

## Flow control of fluids through porous media based on electrokinetic effects

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**Abstract.** *This paper discusses the effect of electrokinetic characteristics of fluids flow in porous media. With regard to findings of the experimental study, the effect of liquid slippage in porous media in accordance with an electrically charged liquid-porous medium boundary is shown. It is shown that the change in the flow velocity profile and pressure gradient is caused by such examples of electrokinetic effects during filtration of polar liquids. Studies have shown that the process of electrolyte solutions flow through a porous medium is accompanied by changes in the flow rate and electric potential. The periodic character of changes in the flow characteristics is explained by continuous charge generation and charge interaction in the diffuse layer. Periodic accumulation and subsequent entrainment of charges along the cross-section of the channels, depending on the acquired charge polarity, as well as compression of the diffuse layer with an increase in the NaCl concentration in an aqueous solution can cause changes in the flow rate of the liquid. It is shown that the studied effects can serve as a tool for controlling the flow of fluids in water-oil-saturated reservoirs and, in particular, the pumping capacity of injection wells by control the electrical conductivity of water injected into the reservoir.*

**Keywords.** electrokinetic · electrical conductivity · flow rate · charge density · electrolyte · slippage effect · multiphase system.

**Mathematics Subject Classification (2010):** 76D55

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### 1 Introduction

Secondary methods of hydrocarbon production are based on injection of water and aqueous solutions of various chemical agents into oil-saturated reservoirs. In most productive formations, there is an extremely uneven flow of the displaced fluid over the volume of the pore space. To a certain extent, this depends on the position in the section of injection intervals in injection wells, the time of commissioning of wells and their transfer to water injection [5, 9, 22].

Fluid flow through porous media has been an important research topic for decades especially in the areas of petroleum engineering, geology, and geophysics. There is a fluid flow mainly in interlayers with higher permeability. Low-permeable pores are involved later or there is no flow of the displacement front at all. Due to the fact that there are practically

no geological conditions for the formation and distribution of inhomogeneous areas for a group of such reservoirs, it is quite difficult to predict the location of drained reserves zones, conversely, stagnant zones with no-permit hydrocarbon reserves.

In order to development the productive reservoirs in conditions of high heterogeneity of the structure in the section and non-sustained along the strike, a more rigid and selective bed stimulation is necessary.

Control of the main physical and chemical characteristics of water injected in the oil saturated reservoir is one of the important tasks of oil production. Incompatibility of the injected fluids, which differ in their physical and chemical properties, leads to a number of complications, which lead to decreasing in the injectivity capacity of injection wells, the formation of fractal structures under fluid displacement, etc. [11, 13].

## 2 Problem statement

Various chemicals are used in the injected water to improve fluid mobility and reservoir coverage in the system of bed stimulation and bottomhole zone treatment: alkalis (for example, NaOH, NaHSO<sub>3</sub>, NH<sub>4</sub>OH), acids, etc. [4, 16].

Henniker in [6] presented the results of his own studies on filtration of water, aqueous solutions of KCl and surfactants through fine-porous porcelain filters and found that the place of rupture when the solid and liquid phases flows relative to each other is always at a relatively large distance from the interfacial boundary.

In reservoirs with low permeability, there are significantly more differences compared to the fluid flow in highly permeable reservoirs. Darcy's law is widely used in petroleum engineering in the study of fluid flow to describe the linear relationship between the hydraulic pressure gradient and the volumetric flow rate in porous media. However, many researchers have reported the phenomenon of the so-called absence of Darcy law in dense layers and observed the nonlinearity of the relationship "pressure gradient - volume flow velocity" [1, 2, 7, 12, 20, 21].

Based on the results of hydrodynamic studies, the authors [7] found that under electrolyte solutions flow in a porous medium, there is a periodic character of changes in flow parameters.

These effects can be explained by adhesion or hydrodynamic slippage under the fluid flow. If the fluid adheres to a solid surface, the average flow velocity is estimated similarly to the provisions given in [8].

Fluid flow in a cylindrical tube at a constant speed ( $\frac{\partial v_x}{\partial \tau} = 0, \frac{\partial v_x}{\partial x} = 0$ ) you can describe it with the following expression:

$$\eta \left( \frac{\partial^2 v_x}{\partial r^2} + \frac{1}{r} \frac{\partial v_x}{\partial r} \right) = -\frac{\partial p}{\partial x} = const, \quad (2.1)$$

where  $x$  is the direction along the flow (along the length of the tube). At the same time, we consider  $\partial p / \partial x$  to be a constant value: after integration, in the range from  $r = 0$  (the tube axis) to  $r = r_c$  (the tube radius), and at  $r = r_c$ , the velocity on the tube wall is zero, the so-called sticking condition [8].

