Hydrodynamic approach to the processing of core sample tests considering microstructural changes

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Abstract. In this paper, authors propose a method to create a complete hydrodynamic model of the polymer displacement process. It is based on the processing of the laboratory tests with core samples, considering the polymer substance properties and microstructural changes occurring in the porous matrix during the adsorption of polymer particles. Based on the adaptation of the mathematical model to the results of tests with polyacrylamide Flopaam and polysaccharide Gum Arabic, calculations of the effectiveness of polymer flooding application on samples of terrigenous deposits are carried out.

1. Introduction
Since the share of hard-to-recover oil reserves continues to grow, the problem of choosing methods for increasing the effective oil recovery coefficient (ORF) requires a modern approach. It is based on a complex of laboratory studies and their in-depth interpretation using modern methods of hydrodynamic modeling, taking into account changes in the microstructure of the pore formation during reservoir treatment.

The use of substances of complex chemical composition, including those based on polymer systems, which affect not only the properties of the filter phases, but also can change the nature of the interaction of filtrates with the mineral matrix of the reservoir, while changing the porosity and permeability, wettability and pore connectivity, has become generally recognized in technological schemes for stimulating production. As a result, the instability of the displacement front decreases, the coverage of the drainage zone increases, and, ultimately, the ORF increases. The choice of the agent to be applied into the reservoir is determined by a whole set of factors: the geological structure of the reservoir, the stage of development, production conditions, stimulation methods applied, etc. As it is known, about 90\% of treatments are carried out with partially hydrolyzed polyacrylamides (PAA) and about 10\% are carried out with biopolymers based on polysaccharides [1, 2]. The criteria for choosing the method of reservoir treatment are determined primarily by the properties of the reservoir itself, so polymer flooding is considered unpromising for low-porous reservoirs with a permeability as of less than 20 mD. Selection of active polymer-based composition should be done considering the molecular weight of the polymer and the hydrolysis degree, as well as the concentration of the solution and the mineralization of the water used, which ultimately determines the degree of solubility, viscosity, rheological properties, and resistance to degradation. It is also important to consider the current state of the reservoir: fracture porosity, cavernous, damaged, water cut, etc., which is often affected by the...
production stimulation methods used in the field development in previous periods. Laboratory studies on the core samples allow to evaluate the final characteristics of displacement after the various substances’ application.

The purpose of this work is to create a methodology for correct experiments processing on core samples with subsequent transfer of results from the micro to the macro scale (within the framework of a real deposit), using an original mathematical model combining hydrodynamic and percolation approaches. The method proposed by the authors makes it possible to track the change in the microstructure of the porous skeleton and all filtration characteristics dynamically at any current point during the injection of various types of chemically active solutions, which makes it possible to predict the effectiveness of increasing oil recovery method application more accurately.

2. Results of laboratory tests on real core samples

The standard method of laboratory research, as a rule, includes the stages of determining the physical and chemical properties of the polymer and its adsorption capacity tests (“chemical adsorption”) [3, 4]. The adsorption activity of a particular polymer depends on the size of the molecules, and the ability to form large aggregates. For example, 1.5–2.5 times increase in the PAA polymer molecular weight can lead to an increase in the size of globules and aggregates from 70 nm to 500 nm. Table 1 shows the properties of two polymers of different types, Flopaam and Gum Arabic, used in experiments of [3, 4] and considered in the numerical study in this paper, respectively.

In experiments [3], the concentration of the polymer Flopaam 5205 VHM at the inlet and outlet of the sample was measured on six different samples, and the dynamic adsorption of the polymer during pumping of four pore volumes was calculated from sub-sample. In the experiment [4], the change in porosity was determined while pumping two pore volumes and the ORF was recorded.

| Polymer     | Polymer type | Hydrolysis degree | Molecular number, mln. g/mol | Molecular size, nm | Globule size, nm |
|-------------|--------------|-------------------|-----------------------------|-------------------|------------------|
| Flopaam     | PAA          | Partial           | 9.56                        | 30                | 70               |
| Gum Arabic | polysaccharide | -                | 2.5                         | 20                | 50               |

