

Hydrodynamic features of the flow and filtration of non-newtonian fluids in porous media

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Abstract: This paper also investigates the filtration of oil and solutions, during which solid particles suspended in oil or emulsion droplets are deposited on the surface of the pore channels. The processes under consideration are among the widely studied phenomena of mass transfer in oil-bearing rocks. An analysis of existing approaches to the rheology of non-Newtonian oils and modeling of their flow in porous media has been carried out, which has shown that it is best to use equations that take into account not only the characteristics of a particular fluid, but also the characteristics of the pore formation. It is noted that when solving mathematical models of these processes, it is necessary to take into account the process of adsorption of the displacing solution in the medium, and also take into account that the coefficients of kinetics and diffusion depend on the concentration of the target component..

Keywords: non-Newtonian oils, rheology, filtration, modeling, viscosity.

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I. INTRODUCTION

The development of modern technologies for the development and operation of hydrocarbon fields is impossible without an in-depth study of filtration in oil reservoirs. For the application of new methods of intensifying the extraction of hydrocarbon raw materials, associated with an active influence on the structure of the reservoir and the nature of the joint flow of oil, it becomes increasingly important to be able to adequately describe these objects and processes.

When considering the transfer process on the basis of classical continuum models, the entire variety of rock structures is determined in the equations describing filtration only by different values of the permeability and porosity coefficients. In this case, the permeability and porosity values themselves are taken from laboratory measurements, and the possible evolution of the medium structure during the flow is taken into account by means of empirical dependencies for these coefficients. Within the framework of this approach, the basis for the analysis of multiphase filtration is the phase permeability of fluids, which require a very laborious experimental determination. At the same time, the obtained experimental curves are integral phenomenological characteristics, which in turn does not allow us to analyze the influence of the structure of the pore space and the physical properties of liquids on them, as well as to establish the corresponding patterns. A similar situation arises when it is necessary to take into account various factors of the physicochemical interaction of fluids with the environment, such as the deposition of particles on the rock matrix, their removal from the pore surface, etc. In this case, it is necessary to write down some additional empirical relationships that do not allow adequately linking the features of interactions with changes in the general parameters of the filtration process [1–6].

The purpose of the study is that, using the available research results, it is possible to establish the dependence of kinetic and diffusion coefficients on the concentration of the injected surfactant solution (surfactant) and the reservoir temperature in order to develop recommendations for improving the rheology of non-Newtonian oils.

This paper also investigates the filtration of oil and solutions, during which solid particles suspended in oil or emulsion droplets are deposited on the surface of the pore channels. The processes under consideration are among the widely studied phenomena of mass transfer in oil-bearing rocks. These phenomena are a complex of various physical-mechanical or physico-chemical processes occurring in the process of movement of liquids containing mechanical or chemical impurities in rocks. The main feature of these processes is the displacement of reservoir fluids, accompanied by interaction (mass transfer) between moving fluids and rock. In this case, the nature of interactions can be different. Thus, studies of liquid (solution) filtration, in which physical and chemical interaction takes place (sorption, ion exchange, dissolution, etc.), occupy a central place in modern problems of hydrogeology in connection with ongoing industrial pollution of groundwater. These studies are

based on a well-developed theoretical apparatus of underground hydrodynamics, taking into account the processes of convective diffusion (dispersion) and the kinetics of mass transfer.

An analysis of experimental data in the field of surfactant adsorption on quartz and oil sands showed that the processes of surfactant adsorption on these sands are best described by the model of nonequilibrium adsorption dynamics on a fixed adsorbent layer, which includes the differential equation for the material balance of the adsorbed substance during one-dimensional motion of a solution in a porous medium, adsorption kinetics and equilibrium equations [16–17]. Here, it is taken into account that the kinetic coefficient and the effective diffusion coefficient in a porous medium depend on the concentration of the target component:

material balance equations

$$m \frac{\partial C}{\partial t} + mv \frac{\partial C}{\partial x} + (1-m) \frac{\partial a}{\partial t} = m \frac{\partial}{\partial x} \left[D_e(C) \frac{\partial C}{\partial x} \right], (1)$$

adsorption kinetics and equilibrium equations

$$\frac{1-m}{m} \frac{\partial a}{\partial t} = \beta(C) \left[C - \varphi(a_{eq}) \right], (2)$$

$$C_{eq} = \varphi(a_{eq}), (3)$$

where C , a ; C_{eq} , a_{eq} - non-equilibrium and equilibrium concentrations of adsorption and adsorbate, respectively; v - linear flow rate of the surfactant solution injected into the reservoir; m - reservoir porosity; $\beta(C)$ - kinetic coefficient; $D_e(C)$ - effective diffusion coefficient; t - time; x is the height coordinate of the adsorbent layer; φ - adsorption equilibrium function.

