The numerical study of the flow regimes of two-phase oil and displacing agent mixtures in straight microchannels simulating a pore or crack in the rock formation

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\textbf{Abstract.} The calculated study of the flow regimes of two-phase oil and water mixture in straight microchannels simulating a pore or crack in the rock formation was carried out. It was shown as a result of the literature survey that all modern, industrially developed methods of the oil recovery from the oil reservoirs is considered as unsatisfactory in all oil-producing countries. The average value of the final oil recovery is varied from 25\% to 45\%, so, it is easy to count, that residual or unrecoverable oil reserves in the subsoil reach an average of 55-75\% of their initial values. Also, it was found, that the use of micro and nanotechnologies in a broad sense is one of the possible and promising ways to solve these problems. A numerical method called «Volume of Fluid» (VOF) was used to simulate the two-phase flows of oil and displacing agents in the considered microchannels. It was proposed to use the dimensionless number, called Regime number, to describe the different flow regimes of oil/water mixture and transitions between these regimes. The plug flow, the slug flow, the parallel flow and the emulsion flow regimes were observed.

1. \textbf{Introduction}

The oil and gas industry is one of the most important sectors of the economy not only in the Russian Federation but also in many foreign countries. The gradual depletion of oil fields is happening everywhere, so the issues of developing and applying new oil production technologies that can significantly increase the oil recovery of already developed formations, as well as used and mothballed fields where it is no longer possible to extract significant residual oil reserves by means of traditional methods, are becoming urgent. The use of micro and nanotechnologies in a broad sense is one of the possible and promising ways to solve these problems. Many research groups around the world are working in this direction. It is noted in many studies that the use of microreactor devices can significantly intensify the physicochemical processes in comparison with classical large-sized reactors [1–3]. In addition, it is possible to use the microchannel chips of a very complex shape with pore sizes of up to several microns, which can be considered as a core simulating system for studying two-phase flows in microchannels mimicking the washing out of oil from a rock. Moreover, such studies can be both experimental and numerical. However, at the moment, it remains only an idea, and there are not many such works [4].

In general, oil production operations are divided into three stages: primary, secondary and tertiary [5]. Primary production is carried out due to the displacing energy that naturally exists in the reservoir, such as displacement by dissolved gas, oil displacement by expansion pressure of the gas cap and
displacement by natural water, etc. [6]. Secondary oil production processes are water flooding and gas injection into the reservoir. Tertiary processes use miscible gases, chemicals, and/or thermal energy to displace additional oil after the secondary extraction process [7]. There are some differences between secondary and tertiary processes. Injected fluids in secondary processes supplement the natural processes of oil displacement from the reservoir. The efficiency of oil recovery mainly depends on the pressure maintenance mechanism. In tertiary processes, the injected fluids interact with the rock/oil system. These interactions can lead to a decrease in interfacial tension, to swelling of the oil reservoir, to a decrease in oil viscosity, or to a change in wettability. In some situations, the so-called tertiary process can be used as a secondary operation. Thus, the term “tertiary extraction” has ceased to be used in the literature, and the designation “enhanced oil recovery” has become more acceptable [7].

As already noted, the efficiency of all modern, industrially developed methods of the oil recovery from the oil reservoirs considered as unsatisfactory in all oil-producing countries. The average value of the final oil recovery is varied from 25% to 45%, while the residual or unrecoverable oil reserves in the subsoil reach, as it is easy to count, an average of 55-75% of their initial geological reserves. Therefore, enhance of oil recovery is of course extremely important.

The only universal tool for calculating the flows of two-component flows of oil and a displacing agent in direct microchannels simulating a pore or a crack in a rock is a direct numerical simulation (DNS) with full resolution of the boundary interface. Examples of such modelling can be found in [8–11]. But in view of the enormous computational costs, this method can be used for a long time only for a narrow class of model problems and for obtaining data to verify other approaches. To partially solve this problem, adaptive computational grids are used [12]. Another detailed fundamental approach is the numerical simulation of two-phase flows of oil and a displacing agent in direct microchannels using methods based on VOF- (Volume Of Fluid) and LES- (Large Eddy Simulation) models [13, 14]. Although all the methods listed above are very demanding on computational resources, they are the only methods that allow resolving the interphase boundary of two-component flows of immiscible fluids and obtaining pictures and flow regimes of such fluids in microchannels close to true.

Thus, conducting the systematic studies of the use of micro- and nanofluidic technologies in the operation of oil wells, both already developed and used or mothballed, is extremely important for the oil and gas industry. Therefore, in this work, the flow of two-phase mixtures of oil and a displacing agent in direct microchannels that simulate a pore or crack in the rock was studied.