The viscosity of the polymer substance can vary by several orders depending on the polymer concentration [5, 6]. An increase of the polymer concentration in the solution, on the one hand, is positive: even at low polymer concentrations, the viscosity of the solution increases significantly, which leads to displacement capacity improvement (by reducing the ratio of phase mobility, the displacement front is leveled). However, it is necessary to consider the opposite factor, a decrease in the filtration rate while viscosity increases. Experiments with polymer compositions pumping through core samples show an increase in sorption capacity with the filtration rate increase [3, 7, 8]. In addition, with concentration increase, the tendency to form aggregates and display non-Newtonian properties of the polymer increases, which in turns reduces the sorption capacity. The adsorption activity also depends on the mineralogical composition of the porous matrix: the rate of adsorption depends on the specific pore surface, which differs significantly for different types of reservoir [3, 9]. The presence of pores of different sizes, cracks and cavities, along with the ability of the polymer to form aggregates of different sizes, determines the so-called "mechanical adsorption". The polymer solution, showing the filtration ability to move along the entire capillary network, passes into thin capillaries, thereby blocking the water channels (as a rule, these are mainly capillaries of the smallest size) not only due to the formation of an adsorption film, but also due to the mechanical overlap of the aggregates of polymer globules of ultrathin capillaries. Hence, in predicting the effectiveness of polymer flooding, not only the values of the initial and final porosity are very important (and the
corresponding change in absolute permeability), but there is a need in special studies to control changes in the structure of the core sample itself before and after pumping the active composition of a particular substance through it. Figure 1 schematically reflects the sequence of necessary laboratory and numerical studies proposed in this paper, which would allow determining the mechanical possibility and physicochemical sorption capacity of the porous matrix and a certain polymer filtrate interaction that affect the final ORF.

The upper part of the figure reflects the stages of the experimental study: the study of the core sample using X-ray computed tomography and other types of porometry studies. They allow evaluating the composition of the mineral matrix, the channels connectivity, the frequency of capillaries of a certain size range of radius (the density of the pore distribution by size). The next stage includes the study of the physicochemical properties of applied composition and its interaction with the mineral skeleton, which allows determining the wettability, capillary forces and static adsorption capacity. Filtration experiments of the 3rd stage serve to determine the dynamic adsorption capacity (chemical and mechanical) depending on the polymer concentration, filtration rate, temperature, etc.

![Figure 1. Sequence diagram of laboratory and numerical experiments.](image)

3. **Hydrodynamic processing of experimental results on real core samples**

All the polymer properties and its interactions with the porous matrix described in the previous section are considered in the mathematical model as semi-empirical model-closing formulas that relate the hydrodynamic characteristics of the process. The lower part of Figure 1 shows the stages of “hydrodynamic processing” of the results of a physical test: constructing the initial pore size distribution function \( f(r) \) (dashed line), determining the initial effective capillary diameter, porosity, permeability, and capillary pressure as well as its change while polymer adsorption (solid line at \( f(r) \) graphs). The adaptation of the mathematical model to the test conditions allows determining the curves of the relative phase permeabilities (RPP) and setting the adsorption function and accounting the change in the viscosity of the solution with the account of the current polymer concentration. Mathematical modeling of the test with polymer composition pumping through the sample allows plotting the saturation curves in dynamics and controlling the adsorption process depending on the number of pumped pore volumes (PV). The choice of a mathematical model that would allow describing the phenomena of static, dynamic and mechanical adsorption of polymers in detail is quite
diverse. As a rule, the models are either narrowly focused on certain physical effects. For example, they describe the process of polymer adsorption in the boundary layer, considering diffusion, or the front instability development features, while others, based on the classical hydrodynamic approach of multiphase hydromechanics, focus on the features of the solution methods.

The method used by the authors of this paper is based on the principle of supplementing the classical mathematical model of the theory of mechanics of multiphase multicomponent filtration [10] with a probabilistic (percolation) approach [11]. Both parts (hydrodynamic and percolation) are connected by end-to-end calculation of parameters on each time layer. Numerical integration of the system of conservation equations describing the process of displacement of a reservoir fluid by an aqueous polymer solution, considering the adsorption of the polymer on the capillary walls, allows controlling changes in macro parameters (the rates of each phase movement, the saturation of the pore space with the corresponding phase, the change in the mass concentration of the polymer, and the ratio of phase viscosities). The closure of the model by "percolation formulas" involves accounting the change in time and space of the pore size distribution function \( f(r) \) (considering the maximum film thickness calculated from the test and the non-flow threshold considering the size of the globules) and calculation of the structural parameters based on it. Thus, at each point of the test sample in real time, corresponding to the current moment of pumping the displaced sample through the core, a decrease in the effective size of the capillary grid is calculated due to the "sticking" of the polymer film, which changes the specific surface of the pore space, the current value of the capillary pressure and affects the change in the adsorption intensity (considering as well as the current concentration of the solution, viscosity and, accordingly, changes in the filtration rate). Finally, the changes in the volume porosity, phase and limit permeabilities are determined. At the end of the adsorption process, which is controlled as in the physical test, the ORF is recorded based on maintaining the polymer concentration in the output section of the sample. Figure 2 illustrates the algorithm of modeling the adsorption process while pumping a Flopaam polymer solution for the initial data corresponding to the laboratory test [3] with a terrigenous core sample No. 1 using a solution of 0.07% concentration. The initial pore size distribution \( f(r) \), which is shown as dashed line in Figure 1, was obtained by processing data from computed tomography of thin sections of a similar terrigenous sample [12]. The final form of \( f(r) \) corresponds to the end of the adsorption process and the growth of the capillary surface polymer film to the limit value.

| Results of core-flooding experiment |
|------------------------------------|
| Porosity, % | Permeability, mD | Polymer concentration, % | Dynamic adsorption, mg/g |
| 20.85 | 515.01 | 0.07 | 0.047 |

Figure 2. Processing scheme of the adsorption tests.

