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The experimental study of the effect of magnetically sensitive elastomers on oil recovery of reservoirs containing high-viscosity oils

Badania eksperymentalne wpływu wrażliwych magnetycznie elastomerów na wydobycie ze złóż rop naftowych o wysokiej lepkości

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ABSTRACT: In world practice, low-viscosity oil accounts for the main share of production. As the development progresses, the share of high-viscosity oil in the total balance increases year on year. The growing unused reserves of high-viscosity oil oblige researchers to solve the issue of developing these reserves, which is an important task for the oil industry. Studies have been carried out to increase oil recovery during the development of oil reservoirs containing high-viscosity oil by pumping a solution of magnetically active polymer, namely silicone oligomer, the matrix of which contains 5–25% Fe^{+3} ions, treated with a constant transverse magnetic field with a strength of H = 51740 A/m. A mixture of 90% by weight of quartz sand and 10% by weight of bentonite clay, with a permeability of k = 1.4 D, was used as a reservoir model. The high-viscosity oil model consisted of St-45 aviation oil. A silicone oligomer of 159–360 brand was used as a matrix with an operating temperature range of 60°C to +300°C, into which particles of gamma-Fe_2O_3 Nano powder with a size of 0.5 nm are introduced, with a degree of filling of the matrix of 5–25% by volume of Fe. Magnetization saturation is 80 emu/g, residual magnetization is 460 emu/g, and coercive force is 670 Oh. Validation of the proposed method was carried out by physical modeling of the process of displacement of high-viscosity oil with a magnetic elastomer on a laboratory installation. The oil recovery coefficient was calculated according to a well-known method. The use of magnetically sensitive polymer can be an effective method of developing heavy oil fields. For each heavy oil field, taking into account its specifics (reservoir properties of the rock, physicochemical properties of oil, etc.), an appropriate magnet active polymer is selected. As the experimental results show, the best indicator of the oil recovery coefficient is achieved at 65%, compared with 48% of recovery in the absence of magnetic field exposure.

Key words: magnetic field, high-viscosity, silicone, oligomer, oil, polymer, physicochemical properties.

STRESZCZENIE: W praktyce światowej główną część produkcji stanowią ropy o niskiej lepkości. W miarę postępu rozwoju udział rop o dużej lepkości w ogólnym bilansie rośnie z roku na rok. Rosnące niewykorzystane zasoby ropy naftowej o wysokiej lepkości obligują badaczy do rozwiązania kwestii zagospodarowania tych zasobów, co jest ważnym zadaniem dla przemysłu naftowego. W czasie zagospodarowania złóż ropy naftowej o dużej lepkości prowadzone były badania nad zwiększeniem wydobycia ropy poprzez tłoczenie roztworu magnetycznie aktywnego polimeru, jakim jest oligomer silikonowy, którego matryca zawiera 5–25% jonów Fe^{+3}, poddanego działaniu stałego poprzecznego pola magnetycznego o natężeniu H = 51740 A/m. Jako model złoża zastosowano mieszaninę: 90% mas. piasku kwarcowego i 10% mas. glinki bentonitowej, o przepuszczalności k = 1,4 D. Modelem ropy o dużej lepkości był olej lotniczy St-45. Jako matrycę o zakresie temperatur pracy od 60°C do +300°C zastosowano oligomer silikonowy marki 159–360, do którego wprowadzone zostały cząsteczki nanoproszku gamma-Fe_2O_3 o rozmiarach 0,5 nm, a stopień wypełnienia matrycy jest w zakresie 5–25% obj. Fe. Nasycenie magnetyczne wynosi 80 emu/g, namagnesowanie szczątkowe wynosi 460 emu/g, a siła koercji wynosi 670 Oh. Walidację proponowanej metody przeprowadzono poprzez fizyczne modelowanie procesu wypierania oleju o dużej lepkości elastomerem magnetycznym w instalacji laboratoryjnej. Współczynnik odzysku oleju obliczono według znanej metody. Zastosowanie magnetycznie czułego polimeru może być skuteczną metodą zagospodarowania złóż ciężkich rop. Dla każdego złoża ciężkiej ropy naftowej, biorąc pod uwagę jego specyfikę (właściwości skały zbiornikowej, właściwości fizykochemiczne ropy itp.), dobierany jest odpowiedni polimer magnetycznie aktywny. Z eksperymentu wynika, że najlepszy współczynnik odzysku oleju osiągnięto na poziomie 65%, w porównaniu z 48% odzysku przy braku ekspozycji na pole magnetyczne.