2. Numerical procedure and computational domain

Numerical modelling is a powerful tool that helps to understand the basic processes occurring inside microchannels that simulate a pore or a crack in a rock, as well as obtain optimal parameters of displacing agents that maximize the oil recovery processes of already developed formations, as well as used and mothballed fields, on which traditional methods to extract significant residual oil reserves is no longer possible. The methods of computational hydrodynamics based on the numerical solution of spatial and non-stationary Navier-Stokes equations, supplemented by the equations of the law of conservation of energy, transfer and diffusion of components are used as the main theoretical approach to solving the problems. Currently, there are a large number of methods for describing microflows, but the hydrodynamic method deserves the most attention [15–17].

The difference analogue of convective-diffusion equations is found using the finite volume method for structured multiblock grids, so, in such case, the resulting scheme is considered conservative automatically. The essence of the method is to obtain finite-difference relations due to the dividing of the computational domain into control volumes and the integrating of the initial conservation equations for each such control volume. The second-order upwind schemes QUICK is approximate the convective terms of the transport equations. The unsteady terms of the hydrodynamic equations are approximated by an implicit second-order scheme. The second-order finite-volume analogues of central-difference relations are used to approximate the diffusion fluxes and source terms. The using of SIMPLEC procedures on combined grids implement the relation between the velocity and pressure

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fields, which ensures the fulfillment of the continuity equation. A monotonizer is introduced into the equations for pressure correction to eliminate the oscillations of the pressure field. It is the Rhi-Chou approach. Difference equations, which were obtain as a result of the original system of differential equations discretization are solved iteratively by means of an algebraic multigrid solver.

To simulate the two-phase flows of oil and displacing agents in direct microchannels, that simulate a pore or crack in a rock, it is proposed to use a numerical method called «volume of fluid» (VOF), which has proven itself to calculate two-phase flows in microchannels [13, 14]. The essence of such method is that fluids are considered as a single two-component medium and the spatial distribution of phases within the computational domain is determined using a special marker function that specifies the volume fraction of the liquid phase in the computational cell. Special attention should be paid to the phenomenon of surface tension while calculating the flow of two-component flows of immiscible fluids. For its simulation within the VOF method, the CSF algorithm will be used, which implies the introduction of an additional force into the motion equation. That force is determined on the surface of the fluid through the gradients of the volume fraction of fluid in the computational cell. It is well known that to solve the problem of direct modelling of the two-component flows of immiscible fluids it is required sufficiently detailed computational grids to resolve the oil/displacing agent interface. To solve that problem, it is proposed to use the technology of gradient adaptation of the computational grid. The computational grid in the process of calculating is automatically condensed in the region of large concentration gradients with the use of that technology. In this case, the gradient of the volume fraction of the fluid is used as the control parameter. The grid cells in the interface area can be fourfold to sixteenfold smaller than in the original grid. Due to that technology, it is supposed to obtain a solution that is acceptable in terms of accuracy available on the calculated grids.

The geometry of the task was T-shaped micromixer. The channel thickness is 200 µm, while the width of its narrow and wide parts is 200 µm and 400 µm, respectively. The four-block grid of 7 million grid nodes was used for calculations in this work. The constant fluid flow rate with a steady-state velocity profile was set at the inlets of micromixer. Neumann conditions meaning zero derivatives of all scalar quantities normal to the outlet surface were set at the outlet of the mixing channel. The walls of the mixer were considered as insulated. The no-slip condition was taken as a boundary condition on the walls of the channels for the velocity vector components. Pure water was supplied to the mixer through one of the inlets with the mass flow rate \(Q_{o,in}\). Its density was 998.2 kg/m³ and the viscosity was 0.001003 Pa·s. The oil, which density was 864 kg/m³ and the viscosity was 0.0079 Pa·s, was supplied through another inlet with the flow rate \(Q_{w,in}\). The explicit formulation of volume fraction parameters of Volume of Fluid method was used. The surface tension coefficient between oil and water was set constant and equal to 2.23 N/cm. The contact angle between oil and water was set constant too and equal to 108°.