With the experimental scheme carried out, the initial and boundary conditions have the form:

$$C(0, t) = C_0; a(x, 0) = 0; C(x, 0) = 0; (4)$$

$$\text{at } x = L \quad \frac{\partial C}{\partial X} = 0; C(L, t) = C^{\text{exp}}(t); (5)$$

where C_0 is the initial adsorbate concentration at the adsorber inlet; C^{exp} the concentration of soap naphtha in the solution at the outlet of the adsorbent layer; L - adsorption tower length.

The task of determining the effective diffusion coefficient and the kinetic coefficient of adsorption, based on experimental data, is reduced to solving a system of differential equations (1) - (5).

Due to the nonlinearity of differential equations (1) - (5), obtaining an exact analytical solution seems impossible. Therefore, the problem is solved numerically using the grid method.

The problem of determining $D_e(C)$ and $\beta(C)$ is reduced to minimizing the functional

$$I(D, \beta) = \int_0^T \left[C(L, t) - C^{\text{exp}}(t) \right]^2 dt; (6)$$

where T is the duration of adsorption. $C(L, t)$ is determined from the solution of problem (1)–(5).

Specifying the desired functions in the form of polynomials

$$\beta(c) = \sum_{i=0}^n b_i c^i; D(c) = \sum_{k=0}^v d_k C^k; (7)$$

we transform the problem of determining these functions b_i, d_k to the determination of constant coefficients.

The minimization of the functional $I(D, \beta)$ was carried out by the method of coordinate descent.

For the numerical solution of the problem, its difference analog is written, choosing steps that are uniform in x and non-uniform in t . The choice of a non-uniform step in t is associated with experimental data, each time layer is chosen in accordance with the measurements carried out on the experimental setup.

As a result of numerical calculations for the desired functions, the following empirical formulas were obtained:

$$D_e(C) = d_0 + d_2 C^2 + d_3 C^3; \beta_0(C) = b_0(C) = b_0 + b_2 C^2.$$

Among the models used to calculate the above tasks, the following main groups can be distinguished: empirical models, regression analysis models and lattice models. Empirical models consider the process of fluid filtration with suspended particles on the basis of macroscopic equations of continuum mechanics, which are supplemented by various empirical relationships that establish a relationship between changes in the main parameters of the process. In this case, the values of the coefficients included in the equations must be measured

experimentally each time when the filtration conditions change. Empirical models are convenient due to the simplicity of their calculations, but they do not adequately explain the influence of the characteristics of suspended particles or the geometry of the pore space on the change in the general parameters of the process.

Thus, there is a need to develop a theoretical approach to modeling the flow of non-Newtonian fluids and their filtration in porous media, which would make it possible to obtain analytical dependences of the parameters of the filtration process on the geometry of the pore space, the rheology of non-Newtonian fluids, and the features of the oil-bearing rock. Ultimately, this would make it possible to connect the nature of the flow of heavy oils at the microlevel (in individual pore elements) with the laws of filtration in the entire porous medium.

II. EXPERIMENTAL PROCEDURE

Within the framework of the study, the following main tasks were solved: development of an analytical method for calculating the absolute and phase permeability coefficients, taking into account the features of the pore space and the rheology of filtering liquids; analysis of the effectiveness of changing the rheology of the displacing agent to increase the oil recovery factor. In most works, a surfactant is used as a displacing agent. There are many works devoted to the description of the features of the filtration of non-Newtonian fluids. An analysis of the practice of developing many oil fields shows that the filtration of formation fluids does not always satisfy Darcy's law.

$$\nabla p = \rho \bar{g} - \frac{\mu}{k} \varphi \bar{V}$$

where p [Pa], ρ [kg/m³], V [m/s] – pressure, density and fluid velocity; μ [Pa·s] – dynamic viscosity of the liquid; g [m/s²] – free fall acceleration; k [m²], φ [-] – permeability coefficient and medium porosity.

This fact is explained by the increased content of tar-asphaltene substances in the oil, which increase the density and viscosity of the oil. When filtering such oils, Newton's linear law of viscous friction is violated, therefore they are called non-Newtonian (or anomalous). In order to give mobility to oils of this kind, it is necessary to overcome a certain threshold (limiting) value of the pressure gradient. Therefore, to describe their motion in a porous medium, the filtration law with a limiting gradient is most often used, in which the value of the limiting gradient itself is usually determined from experiments. Viscoplastic fluids are Shvedov-Bingham bodies, the flow of which is described by the following law:

$$\tau = \tau_0 + \eta \cdot \frac{dU}{dr}$$

where τ_0 is the static shear stress, at $\tau < \tau_0$ the liquid behaves like a solid body; η is the plastic viscosity, U is the velocity of the fluid.

The Shvedov-Bingham law is valid for clay drilling fluids, water-oil emulsions, suspensions of solid particles of regular rounded shapes [1-7].

