The investigation of the efficiency of oil displacing from the pore in the rock formation depending on the width and height of the pore using nanosuspension as a displacing agent

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Abstract. The numerical investigation of the two-phase fluid flow in a microchannel was carried out. The effect of the pore width and height on the oil displacing efficiency by nanofluids for various Reynolds numbers was studied. The computational domain was a T-shaped microchannel with a horizontal main flow channel and a vertical channel that imitated the pore in the rock formation, called a pore channel. The main channel width and height were 200 µm, and the pore channel width and height were varied in the range from 100 µm to 800 µm. The Reynolds number was varied from 0.1 to 100. The main studied characteristic was the oil recovery coefficient, defined as the ratio of the volume of oil remaining in the pore to the volume of the pore. That characteristic, obtained for a case, when the nanofluid was used as a displacing agent, was compared to the similar one obtained for a case, when pure water was used as a displacing agent. A single-phase fluid with properties, determined experimentally, was considered the nanofluid. The mass concentrations of SiO₂ nanoparticles were 0.25% and 0.5%. The average diameter of nanoparticles was equal to 5 nm. It was found, that the oil recovery coefficient increased with an increase in width of the pore channel and a decrease in its height. It was obtained that the nanofluid can enhance the oil recovery in several times as compared to pure water. It was also found that the main factor affecting the efficiency of oil recovery is the contact angle of wetting.

1. Introduction

Recently, more and more information appears that oil reserves on Earth are rapidly depleting, and they will only last for the next hundred years. This is partly true, but this is due to a completely different aspect, namely, even using the most modern technologies, only about 35% of oil contained in the reservoir can be extracted from the depths. In recent years, there have been more and more proposals for the use of micro- and nanofluid technologies to increase the oil recovery factor and enhance oil recovery. For example, one of the possible options for using micro- and nanofluid technologies is the use of nanofluid as a displacing agent. Active interest in suspensions with nanoparticles appeared more than 25 years ago and has been steadily growing since then. Due to their small size, nanoparticles have a number of unusual properties that are absent in macroscopic dispersed particles, which, in turn, leads to non-standard properties of nanofluids. As a result, a very important application in which nanofluids can become very promising is the problem of increasing the oil recovery factor, which allows a significant increase in the oil recovery of reservoirs. Some potential mechanisms for increasing oil recovery through the use of nanofluids have been proposed by various researchers [1-3],
namely: a change in wettability; a reduction of interfacial tension of the surface of oil/water systems; a change in wedging pressure; increasing the viscosity of the aqueous solution; a decrease in oil viscosity; appearance of an ascending film and projectile-like displacement [4]. In addition, the ideas about the possibility of using microchannel chips of a very complex shape with pore sizes of up to several microns, which can be considered as a system that simulates a core for studying two-phase flows in microchannels that simulate oil washing out of the rock, have been expressed. Moreover, such studies can be both experimental and numerical. However, at the moment all this remains at the level of an idea, and there are not very many such works [5-8]. There is also a large number of works that show enhanced oil recovery when using nanofluids as a displacing agent. Thus, in [9] an increase in oil recovery by 7-24% due to a decrease in the contact angle of wetting was shown. Nanoparticles of aluminum, titanium and silicon dioxide with a size of 17-40 nm and a mass concentration of 0.05 wt.% were used. In [10], an increase in oil recovery by 12% was shown when using nanoparticles of aluminum oxide with a size of 10-70 nm. The main mechanisms that caused such an increase in this work were the decrease in the interfacial tension and viscosity of oil, as well as the change in the contact angle of wetting. In [11], an increase in oil recovery by 22% was found due to a decrease in interfacial tension and contact angle of wetting when using silicon dioxide nanoparticles with a size of 4-20 nm and a mass concentration of 10 wt.%. In [12], an increase in oil recovery by 5-35% was found due to a change in the contact wetting angle and formation of a blockage. As in the previous work, silicon dioxide nanoparticles were used here, but 5-60 nm in size and with a volume concentration of 0.01-3 vol.%. Based on the conducted literature review, it can be concluded that the research in this area is very relevant.

The flow of two-phase mixtures of oil and nanosuspension, used as a displacing agent, in direct microchannels simulating a pore or crack in the rock was investigated. Maps of flow regimes and washout efficiency vs. the Reynolds number were constructed, and dependences of these characteristics on the geometric parameters of a microchannel simulating a pore or crack, such as its width and depth, were obtained. The obtained values were compared with those for identical channels, but using water [13] as a displacing agent.

