Rheological properties of polymer solutions and ways to improve the efficiency of development of high-viscosity oil fields in Uzbekistan

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Abstract. The results of experimental research on studying the filtration properties of polymer solutions and the mechanism of the displacement process in porous medium were presented in this article. The methodology of experimental studies in a specially designed laboratory setup is given. In the present work the rheological properties of polymer K-9 are considered. At the same time, the relaxation time of viscoelastic particles of K-9 polymer filtered in porous medium is experimentally found. Also, the results of experimental studies on oil displacement of fields with high content of asphaltene-resinous substances by polymer solutions on artificially created reservoir models to determine the optimal concentration of polymer solution and the size of the rim with the purpose of increasing oil recovery. Experimental studies on displacement of high-viscosity oils with a thickened water rim established that this method gives the greatest increase in water-free and ultimate oil recovery of reservoirs, within the range of change in the concentration of polymer solution 0.2-0.4%, with the size of the rim more than 70% of the oil saturated volume of the reservoir. Studies on displacement of high-viscosity oils by polymer solutions show that the use of this method of increasing oil recovery factor in practice is not always economically feasible, because of the need to ensure high injection pressures and high concentration of expensive polymer solution.

1 Introduction

In recent years, oil fields with complex geological structure have been discovered in many oil and gas bearing regions of the world [1, 2]. These fields are characterized by low oil saturated thickness of reservoirs, low filtration-capacity properties of reservoirs, high viscosity of reservoir oil and heterogeneity of productive horizons, etc [3]. In addition, the depth of occurrence of promising structures and the costs of geological exploration are increasing [4, 5].

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Under these conditions, one of the ways to increase oil production is to increase the recovery factor of Geologic Oil Reserves (GOR) remaining in the fields under development. This task is especially urgent for fields with high-viscosity oil, since the achieved values of GOR at such objects are two or more times lower than at fields with low-viscosity oil [6].

In addition, the design of oil field development and well operation is based on the laws of underground hydraulics [7, 8]. Many issues, such as the placement of wells in the reservoir, the sequence of putting them into operation, maintaining reservoir pressure by pumping various working agents into the reservoir, regulation and direction of movement of reservoir fluids, are solved on the basis of the methods of underground hydraulics. The technological and economic effect of oil and gas production from hydrocarbon deposits depends on the correct solution of these issues [9-11].

Considering that nowadays the main technology of oil reservoirs development is connected with oil displacement by water, it is urgent to increase the efficiency of this process by using various solutions [12, 13]. One of the ways to increase the efficiency of oil displacement from reservoirs is the use of water-soluble polymers as additives to the water injected into the reservoir [14]. Injection of polymer solutions represents unsteady filtration. In this connection it is necessary to study rheological and filtration properties of formation fluids and reagents [15-17].

Thus, increasing the efficiency of development of fields with highly viscous oils requires appropriate expansion and deepening of scientific research related to the development of a number of important laboratory and theoretical works. One of the most important issues in increasing the degree of oil recovery from the subsurface is the study of structural and mechanical properties of polymer solutions, their influence on the filtration process in the reservoir and ways to regulate them.

At present, a large amount of theoretical and experimental material has been accumulated to study the structural and mechanical properties and flow characteristics of non-Newtonian oils [1-14]. Studies have shown that during the development of wells that have opened deposits of heavy high-viscosity oils, there are complications associated with the difficulty of lifting oil to the surface. The high content of asphaltene-resinous substances causes the manifestation of initial pressure gradients and relaxation processes in the oil-collector system during filtration, large pressure losses in wellhead communications and oil flow rates [1-5], leads to a significant reduction in oil recovery.

A characteristic feature of heavy oil producing wells is also a sharp increase in water cut at the initial stage of development. The combined movement of high-viscosity oil and water in the bottom-hole zone of the formation, along the wellbore and in the gathering system leads to their mixing with the formation of persistent and heavy emulsions. The above-mentioned characteristic features of heavy high-viscosity oils lead to a sharp decrease in the efficiency of field development and leave in productive formations a significant part (up to 80-90%) of their geological reserves.

As a consequence, the current state of development of deposits with high-viscosity oils is characterized by low value of achieved oil recovery at high water cut of produced well products. Therefore, in order to improve the implemented development systems to increase the oil recovery factor, there is a need to study the rheological and filtration characteristics of high-viscosity oils.

