion medium, and their mutual orientation in space relative to the electric field strength vector.

The studies were intended for the experimental proof of the hypothesis of the systematic nature of research objects – dispersed materials in the technologies for their separation. The results of the research showed that:

- in the case of electroosmotic separation of wet dispersed materials in variable asymmetric current at the industrial frequency, the specific energy costs are reduced due to a decrease in the effect of the polarization relaxation of the dispersed phase dielectric, polarization of electrodes, polarization of the electrolyte of the dispersion medium, electrochemical processes, acceleration of mass transfer under the action of electrodiffusion, magnetodiffusion and etc.;
- with electroosmotic transfer of moisture with introduction of an underlying layer with better electrokinetic characteristics in the material than in the dispersed phase of the dewatered material, the area of rational use of the method lies within the maximum of the relative thickness of the layer and the maximum dispersion (the range studied), which indicates a significant effect on the energy process phenomena of thickening the lines of force of the electric field in the region of space with large values of the permittivity;

- with electroosmotic mass transfer in the "running pulse" mode, the effect of reducing energy costs can be achieved by reducing the losses for electric heating of the pre-anode zone;

- in the case of a short-time power supply, the effect of reducing energy costs is achieved through the use of the phenomenon of relaxation of heat and moisture fields in the volume of the material being processed and the thermal conductivity.

The implementation of the system analysis of the obtained data is presented in the form of a scale of parametric bases of objects subject to electrokinetic processing (Table 1).

### Table 1. Scale of characteristic parameters of processes and objects of electrokinetic energy and mass transfer

| Level of hierarchy of processing objects | Type of polarization | Size of the object, m | Relaxation time, s | Frequency of the field of action, Hz | Impact type |
|------------------------------------------|----------------------|-----------------------|-------------------|-------------------------------------|-------------|
| Microlevel                               | 1. Electronic and atomic | $0.5 \times 10^{-10}$ | $10^{-14} \ldots 10^{-17}$ | $3 \times 10^{16}$ | IR heating |
|                                          | 2. Ionic             | $3 \times 10^{-10}$ (OH) | $10^{-12} \ldots 10^{-13}$ | $3 \times 10^{12}$ | Microwave |
|                                          | 3. Dipole            | $3 \times 10^{-10}$ (H$_2$O) | $10^{-7} \ldots 10^{-13}$ | Microwave |
|                                          | 4. Structural        | $3 \times 10^{-10}$ (H$_2$O) | $10^{-3} \ldots 10^{-8}$ | Microwave |
| Dispersed particles, capillaries         | 5. Electrolytic      | $0.1 \ldots 0.01$ | $10^{4} \ldots 10^{2}$ | $10^{2} \ldots 10^{3}$ | Electroosmosis asymmetric current. |
|                                          | 6. Electrokinetic    | $0.3 \ldots 0.4 \times 10^{-4}$ | $0.01 \ldots 0.001$ | $0.4 \ldots 0.5 \cdot 10$ |
|                                          | (experiment)         | $3.0 \ldots 4.0$ | $1.8 \ldots 2.0 \times 10^{3}$ | |
|                                          | 7. Thermogradients   |                        | $1.8 \ldots 2.0 \times 10^{3}$ | |
|                                          | (experiment)         |                        | $1.8 \ldots 2.0 \times 10^{3}$ | |
| Mesolevel                                |                      |                       | $10^{5} \ldots 4.0$ | $0.4 \ldots 0.5 \cdot 10$ |
| Macrolevel                               |                      |                       | $10^{5} \ldots 4.0$ | $0.4 \ldots 0.5 \cdot 10$ |
| Natural accumulations of dispersed particles and water (geological objects) | no | $>10 \rightarrow \infty$ | $\rightarrow \infty$ | 0 |

5. Discussion of results

Obviously, the proposed scale [10] allows us to establish not only the hierarchy level by the characteristic size of the object, but also the type of processing by the characteristic relaxation time of the humidity field in the object.
6. Conclusion
In addition, it is possible to determine the sequence of physical impacts during a technological operation of energy and mass transfer, and in the presence of data on the electrokinetic characteristics of the object – to determine the necessary number of physical impacts.

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