2. The computational domain and the mathematical model

The computational fluid dynamics method, namely, the numerical solution of the unsteady Navier-Stokes equations, was used:

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0, \quad \frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot (\rho \mathbf{u} \mathbf{u}) = -\nabla p + \nabla \tau,
\]

where \( \rho \) is the fluid density, \( \mathbf{u} \) and \( p \) are the fluid velocity and pressure, \( t \) is the time, \( \tau = \mu (\nabla \mathbf{u})^\dagger \) is the viscous stress tensor, \( \mu \) is the fluid viscosity, and \( (\nabla \mathbf{u})^\dagger \) is the symmetric divergence-free tensor of the second rank. This approach has been widely described in many studies [13-18]; further the main points of the numerical technique are noted. The difference analogue of convective-diffusion equations is found using the finite volume method for structured multiblock grids. The approximation of the convective terms of the transport equations is carried out using upwind schemes of the second order. The connection between the velocity and pressure fields, which ensures the fulfillment of the continuity equation, is implemented using the SIMPLEC procedure on aligned grids [19]. The difference equations obtained as a result of discretization of the original system are solved iteratively using an algebraic multigrid solver. The Volume-of-Fluid method is used to describe the two-phase flow and interaction. It is shown in detail in [13]. The computational domain, whose scheme is shown in figure 1, is a T-shaped microchannel with a horizontal main flow channel and a vertical channel that imitates the pore in the rock formation, called a pore channel. The width \( d_{fc} \) in figure 1) and height \( h_{fc} \) in figure 1) of the main channel equal 200 \( \mu \)m, and the width \( d \) in figure 1) and height \( h \) in figure 1) of the pore channel vary from 100 \( \mu \)m to 800 \( \mu \)m. At the initial time moment, the entire considered channel is filled with oil, which is then washed out using a displacing agent. The viscosity and the density of oil are equal to 0.0079 Pa·s and 864 kg/m\(^3\), respectively. Pure water or nanofluid is used as
the displacing agent. The viscosity and the density of water are equal to 1.003 mPa·s and 997 kg/m³, respectively. The surface tension coefficient is 2.23 N/cm and the contact angle between water and oil is 72°. The nanofluid is considered using the single-fluid approach. The nanofluid properties depend on the weight concentration of SiO₂ nanoparticles with the 5-nm average diameter, taken from the experiment [20]. At 0.25 wt.% the viscosity of nanofluid is 1.015 mPa·s, the density is 998.36 kg/m³, interfacial tension coefficient is 2.12 N/cm and the contact angle of wetting is 105°. At 0.5 wt.% the viscosity of nanofluid equals 1.027 mPa·s, the density equals 999.73 kg/m³, the interfacial tension coefficient equals 2.04 N/cm, and the contact angle of wetting was equals 151°. The constant flow rate with parabolic velocity profile, which corresponds to the respective Reynolds number, is set at the inlet of microchannel. The no-slip boundary conditions are set on the channel walls. The mesh of about 2.5 million cells is used. This amount is enough to obtain a mesh-independent solution. The Ansys Fluent CFD package is used.

Figure 1. The scheme of the computational domain.

3. Results and discussion
Numerical studies of the effect of the width and height of the pore in the rock formation on the efficiency of oil displacement by water or nanofluid were carried out. The Reynolds number was varied from 0.1 to 100. The main investigated quantity was the oil recovery coefficient. The results obtained for nanofluids were compared with the similar values obtained for pure water.

As a result of processing the calculated data, graphs of the dependence of the oil recovery efficiency on the Reynolds number were plotted for various values of the height and width of the pore channel, which are shown in figure 2. As one can see, pure water can displace oil only from the pore of a huge width or very small height. Hence, it can be concluded that oil is retained in the pores due to interfacial tension forces, and the main parameter affecting the efficiency of oil recovery is the contact angle of wetting. Since for water this angle is only 72°, it cannot efficiently extract oil from narrow and deep pores. For nanofluid with a mass concentration of 0.25%, the contact angle is about 105°, therefore, similar results should be obtained for it as for pure water. Indeed, according to figure 3, which shows the dependences of the oil recovery factor on the Reynolds number for different pore sizes, it can be seen that these dependences are almost identical to those shown in figure 2.

Another interesting fact is that the oil recovery factor decreases as the Reynolds number increases, however, when the Reynolds number is 50, there is a slight increase in this value. Most likely, this is due to the appearance of a separated flow in the region where the pore joins to the main channel. But the influence of these flows on the oil recovery factor requires further more detailed studies. The same values, but for nanofluid with a mass concentration of 0.5% are shown in figure 4. Due to the fact that at a given concentration the contact angle is 151 degrees, much more efficient oil recovery should be expected than in previous cases. Indeed, as it can be seen from this figure, the oil recovery factor for
any pore size is much higher than in the previous cases. Moreover, for the widest and shortest pores, this coefficient is almost 100%.

**Figure 2.** The dependences of the oil recovery coefficient on the Reynolds number for different widths (a) and heights (b) of pore. Pure water as displacing agent.

**Figure 3.** The dependences of the oil recovery coefficient on the Reynolds number for different widths (a) and heights (b) of pore. The 0.25 wt.% nanofluid as displacing agent.

