The investigation of the average diameter of the SiO$_2$ nanoparticles effect on the oil displacing efficiency from the pore in the rock formation using nanosuspension as a displacing agent

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Abstract. The numerical investigation of the nanofluid flow, which displaced the oil, in a microchannel was carried out. The effect of the average diameter of the SiO$_2$ nanoparticles on the oil displacing efficiency by nanofluids for different sizes of microchannel at various Reynolds numbers was studied. A T-shaped microchannel with a vertical channel, called a pore channel, which imitated the pore in the rock formation was considered as a computational domain. The main flow channel width and height were 200 µm. The width and height of the pore channel were varied in the range from 100 µm to 800 µm. The Reynolds number varied from 0.1 to 100. The oil recovery coefficient, which is defined as the ratio of the displacing volume of oil from the pore to the volume of the pore was considered as the main studied characteristic. The nanofluid is considered a single-phase fluid with experimentally obtained properties. The mass concentration of SiO$_2$ nanoparticles was 0.5%. The average diameters of nanoparticles were 5 nm, 18 nm, and 50 nm. It was found, that the oil recovery coefficient increased with a decrease in the average diameter of nanoparticles. It was obtained that the nanofluid can enhance the oil recovery several times compared to pure water.

1. Introduction

Modern oil recovery methods are considered unsatisfactory because average values of the oil recovery factor range from 25% to 40%. Therefore, it is necessary to develop enhanced oil recovery technologies. There are three main categories of such technologies available: Thermal methods, which mainly introduce heat into heavy oil reservoirs to improve the ability of heavy oil or bitumen to flow in reservoirs by changing their physical properties (viscosity and density); Gas methods, which use hydrocarbon or non-hydrocarbon gases dissolved in oil, capable of improving oil recovery by reducing the viscosity and increasing the volume of oil; Chemical methods, which mainly involve the use of long-chain molecules (polymers) to increase waterflooding efficiency or surfactants like detergents to reduce interfacial tension, which often prevents oil from being lost as it flows through the formation. However, it was shown that all these traditional methods of enhanced oil recovery have a number of serious problems, which can be solved with the use of nanoparticles with some unique useful characteristics.

Shortly, all of these enhanced oil recovery methods allow more oil to be recovered from reservoirs through various mechanisms such as interfacial tension reduction, wettability change, mobility control,
physical properties change, and gravity drainage. However, all these traditional methods of enhanced oil recovery have a number of serious problems. For example, in gas methods, injected gas often seeps through the reservoir from injection to production wells too quickly due to the high mobility of the injected gas and oil, as a result of which a large amount of residual oil remains unrecovered from the reservoir \[1, 2\]. Chemical methods are often limited by the high cost of chemicals, possible formation damage, and chemical losses \[3, 4\]. Therefore, there is a need for less expensive, more efficient, and environmentally friendly methods of enhanced oil recovery. To solve such problems, it is possible to use nanoparticles \[5\], which, unlike liquids used in traditional enhanced oil recovery processes (gas, water, and chemicals), have some useful characteristics:

1. Ultra-small size. One of the main problems of chemical methods, which must be addressed in the first place, is the clogging of the pores and the locking of the injected chemicals in the porous medium. This leads to a decrease in the formation permeability and an increase in the cost of injection \[6\]. The most commonly used nanoparticles, such as SiO\(_2\), TiO\(_2\), and Al\(_2\)O\(_3\), have sizes on the order of 1–100 nm, which is much smaller than the pore and throat sizes \[7\]. Thus, they can easily flow through a porous medium without significantly reducing the formation permeability or blocking the injected material, which increases the efficiency of enhanced oil recovery methods due to the injected fluids. In addition, due to the ultra-small size of nanoparticles, they are able to penetrate into some pores, where traditionally used liquids cannot get into. Thus, the nanoparticles can contact a large number of zones covered by the displacement, which makes it possible to increase the macroscopic displacement efficiency.

2. Very high surface area to volume ratio: Due to their small size, nanoparticles have a very high surface-to-volume ratio. It is clear that a large surface area increases the fraction of atoms on the surface of nanoparticles \[8\], thereby increasing their ability to modify various properties of displacing agents.

3. Low cost and environmental friendliness: One of the problems of using chemicals in the field is the high cost of pumping fluids. Since the price of nanoparticles is generally lower than that of chemicals, they can be widely used to enhance oil recovery in oil fields. In addition, most of the nanoparticles used are environmentally friendly materials compared to chemicals. For example, nanoparticles of silicon dioxide, which is the main component of sandstone, are often used.

