Computational study of enhanced oil recovery from a porous medium using nanosuspension

D V Guzei¹², S V Ivanova¹, D V Platonov¹², A I Pryazhnikov¹

¹ Siberian Federal University, 79 Svobodny pr., Krasnoyarsk, 660041, Russia
² Institute of Thermophysics SB RAS, 1 Acad. Lavrentiev pr., Novosibirsk, 630090, Russia

E-mail: gudimas@yandex.ru

Abstract. The paper presents the results of direct numerical simulations of the process of oil displacement by nanosuspension with SiO₂ particles from two-dimensional micromodels of a porous medium with different values of permeability. In the calculations, the experimentally measured values of the interfacial tension coefficient and the contact angle of wetting were used. The calculations were performed for pure water and a suspension of silicon oxide nanoparticles with a mass concentration of 1%. The computational study was performed using the VOF method. The influence of the displacement fluid flow rate, nanoparticle concentration and core permeability on the efficiency of oil displacement by nanosuspension was studied. As a result of the work, it was shown that the use of nanosuspensions makes it possible to increase the oil recovery factor. It is shown that with an increase in the mass concentration of particles, the value of the oil recovery factor increases.

1. Introduction

One of the most common methods of oil production from terrigenous reservoirs is reservoir flooding, in which oil from a porous medium is displaced by water or solutions with surfactants or polymer additives. Modern production methods make it possible to achieve values of the oil recovery factor from 20 to 40%, therefore, the task of increasing the efficiency of oil displacement from the reservoir is very relevant.

Recently, works have appeared in which it is proposed to use a suspension (usually based on water) with the addition of nanoparticles of various compositions as a promising agent for waterflooding and increasing oil recovery [1-8]. Concerning the oil displacement process, the most important physical properties are viscosity, wettability angle and interfacial tension coefficient. These properties of nanosuspensions substantially depend on the type, concentration and size of nanoparticles. This makes it possible to control the properties of the flooding fluid.

In this regard, a large number of studies have recently been carried out with the aim of studying the possibility of using various nanosuspensions to increase oil recovery during waterflooding. Both laboratory experiments [1-3] and various numerical models [4-8] are used for studying the process of oil displacement with the use of nanofluids.

2. Mathematical model
The numerical technique is based on solving the system of Navier-Stokes equations. The VOF method was used to describe the flow of a two-phase flow in a porous medium [9]. This model can simulate immiscible liquid–liquid multicomponent flow by solving the momentum equations and using the volume fraction of each phases.

Figure 1. The geometry of the computational domain.

Figure 1 shows the calculated 2D geometry used in the calculations. The geometry of the computational domain is a cross-section of a rectangular parallelogram with a porous medium modeled by random filling with spherical balls of various sizes. At the initial moment of time, the void space is filled with oil. During the calculation process, the computational domain is filled with a displacing fluid, which leads to the displacement of oil.

At the inlet to the computational domain, the velocity of the displacing fluid was set. The no-slip condition was specified on the walls of the computational domain. At the outlet from the computational domain, the Neumann conditions were set.

The difference analogue of convective-diffusion equations is found using the finite volume method for structured multiblock grids, when applied, the resulting scheme is automatically conservative. The coupled between the velocity field and pressure is realized using the SIMPLEC algorithm.

For correct modeling of the process of oil displacement from a porous medium, data on interfacial tension and contact angle at the oil/water/rock interface are required. Experimental studies of interfacial tension and surface wettability in nanosuspension/oil/rock systems were carried out. Measurement of interfacial tension and the wetting angle was carried out by means of IFT-820-P automatic tensiometer [10].

Also, the dependence of the viscosity of nanosuspension on the mass concentration of particles in the range from 0 to 1 wt% and the viscosity of the oil used were determined experimentally. During the calculation, the value of the oil recovery factor and the value of the pressure drop during fluid injection are determined. The oil recovery factor is defined as the ratio of the volume of oil displaced to the initial volume of oil in the pore space.