The purpose of this study was to determine the effect of temperature change on the rheological properties of heavy and high-viscosity oils and non-equilibrium phenomena during their filtration in a porous medium.

Proceeding from the set goal, the following tasks were solved by the authors to achieve it:

- experimental studies of nonequilibrium effects during filtration of high-viscosity oils and polymer solutions in porous medium;

- evaluation of oil displacement efficiency by polymer thickeners.

2 Materials and methods

To study the filtration process, a specially designed installation was used (Fig. 1), the schematic diagram of which is shown in Fig. 2. Its main elements are a column (core holder) with a water jacket, a tank for oil, a thermostat and a high-pressure air cylinder (compressor). The water-jacketed core holder allowed to conduct research under isothermal conditions. The thermostatic liquid circulated according to the scheme thermostat-water jacket-thermostat. The pressure drop in the core holder was created by air from a cylinder (using a compressor).

The homogeneous porous medium was modeled by quartz sand of a certain fraction. To create low-permeability media, quartz sand was passed through a drum mill, where it was broken. The crushed sand was fractionated on sieves into individual fractions. The permeability coefficient varied depending on the grain diameters of the fraction. The smaller the particle diameter, the lower the permeability. The washed and dried sand is filled into the core holder and tamped to a certain porosity value. At the beginning of the experiment the unit is checked for tightness. The experiments were performed on the setup shown in Fig. 1.

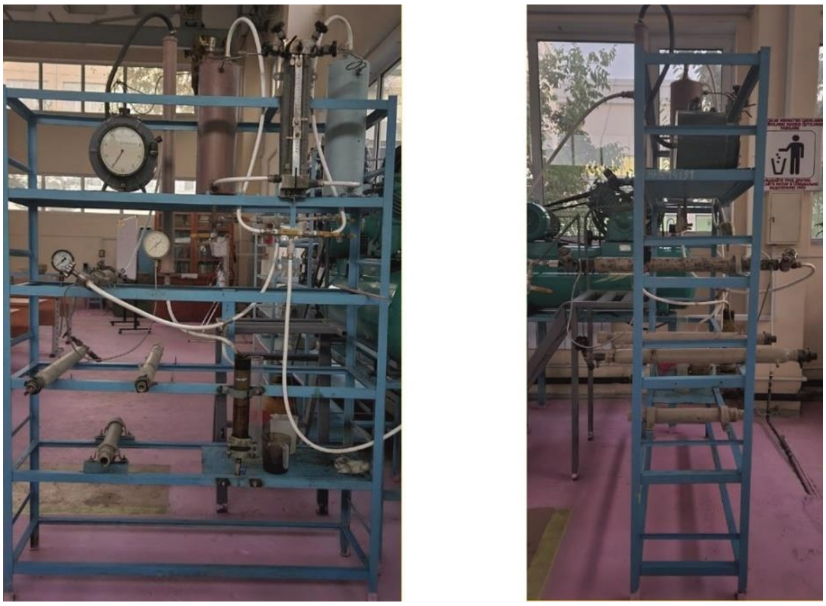

Fig. 1. Experimental setup.

After permeability determination, the column was saturated with oil. For saturation, the column was placed in a vertical position and the saturation process was carried out at high temperature and low filtration rate. These conditions are necessary for more complete saturation of the porous medium. After oil circulation in the amount equal to three times the pore volume, the column was ready for experiments.

The experiment consisted in removal of dependence between flow rate and pressure drop at oil flow through porous medium. Practically filtration was carried out as follows. Constant temperature of oil and column was maintained by thermostat. Oil was supplied to the column from the tank by means of compressed air. The liquid flow rate was regulated by a flow regulator, and the pressure at the column inlet was recorded by an exemplary manometer. After some time, the oil movement was stabilized (Fig. 2). The oil was then taken over a period of time. Knowing the amount of flowed out liquid, its density and flow time, the volumetric flow rate was found [15-17].

