Application of microfluidic technologies for enhanced oil recovery

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Abstract. This paper presents the results of testing microfluidic technology for oil displacement problems using cheap and quickly manufactured chips made of polymethylmethacrylate (PMMA) by milling. The oil displacement process from a microfluidic chip simulating a homogeneous porous medium is studied. The microfluidic chip was manufactured by milling of polymethylmethacrylate. The size of the microchannels was 200 microns. The paper presents the results of visualization and microscopy of the oil displacement process. The effect of water flow on the efficiency of oil displacement from the microfluidic chip was studied.

Introduction

One of the most relevant and promising areas of contemporary fluid mechanics is microfluidics [1-8]. The development of microfluidics is associated with a significant reduction in the size of devices and improvement of their technical characteristics. Modern microfluidic devices, in which the characteristic channel size ranges from several microns to hundreds of microns, are used as microreactors for mixing and synthesis, particle microseparators, in biomedicine, as cooling components for microelectromechanical systems (MEMS), and microsensors for environmental monitoring [1-6]. In recent years, microfluidic chips have been actively used to study methods for enhancing oil recovery during reservoir flooding [7-8]. The relevance of recent studies is related to the need to increase the oil displacement efficiency during flooding with various displacing liquids and gases, as well as to study the permeability of a microporous medium. This paper presents the results of testing microfluidic technology for oil displacement using cheap and quickly manufactured chips made of polymethylmethacrylate (PMMA) by milling.

1. Fabrication of a microfluidic chip

In this work, a microfluidic chip with a regular lattice was made for modeling a porous medium (Fig. 1). The chip was made by the milling method and thermal bonding. The capillary network pattern with an aspect ratio of elements of no more than one was made by milling the surface of...
polymethylmethacrylate (Novattro, Russia). Milling mode in water for a two-pronged cutter with a diameter of 200 microns and a length of working body 0.6 mm (RM-0020.3.006.40, RDM, Russia) was as follows: the cutting speed was 9.42 m/min; the feed per prong was 2.5 microns; the cutting depth was 30 microns. Water milling mode for a single-point milling cutter with a diameter of 0.5 mm and a working body length of 1.5 mm (0068005E, Datron, Germany) was as follows: the cutting speed was 23.56 m/min; the feed per single-point was 5 microns; the cutting depth was 50 microns. The resulting PMMA chip was glued to the bottom of a Petri dish of suitable sizes using double-sided adhesive tape. The mixed and degassed MixArt Resin epoxy compound was poured into a Petri dish so that the chip was hidden under its layer by at least 5 mm. Then degassing was repeated. Floated air bubbles were removed using Debubblizer spray (KERR manufacturing comp., USA). The sample was left overnight, after which the final polymerization was performed at a temperature of 80°C for one hour. The plate was removed at room temperature using a lever. Dust extraction was carried out by air jet. The resulting master mold was filled with mixed and degassed PDMS Sylgard-184 (DowCorning, USA) and its polymerization was carried out according to the manufacturer's instruction manual. Sealing of chips made of PDMS was performed by glass slides. To do this, the slides were washed in isopropanol OSCh OP-1 (Vecton, Russia) and distilled water, the remaining liquids were blown off with an air jet, the remaining dust particles were removed using office adhesive tape FT510281676 Scotch "Magic" (3M, USA). After that, plasma cleaning and activation of the connected surfaces were performed for two minutes using the d'Arsonval DE-212KARAT device (SMP, Russia) with an all-metal electrode which was repeatedly swept over the treated surface at a distance of 1-2 mm. After processing, they were tightly pressed against each other to join through the adhesion, though not too strongly, to avoid deformation of the chip topology. Then the resulting microfluidic chip was heated at a temperature of 125°C for 15 minutes.

![Figure 1. Photo of a chip with microchannels.](image)

2. Results and discussion

To develop the methodology for studying the oil displacement process, a microchannel chip was fabricated, whose geometry is shown in Fig. 1. The number of cells is 30x30 (the number of microchannels is 31x31), the cell side size is 250 microns. The width and height of the microchannels are 250 and 200 microns, respectively, the length of the inlet section is 2.36 mm. The length of the outlet section is 4.9 mm. At the initial moment, the grid is completely filled with oil. Light crude oil with a density of 851 kg/m³ and a viscosity of 24.6 mPa·s was used in the work. Distilled water was supplied to the chip inlet. Using a video camera and a microscope, the dynamic of oil displacement
was obtained, and the pressure drop behavior over time was measured at a fixed flow rate. The displacement water flow rate varied within the range from 25 to 500 µl/min.