3. Results and discussion

The flows of immiscible fluids in straight channels and microchannels are characterized by different flow regimes [18–21]. It’s usually observed following flow regimes: droplet flow, plug flow, slug flow, parallel or stratified flow, deformed interface flow, annular and annual droplet flow, and dispersed flow. The emergence of a certain flow regime is determined by the balance of the forces. In addition, the flow regime depends on the balance of inertia and surface tension forces, which expressed by Weber number \(\text{We}\). Here and next, we will call that dimensionless complex as “the regime number” (Rn). So \(\text{Rn} = \text{We} \cdot \text{Oh}\), the Weber number is defined as \(\text{We} = \rho \cdot L \cdot v^2 / \sigma\) and the Ohnesorge number is defined as \(\text{Oh} = \mu / (\sigma \cdot \rho \cdot L)^{0.5}\). Here \(\rho\) is the density of the fluid, \(v\) is its velocity, \(L\) is its characteristic length, \(\sigma\) is the surface tension, \(\mu\) is the dynamic viscosity of the fluid. On the other hand, we can recombine these parameters: \(\text{Rn} = \rho \cdot L \cdot v^2 / \sigma \cdot \mu \cdot (\sigma \cdot \rho \cdot L)^{0.5} = \mu \cdot 0.5 \cdot L^{0.5} \cdot v^2 / \sigma^{1.5} = (\mu / \sigma)^{0.5} \cdot (\rho \cdot L \cdot v / \mu)^{0.5} = \text{Ca}^{1.5} \cdot \text{Re}^{0.5}\), where \(\text{Ca}\) is the capillary number and \(\text{Re}\) is the Reynolds number. In many studies (for example, [19], where the flow of castor and paraffin oils was studied) it was shown that the use of the regime number allows one to
construct an obvious map of the flow regimes of two immiscible fluids in microchannels. In the T-shaped microchannel, droplet flow, plug flow, slug flow and parallel flow regimes are most often implemented. As a result of numerical studies of the flow of water and oil in the T-mixer, it was found that the regimes defined in [19] correspond approximately to the regimes defined in this work. Figure 1 represents the concentration profiles of water and oil in the central longitudinal section of a T-shaped micromixer for various flow regimes. It was found that a feature of such a system is the absence of a droplet regime, namely, as the flow rates of fluids increase, the flow from slug flow goes directly to parallel flow. Most likely this is due to the fact that in all the previously considered works, the contact angle of wetting of the channel wall with fluids is not taken into account. This parameter is critically important in determining the oil recovery coefficient; its effect will be investigated in the future. After the slug flow regime, it begins the parallel flow regime (Fig. 1c). As the flow rates of the fluids further increase, another interesting regime, called the emulsion flow regime, occurs (Fig. 1d). Such a regime is rather unusual because it realized at significantly high values of fluids flow rates. However, it is necessary to know the properties of that regime because it provides quite high values of oil recovery coefficient.

![Figure 1](image_url)

**Figure 1.** The concentration profiles of water and oil in the central longitudinal section of a T-shaped micromixer for various flow regimes: a) The plug flow regime, \( R_{n_w} = R_{n_o} = 10^{-6} \); b) The slug flow regime, \( R_{n_w} = 4 \cdot 10^{-6}, R_{n_o} = 7.5 \cdot 10^{-4} \); c) The parallel flow regime \( R_{n_w} = R_{n_o} = 10^{-4} \); d) The emulsion flow regime, \( R_{n_w} = R_{n_o} = 10^{-5} \)

**Conclusions**

The flow regimes of two-phase oil and displacing agent mixture in straight microchannels simulating a pore or crack in the rock formation were numerically investigated. The pure water is considered as a displacing agent. The literature review was carried out in this work. It was found, that the efficiency of all modern, industrially developed methods of the oil recovery from the oil reservoirs considered as unsatisfactory in all oil-producing countries, and the average value of the final oil recovery is varied
from 25% to 45%, while the residual or unrecoverable oil reserves in the subsoil reach, as it is easy to
count, an average of 55–75% of their initial geological reserves. Moreover, the gradual depletion of oil
fields is happening everywhere, so the issues of developing and applying new oil production
technologies that can significantly increase the oil recovery of already developed formations, as well
as used and mothballed fields where it is no longer possible to extract significant residual oil reserves
by means of traditional methods, are becoming urgent. The use of micro and nanotechnologies in a
broad sense is one of the possible and promising ways to solve these problems.

The only universal tool for calculating the flows of two-component flows of oil and a displacing
agent in direct microchannels simulating a pore or a crack in a rock is a direct numerical simulation
(DNS) with full resolution of the boundary interface. A numerical method called «Volume of Fluid»
(VOF) was used to simulate the two-phase flows of oil and displacing agents in the considered
microchannels.

It was proposed to use the dimensionless number, called Regime number, to describe the different
flow regimes of oil/water mixture and transitions between these regimes. That number defined as the
product of the Weber (We) and Ohnesorge (Oh) numbers. On the other hand, the Regime number can
be defined as the multiplication of the capillary number (Ca) in the power of 1.5 to Reynolds number
(Re) in the power of 0.5. It was observed, that the plug flow regime was observed at \( R_n = R_n^p = 10^6 \),
the slug flow regime was observed at \( R_n = 4 \cdot 10^4 \), \( R_n^w = 7.5 \cdot 10^3 \), the parallel flow regime was
observed at \( R_n = R_n = 10^4 \) and the emulsion flow regime was observed at \( R_n = R_n = 10^{-2} \).

It was found that a feature of such a system is the absence of a droplet regime, namely, as the flow
rates of fluids increase, the flow from slug flow goes directly to parallel flow. Most likely this is due to
the fact that in all the previously considered works, the contact angle of wetting of the channel wall
with fluids is not taken into account. This parameter is critically important in determining the oil
recovery coefficient; its effect will be investigated in the future.

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