Słowa kluczowe: pole magnetyczne, wysoka lepkość, silikon, oligomer, olej, polimer, właściwości fizykochemiczne.

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Introduction

In world practice, low-viscosity oil accounts for the main share of production. As the development progresses, the share of high-viscosity oil in the total balance increases year on year. The growing unused reserves of high-viscosity oil oblige researchers to solve the issue of developing these reserves, which is an important task for the oil industry (León-González and Perez-Arribas, 2000).

Compared to low-viscosity oil, high-viscosity oil contains a wide range of hydrocarbons, therefore it is used in various industries. The need for it increases over time, which determines the relevance of the work. At the present stage, a significant part of scientists and specialists associate an increase in the efficiency of production of high-viscosity oil reserves with the use of physico-chemical methods (Betancur et al., 2020).

These include the impact on the formation with chemical reagents, thermal impacts such as heated steam, hydro-fracturing of the formation with a strong increase in pressure in the well and methods of exposure to intense acoustic waves (Ahuja et al., 2021). All of the above methods give good results in the laboratory, however, due to the difficulty of implementation in production, they are used when absolutely necessary (Liao et al., 2022.).

Problem statement

In production, the method of displacing high-viscosity oil with polymer fringing solutions has proven to work best. In this case, the viscosity of the displacing liquid (water) is regulated by selecting a polymer, the choice of which is determined by the temperature of the reservoir, the mineralization of the injected water, the permeability of the reservoir (Yan et al., 2012). Polymers are usually used in the form of slightly concentrated aqueous solutions, which are pumped into the reservoir pressure maintenance system, while the oil recovery coefficient increases (Sun et al., 2019). However, the probability of the technical effectiveness of the polymer effect is limited by many criteria, for example, the reservoir temperature should be below 140°C, permeability above 10 133 mD, while oil viscosity in the reservoir <10 Pa·s.

Problem solution

A method of increasing oil recovery during the development of oil reservoirs by polymer flooding is known, which involves a preliminary analysis of reservoir temperatures and the degree of mineralization of reservoir and injected waters, the injection into the oil reservoir, through a well, a polymer solution based on polyacrylamide (PAA) containing additionally acrylamide-butyl-sulfonate (ATBS) monomers or a mixture of ATBS and N-vinyl-pyrrolidone (NVP) in the amount of 15–40 mol.% depending on the reservoir temperature and the degree of mineralization of the solution (Mei-Long et al., 2011). The disadvantage of this method is the limited effectiveness of polymer flooding due to the reservoir temperature (up to 140°C), as well as a decrease in the viscosity of the solution over time due to the destruction of the polymer (Drobny, 2014).

The novelty of the invention lies in the use of a silicone oligomer treated with a permanent magnetic field as a displacing liquid (Mustafayeva, 2019). Composite silicone materials polymerized by the poly-coupling mechanism or under the action of radiation are intended for use in medicine, electronics, electrical and radio engineering, fiber optics and optoelectronics, aviation and other industries (Xuan et al., 2015).

Problem solution method

The objective of the present invention is to increase the efficiency of high-viscosity oil production while expanding the technological capabilities of the method. The task was solved by the proposed method of increasing oil recovery in the development of oil reservoirs containing high-viscosity oil by pumping a solution of magnetically active polymer, namely silicone oligomer, the matrix of which contains 5–25% Fe^{+3} ions, treated with a constant transverse magnetic field with a strength of $H = 51740$ A/m.

