The numerical investigation of the oil displacing efficiency from the pore in the rock formation depending on the width and height of the pore

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Abstract. The calculated study of the oil displacing by the water from straight microchannels, which simulate a pore in the rock formation, was carried out. The Reynolds numbers were varied in the range from one to 1000. The channel’s width and height were in the range of 100 μm to 800 μm. The «Volume of Fluid» (VOF) numerical method with the «Continuum Surface Force» (CSF) algorithm was used. It was found that the oil recovery coefficient increases with a decrease in the height of the pore microchannel and with an increase of its width. In case of constant channel width, the oil recovery coefficient: increases in the ranges of Reynolds numbers from 1 to 50 and from 100 to 400 and decreases in the ranges of Reynolds numbers from 50 to 100 and from 400 to 1000. In case of constant channel height, the oil recovery factor behaves as follows: at \( h = 100 \mu m \) it slightly increases in a whole range of Reynolds numbers; at \( h = 200 \mu m \) its behaviour is the same the in case of constant channel width; at \( h = 400 \mu m \) it sharply increases in the ranges of Reynolds numbers from one to 50 and slightly decreases in the ranges of Reynolds numbers from 50 to 1000; at \( h = 800 \mu m \) it sharply increases in the ranges of Reynolds numbers from one to 100 and sharply decreases in the ranges of Reynolds numbers from 100 to 1000. Such behaviour in both cases can be explained by the competition between the forces of inertia and capillary, but further research is needed for a more complete understanding. It was also found that, in almost all cases, the oil recovery coefficient does not exceed 10%. It follows that water is a poor washing agent in terms of oil recovery from reservoirs.

1. Introduction
In the past several decades in the Russian Federation, as well as in other countries the oil and gas industry became the most important economic sectors. Unfortunately, oil reserves will not endless and the oil fields are gradually depleting. That is why develop and apply the new oil production technologies are strongly needed. Their use will allow significantly increasing the oil recovery of both already developed and used and mothballed fields. The significant residual oil reserves in them cannot be extracted due to traditional methods, but to solve these problems it is possible to use the micro and nanotechnologies. It can be stated that interest in capillary hydrodynamics and heat transfer in microsystems has significantly increased at present, and there is a rapid increase in the number of studies in that field [1-3]. The microreactor devices can intensify the physicochemical processes in contrast to classical large-sized reactors, as it was noted in many studies [4, 5]. In addition, ideas about
the possibility of using microchannel chips of a very complex shape with pore sizes up to several microns, which can be considered as a system that simulates an oil core, are being expressed. The two-phase flows in microchannels that simulate oil washing out of the rock can be studied using such chips. Moreover, such studies can be not only experimental but numerical too. However, at the moment, all this remains at the level of an idea, and there is just a little number of such works [6].

In general, the most common oil production operation is water flooding into the reservoir, but the efficiency of such a method is unsatisfactory and the unrecoverable oil reserves in the stratum reach an average of 55-75%. Therefore, oil recovery enhancement is extremely important.

A direct numerical simulation (DNS) with full resolution of the boundary interface can be considered as the only universal technique to simulate the two-component flows of oil and a displacing agent in straight microchannels, which modelling the pore or the crack in the rock formation [7]. Unfortunately, this method has a very high computational cost, so it can be used only for a few numbers of tasks or to obtain the data, which verify other approaches. The use of adaptive computational grids can partially solve that problem [8]. On the other hand, there are less expensive in terms of computational cost method called VOF-method (Volume Of Fluid). That fundamental approach has proven itself well in simulating the two-phase flows of oil and a displacing agent in straight microchannels [9, 10]. Both methods are very demanding on computational resources, but only these approaches allow to resolve the interphase boundary between two immiscible fluids and to obtain the flow patterns and regimes in such microchannel system, which close to true.

Thus, the oil and gas industry is in great need of technologies, which enhance oil recovery from fields, both developed and mothballed. Therefore, it is extremely important to conduct numerical studies of the flow of two-phase mixtures of oil and a washing agent in straight microchannels, which simulate a pore or crack in the rock. That study was carried out in this work.

2. Numerical procedure and computational domain

The computational fluid dynamics approach was used in the study. The microflows of incompressible multi-component fluids were simulated by means of the solving of the Navier-Stokes equations system:

\[
\frac{\partial \rho}{\partial t} + \nabla (\rho \mathbf{v}) = 0, \quad \frac{\partial \rho \mathbf{v}}{\partial t} + \nabla (\rho \mathbf{v} \mathbf{v}) = -\nabla P + \nabla \mathbf{T},
\]

where $\rho$ is the fluid density, $\mathbf{v}$ is its velocity, $P$ is the pressure and $\mathbf{T}$ is the viscous stress tensor, which components are defined as follows:

\[
\mathbf{T}_{ij} = \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right).
\]

Here $\mu$ is the viscosity of the mixture, $u_{ij}$ is the components of the velocity vector. The density and the viscosity of the mixture are defined by means of the mass fractions of the mixture component $f$ and partial densities $\rho_{1,2}$ and molecular viscosities $\mu_{1,2}$ of pure components of the mixture:

\[
\mu = f \mu_1 + (1 - f) \mu_2, \quad \frac{1}{\rho} = \frac{f}{\rho_1} + \frac{(1 - f)}{\rho_2}.
\]

The evolution of mass concentrations is defined as follows:

\[
\frac{\partial \rho f}{\partial t} + \nabla (\rho f \mathbf{v}) = \nabla (\rho D \nabla f).
\]

Despite a large number of methods for describing microflows, the hydrodynamic approach, described above, remains the most common and convenient [11–15].