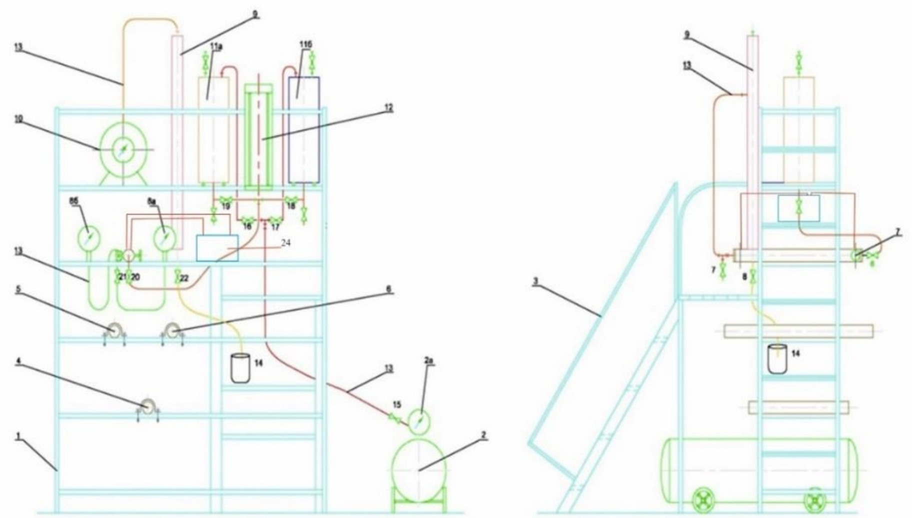

Fig. 2. Principal scheme of the experimental installation: 1 - rack; 2 - compressor; 3 - platform; 4, 5, 6, 7 - core holders; 8a, 8b - pressure gauges; 9 - separator; 10 - gas meter; 11a, 11b - vessels; 12 - level gauge; 14 - measuring vessel; 15-23 - valves; 24 - thermostat.

3 Results and discussion

From the results of the above experimental studies [15-17] on the study of filtration properties of viscous and high-viscosity oils through porous media, with low-permeability and high-permeability reservoir models, the question of choosing the optimal concentration and volume of polymer solution for oil displacement arises.

One of the ways to improve waterflooding efficiency is the use of water-soluble polymers as additives to the water injected into the reservoir. Injection of polymer solutions represents non-steady filtration.

In the process of conducting experiments on filtration of some viscoelastic liquids (high-viscosity oils, polymer solutions) in a porous medium at a constant pressure drop, it was found that the filtration flow rate during the experiment did not remain constant, but gradually decreased until it reached a certain steady-state value. At that, the time of stabilization of filtration flow rate was of the order of several hours.

After stabilization of the flow rate, filtration was stopped for some time. Then the same differential pressure was applied and filtration flow was again generated. However, the flow rate after the breakthrough was greater than before the flow shutoff. Gradually, the flow rate decreased again and after some time reached the stationary value.

According to the described scheme, a series of experiments with solutions of polymer K-9. Uncemented porous medium with permeability 0.45 Darsi, at a temperature of 30 °C and a pressure drop of 1.008 atm were carried out.

The first series of experiments was carried out on 0.2 % solution of polymer K-9 prepared on fresh water. After saturation of the porous medium with K-9 solution and pumping of one volume of pores, continuous measurement of the liquid flow rate in time was performed until the steady-state regime was established. Then filtration was stopped (for 16

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hours), after which the initial pressure drop was set again and the flow rate was measured until it stabilized. Fig. 3 reproduces graphically the process of the experiment.

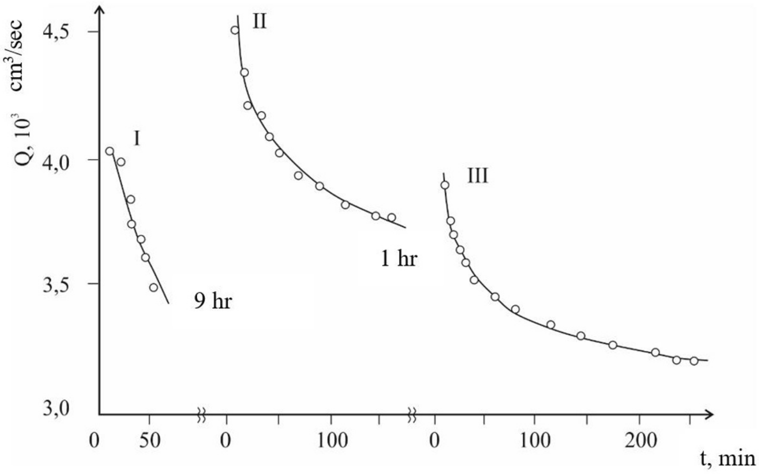

Fig. 3. Dependence of 0.2 % K-9 solution flow rate on filtration time at constant pressure drop (Experimental temperature 30°C; Constant pressure drop 1.008 atm; Permeability 1.25 Darcy).

