Multifactorial electrokinetic technology and electroosmotic model of irrigation of biogeocenoses

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Abstract. The problem of reclamation of sludge pits at oil industry facilities has not been solved. A mechanism for implementing an accelerated technology of sludge dewatering by electroosmotic impacts has been developed. In order to specify processes, the concept “specific energy consumption for a mass transfer” was introduced. In order to eliminate the influence of relaxation of gradient fields, it was proposed to change electrical energy parameters.

1. Introduction

Sludge pits are pits with a diameter of 100 meters. They are created around boreholes for storing drilling waste: waste solutions with or without oil, crushed rock, clay, water, chemicals. About 500 cubic meters of drilling waste per well is stored in each pit. Drilling waste diluted with water is a creamy toxic mass.

In the construction of wells, in order to eliminate the risk of damage to the environment, a procedure for reclamation of sludge pits has been implemented. There are several ways of reclamation: backfilling with sand, natural evaporation, thermal and chemical treatment, injection into dry absorbing layers, “pressing” in narrow trenches, exportation to evaporation fields. These procedures are long-term and costly.

It is necessary to use 4–5 thousand cubic meters of sand. At the same time, in order to transport sand from other places, it is necessary to destroy forests, or extract it from a lake or a swamp.

The purpose of this study is to accelerate reclamation of sludge pits, saving primary energy sources and improving environmental safety of oil fields.

2. Materials and methods

The study solves the following tasks:

a) identification of an optimal method of sludge dewatering,

b) calculation of the technological cycle of the reclamation system,

c) development of conceptual schemes of the technology and electrical circuitry for electroosmotic
reclamation of sludge pits.
An analysis of results of intellectual property in the field of reclamation technologies for 1975-2008 showed (Fig. 1) that
1) distribution of repeated applications is uniform which indicates the relevance of reclamation at this stage and the absence of effective, comprehensive solutions.
2) an increase in the number of applications reflects the increasing relevance of technical solutions of land reclamation using modern technical methods.
3) the lack of radical revolutionary solutions and traditional methods.
4) development of a hypothesis about the application of the method of electroosmotic dewatering.

3. Results
Based on the analysis of the patent situation, electroosmosis for dewatering sludge pits is not applied in this industry due to hard prediction and the lack of practical recommendations.

Implementation of the electroosmosis procedure allows for lowering the moisture content of the dispersed material ala and removing hardness salts which will accelerate the reclamation process. The first quantitative studies of electroosmosis were carried out by Wiedemann in 1852. He showed that velocity $V$ of the electroosmosis is proportional to current $I$ under other constant parameters. Ratio $V/I$ does not depend on the cross-sectional area and thickness of the diaphragm [1]. The first quantitative characteristic of the process was the volumetric rate which, according to Lomize [2], showed the consumption of electroosmotic transferred water, referred to the unit of the total cross section of the dehydrated material occupied by the skeleton and pores. With the deepening of knowledge in the field of colloid chemistry and dispersed systems, the main indicator of electrokinetic properties of a material $\xi$ - potential [3] (Helmholtz and Perrin) measured in volts (V). This indicator reflects physical phenomena, but in practice it is inconvenient, since its calculation requires precise measurements of dielectric constant and viscosity.

In 1940, B.F. Reltov introduced a new indicator - the electroosmosis coefficient - to determine the effectiveness of the process - $K_e$ [4]. The coefficient of electroosmosis determines the influence of solid and liquid components on the volumetric rate of electroosmosis and is equal to the fictitious velocity of water movement under the influence of an external electric field at field strength $E$ V/cm. The coefficient is calculated by formula:

$$K_e = \frac{\rho \xi}{4\pi \eta} ;$$  \hspace{1cm} (1)

$K_e$ is the proportionality coefficient between $V_e$ and $E$, and the integral parameter:

$$V_e = K_e \cdot E ;$$  \hspace{1cm} (2)

At the same time, it is an auxiliary characteristic for determining the volumetric rate. This was further developed in the coefficient of electroosmosis current $K_{ei}$ (m$^3$/A·s) suggested by Ziangirov [5]. Unlike $K_e$, it is a coefficient of proportionality between $V_e$, $\sigma$ - current density:

$$V_e = K_{ei} \sigma ;$$  \hspace{1cm} (3)

The coefficient of electroosmosis is associated with the coefficient of electroosmosis through the dependence:

$$K_e = \gamma K_{ei} ;$$  \hspace{1cm} (4)

where $\gamma$ - conductivity of the material, Ohm$^{-1}$·m$^{-1}$. These coefficients make it possible to determine the liquid output when using direct current and calculate electric power costs in amps, given the required volume of water. However, when using alternating or alternating asymmetric currents, this procedure is
hard to implement. In connection with the need to use variable asymmetric current, it is necessary to calculate $K_{ei}$ and $V_e$.