In contrast, the speed of hydrodynamic sliding contributes to the value of the speed  $v$  of the visible flow. It is defined as  $v_{hs}$  from the following relations [8]:

$$v_{hs} = -k_{hs} \left( \frac{\partial v}{\partial y} \right)_w = -k_{an} \left( \frac{\partial v_x}{\partial r} \right)_{r=r_c} \quad (2.2)$$

where  $\left(\frac{\partial v}{\partial y}\right)_w$  - near wall velocity gradient, equal to  $\left(\frac{\partial v_x}{\partial r}\right)_{r=r_c}$  :

$$\left(\frac{\partial v_x}{\partial r}\right)_{r=r_c} = \frac{r_c}{2\eta} \frac{\partial p}{\partial x}. \quad (2.3)$$

for a capillary on  $\delta - v_x$  will be:

$$v_x = -\frac{r_c^2 - r^2}{4\eta} \frac{\partial p}{\partial x} - k_{hs} \frac{r_c}{2\eta} \frac{\partial p}{\partial x} = -\frac{(r_c^2 - r^2 + 2k_{hs}r_c)}{4\eta} \frac{\partial p}{\partial x}. \quad (2.4)$$

The average velocity of the fluid flow:

$$v = \bar{v}_x = -\left(\frac{r_c^2}{8\eta} + \frac{k_{\bar{a},\bar{n}}r_c}{2\eta}\right) \frac{\partial p}{\partial x} = -K \frac{\partial p}{\partial x}, \quad (2.5)$$

where

$$K = \frac{r_c^2}{8\eta} + k_{hs} \frac{r_c}{2\eta}. \quad (2.6)$$

Thus, the effects of the so-called absence of Darcy regularity and the periodic nature of the flow in porous media probably due to the conditions of adhesion or hydrodynamic slippage.

Under the fluid flow, these effects in a porous medium can be enhanced due to various interfacial transport effects, such as the manifestation of the electrokinetic properties of the systems under study.

In [13 - 15], the authors considered electrokinetic effects in various materials and investigated different control methods. The electric potential arising under the fluid flow strongly depends on the nature of the surface of the contacting phases. It is quite natural to assume and confirm by research, that the relative phases flow along the interface directly depends on the electrokinetic potential. According to this theory (the diffuse structure of the double electric layer - DEL), the distribution of ions in solution near the surface of the solid phase is determined, with the electrokinetic property of the solid phase, which tends to attract an equivalent number of ions as close to the surface as possible, in the volume of the liquid phase. As a result, the counterions forming the outer lining of the DEL do not lie in a single plane. The concentration of counterions is greatest near the charged surface of the solid phase and decreases as the distance from the interface increases towards the interior of the solution.

In this case the potential does not change linearly, but exponentially, due to the fact that the compensating counterions are distributed unevenly. The change in the curve is steeper in places where there are more compensating counterions, and, conversely, the curve is steeper where there are fewer compensating counterions. Thus, an equilibrium diffuse layer of counterions appears, and the equilibrium of this layer is dynamic [1].

Here, the size of the ions is not taken into account. The ions considering as point charges, and this does not explain the so-called phenomenon of solid phase recharge when an electrolyte with a multivalent ion is introduced into the system, the charge of which is opposite in sign to the charge of the dispersed phase.

Stern combined the schemes of the DEL structure, assuming that real ions have finite sizes and, consequently, the ion centers cannot be located closer to the surface of the solid phase than at the distance of the ion radius [1]. Stern also took into account the adsorption interaction of ions with the surface of the solid phase. In the adsorption layer, the counterions are Packed tightly, and its width does not change due to changes in the external conditions of the colloidal system - concentration, electrolyte, and temperature. The diffuse layer of counterions has a variable thickness depending on the concentration of the electrolyte

in the medium. It should be remembered that there is a dynamic equilibrium between the counterions of the adsorption and diffuse layers, when an equal number of counterions leave the adsorption layer and the same number return to it from the diffuse layer.

Counterions located in the adsorption layer near a solid surface are considered stationary. When the electrolyte is introduced into the system, the dynamic equilibrium between the counterions shifts towards the adsorption layer, while part of the counterions of the diffuse layer passes into the adsorption layer. The diffuse layer is compressed, and the value of the  $\xi$  -potential decreases. The value of the  $\xi$  - potential is closely related to the thickness of the diffuse layer of counterions [1].

