Displacement of oil by SiO$_2$-nanofluid from a microporous medium: microfluidic experiments

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Abstract. In this work, the process of displacing oil from a microfluidic chip that simulates a porous medium is studied. Experimental photographs of the process of oil displacement by water and SiO$_2$-nanofluid are presented. It is shown that the use of nanofluid increases the oil displacement efficiency by 16%.

1. Introduction

Currently, methods for improving oil recovery are being actively investigated. One of the most relevant and promising methods for improving oil recovery is nanofluid flooding [1-4]. A nanofluid means a dispersed system consisting of a carrier liquid (for example, water) and nanoparticles [5].

Microfluidic studies using microporous rock models are becoming an alternative to conventional core flooding. [6-7]. Microfluidics (μικρός (micros) - small, fluidis - fluid) is an interdisciplinary science that describes the behavior of small (volume of the order of micro- and nanoliter) flows of liquids. The essential advantages of microfluidic studies are excellent visualization of the processes of oil displacement from the porous medium model, simple cleaning and the possibility of multiple use of the microfluidic chip.

This article presents the results of an experimental study of oil displacement by SiO$_2$ nanofluid from a microporous medium. The dynamics of the displacement process is shown. The study was carried out using the "lab-on-chip" microfluidic technology. It is found that the use of nanofluid improves the oil displacement efficiency.

2. Experimental materials and methods

This section describes the fluids used, microporous media, experimental setup, and procedure.

2.1. Properties of used fluids

In the work, crude light oil with a density of 856 kg m$^{-3}$ and a viscosity of 24.6 mPa s was used. Distilled water and a suspension of nanoparticles of silicon dioxide were used as displacement fluids. The mass concentration of nanoparticles was 2%. The nanofluid was obtained by diluting a Ludox TM-50
suspension (Sigma-Aldrich) with distilled water. The viscosity coefficient of the nanofluid, measured by the method in [8], was 0.939 mPa s. The nanoparticles had a spherical shape with the primary particle size of 22 nm. An image of SiO$_2$ nanoparticles obtained by a Hitachi S-5500 ultra-high resolution scanning electron microscope is shown in figure 1.

![Image of SiO$_2$ nanoparticles](image1.png)

**Figure 1.** SEM photo of SiO$_2$ nanoparticles.

The particle size distribution in liquid was obtained using an acoustic and electroacoustic spectrometer DT1202 (see figure 2). Suspension of nanoparticles of silicon oxide had a high stability (zeta potential is -31 mV). The average hydrodynamic particle size was 30 nm [9].

![Particle size distribution](image2.png)

**Figure 2.** Particle size distribution of nanoparticles in liquid.

2.2. *Microfluidic chip*

In this work, a microfluidic chip (Dolomite: 3200284) is used to simulate the complex porous structure of the rock. The chip is made of glass. The porous area is 10×60 mm. The chip has one inlet and outlet. The porous area is formed by repeating (150 times) a 2×2 mm square (see Figure 3). The channel arrangement in the square is an 8×8 channel grid. Channels in the mesh have constrictions or "pores" that are randomly distributed. The mesh contains 38 pores with Ø63 µm, 40 pores with Ø85 µm and 50 direct channels (Ø100×110 µm). The pore volume is 38 µl.
2.3. Experimental setup and procedure
The displacement fluid flow is controlled using an Elveflow OB1 MK3+ microfluidic pressure controller. The controller is equipped with a pressure channel from 0 to 8 bar, the accuracy of pressure maintenance is 100 Pa. The controller requires an external pressure source to operate. The compressed air from the pressure controller enters the sealed reservoir with the investigated displacing liquid (water or nanofluid). The microfluidic chip is connected to the reservoir with a 1/16 “OD PTFE tubing. The microfluidic chip is placed horizontally on a glass slide. The high-speed camera is located at the top above the chip, and the source is at the bottom. An MFS3 flow sensor, operating in the range 2.4 to 80 µl min$^{-1}$ with an accuracy of ± 5% of the measured value, is used.

The empty chip was first filled completely with oil, and then the process of flooding with fluid displacement took place at a fixed flow rate. Two to three pore volumes (PV) were pumped. The picture of the waterflooding process was recorded by a high-speed camera. After each experiment, the microfluidic chip was thoroughly sequentially washed with dichloroethane, isopropanol, distilled water, and air.

3. Results and discussions
First, an experimental microfluidic waterflooding was carried out. The microfluidic chip, completely filled with oil, was supplied with water at a volumetric flow rate of 45 µl min$^{-1}$. This corresponded to the capillary number Ca (a dimensionless parameter that determines the ratio of viscous forces to interfacial tension forces) of 1.6·10$^{-3}$. The dynamics of the process of oil displacement by water is presented in figure 4.

A special application was developed to calculate the oil displacement efficiency based on photographs of the distribution of oil and the displacing liquid in the pore space of a microfluidic chip. A set of images was obtained by converting video recordings using the free FFmpeg library. To develop the application, the BlackBox Component Builder component framework (Oberon microsystems, Switzerland) and the FreeImage library were used. The HSV (Hue-Saturation-Value) color model was used when analyzing the proportion of oil in a microfluidic chip. This application could detect the pixels occupied by oil, and thus water and oil saturation at a given time was determined.

Figure 4 shows the photos of the process of oil displacement by water at different points in time. The front of the water flow moves in the form of jets. Such jets quickly break through to the outlet, in about 10 s. After all the jets reach the outlet, the flow stabilizes. The displacement of oil stops.
The displacement of oil by nanofluid from a microporous medium occurs in a significantly different way. As it is shown in figure 5, the movement of nanofluid occurs with a more uniform front throughout the entire volume of the microfluidic chip. The nanofluid breaks through to the outlet from the microporous model later than water. The breakthrough time of the nanofluid before leaving the microfluidic chip is 15 s. Therefore, more oil is displaced with the help of nanofluid as compared to water.

The final distributions of oil fraction during displacement by water and nanofluid (see the last experimental flow patterns in Figures 4-5) differ significantly. It is clearly seen that when displaced by water, large areas filled with oil remain, which are held by capillary forces. When using a nanofluid as a displacing fluid, there are much fewer such regions.
Figure 5. Photos of the process of displacing oil from a microfluidic chip by nanofluid.

The dependence of the oil displacement factor on time is shown in figure 6. Figure 6 shows that at the initial moment, the oil recovery factor (ORF) increases linearly (in proportion to the flow rate of the displacing fluid). After the displacement fluid reaches the outlet, the growth of ORF is slowed down. After pumping one pore volume, the ORF value does not change. It was found that ORF during water flooding was 60%, and it was 76% during nanofluid flooding.

There are many factors influencing the oil displacement efficiency. These factors include viscosity, density, interfacial tension, and wettability. However, as it is noted earlier [10], the main factor is wettability. Nanofluid affects the wettability, contributing to the washing out of capillary retained oil [11].
Figure 6. Dynamics of change in the oil recovery factor in time.

4. Conclusions
In this work, an experimental study of the process of displacing oil with water and 2% SiO\textsubscript{2}-nanofluid from a microporous medium was carried out. The study was carried out using the "laboratory on a chip" technology. Microfluidic chip with microporous medium simulating rock was used.

As a result, the dynamics of the oil displacement process versus the time of the displacing fluid (water and nanofluid) was obtained. It is shown that 2% -nanofluid increases the oil recovery factor by 16% as compared to water.

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