Let us calculate the specific energy used for fluid release:

$$w_e = \frac{W}{M}; \quad [\text{kWh/kg}], \quad (5)$$

where $W$ - the amount of electricity spent on the dehydration process, kWh;

$M$ - the mass of water released by electroosmotic pressure, kg.

Specific power is calculated by formula:

$$p_e = \frac{w_e}{\tau} = \frac{W}{M\tau}; \quad [\text{kWh/kg}], \quad (6)$$

where $\tau$ - treatment time, h.

The same system of energy assessment was adopted by Locart [7-9]. The advantage is as follows. It is not particularly difficult to calculate the required power and operating current of the installation, knowing the specific energy consumption and setting the required depth of dehydration and processing time. It is obvious that in each experiment, calculation of the specific energy cost is required. Since in all the dispersed materials of the soil, there are mineral particles, the electrokinetic energy-mass transfer has its own characteristics:

a) heterogeneity of the capillary sizes (heteroporosity of the dispersed phase) depending on the large spread of particle sizes causing excessive energy consumption for heating the dispersion medium in large capillaries.

b) the presence of indifferent and non-indifferent electrolytes (the multicomponent electrolyte composition of the dispersion medium) decreasing the electrokinetic potential as a result of an increase in the concentration of countercations with an increase in the concentration of electrolytes and the ability of electrolyte ions to complete the crystalline disperse phase lattice decreasing the electrokinetic potential.

c) the difference between the hydrogen component of the medium indicator can affect the electrokinetic potential of dispersed particles, since “hydrogen and hydroxyl ions have a high ability to adsorb; the first ones - due to the small radius which allows them to come close to the surface of the solid phase; the latter one - due to the large dipole moment” [13]. The composition of the pH changes.

d) when diluting the colloidal system, the electrokinetic potential should increase, reflecting the dependence on the concentration of the dispersed phase, since the thickness of the electrical double layer increases as a result of a decrease in the concentration of counterions. In case of dilution, a potential-determining ion can be desorbed from the surface of the dispersed phase which decreases the electrokinetic potential. This effect is characteristic of electrophoresis in highly diluted sewage.

e) the dependence on a temperature level - with an increase in temperature, the $x$-potential should increase due to an increase in the intensity of thermal motion of counter-ions and an increase in the thickness of the electric double layer, but the desorption of potential-determining ions increases as well and the $x$-potential decreases.

f) instability of electrophysical and electrochemical properties of the dispersed phase derived from the physical nature of particles of the dispersed phase and the chemical activity of the dispersion medium.

The main feature of electrokinetic treatment of dispersive materials is as follows:

- relatively high specific energy consumption,
- the dependence of the specific energy consumption on a large number of uncontrollable factors due to the inadequacy of the existing theory and technology.

When there is a mismatch between the external force and the capillary axis and the harmonic external force action, it is necessary to solve the problem in the spatial coordinate system corresponding to the real physical space. The movement of moisture in the dispersed material can be expressed as a sum of components, each of which shows the influence of a particular factor on the electrokinetic energy and mass transfer (electroosmosis):
\[ W_\Sigma = \Delta H_{mg} + a_1 \Delta BL \tau + a_2 \Delta CL \tau + k_e m_e + k_g m_g + k_n E^2 SL + I^2 R \tau + a_3 E \tau + a_4 z \Delta T + a_5 z \Delta T; \]  

(7)

where

- \( mg \Delta H \) - pressure loss;
- \( a_1 \Delta LB \) - moisture loss;
- \( a_2 \Delta LC \) - osmosis loss;
- \( k_e m_e \) - electrolytic dissolution loss of electrodes;
- \( k_g m_g \) - electrolytic gas loss;
- \( k_n E^2 SL \) - polarization loss of the dispersed phase dielectric;
- \( I^2 R \tau \) - energy of electric heating;
- \( a_3 z \Delta T \) - operation of thermal conductivity (thermal osmosis);
- \( a_4 E \tau \) - operation of electrical osmosis.