The method of pumping magnetized water into the reservoir cannot be used to increase the recovery coefficient of high-viscosity oil. This is because the viscosity of water is much lower than the viscosity of oil; when using it, magnetized water, at best, breaks through the channel through the oil, while all the energy of the impact is spent on the movement of water. At the same time, there is no increase in oil extraction. An attempt was made to magnetize polymer solutions used in the oil industry. However, no positive result was obtained, since there are no magneto-active elements in the composition of the polymer used in oil production (Mammad-Zadeh, 2010).

The viscosity of the magneto-active polymer is selected depending on the viscosity of the extracted oil in reservoir conditions. The strength of the magnetic field is selected depending on the composition of the porous medium of the rock according to a known technique.

By introducing ions of a magneto-active element, oligomer radicals are cross-linked, forming a stable polymer called a magnetic elastomer (Mustafayeva, 2020). When an external magnetic field is applied, the magneto-active ions orient themselves in the direction of the magnetic lines of force, thereby further strengthening the bonds. This leads to at least the preservation of the initial viscosity, and sometimes to its increase. It also prevents the destruction of the polymer during its filtration through a porous medium, which leads to an increase in oil recovery. In addition, the magneto-active polymer is a conductor of a magnetic field that penetrates into the rock, interacts with the rock field, compensates for it. This leads to the detachment of the polymolecular part of the adsorption layer, which leads to an increase in the amount of extracted oil.

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A mixture of 90% by weight of quartz sand and 10% by weight of bentonite clay, with a permeability of k = 1.4 D, was used as a reservoir model. The high-viscosity oil model consisted of St-45 aviation oil. A silicone oligomer of the CIEL 159–360 brand was used as a matrix with an operating temperature range of 60 to +300°C, into which particles of gamma-Fe_2O_3 nanopowder with a size of 0.5 nm are introduced, with a degree of filling of the matrix of 5–25% by volume of Fe. Magnetization saturation is 80 emu/g, residual magnetization is 460 emu/g, coercive force is 670 Oh.

Validation of the proposed method was carried out by physical modeling of the process of displacement of high-viscosity oil with a magnetic elastomer on a laboratory installation (Figure 1).

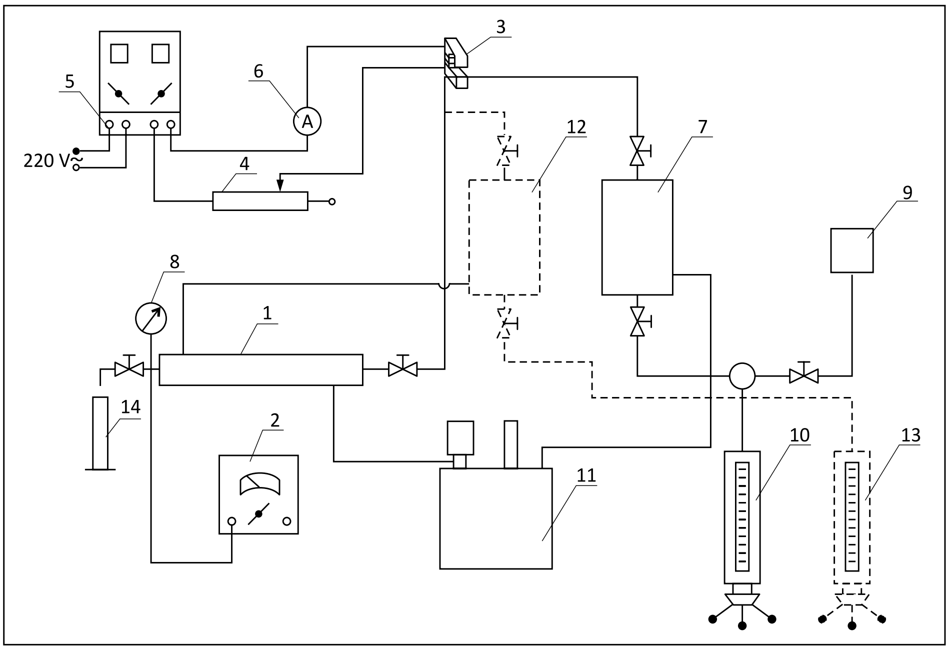

Figure 1. Scheme of the stand for modeling the increase of oil recovery from reservoirs containing high-viscosity oils