The latter case is typical for pseudoplastic liquids: for solutions of polymers and other liquids with large elongated molecules; for conventional and colloidal suspensions with solid asymmetric particles.

At low shear rates, the molecules or particles of such systems are "intertwined" with each other. At high shear rates, the molecules "adjust" to each other, reducing the apparent viscosity. At very low shear rates, the effect of the "entanglement" of molecules is small; at very high shear rates, the "weave" itself is small.

In addition to formation oils, non-Newtonian properties can also be exhibited by various substances injected into oil-bearing formations in order to increase hydrocarbon production. Thus, in particular, methods of enhanced oil recovery using polymer solutions, the rheology of which is non-Newtonian, have become widespread.

Due to its applied importance, the theoretical study of the filtration of non-Newtonian fluids has acquired an independent significance. The effect of non-Newtonian fluid rheology on its phase permeability was studied in experimental works. As noted in [1-3], the analysis of experimental data shows that the value of the limiting gradient depends not only on the viscoplastic properties of fluids and the structure of the pore space, but also on the saturation of the rock with this fluid. Thus, for a general description of the filtration of a viscoplastic fluid, it is necessary to know the specific form of the dependence of both the phase permeabilities and the limiting gradient on the above factors. In [4], the values of the phase permeabilities and the limiting gradient were determined on the basis of direct numerical calculations of the flow of a viscoplastic fluid through a capillary lattice. However, this approach, as well as experimental measurements, does not allow one to obtain a general view of the functional relationships for setting these parameters. Analytical relationships for determining the dependence of phase permeabilities on fluid rheology were proposed in [7] using the percolation approach.

Previously, in [8-9], the results of studies of kinetic and diffusion coefficients for surfactant adsorption on oil-bearing rocks in the nonlinear region of the isotherm were presented without taking into account the influence of reservoir temperature, and a numerical method was presented for determining the parameters of the equations of

the mathematical model of surfactant adsorption on oil-bearing sand using experimental data. It was taken into account that the kinetic coefficient and the effective diffusion coefficient in a porous medium depend on the concentration of the target component. As an adsorbent, a solution of soap-naphtha was used, which is a technical product, which consists mainly of a mixture of sodium salts of naphthenic acids.

III. RESULTS AND DISCUSSIONS

With the help of experimental data and the developed technique, empirical equations for the kinetic coefficient and effective diffusion coefficient of the process were determined. It is noted that these coefficients vary within very large limits, which allows us to conclude that the developed numerical methods for determining the parameters of the equations of mathematical models of surfactant adsorption on oil and quartz sands give the adequacy of the calculated data of the adsorbate and adsorbate to the experimental data.

In [10-16], a generalized model was constructed to describe the adsorption of surfactants, taking into account the geometry of the pore space, the saturation of filtered oils and their rheology. New methods for calculating the coefficients of phase permeabilities for Newtonian, viscoplastic and power-law fluids, as well as the magnitude of the limiting gradient for filtering a viscoplastic fluid are presented.

Lattice models are a discrete description of the oil flow process. Historically, this approach was preceded by filtration models based on continuum mechanics. Continuum models represent a classic engineering approach. To describe the flow process of non-Newtonian fluids, they use differential equations of continuum mechanics, as well as various empirical relationships, kinetic and diffusion coefficients, as well as averaged parameters characterizing certain macroscopic properties of the medium. The coefficients are determined by means of experimental measurements.

A discrete approach is being developed to model the transfer process at the micro level, in order to then obtain its macroscopic description. Discrete models are based on various geometric representations of the structure of the pore space of the medium. The general nature of the structure of porous media is determined by dimensional and geometric factors. A real porous medium has a stochastic structure, in which the sizes of pores and pore channels, as well as their mutual arrangement and connection, are random. Features of the geometry and spatial arrangement of pores form the basis for the geometric modeling of porous structures.

The greater adequacy of lattice models to real porous media has predetermined their widespread use in recent years in describing a wide variety of physicochemical processes occurring in porous media: filtration, displacement, dispersion, adsorption and desorption, etc. [17-20].

IV. CONCLUSION

The analysis of existing approaches to the rheology of non-Newtonian oils and modeling of their flow in porous media showed that it is best to use equations that take into account not only the characteristics of a particular fluid, but also the characteristics of the pore formation. When solving mathematical models of these processes, it is necessary to take into account the process of adsorption of the displacing solution in the medium, and also take into account that the kinetic and diffusion coefficients depend on the concentration of the target component. Among the mathematical descriptions of the lattice conductivity, it is worth noting models based on analytical approaches. These approaches were developed from the theoretical description of the conductivity of various lattice structures, which became the basis for determining the absolute permeability of a porous medium. The most significant of them used the effective medium theory or filtration theory.

Conflict of interest

There is no conflict to disclose.

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