The analytical model of the energy balance of the kinetic energy transfer can be written as follows:

\[
\begin{align*}
A_{ps} &= mg(z_k - z_a) + mg \frac{P_k - P_a}{\gamma_w} + \frac{am}{2} (V_k^2 - V_a^2) \\
A_{p} &= -c_a M_0 (\theta_k - \theta_a) \left[ g(z_k - z_a) + \frac{\alpha}{2} (V_k^2 - V_a^2) \right] \\
A_{com} &= i RTSL (c_a - c_k) \\
A_{end} &= \frac{2 \sigma T g}{T_k} (T_k - T_a) \\
A_{re} &= I_a \tau (B + \frac{RT}{\varepsilon F} \ln I_a) \\
A_{go} &= \left( \frac{A_{ho}}{\varepsilon F} \right) I \tau \\
A_{ped} &= \frac{e^\tau}{k_c} \\
A_{pd} &= \frac{e - e_0 - U_0 I \tau}{e + 2 \varepsilon e_0} \\
A_{pef} &= \frac{RT \tau}{F} \ln \frac{\varepsilon_n}{\varepsilon_0} \\
A_{pd} &= \frac{e - e_0 - U_0 I \tau}{e + 2 \varepsilon e_0} \\
A_{pef} &= \frac{RT \tau}{F} \ln \frac{\varepsilon_n}{\varepsilon_0} \\
A_{en} &= 3.604 I_a \left[ U_0 - 0.0434 \sum \frac{x_i A_i}{z} \right] \\
A_a &= A_{en} = \frac{2E \varepsilon \xi \tau}{\pi r^2} \\
A_a &= -SLRT (\gamma_0^+ \nabla \mu_1^+ + \gamma_0^- \nabla \mu_1^-) 
\end{align*}
\]  

(8)
Depending on the variables, specific energy consumption will be redistributed. Only some processes and phenomena do useful work:
- electroosmosis,
- thermal and moisture conduction,
Other ones are parasitic and not energy-generating.

The following hypothesis was suggested:

a) physical processes: loss of piezometric pressure, loss of moisture conductivity and loss of osmosis affect the energy of dehydration, but it is very difficult to isolate their effects;

b) parasitic electrical processes contribute to the total energy loss;

c) in order to eliminate the influence of parasitic electric processes on energy consumption, it is necessary to change parameters of electricity - to replace the treatment with direct electric current by the treatment with other types of electric energy.

When there are no data on the energy ratio in the total energy balance and boundary conditions for variables, the analytical solution of the system of equations is very difficult. The energy diagram is shown in Fig.3.

The specified energy diagram of electrokinetic dehydration of dispersed material: $a_{1} \Delta \zeta$ - loss of piezometric pressure; $a_{2} \Delta V^2$ - friction resistance loss; $a_{3} \Delta \theta$ - losses to overcome the forces of moisture; $a_{4} e^2$ - loss to overcome the polarization of electrodes; $a_{5} UI\tau$ - losses to overcome the polarization of the disperse phase dielectric; $a_{6} c_n/c_0$ - electrolyte polarization loss; $a_{7} I_a$ - electrode dissolution loss; $a_{8} I_a$ - loss of electrolytic gas formation (water decomposition); $a_{9} I/R\tau$ - energy of electric heating; $a_{10} \Delta T\tau$ - heat loss to the external environment; $a_{11} \Delta T\tau$ - work of thermal conduction

forces; $a_{12} I_a\tau$ - work on the movement of electrolyte ions - losses to create a concentration difference; $a_{13} \tau$ - osmosis loss due to the removal of electrolytes from the cathode space; $a_{14} \Delta c$ - work of ionophoresis moving the dispersion medium - water; $a_{15} \Delta c$ - ionosmosis losses – a counter liquid flow.

1 - macrophysical processes; 2 - electrophysical processes; 3 - electrochemical processes; 4 - work of electrokinetic energy and mass transfer; 5 - diffusion processes; 6 - thermal diffusion processes; 7 - energy consumed from the source.

The energy flow $a_{1} \Delta \zeta$ says that the piezometric pressure can create opposition to the mass transfer and increase the strength of electroosmotic pressure. This position is confirmed experimentally [14] and is consistent with theoretical provisions.

The distribution of energy flows that characterizes thermal diffusion and electrodiffusion processes determines the loss of electrical energy, while another part will participate in the efficient mass transfer as thermal conduction, ionosmosis and iontophoresis. The distribution of energy flows in other diffusion processes is similar.

The electrokinetic process is a system of physical, electrophysical, electrochemical, thermal diffusion processes. For electrophysical and electrochemical processes, polarization at the molecular and ionic levels and electrolysis are characteristic. They cause excessive losses. The simplest solution for removing polarization is the use of alternating asymmetric current. Some researchers indicate the "orientational ordering of particles" and formation of "chain structures" under the influence of polarization forces. Under variable asymmetric feeding, the procedure is implemented to reduce the field weakening effect of the diffusion layer relaxation and increase the water yield at the same energy consumption.