The second series of experiments was carried out on 0.4 % solution of polymer K-9. Differential pressure and temperature of the experiments remained the same. After filtration of the solution for 95 minutes before reaching the steady-state mode, a stop was made for 16 hours. The process of the experiment is shown in Fig. 4.

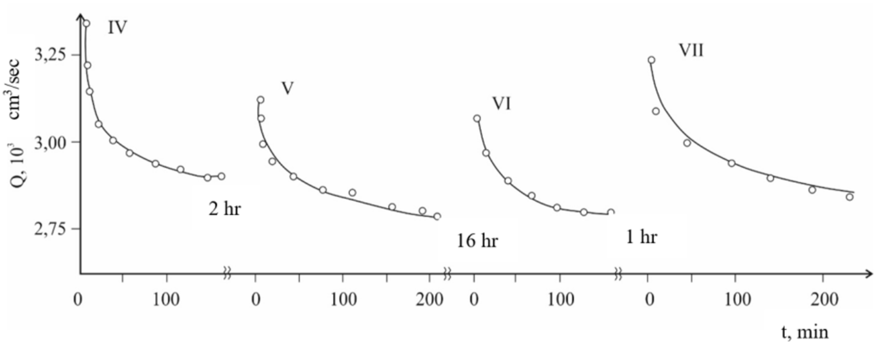

Fig. 4. Dependence of 0.4% K-9 solution flow rate on filtration time at constant pressure drop (Experiment temperature 30°C; Constant pressure drop 1.008 atm; Permeability 1.25 Darcy).

The observed phenomena in the above experiments are explained by a peculiar non-uniformity of viscoelastic fluid flow and can be described as follows. The process of filtration of polymer solutions in a porous medium is accompanied by adsorption phenomena or capture of individual associates and macromolecules by the porous medium, which leads to the accumulation of polymer in the form of microgels in the channels of the porous medium. The retained polymer has viscoelastic properties under the action of the applied gradient, providing certain resistance to the filtering liquid. Moreover, the amount of retained polymer depends on the value of the applied pressure drop. Continuous process of accumulation and removal of separate particles goes on time, i.e. dynamic equilibrium is

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established between particles dislodged and fixed in one or another place of porous medium.
Decrease of flow rate at the beginning of the experiment at constant pressure drop is caused by accumulation of particles in the pore space. The distribution of the retained particles in the pore space, apparently, occurs in such a way that part of them under the action of the applied pressure gradient locks some pores for a certain period of time, after which the particle is pushed through the pores, and its place can be taken by another similar particle. At the beginning of their movement the particles are malleable, they move with the fluid, passing through different channels and undergo deformation. Then they are fixed in some place in the pore space, thus providing additional resistance to the filtering liquid, which leads to additional elastic deformation of the particle.
When the filtration flow stops, the particles begin to relax and the fluid starts to return to the initial state. Individual particles, previously locked in the pore constrictions under the action of normal stresses, are pushed into the pore expansions and acquire the former pliability.
When filtration is resumed after the stop, the initial fluid flow rate may slightly exceed the steady-state flow rate that occurred before the stop, which is clearly shown in Figures 3 and 4. This is explained by the fact that at the initial moment of time after stopping, some elastic particles occupy the positions in the pore space most favorable from the energy point of view, while having a certain mobility in the pore expansions.
Further, the picture described above is repeated, i.e. the search for those places where they lock the pores and undergo significant elastic deformation for some characteristic time equal to the relaxation time begins. Moreover, this relaxation time, associated with the time of search by particles for places of fixation and their further elastic deformation, is several minutes or even several hours. While in free volume (not in porous medium) the relaxation time for K-9 type polymer solutions is about 10^{-4}-10^{-5} sec.
The above qualitative picture and general considerations about nonequilibrium phenomena in a porous medium [6-7] to propose a quantitative theory of the phenomenon, according to which the following relationship between the current flow rate of viscoelastic fluid in a porous medium and the relaxation time is established:

$$-\ln\frac{Q_t-Q_\infty}{Q_0-Q_\infty}=\frac{t}{\tau},$$

where, Q_t, Q_∞, Q_0 – respectively current, equilibrium and initial filtration flow rate; t – time from the start of filtration after stopping until the current flow rate established; τ – relaxation time.