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 the water and oil saturation at a given time was determined.

![Figure 2. Photo of a microchip after displacement of oil by water at different flow rates, a) 25 µl/min b) 50 µl/min c) 100 µl/min d) 250 µl/min.](image-url)

Figure 2 shows enlarged photos of the microchip after pumping three pore volumes of oil through it at different flow rates. In this case, one pore volume of the chip is equal to 27.3284 µl. The water flow was directed diagonally from the lower-left corner to the upper right corner. The capillary number \(Ca = \mu U / \sigma\) was determined by the properties of the displacing liquid and the average discharge.
velocity varied from $4 \times 10^{-4}$ to $8.7 \times 10^{-3}$. This corresponded to the pressure displacement mode. As can be seen, at this displacement mode, large areas of capillary-retained oil remain in the corners of the chip. With an increase in water flow rate, these areas decrease. Besides, significant residual oil saturation remains in the washed area. Here, the oil remains in the form of liquid bridges between the grains of a porous medium. This is seen in Fig. 3, which presents a photo of a microchip under a microscope. Microscopy allowed establishing that another source of oil, retained after flooding, is very thin oil films enveloping the grains of a porous medium. At that, the proportion of these films does not change with an increase in the displacing liquid flow rate. To wash them out, it is necessary to use surfactant solutions that change the wetting angle changing thereby surface tension forces.

![Figure 3](https://via.placeholder.com/150)

**Figure 3.** Photo of residual oil in a microchip under a microscope a) 25 µl/min; b) 250 µl/min.

The dependence of the enhanced oil recovery (EOR) on the time during the displacement process is shown in Fig. 4. In the initial section, the dependence of EOR on time is linear and corresponds with high accuracy to the injected liquid volume determined by the water flow rate set by the pump. After the water breaks through to the microchip outlet, the growth in the EOR slows down sharply, especially at low flow rates. With an increase in the flow rate of the displacing fluid, the breakthrough time monotonically decreases. Minor fluctuations in the EOR at the final stage of displacement are associated with the rearrangements of the bridges and the separation of small oil droplets.

![Figure 4](https://via.placeholder.com/150)

**Figure 4.** The EOR dynamic pattern during oil displacement from a microfluidic chip at different water flow rates.
The dependence of the EOR on the flow rate and the capillary number is shown in Fig. 5. With an increase in the flow rate of the displacing liquid, the EOR monotonically increases. This corresponds to the pressure displacement mode. When the water flow rate increases 20 times, the EOR increases by 23%.

![Figure 5](image.png)

**Figure 5.** The dependence of the EOR on the flow rate of the displacing liquid (a), and the capillary number (b).

**Conclusion**

The development of pilot versions of experimental micro-scale models for studying filtration processes during oil displacement has been carried out. Micro-scale models of porous media are developed based on microfluidic chips. The laboratory-on-a-chip technology was chosen for the production of microfluidic chip models. This technology makes it possible to produce layer-by-layer microchips: a buried pattern is formed on the surface of a plate made of some material, which is sealed by the smooth surface of another plate, forming a capillary network at the junction between the plates.

This paper presents the results of testing microfluidic technology for oil displacement using cheap and quickly manufactured chips made of polymethylmethacrylate (PMMA) by milling. The main advantages of this material are its low cost, ease of processing, sufficient strength, and resistance to a large number of chemical reagents used to enhance oil recovery. A study of the oil displacement process, as well as its visualization, was carried out employing a microchip, fabricated using described technology. The dependences of the oil displacement efficiency on the time and flow rate of the displacing agent were obtained. It is shown that with an increase in water flow rate, the oil displacement efficiency increases. The microstructure of residual oil on the microchip walls was studied using microscopy. Thus, the possibility of using microfluidic chips made of PMMA by milling was demonstrated when studying methods of enhancing oil recovery.

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