3. The simulation results

Numerical modeling of the processes of oil displacement from the porous medium model was carried out. In the calculations, water and nanosuspensions based on water with particles of silicon oxide SiO$_2$ were considered as displacing fluids. The mass concentration of particles in the calculations was 1%. The calculations were carried out for oil with the following physical properties: density 893 kg/m$^3$, viscosity 7.8 cP. In the calculations, the values of the velocity of the displacing fluid at the entrance to the computational domain were varied. The speed varied in the range from $1\times10^{-3}$ to $1\times10^{-1}$ m/s. This range of velocities corresponded to the values of the capillary number ($Ca$) from $5\times10^{-6}$ to $7.5\times10^{-3}$. The figure 2 shows an illustration of the oil displacement process, where oil is shown in blue, and the displacing fluid (water or silica nanosuspension) is shown in red. These distributions were obtained at a constant inlet velocity equal to $1\times10^{-3}$ m/s, both for water and for nanosuspension.
As can be seen from the illustrations presented in figure 2, oil displacement from the porous medium occurs in different ways. Water breaks through the porous medium in separate thin jets, leaving large areas filled with oil. Nanosuspension, unlike water, breaks through in wider jets and displaces more oil from the rock.

In the course of calculations, the dependence of the oil recovery factor on the capillary number (Ca) was obtained. The graph of this dependence is shown in figure 3. As can be seen from the graph, the use of a nanosuspension to displace oil from a porous medium makes it possible to intensify the value of the oil recovery factor in a wide range of capillary numbers. The greatest intensification of the oil recovery ratio is observed at low values of the capillary number. So at $Ca=5 \times 10^{-6}$, the use of a nanosuspension with a mass concentration of particles of 1% makes it possible to increase the oil recovery factor by 40% compared to water. With an increase in the values of the capillary number, the intensification of the values of the capillary number decreases. So for $Ca=5 \times 10^{-4}$, the oil recovery factor with the help of nanosuspension is 18% higher than the oil recovery factor for water.

**Figure 2.** Distribution of water (a) and nanosuspension (1 wt.%) (b) in a porous medium at different moment in time.
Conclusion

The paper presents the results of direct numerical modeling of the process of oil displacement by nanosuspension with SiO$_2$ particles from two-dimensional micromodels of a porous medium with different values of permeability. To describe this process, we used a model of the flow of two immiscible liquids taking into account the forces of surface tension and the contact angle of wetting. The calculations used the data of a systematic experimental study of the values of the interfacial tension coefficient and the wetting angle at the oil/nanosuspension/rock interface.

The calculations were performed for pure water and a suspension of silicon oxide nanoparticles with a mass concentration of 1%. Shown are the characteristic patterns of the distribution of oil and displacing fluids (water and nanosuspensions) in a porous medium. It is shown that the use of nanosuspensions makes it possible to increase the oil recovery factor. The largest increase in the oil recovery factor when using nanosuspensions is observed in the capillary flow regime and exceeds the oil recovery factor for water by 40%.

Acknowledgments

This study was performed within the framework of a state contract for the Siberian Federal University (contract no. FSRZ-2020-0012).

We are grateful to the Krasnoyarsk Regional Shared Research Center (Krasnoyarsk Scientific Center, Siberian Branch, Russian Academy of Sciences) and Shared Research Center of Siberian Federal University for taking characterization of nanosuspension.

References

[1] Hendraningrat L, Li S, Torsæter O 2013 J. Petrol. Sci. Eng. 111 128-138
[2] Roustaei A, Bagherzadeh H 2015 J. Petrol. Explor. Prod. Technol. 5 27-33
[3] Yoon K Y, Son H A, Choi S K, Kim J W, Sung W M, Kim H T 2016 Energy Fuels 30(4) 2628–2635
[4] Yu J, Berlin J M, Lu W, Zhang L, Kan A T, Zhang P 2010 SPE International Conference on Oilfield Scale. Society of Petroleum Engineers.
[5] Rahmani A R, et al. SPE J. 20(5) 1067–1082
[6] Zhao J, Wen D 2017 *RSC Adv.* 7(66) 41391–41398

[7] Patel H V 2019 Direct numerical simulations of multiphase flow through porous media. (Eindhoven: Technische Universiteit Eindhoven) p 160

[8] Gharibshahi R, et al 2015 *RSC Adv.* 5(37) 28938–28949

[9] Hirt C W, Nichols B D 1981 *J. Comput. Phys.* 39(1) 201-225

[10] Minakov A V, Pryazhnikov M I, Suleymana Ya N, Meshkova V D 2020 *Tech. Phys. Lett.* 46 (24) 30-32