The method of finite volumes for structured multiblock grids was used to find the difference analogue of convective-diffusion equations. In this case, the resulting scheme can be automatically considered as conservative. In the method of finite volumes, the finite-difference relations have been obtained by partition to control volumes of the computational domain and then the initial equations of conservation have been integrated by each control volume. The convective terms of the equations of
transport have been approximated by the QUICK scheme, which is second-order upwind. The non-stationary terms of the equations of hydrodynamic have been approximated by an implicit second-order scheme. The source terms and the diffusion fluxes have been approximated by the second-order finite-volume analogues of central-difference relations. The fulfillment of the continuity equation has been ensured by SIMPLEC procedures on combined grids, which allow implementing the relation between the pressure velocity fields. The oscillations of the pressure field were eliminated due to the Rhi-Chou approach, which consists of pressure correction by means of the introduction of a monotonizer into the equations. An algebraic multigrid solver has been used to solve iteratively the differential equations, which were obtained as a result of the discretization of the original system of equations.

In this work, a numerical technique based on the Volume of Fluid method [16] was used to simulate two-phase flows. This technique has proven itself well for calculating macroscopic flows with a free surface [17]. The idea behind this method is that different fluids are considered as a single two-component medium. The spatial distribution of phases within the computational domain is determined using a special marker function \( F(x, y, z, t) \). The value of that function sets the volume fraction of the phase of each fluid in the computational cell as follows:

\[
F(x, y, z, t) = \begin{cases} 
0, & \text{if the cell is empty} \\
> 0 \text{ and } < 1, & \text{if a phase boundary passes through the cell} \\
1, & \text{if the cell is fully filled with the fluid}
\end{cases}
\]

Figure 1 shows an example of representation of the phase boundary of fluids using the fraction of one fluid in a cell.

\[ \frac{\partial F_f}{\partial t} + v \nabla F = 0, \]

where \( v \) is the velocity vector of a two-component medium, which found from the solution of the equations system of hydrodynamics, that consisting of the mass conservation equation or the equations of the continuity and the motion or the law of momentum conservation (1).

When considering flows of fluids with the phase boundary interface, one has to face the phenomenon of surface tension, which cannot be neglected in the case of flow in microchannels, since it plays a key role in them. The study of flows controlled by the surface tension forces is very difficult. The VOF method makes it relatively easy to take into account the effect of surface tension forces, which can also be attributed to the advantages of this method.

Most often, to simulate the surface tension within the VOF method, the CSF (continuum surface force) algorithm [18] is used. Its essence is to introduce an additional volume force \( F_S \) into the equations of motion. The magnitude of the body force is determined through the surface tension coefficient and the curvature of the phase boundary interface, which is the divergence of the normal vector. The normal to the phase boundary interface is calculated, in turn, as the gradient of the volume fraction of one of the fluids in the cell. In this case, on a solid wall, the value of the normal vector is determined by the contact angle of wetting.
The geometry of the task was the straight microchannel with T-shaped dividing. The width and height of the channel were equal to 200 µm. The width and the height of the channel, simulating the pore in the rock formation were varied. The channel’s width and height were in range of 100 µm to 800 µm, which according to 0.5$d_h$ to 4$d_h$ ($d_h$ is hydraulic diameter equals to 200 µm). The two-block grid of 10 million grid nodes was used. A steady-state velocity profile, which according to constant flow rate, was set at the inlet. Zero normal to the outlet surface derivatives of all scalar quantities were set at the outlet. On the walls of the channels were set the no-slip boundary conditions. At first, the channel is filled with oil, which density and viscosity were equal to 864 kg/m³ and 0.0079 Pa·s, respectively. The pure water was supplied to the mixer through the inlet. Its density and viscosity were equal to 998.2 kg/m³ and 0.001003 Pa·s, respectively. The explicit formulation of volume fraction parameters of the Volume of Fluid method was used. The surface tension coefficient and the contact angle between oil and water were set constant and equal to 2.23 N/cm and 108°, respectively.

3. Results and discussion
The flow regimes of fluids in straight microchannels, as well as the conventional channel, are depended on the Reynolds number. Nevertheless, due to their small sizes, the Reynolds numbers in them rarely reach 1500. Therefore, in this work the Reynolds numbers were varied from one to 1000. The results of the simulation are shown in figure 2. The concentration profiles in different microchannels at Reynolds numbers equal to 100 and 250 are shown in figures 3 and 4. Red colour corresponds to water, blue colour corresponds to oil.