It is known the relationship between hydraulic and electrical phenomena under fluid flow in a pipe and a capillary-porous reservoir, due to the action of surface molecular and electrical forces at the solid-liquid interface [18]. This kind of electrophysical effects can significantly determine the nature of the fluid flow.

Electrokinetic coupling effects arising as a result of the interaction of electric charges in a liquid and on solid walls. The inhomogeneity of the electric charge distribution on the surface can significantly change the magnitude of the force and the nature of their interaction [10, 17], and the transfer effects can be enhanced near an inhomogeneously charged flat surface due to electrokinetic convection [19].

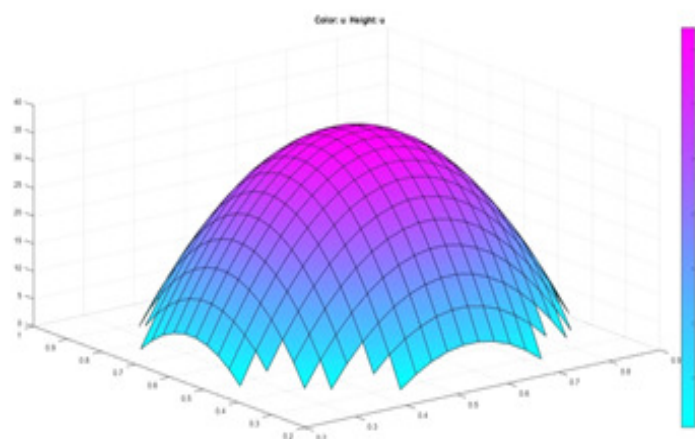
The authors of [18] simplified the Navier-Stokes equation in a stationary state with a net charge density and without taking into account inertial conditions [19] as follows (assuming that the fluid is incompressible):

$$-\nabla P + \eta \nabla^2 v - \rho_e \nabla \varphi = 0 \quad (2.7)$$

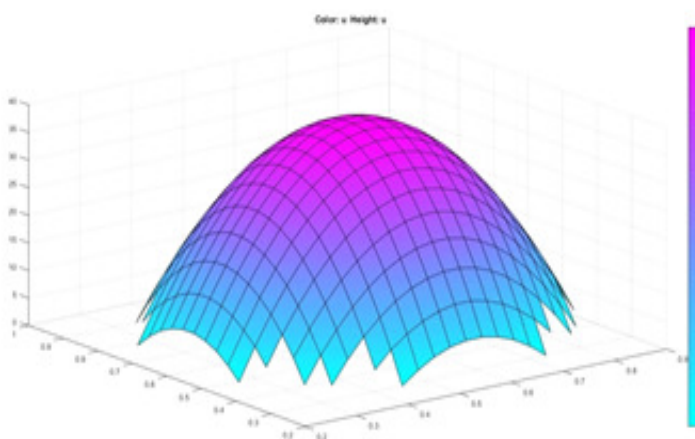
where  $\nabla P$  is the pressure gradient,  $\nabla \varphi$  is the potential flow gradient;  $v$  is the velocity, and  $\eta$  is the dynamic viscosity.

Using the boundary condition of slippage on the capillary wall and assuming that the pressure and gradient of the flow potential are given constants, we can numerically calculate the velocity  $v$ , and then obtain the volume flow velocity by integrating the velocity over the entire cross section.

However, there are no simple analytical solutions for capillaries of arbitrary cross-sections. The paper offers a numerical estimation of the velocity distribution profile in a circular capillary  $r = x = y$ ) for different values of  $\rho_a$  and  $\nabla \varphi$  with and without the electrokinetic factor. The equation is solved numerically in MATLAB to obtain the velocity profile, the pressure gradient in this case is assumed to be constant  $\nabla p = const$ . The graphs show that the velocity distribution plot near the capillary wall in the boundary layer has different values. At constant pressure and changing the gradient of the potential flow (charge density), the velocity on the capillary walls is not zero (Fig. 1 and 2).