Due to the aforementioned characteristics of nanoparticles, they can solve many of the existing problems faced by traditional methods of enhanced oil recovery. In this case, not the nanoparticles themselves, nanofluids, nanoemulsions, and nanocatalysts based on them are usually used. It has been shown in many works that flooding with nanofluids makes it possible to increase oil recovery, and in different studies the magnitudes of such intensification are different: up to 10% \[9, 10\], up to 20% \[11, 12\] and up to 30% \[11, 13\], and work \[14\] shows an increase in oil recovery by 28–40%. Based on the conducted literature review, it can be concluded that the research in this area is very relevant.

It was investigated in this paper the two-phase flow of oil and nanofluid mixtures in the direct microchannels, which simulate a pore in the rock formation. The nanofluid was used as a displacing agent. The dependences of the oil recovery coefficient and the displacing efficiency on the average diameters of the nanoparticles were obtained. Two cases, when pure water was used as a displacing agent \[15\] and when nanofluid was used as it, were compared.

2. The computational domain and the mathematical model
The computational fluid dynamics method, namely, the numerical solution of the unsteady Navier-Stokes equations, were 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, \(\tau = \mu(\nabla \mathbf{u})^\sim\) is the viscous stress tensor, \(\mu\) is the fluid viscosity, and \((\nabla \mathbf{u})^\sim\) is the symmetric divergence-free second rank tensor. The full description of such approach can be found in many studies \[15-18\], so further in this paper will be given only the main points of the numerical technique. The method of finite volumes was used to find the difference analogue of convective-diffusion equations. The used calculation grids were
structured and multiblock. The second-order upwind schemes were used to carrying out the approximation of transport equations convective terms. The connection between the fields of the velocity and of the pressure is realized using the SIMPLEC procedure on combined grids [19]. Such connection ensures the fulfilment of the continuity equation. To obtain the difference equations the original system was discretized. An algebraic multigrid solver was used to iterative solving those equations. To describe the two-phase interaction and flow it was used the Volume-of-Fluid method, which is detailly considered in [15]. The scheme of the computational domain is shown in figure 1. The pore in the rock formation was simulated using a T-junction microchannel with a vertical channel, called a pore channel, which imitated the pore in the rock formation, and a horizontal main flow channel. The width and height (\(d_{fc}\) and \(h_{fc}\) in figure 1, respectively) of the main channel were equal to 200 µm. The width and height (\(d\) and \(h\) in figure 1, respectively) of the pore channel were varied from 100 µm to 800 µm. The entire channel is filled with oil at the initial time moment, then it is washed out by a displacing agent. The viscosity of the oil was equal to 0.0079 Pa·s and its density was equal to and 864 kg/m\(^3\). Pure water or nanofluid was used as the displacing agent. The viscosity of the water was equal to 1.003 mPa·s and its density was equal to 997 kg/m\(^3\). The surface tension coefficient of the water was equal to 2.23 N/cm and the contact angle between water and oil was equal to 72°. The nanofluid was considered using the single-fluid approach. The nanofluid properties were depended on the weight concentration of SiO\(_2\) nanoparticles of different average diameters and were taken from the experiment [20]. The parabolic velocity profile with the constant flow rate was set at the inlet of the main flow channel. The no-slip boundary conditions were set on the channel walls. The calculation grid consisted of about 2.5 million cells. This amount was enough to obtain a mesh-independent solution. The calculations were carried out in the CFD-package Ansys Fluent.

![Figure 1. The scheme of the computational domain](image)

3. Results and discussion
Numerical studies of the effect of the nanoparticles average diameters on oil displacing efficiency by the nanofluid were conducted. The Reynolds numbers varied from 0.1 to 100. The oil recovery coefficient, which defined as the ratio of the displaced volume of oil from the pore to the volume of the pore, was considered as the main investigated quantity. The results obtained for the pure water are shown in figure 2. As can be seen, pure water is a bad displacing agent, because only for pores with very huge width or very small height the oil displacing coefficient was higher than 10%. This once again confirms that oil is retained in the pores due to interfacial tension forces, and the contact angle of wetting is the main parameter affecting the efficiency of oil recovery. It is known that this angle is only 72° for water, so it cannot efficiently extract oil from narrow and deep pores. As was established in [20], for a nanofluid with a particle size of 5 nm, its value was 151°, for particles with a size of 18 nm, the contact angle was 117°, and for particles with a size of 50 nm, it was 90°. Thus, it should be expected that the oil recovery factor will decrease with an increase in the average nanoparticle size. As a result of numerical studies, it was found that this is indeed the case. It can be seen from figures 3-5, which represented the
dependences of the coefficient of oil recovery by nanofluid on the Reynolds number for different pore sizes and for average nanoparticle sizes of 5 nm, 18 nm and 50 nm, respectively. It should be noted, that each configuration has been studied at the same Reynolds numbers, however, if the resulting value were lower than 0.1%, it was considered as zero. That is why some points are absent in figures 3-5.