Application of the method of numerical simulation, considering changes in the structure of the porous grid of the sample, allows tracing the dynamics of changes in all hydrodynamic and capacitive
parameters while pumping a polymer solution through a real core sample. The final pore size distribution in Figure 2 at the time of 160 min reflects the end of adsorption when the maximum calculated value of the polymer film thickness is reached at 5.221 nm, which in this case corresponds to pumping four pore volumes of the polymer substance (with a pore volume of 154.03 ml in the control sample of the initial porosity of 20.85%), accounting test data on the sub sample. Tab.2 shows the calculated results of processing tests [3, 4] for two types of polymer substances with different concentrations of polymer solutions Flopaam and Gum Arabic applied in practice, and the results reflect how the porosity, permeability, and capillary pressure have changed.

**Table 2.** Results of displacement simulation using Flopaam and Gum Arabic

| Polymer          | Solution concentration, % | Polymer film thickness, µm | Porosity decrease, % | Capillary pressure increase, % |
|------------------|---------------------------|----------------------------|----------------------|--------------------------------|
| Flopaam          | 0.07                      | 5.22                       | 6.46                 | 20.00                          |
| Gum Arabic       | 3.00                      | 5.13                       | 8.83                 | 25.54                          |

**Figure 3.** The change in the film thickness depending on the pumped volumes of the solution.

**Figure 4.** Porosity distribution in the sample at different concentrations of the polymer.
In dynamics, Figure 3 shows a graph of changes in the thickness of the polymer film in the current cutoff, depending on the time of exposure, which correlates with the number of pumped volumes of the Flopaam polymer solution. The change in adsorption process intensity is shown in Figure 4. It indicates how the porosity of the entire sample film decreased while pumping two pore volumes of the polymer solution at different initial concentrations (the dashed line corresponds to the initial value of the porosity of the sample).

**Conclusions**

Numerical simulation of physical tests [3, 4] on terrigenous samples using the lognormal pore size distribution and its transformation during polymer adsorption served to track all the hydrodynamic characteristics of the process in real time and to obtain changes in the reservoir properties according to the conditions of tests on real core samples. For PAA Flopaam (sample No. 1 in [3] at a solution concentration of 0.07% and an initial viscosity of 6 MPa\(\times\)s), a change in the pore size distribution corresponds to a decrease in the effective radius by 16.9%, which conforms with an increase in capillary pressure from 85.78 kPa to 102.93 kPa, a change in the initial porosity from 20.85% to the final 14.39%, and a decrease in the absolute permeability of the sample from 515 mD to 343.6 mD. In comparison with water displacement, the ORF increased to 34.6 %, that is, by 5 %. The calculation for polymer displacement with solution concentration increase from 0.03% to 0.07% has shown a relative increase in the ORF. A further increase in concentration has led to a more than two times increase in solution viscosity compared to the initial one, due to which the ORF reduces. This proves the soundness of the chosen PAA Flopaam concentrations of 0.07%.

For Gum Arabic polysaccharide (sample no.7 in [4] at a solution concentration of 3% and an initial solution viscosity of 1.94 MPa\(\times\)s), a change in the pore size distribution corresponds to a decrease in the effective radius by 19.43%, which agrees with capillary pressure increase from 96.7 kPa to 121.4 kPa, a change in the initial porosity from 25.23% to the final 16.4%, and a decrease in the absolute permeability of the sample from 245mD to 103mD. As a result, the ORF has reached a value of 39.5% with polymer application. So it has increased by 5.2% compared to the displacement with water without polymer addition, which is actually congruent with the data of a laboratory test [4], showing an increase in ORF to 38.2% with polymer displacement. The calculation of the ORF with an increase in the polymer concentration to values as of 5% demonstrates a monotonous growth with a “plateau” of constant values with a relative additional increase to 1.5 %, which explains the inexpediency of using solutions of increased concentrations. The results of mathematical modeling are qualitatively and quantitatively consistent with the results of measurements [3, 4] on different types of polymers, which proves the adequacy of the hydrodynamic approach based on the transformation of the pore size distribution curve, which allows for the correct calculation of all reservoir parameters.

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