The dependences of the relative oil recovery coefficient on the Reynolds number for nanofluids with mass concentrations of 0.25% and 0.5% are respectively shown in figures 5 and 6. This dependence is obtained by dividing the nanofluid oil recovery coefficient by the pure water oil recovery coefficient. In these figures, the dash-dotted line indicates the values for pure water, that is, all values above this line indicate an increase in the efficiency of oil recovery. As you can see, the 0.25 wt.% nanofluid in some cases shows an increase in the efficiency of oil recovery, and in other cases, this efficiency decreases. The 0.5 wt.% nanofluid shows a significant increase in the efficiency of oil extraction, in some cases hundreds and thousands of times. Thus, the use of nanofluids as displacing agents allows an increase in the efficiency of oil recovery, but it is necessary that such nanofluid has a high value of the contact angle.
**Figure 4.** The dependences of the oil recovery coefficient on the Reynolds number for different widths (a) and heights (b) of pore. The 0.5 wt.% nanofluid as displacing agent.

**Figure 5.** The dependences of the relative oil recovery coefficient on the Reynolds number for different widths (a) and heights (b) of pore. The 0.25 wt.% nanofluid as displacing agent.

**Figure 6.** The dependences of the relative oil recovery coefficient on the Reynolds number for different widths (a) and heights (b) of pore. The 0.5 wt.% nanofluid as displacing agent.
4. Conclusion

The numerical studies of the effect of the width and height of the pore in the rock formation on the oil displacing efficiency by water or nanofluid were carried out. It is found that the oil recovery coefficient increases with an increase in the width of the pore channel and with a decrease in its height both for the case when a nanofluid is used as a displacing agent and for the case when water is used as this agent. It is also found that pure water can displace oil only from the pore of a huge width or very small height. The 0.25 wt.% nanofluid shows the similar results. It can be explained that the contact angle of wetting for pure water is very close to that for nanofluid. However, not only this parameter affects the oil recovery coefficient, another important parameter is the viscosity of the displacing agent. Since the nanofluid has a higher viscosity, in some cases it displaces oil from the pore more effectively, than pure water. The 0.5 wt.% nanofluid shows a significant increase in the efficiency of oil extraction, in some cases hundreds and thousands of times. Thus, the use of nanofluids as displacing agents allows an increase in the efficiency of oil recovery, but it is necessary that such a nanofluid has a high contact angle value.

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References

[1] Wasan D., Nikolov A., Kondiparty K. 2011 Curr. Opin. Colloid Interface Sci. 16(4) 344–349
[2] Torsater O., Li S., Hendraningrat L. 2013 Soc. Petrol. Eng. art. № SPE-165283-MS
[3] Torsater O., Li S., Hendraningrat L. 2013 Soc. Petrol. Eng. art. № SPE-165955-MS.
[4] Luo D., Wang F., Alam M.K., Yu F., Mishra I.K., Bao J., Willson R.C., Ren Z. 2017 Chem. Mater. 29 3454–3460
[5] Nilsson M.A., Kulkarni R., Gerberich L. 2013 J. Non-Newton. Fluid Mech. 202(9) 112–119
[6] Conn C.A., Ma K., Hirasaki G.J. 2014 Lab on a Chip 14(20) 3968–3977
[7] Quennouz N., Ryba M., Argillier J.F. 2014 Oil Gas Sci. Tech. – Rev. IFP Energies nouvelles 69(3) 457-466
[8] Rosero G., Peñaherrera A., Olmos C., Boschan A., Granel P., Golmar F., Lasorsa C., Lerner B., Perez M. 2018 Revista Matéria 23(2) art. № e-12129
[9] Hendraningrat L., Torsaeter O. 2014 Proc. Offshore Tech. Conf.-Asia art. № OTC-24696
[10] Ogolo N.A., Olafuyi O.A., Onyekonwu M.O. 2012 Soc. Petrol. Eng. art. № SPE-160847-MS
[11] Mcelfresh P.M., Holcomb D.L., Ector D. 2012 Soc. Petrol. Eng. art. № SPE154827
[12] El-Diasty A.I., Aly A.M. 2015 Soc. Petrol. Eng. art. № SPE-175806-MS
[13] Lobasov A.S., Minakov A.V. 2021 J. Phys.: Conf. Series 1867 art № 012028 1–6
[14] Lobasov A.S., Minakov A.V. Rudyak V.Ya. 2016 Fluid Dyn. 53(3) 381–8
[15] Lobasov A.S., Minakov A.V. Rudyak V.Ya. 2018 J. Eng. Phys. & Thermophys. 91(1) 124–35
[16] Lobasov A.S., Minakov A.V. 2018 Chem. Eng. & Proc.: Proc. Intens. 124 11–23
[17] Lobasov A.S., Minakov A.V. Rudyak V.Ya. Shebeleva A.A. Kuznecov V.V. 2018 Chem. Eng. & Proc.: Proc. Intens. 134 105–14
[18] Lobasov A.S., Minakov A.V. Shebeleva A.A. 2019 J. Sib. Fed. Uni. Math.&Phys. 12(2) 202–12
[19] Patankar S. 1980 Numerical heat transfer and fluid flow (New York: Hemisphere Publishing Corporation/McGraw Hill Book Company) p 197
[20] Minakov A.V., Pryazhnikov M.I., Suleymana Y.N., Meshkova V.D., Guzei D.V. 2021 J. Molec. Liq. 327 1–10