**Fig. 1** Velocity distribution on capillary walls (for  $\nabla p = 1,0 Pa$ )



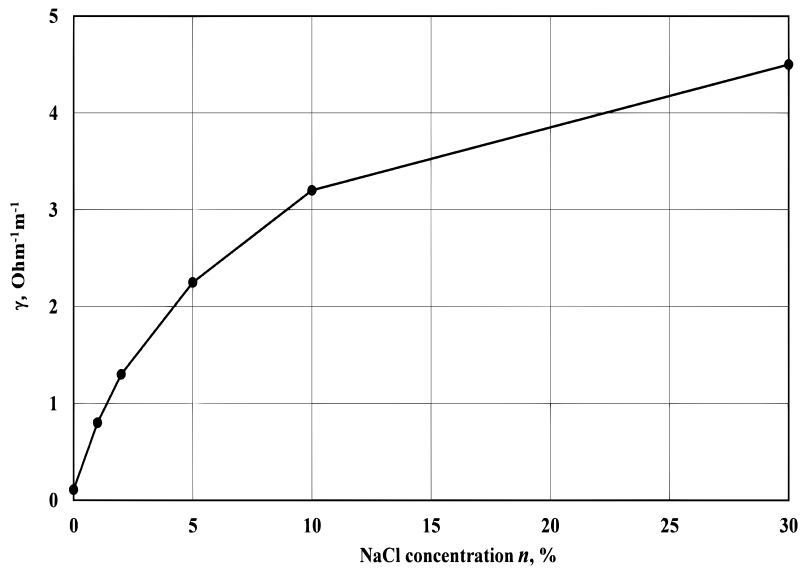
**Fig. 2** Velocity distribution on capillary walls (for  $\nabla p = 1,0 Pa$ ;  $\rho_e = 10^3 Kl/m^2$ ;  $\sigma, \varphi = 3V$ )

### 3 Laboratory experiments

Further, some electrokinetic effects for the electrolyte solution on the wall of thin quartz capillaries are experimentally investigated. In this case, we were mainly interested in the effects that impact the flow of liquids-electrolytes (for example, an aqueous solution of sodium chloride  $NaCl$ ). Changes in the specific electrical conductivity of fresh water (Shollar type, Azerbaijan, Table. 1) from the  $NaCl$  concentration is shown in Fig. 3.

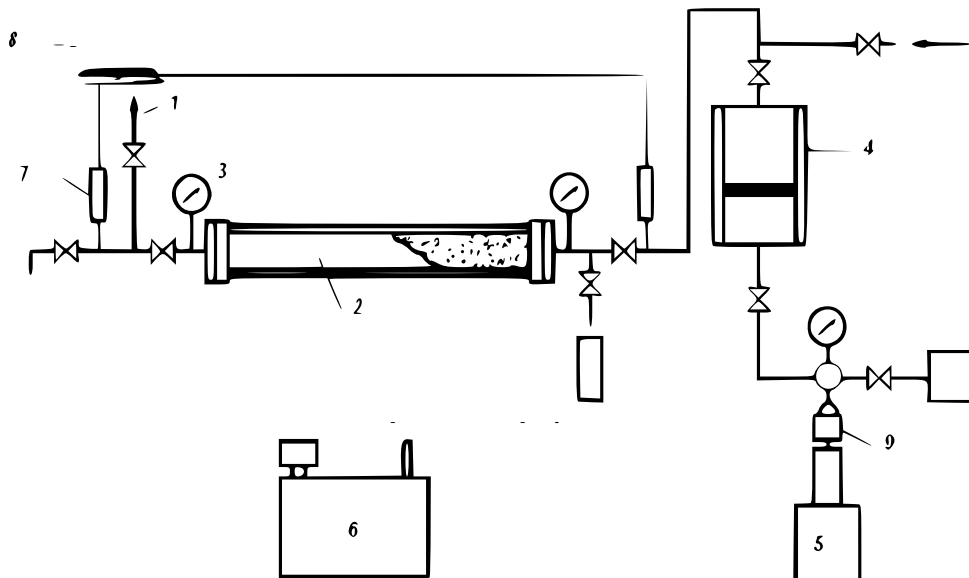
**Table 1** Chemical composition of fresh water (Shollar water, Azerbaijan)

$Na^{2+}$	$Mg^{2+}$	$Ca^{2+} + Mg^{2+}$	$Na^+$	$Cl^-$	$SO_4^{2-}$	$HCO_3^-$	$\Sigma K$	$SiO_3^{2-}$
mg. eq/l								
3,8	2,2	6,0	0,5	0,2	1,9	4,4	6,5	18,2



**Fig. 3 Dependence of the specific electrical conductivity  $\gamma$   $\text{Ohm}^{-1}\text{m}^{-1}$  of water on the concentration of  $n$  (%) NaCl**