To reduce dielectric losses, it is advisable to reconcile the relaxation time of the DEL from the material and the frequency of the electric field change; the period of oscillations of the electric field
strength should not exceed the relaxation time. All polarization processes are characterized by a finite relaxation time, so that at high frequencies, when the field period is commensurate with the relaxation time, a phase shift between the polarization and the field becomes noticeable which manifests itself in dielectric losses. According to [15], the relaxation time for electrolytic polarization is $10^{-2} \ldots 10^{-4}$ sec. Experiments showed that the least relaxation of DES affects frequencies $f = 20 \ldots 320$ Hz.

Researchers observed “heating and overdrying of the soil adjacent to the anodes” [2]. The drainage of the material increases resistivity of the material and the voltage drop in the area adjacent to the anode. A decrease in voltage increases heating and desiccation of the material. Near the anode, overheating and drying of the material can occur which limits possibilities of the electroosmotic installation.

We identified that the specific energy consumption increases as the drainage of the anode zone increases. Switching the positive pole of the source from one anode to another one located on the line connecting the most distant anode to the cathode, should provide the most favorable mode of operation of each anode, since switching can be done before the dry zone develops. It reduces heat losses in the near-anode zone. It is advisable to measure parameters of the electric current through the material, and connect the anodes to the source of electrical energy sequentially in the direction of the electric field. Disconnection of the first anode from the positive pole and connection of the next one should be carried out taking into account the measured value of electric current. The setting value of the current relay is its value at which the specific energy consumption will be economical.

The theory of continuum mechanics for a finite volume says that electroosmosis is a process with diffusion; the first component (moisture) moves in one direction relative to the original volume, the second (dispersed phase - solid dielectric) moves in other direction. When studying the movement of multicomponent mixtures, it is necessary to combine the laws of continuum mechanics with the laws of physics and chemistry to change the mass of a mixture component per unit time per unit volume; electrokinetics cannot be considered in isolation from continuum mechanics, especially when working with closed volumes of processed materials, since the mass of each component in local volumes changes causing changes in the electroosmosis coefficient, power (specific electron-conductivity) and electricity (specific energy consumption for moisture release).

The continuum theory takes into account the movement of each component relative to the initial: the principle of superposition which was not taken into account in previous works on electrokinetics due to the fact that processes in unlimited volumes that occur only during the dehydration of soils were analyzed [2].

When dewatering dispersed materials by electroosmosis in closed volumes, there is a continuous change in the physicochemical characteristics of the material: an increase in specific electrical resistance in the near-anode zone and a decrease in the cathode zone. There is a stable relationship between electrical resistivity and power consumption.

In practice, dewatering of the near-anode causes losses of electrical conductivity of the near-anode zone, an increase in specific energy consumption and termination of the dehydration process until obtaining satisfactory characteristics of the materials.

The greatest influence on the growth of energy consumption in the process of electroosmotic dehydration in a closed volume is exerted by the accelerated drainage of the anode zone and changes in heat losses on the increased electrical resistance of the anode zone; the relationship of electrical resistance and moisture is obvious and was experimentally proven. Moreover, the drained near-anode zone is small (it ranges from 0.05 ... 0.1 m) but sufficient to interrupt the electrical circuit. The main part of the supply voltage falls on the dried anode zone which has large electrical resistance, and on the rest of the material; the field strength is insufficient for breaking loosely bound water and the process of electroosmosis does not occur. Electric energy is consumed only when heating the dried near-anode zone. In order to move loosely bound water, it is necessary to re-create the electric field strength in the dehydrated mass above the threshold. This result can be achieved in several ways:
- using the anode effect,
- switching power supply from the anode to the anode - implementation of the “running pulse” procedure,
- an intermittent mode of operation of the source of electricity.

Experts argue that no one paid attention to the possibility of flow simultaneously with electroosmosis of other relaxation phenomena; electroosmosis should be carried out using direct current.

Dehydration should be based on alternate asymmetric electric current making it possible to remove the negative effect of electrical polarization of the electrodes [10]; relaxation of the hydrostatic polarization of the dispersion medium is removed by pulsed power supply [11]; the effect of relaxation of thermal-conductivity forces is removed by applying a “running pulse” to the power supply [12]. Implementation of these methods is the most effective solution; the costs decrease 10-11 times.

4. Conclusions

Based on the experiments and the fundamental laws of physics and chemistry describing processes and phenomena of sludge dewatering, it has been established that the most effective approach is electroosmosis.

In order to optimize resources and duration of reclamation of sludge pits, it is advisable to remove the re-laxation of force gradient fields by changing the parameters of electricity supplied to the electrodes.

The reclamation technological cycle should be implemented for one summer season, during which electroosmosis can reduce sludge moisture and concentration of chemical contaminants, plant green manure and pre-pare the agricultural area for further use.

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