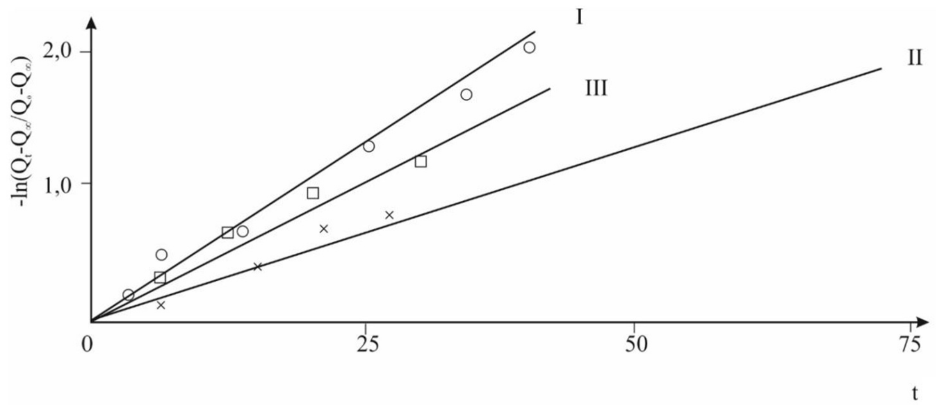

Fig. 5. Graph for determining the relaxation time of 0.2% K-9 solution in porous media.

The results of experimental data processing are presented in Figs. 5 and 6, where the $-\ln\frac{Q_t-Q_\infty}{Q_0-Q_\infty}$ values are plotted along the ordinate axis and the time in minutes along the abscissa axis. As can be seen from Figures 5 and 6, these results are mostly in good agreement with the above formula.

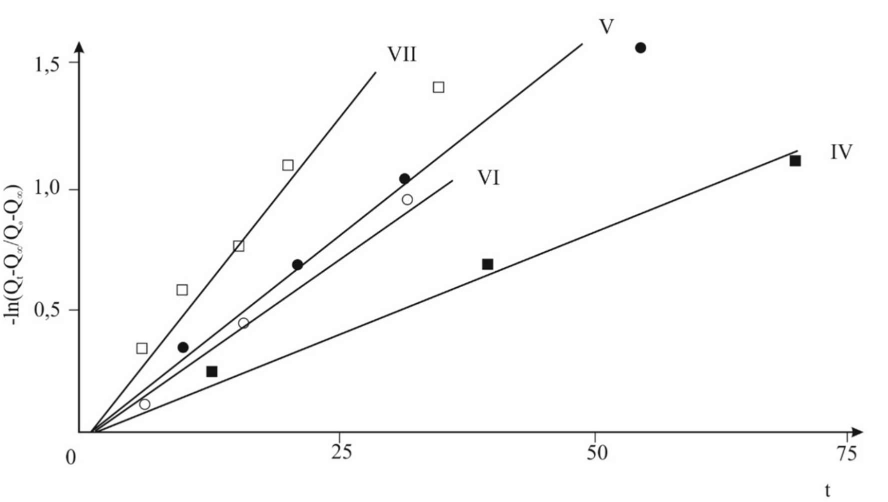

Fig. 6. Graph for determining the relaxation time of 0.4% K-9 solution in porous media.

The scatter in the slope of the straight lines can be partly attributed to the inaccuracy of the steady-state determination. The values of relaxation times were determined from the plots and are presented in Table 1.

Table 1. Calculated values of relaxation time.

No. of experiments	No. of trials	Relaxation time, min
Series 1: 0.2% K-9 solution	1	19
	2	39
	3	24
Series 2: 0.4% K-9 solution	1	62
	2	32
	3	35
	4	19

Let us conduct a brief analysis of works devoted to the study of the flow mechanism of polymer solutions. The considered phenomena that occur during filtration in a porous medium are determined by a combination of factors: adsorption processes, elastic deformation of the adsorbed part of the polymer and elastic properties of the flowing solution. In the light of the discussed theories, the flow of the K-9 polymer is considered.

The relaxation time of viscoelastic particles of polymer K-9 filtered in a porous medium was experimentally found. For K-9, the relaxation time is 16-60 minutes, while in the free volume the relaxation time for this polymer is 10^{-3}-10^{-4} sec.