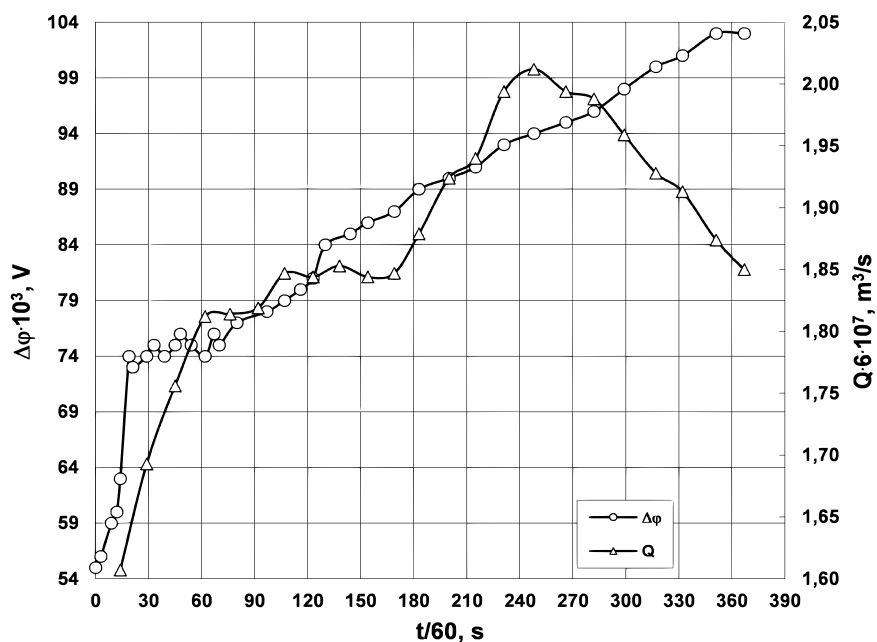
In the course of research on the model of a porous medium, water and an aqueous solution of  $\text{NaCl}$  of different concentrations were filtered. The experiments were performed on a laboratory installation that simulates the displacement of liquids in an artificial sample of a porous medium, the model of which was a mixture of quartz sand and quartz dust (Fig. 4). The water permeability of the medium was  $0.08 \text{ mm}^2$ . The porous medium was previously saturated with fresh water, and then the liquid saturating the porous medium was displaced by an aqueous solution of sodium chloride of various concentrations.



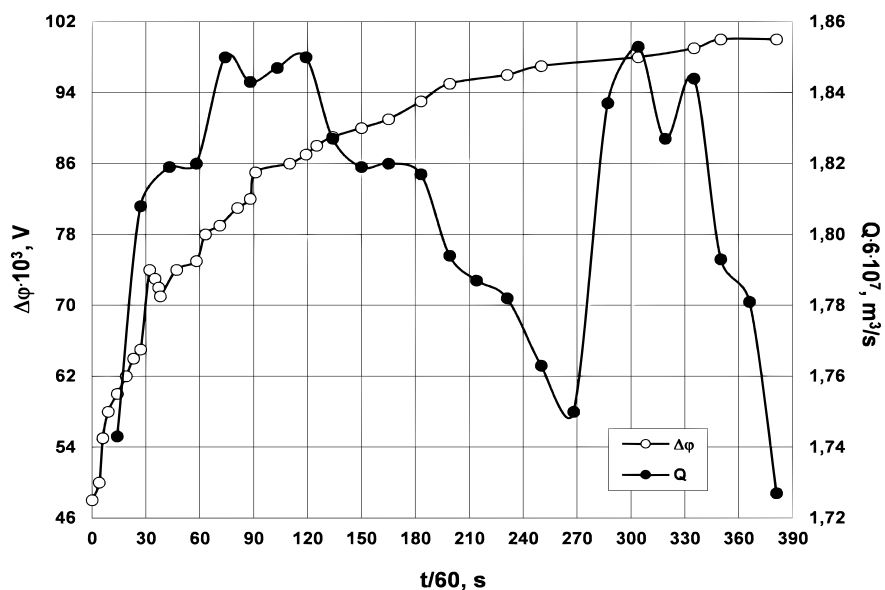
**Fig. 4 Experimental setup: 1 - vacuum line; 2 - porous medium; 3 - standard pressure gauge; 4 - PVT cell; 5 - measuring press; 6 - ultrathermostat; 7 - pressure sensor; 8 - monitor; 9 - manifold**

Studies have shown that the water displacement by an aqueous solution of an electrolyte in a porous medium is accompanied by a change in the flow rate and the value of the flow potential. The dynamics of changes in the studied parameters is monotonically increasing in

combination with periodic fluctuations of values. Shown in Fig. 5 and 6 dependences show changes in the flow rate of the liquid and the electric potential of the liquid flow in a porous medium for certain concentrations of sodium chloride in an aqueous solution.