Rysunek 1. Schemat stanowiska do modelowania zwiększenia wydobycia ropy ze złóż ropy o dużych lepkościach

The laboratory installation contains: a reservoir model 1, a potentiometer 2, an electromagnet 3, a rheostat 4, an electric current rectifier 5, an ammeter 6, a PVT bomb 7 for an elastomer designed to be exposed to a magnetic field, a pressure gauge 8, a container for an elastomer 9, a measuring press 10 for an elastomer designed to be exposed to a magnetic field, a thermostat 11, "PVT bomb" for reference elastomer 12, measuring press for reference elastomer 13, beaker 14. They make up a porous medium containing 90% quartz sand + 10% clay.

The reservoir model 1 is filled with a porous medium and the air permeability and porosity of the reservoir model are determined according to the standard method. The reservoir model 1 is saturated with aviation oil St-45. With the help of the press 13 from the "bomb" 12, the aviation oil St-45 is transferred to the reservoir model 1, while using the divisions of the press 13, the amount of liquid entering the porous medium (V_0) is measured. The volume of presses 10, 13 was 200 cm^3 and the amount of liquid under study was 2000 cm^3 or more. Additional liquid for pumping the test liquid is stored in the container for storing liquid 9. Using the thermostat 11, the temperature in the system is set to 25°C. A magnetic elastomer is inserted into the "bomb" 12.

After establishing a constant temperature in the system, the viscous liquid is displaced from the reservoir model 1 by pumping a magnetic elastomer from the bomb 12 using the press 13. The temperature setting is controlled by pressure gauges 8. When the valve installed at the outlet of the reservoir model 1 is closed, the reading of pressure gauges 8 increases with an increase in temperature. When the temperature stabilizes, the readings of the pressure gauges 8 remain constant. With the help of measuring press 13 in the reservoir model 1, the pressure is raised. The valve at the outlet of the reservoir model 1 is opened when the pressure begins to drop on the inlet pressure gauge 8. With the help of the press 13, the pressure is kept constant at a certain level.

Thus, a constant pressure drop is established; at the same time, with the help of the potentiometer 2, the potential difference at the inlet and outlet of the reservoir model 1 is measured. The aviation oil St-45 displaced from the reservoir model 1 enters the beaker 14, where the amount of extracted aviation oil (V1) is measured.

The oil recovery coefficient is calculated: $\eta = V_1/V_0$ 100%.

Table 1. Oil recovery coefficients
Tabela 1. Współczynniki sczerpania ropy

Fe^{+3} content in elastomer	Magnetic field strength	Volume of injected oil	Volume of extracted oil	Oil recovery coefficient	Increment of the oil recovery coefficient
[%]	[A/m]	[cm^3]	[cm^3]	[%]	[%]
5	0	322	135	42	12
	51740	316	171	54	
12	0	324	156	48	17
	51740	321	209	65	
25	0	318	140	44	15
	51740	323	190	59	

Studies in this sequence allow us to determine the extraction coefficient in the absence of the action of a magnetic field. These results are taken as reference (Table 1).

To obtain the results of using a magnetic elastomer treated with a constant transverse magnetic field with a strength of $H = 51\,740$ A/m, it is necessary to perform the entire sequence indicated above.

A magnetic elastomer is filled into the "bomb" 7, which is passed through the core of the magnet 3, then aviation oil is displaced from the reservoir model 1 using the press 10. The constant strength of the magnetic field of the magnet 3 is achieved using a direct current received by the rectifier 5. The magnetic field strength is set by the rheostat 4 and the ammeter 6.

Conclusion

As the experimental results show, the best indicator of the oil recovery coefficient reaches 65% compared to 48% recovery in the absence of magnetic field exposure. The experimental data obtained confirm the effect of using a magneto-active polymer treated with a transverse magnetic field with a strength of $H = 51\,740$ A/m.

The use of magneto-active polymer can be effective for the development of heavy oil fields. For each heavy oil field, taking into account its specifics (reservoir properties of the rock, physicochemical properties of oil, etc.), an appropriate magneto-active polymer is selected.

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