In this regard, experimental studies were carried out to determine the optimal volume and concentration of the polymer solution. For this purpose, experimental studies were carried out on artificial reservoir models to determine the displacement capacity of the "thickened water rim", in which the dimensions of the "thickened water rim" were 10-75% of the pore volume.

In the process of conducting experiments on the filtration of some viscoelastic liquids (high-viscosity oils, polymer solutions) in a porous medium at a constant pressure drop, it was found that the filtration flow rate did not remain constant during the experiment, but gradually decreased until it reached a certain steady-state value. At the same time, the time for stabilization of the filtration flow was about several hours.

After the flow rate stabilized, filtration stopped for some time. Then the same pressure difference was applied, and filtration flow occurred again. However, the flow rate after the breakthrough turned out to be greater than before the flow was blocked. Gradually, the flow rate decreased again and after some time reached a stationary value.

According to the described scheme, a series of experiments were carried out with solutions of the K-9 polymer. Polymer solution K-9 is a local raw material, developed by the Institute of Chemistry and Physics of Polymers of the Academy of Sciences of the Republic of Uzbekistan. In addition, the improved type of reagent K-4 is high-molecular. Widely used in the oil and gas industry (drilling, production). Previously, the filtration characteristics of the K-9 reagent were not studied in the works, but the filtration characteristics of the K-4 reagent were studied [10]. In this regard, the K-9 reagent was chosen.

Based on the results of experimental data, a summary Table 2 was compiled, which shows a curve characterizing the increase in oil recovery depending on the volume of thickened water.

The results of the study showed that when displacing oils with a viscosity of 6-10 cP, it is enough to bring the viscosity of the K-9 aqueous solution to 2.5 cP. An aqueous solution of K-9 polymer of such viscosity corresponds to 0.4% concentration of K-9 polymer in water, i.e. optimal polymer concentration when displacing low-viscosity oils.

Table 2. Summary of experimental results for oil displacement.

Air permeability, Darcy	Concentration K-9, %	V_{ot}, cm³	$V_{v.n.}$, cm³	$\frac{V_n}{V_{vn}} \cdot 100\%$	V_{ag}	Oil recovery	
						α_b, anhydrous	α_k, final
26.5	0.2	Solid	18.0	100	76	0.46	0.70
19	-	4.9	17.9	29	73	0.31	0.48
20.25	-	2	18.1	11	60	0.29	0.46
18.71	-	13.3	17.8	75	78	0.44	0.65
27.3	Water	0	19.8	0	0	0.35	-
-	-	-	-	-	39	-	0.42
-	-	-	-	-	90	-	0.56
-	-	-	-	-	140	-	0.61
-	-	-	-	-	190	-	0.65
-	-	-	-	-	240	-	0.67
-	-	-	-	-	-	-	-
25.04	0.4	Solid	18.5	100	60	0.68	0.77
17.2	-	1.93	18.0	10.7	103	0.40	0.54
28.5	-	6.4	18.3	35.0	68	0.44	0.63
22.4	-	10.2	18.1	56.5	71	0.52	0.72
27.8	-	13.3	18.3	73.0	66	0.60	0.76

Based on the experimental results, as well as the nature of the dependence curves, we can conclude: displacement by the slug method leads to the desired results only when the slug size reaches more than 70% of the pore oil volume.

4 Conclusions

Experimental studies on the displacement of oil with polymer solutions were carried out on reservoir models filled with quartz sand, while the analyzed deposits were represented by carbonate rocks-limestones. The results obtained on oil displacement by polymer solutions on reservoir models with terrigenous reservoirs are considered possible for use on objects with carbonate reservoirs with a qualitative justification of the polymer flooding method.

Experimental studies on the displacement of oil from fields with a high content of asphaltene-resinous substances with a rim of thickened water have established that this method gives the greatest increase in anhydrous and final oil recovery of formations, within the range of changes in the concentration of the polymer solution of 0.2-0.4%, with a slug size of more than 70% of the oil-saturated volume of the reservoir.

Research on the use of the method of displacing high-viscosity oils with polymer solutions to increase the oil recovery factor in practice is not always economically feasible. To achieve high oil recovery rates, it is recommended to provide high injection pressures and high concentrations of the polymer solution, which in practice will require justification for implementation through a separate study of the selected object.

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