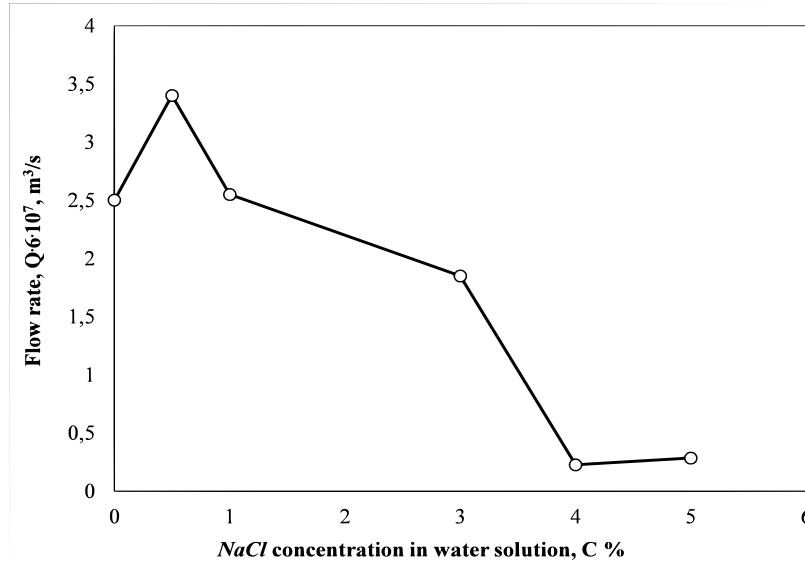
**Fig. 5** Dynamics of changes in the difference between the electric potentials  $\Delta\varphi$  and the liquid flow rate  $Q(t)$  over time when water is displaced by 1% aqueous solutions of sodium chloride NaCl



**Fig. 6** Dynamics of changes in the difference between the electric potentials  $\Delta\varphi$  and the liquid flow rate  $Q(t)$  over time when water is displaced by a 3% aqueous solution of sodium chloride NaCl

A possible explanation for the observed effects is the continuous charge formation and charge interaction that occurs in a diffuse layer when a liquid moves in a porous medium. Periodic accumulation and possible subsequent entrainment of charges during the fluid flow

in the channels, depending on the acquired charge sign, as well as compression of the diffuse layer with an increase in the  $NaCl$  concentration, can cause changes in the electrolyte flow rate in a porous medium (Fig. 7). The accumulation of charges in some areas of pore capillaries leads to “blockage” of channels and a temporary decrease in fluid flow. Within the framework of the mechanism of charge formation and charge interaction, it can be assumed that in a diffuse layer, a layer of charged centers is continuously generated and the sign of interacting charges changes, leading to a change in the fluid filtration rate.



**Fig. 7** Change in flow rate during the flow of an aqueous electrolyte solution depending on the concentration of sodium chloride  $NaCl$

This assumption is consistent with the mechanism of the so-called optimal recharge of the surface of a porous medium, proposed by the author in [17]. The proposed model is based on the presence of  $N_e$  charged centers and  $N_n$  - neutral centers on the surface. The number of charged centers is determined by the charge density from the beginning of adsorption to  $\sigma_0$  on the surface of a porous medium. On the channel walls,  $N_e = \sigma/e$ , where  $e$  is the electron charge.

At the first stage, the charges are adsorbed according to the electrostatic principle (the adsorption layer), and then the layers are formed (the diffuse layer), possibly in the form of “hemimicellae”, which causes the fluid slippage. Saturation of the layer with charges is followed by entrainment of charges. Such a rearrangement at the interface leads to a change in the pressure gradient, which, apparently, is the cause of fluctuations in the flow rate during filtration of the electrolyte solution.

The conducted research suggests the possibility of regulating the process of liquid filtration in a porous medium by adding electrolyte to water systems.

#### 4 Conclusions

The effect of electrokinetic coupling on fluid flow in porous media is studied. The effect of fluid flow slippage in porous media is revealed. The simulation results showed that if the electrokinetic coupling effect is taken into account, the flow velocity profiles and pressure gradients change.



The identified effects are of practical significance and can be used in the development of oil fields by flooding. Control of the electrophysical and electrokinetic characteristics of injected fluids allows to provide the necessary parameters of the well injectivity.

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