![Figure 2](image-url)  
**Figure 2.** The dependencies of volume fraction of oil in the pore on the Reynolds number at different widths (a) and heights (b) of the microchannel, which simulates pore in the stratum.

As one can see, the oil recovery coefficient increases with a decrease in the height of the pore microchannel. When the width of the pore microchannel increases the oil recovery coefficient, on the contrary, increases. It is expected result, because, in case of constant pore channel width, the capillary force is the same for channels with different height, as well as the amount of the oil, which washing out. At the same time, the volume of the pore channel, and consequently the volume of the oil increases as the channel height increases, so the ratio of the amount of remaining oil to its initial amount decreases with an increase of the channel height. The same conclusions can be applied to explain the behaviour of the dependence of the oil volume fraction at a constant channel height and an increase in its width. As the channel’s width increases the capillary force decreases and the water more easily washing out the oil from the pore.
More interesting the behaviour of the dependence of the volume fraction of oil on the Reynolds number. In case of constant channel width, the relative remaining amount of oil is divided into four regions. At first, the oil recovery coefficient increases (this corresponds to a decrease in the relative amount of the remaining oil in figure 2b) till the Reynolds number equals to 50. Then, at Reynolds number equals to 100 the oil recovery coefficient returns to the value, corresponding the one at Reynolds number equals to one. In the next region, the oil recovery coefficient starts to increase again until the Reynolds number equals to in average 400, and after that, this value begins to decrease. In case of constant channel height, approximately the same behaviour is observed: there is some critical Reynolds number, at which the increase of the oil recovery coefficient changes to decrease. Such behaviour in both cases can be explained by the competition between the forces of inertia and capillary, but further research is needed for a more complete understanding.

4. Conclusions
The oil displacing by the water from straight microchannels, which simulate a pore in the rock formation, were numerically investigated. The Reynolds numbers were varied in the range from 1 to 1000. The channel’s width and height were in the range of 100 μm to 800 μm, which according to 0.5$d_h$ to 4$d_h$, where $d_h$ is hydraulic diameter equals to 200 μm. The «Volume of Fluid» (VOF) numerical method with the «Continuum Surface Force» (CSF) algorithm was used to simulate the two-phase flows in considered microchannels. A steady-state velocity profile and Neumann conditions were used as boundary conditions. The no-slip boundary conditions were set on the walls of the channels.

It was found that the oil recovery coefficient increases with a decrease in the height of the pore microchannel and with an increase of its width. It can be explained because the capillary force is the same for channels with different height and constant width, but increases at a constant channel height and an increase in its width. The behaviour of the dependence of the volume fraction of oil on the Reynolds number is more interesting. Namely, in case of constant channel width, the relative remaining amount of oil is divided into four regions: the oil recovery coefficient increases in the ranges of Reynolds numbers from one to 50 and from 100 to 400 and decreases in the ranges of Reynolds numbers from 50 to 100 and from 400 to 1000. In case of constant channel height, the oil...
recovery factor behaves as follows: at \( h = 100 \, \mu\text{m} \) (0.5\( d_h \)) it slightly increases in a whole range of Reynolds numbers; at \( h = 200 \, \mu\text{m} \) (1\( d_h \)) its behaviour is the same the in case of constant channel width; at \( h = 400 \, \mu\text{m} \) (2\( d_h \)) it sharply increases in the ranges of Reynolds numbers from one to 50 and slightly decreases in the ranges of Reynolds numbers from 50 to 1000; at \( h = 800 \, \mu\text{m} \) (4\( d_h \)) it sharply increases in the ranges of Reynolds numbers from one to 100 and sharply decreases in the ranges of Reynolds numbers from 100 to 1000. Such behaviour in both cases can be explained by the competition between the forces of inertia and capillary, but further research is needed for a more complete understanding. Another important conclusion is that, as can be seen from figure 2, in all cases, except the case, \( h = 800 \, \mu\text{m} \) (4\( d_h \)), the oil recovery coefficient does not exceed 10%. At \( h = 800 \, \mu\text{m} \) (4\( d_h \)), the oil recovery factor reaches 30% with the Reynolds number equal to 100, but pores of this width are quite rare. It follows that water is a poor washing agent in terms of oil recovery from reservoirs, and it is necessary to look for ways to increase the oil recovery factor. The most promising are the ways of changing the surface tension coefficient and capillary force. Such studies will be conducted in the future.

Acknowledgments

The work is performed at partial financial support of the Russian Foundation for Basic Research, Government of Krasnoyarsk Territory, Krasnoyarsk Region Science and Technology Support Fund (Contract No. 19-48-240015: «Investigation of the oil recovery enhancement of the hydrocarbon-bearing stratum through using microfluidic technologies and by means of the nanosuspensions as the displacing agent»).

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