**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. 0.5 wt.% nanofluid of 5 nm particles as displacing agent

The shown above tendency was confirmed by analysis of the dependences of the relative oil recovery factor for nanofluids with different average nanoparticle sizes. Namely, with an increase in the particle size, the oil recovery efficiency decreases. These dependences were obtained by dividing the nanofluid oil recovery coefficient by the pure water oil recovery coefficient. It was established that for a nanofluid with an average particle size of 18 nm, the relative oil recovery factor is greater than one for all considered geometries, except for the widest pore, and for a nanoparticles size of 50 nm, for the narrowest and widest pores. The nanofluid with the nanoparticles of 5 nm average size shown the greatest results, namely, for each considered geometry its relative oil recovery factor was greater than one. Moreover, in some cases, it reached several thousand, but it needs to be careful with the values of this quantity because such an increase is explained by the extremely low values of the oil recovery coefficient for water. For example, as can be seen from figures 2a and 3a, for a case, when the pore size was 200 µm and the Reynolds number was equal to 50, the oil recovery coefficient obtained using water as a displacing agent was almost zero, and the oil recovery coefficient obtained using nanofluid with the nanoparticles of 5 nm average size as a displacing agent was about only 8%, but it is higher than the value for water in several hundred times. Despite the lower efficiency, the values of the oil recovery
factor obtained for nanofluids with larger nanoparticles can also exceed the corresponding values for pure water hundreds and thousands of times. At the same time, nanofluid based on nanoparticles with an average size of about 50 nm did not show a significant increase in the oil recovery factor in comparison with a similar value for pure water, because the values of the contact angle for such a nanofluid and pure water are quite close. In addition, it can be seen that the efficiency of oil recovery decreases with an increase in the Reynolds number. This is due to the fact that with an increase in the Reynolds number, separated flows begin to form in a channel of this configuration, whereas at low Reynolds numbers, there are no such separated flows. At even higher Reynolds numbers, such separated flows do not always fall inside the pore but pass over it. This situation takes place at small values of the channel width, therefore, e.g. for the channel width \( d = 200 \, \mu\text{m} \) at the Re = 50, such a dip in the value of the oil recovery factor is observed. Nanofluid significantly changes the displacement pattern, primarily due to the fact that it has a significantly higher contact wetting angle. This confirms the assumption that the main mechanism for increasing the efficiency of oil recovery due to the use of nanofluids is a significant increase in the contact angle of wetting when using the latter as a displacing agent in oil production technologies.

**Figure 4.** The dependences of the oil recovery coefficient on the Reynolds number for different widths (a) and heights (b) of pore. 0.5 wt.% nanofluid of 18 nm particles as displacing agent

**Figure 5.** The dependences of the oil recovery coefficient on the Reynolds number for different widths (a) and heights (b) of pore. 0.5 wt.% nanofluid of 50 nm particles as displacing agent

4. Conclusion
The numerical studies of the effect of the average diameters of nanoparticles on the oil displacing efficiency by the water or nanofluid were carried out. It was found, that the oil recovery coefficient increased with a decrease in the nanoparticles average diameters. It was found, that the pure water can
displace the oil from the pore only with huge width or very small height. The nanofluid with nanoparticles of 50 nm average diameter shown the similar results. It can be explained that the contact angle of wetting for pure water is very close to one for nanofluid. However, not only that one parameter affected the oil recovery coefficient, another important parameter is the viscosity of the displacing agent. Because the nanofluid has higher viscosity, in some cases it displaced the oil from the pore more efficient, than the pure water. The 18 nm and especially 5 nm nanofluid shows a significant increase in the efficiency of oil extraction, in some cases hundreds and thousands of times. This confirms the assumption that the main mechanism for increasing the efficiency of oil recovery due to the use of nanofluids is a significant increase in the contact angle of wetting when using the latter as a displacing agent in oil production technologies. Thus, the use of nanofluids as a displacing agent makes it possible to increase the efficiency of oil recovery, but it is necessary that such nanofluid has a high value of the contact angle of wetting.

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