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Investigation of fluid flow in a digital core model

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Abstract. The impact of imposed oscillations on the flow of liquid in porous medium is examined in this paper. Two models of porous medium were used. The first model is presented as a capillary, radius of which varies sinusoidally. The second model is two-dimensional area of flow, received from the results of X-ray microtomography of a real core sample out of carbonate reservoir. Geometrical sizes of calculated areas match real sizes of seeds of core samples. Mathematically, liquid flow process in such channels are described by equations of continuity and Navier-Stocks. Numerical calculations of flow in developed models of steam space were conducted in software FlowVision. Computer modeling was conducted both for steady flow and for flow with imposed oscillations. As a result of series of numerical calculations fields of velocities and forces were found. Received data allowed defining the laws of flow and the impact of imposed oscillations on these laws.

1. Introduction

Modeling flows in microchannels is a relevant problem which is caused by their engineering applications. This topic is also relevant in the technology of “digital core model”, which is often used for the research of filtration properties of core samples by methods of calculated experiments. The main explored parameter of porous mediums is permeability. Diversions in permeability, that was received as a result of mathematical modeling and natural experiment, are explained by slippage effect of gas on the solid border. This is typical for rarefied flows. The degree of rarefaction is characterized by Knudsen number \( Kn = \lambda / L \), where \( \lambda \) is length of free roll of molecules, \( L \) is space aspect of the problem.

For \( Kn < 10^{-3} \) the flow of gas is modeled by Navier-Stokes equations with boundary condition of adhesion [1]. For decreasing range of application of Knudsen number \( (10^{-3} < Kn < 10^{-1}) \) papers [2] offer modification of mathematical models replacing classical condition of adhesion with Maxwell condition of slippage. Another modification of the classical Navier-Stokes equations is the quasi-hydrodynamic equations [3-4]. The essence of this modification is to add to the original equations the additional small terms of dissipative nature. This approach allows, on the one hand, to use logically simple difference schemes, and, on the other hand, gives a good agreement between the calculated results and experimental data for flows in microchannels. An overview of other models and methods in this area can be found, for example, in papers [5].

Full-scale experiments carried out in laboratory and field conditions indicate the effect of imposed oscillations on the filtration properties of porous medium [6]. This led to the development of various...
technologies of wave impact on oil extraction [7]. Their use in field conditions allows to increase oil flow rate, reduce water content and reduce energy costs [8]. The results of the laboratory experiments conducted by the authors indicate two factors of the influence of elastic oscillations on the permeability of the porous medium [9]. At the beginning of the action, the skeleton of the porous medium is weakened. Small particles of rock are separated into a filtration flow. This results in an irreversible change in permeability. The second factor is that under the influence of elastic vibrations, the permeability of the porous medium increases, and after the termination of the action it returns to the initial values. This work is devoted to the study of this mechanism by numerical methods.

2. Object of research and formulation of the problem
Two models of porous medium were used as objects of research (Fig.1). The First model is a capillary channel radius of which varies sinusoidally. That is, within the channel there is an alternation of pores and narrow isthmuses connecting adjacent pores. Characteristic dimensions of the channel: pore diameter \( D = 3 \times 10^{-5} \) m, diameter of the channel passage section (narrowing) – \( d = 0.1 \times D \). The surface of the computational domain is a set of flat polygons – facets, on which the boundary conditions are determined.

The second model is two-dimensional area of flow, received from the results of X-ray microtomography of a real core sample out of carbonate reservoir (Fig.1 b). Geometrical sizes of calculated areas match real sizes of seeds of core samples.

![Figure 1](image-url)

**Figure 1.** Calculation are: (a) – the capillary channel; (b) – carbonate reservoir.

In the description of flow hydrodynamics in this work, the laminar fluid model was used as a mathematical model, which describes the flow of a viscous fluid at low Mach and Reynolds numbers. The model includes the Navier-Stokes and continuity equations, which are solved by the finite volume method using an implicit splitting algorithm on physical variables using the FlowVision software. Computer modeling was conducted both for steady flow and for flow with imposed oscillations. The pulsations of the fluid velocity, specified at the inlet of the calculation area, modeled wave impact on the filtration process.

Since in our case the flow of water in models of porous medium is investigated, the value of the Knudsen number is very small. The following boundary conditions can be used in the formulation of our problem:

1) Wall – the condition of adhesion is defined on the boundary of the region:

\[
U_b = 0
\]  

2) At the entrance to the channel, the dependence of the normal speed on time \( t \) is set:
\[ U(t) = U + U_0 \times \sin(2\pi f t + \varphi), \]  

(2)

where \( U \) is average speed, m/s; \( U_0 \) is amplitude of velocity oscillations, m/s; \( f \) is frequency of oscillations, Hz; \( \varphi \) is the initial phase of oscillations.

3) Output section – free output with zero pressure at the boundary.

The properties of the liquid are specified in the database of FlowVision: clean water. Physical characteristics of the liquid: density – 998 kg/m\(^3\), viscosity – 0.001 Pa\( \times \)s. Reference values: temperature – 293 K, pressure – 101 kPa.

3. Results of numerical studies

To study the influence of various factors (amplitude and frequency of oscillations) on the unsteady process of fluid flow in the channel, a series of calculations in an identical computational domain and an identical computational grid was performed. The value of the amplitude of the velocity oscillations varied from \( 10^{-5} \) to \( 10^{-2} \) m/s, the frequency varied from 0 to 10 kHz. The specified range of oscillatory velocity meets the values of the amplitude of pressure oscillations in a porous medium from 100 Pa to 100 kPa. During the numerical experiment for each series was given a time step equal to \( 1/(100 \times f) \).

The numerical experiment was carried out for different values of the initial phase of oscillations at the input boundary. It is established that the initial phase value does not affect the quasi-stationary process under study.

Figures 2 and 3 show the characteristic pressure and velocity distribution in the capillary channel plane and the carbonate reservoir model in steady flow. From these figures it follows that the pressure inside the "pores" is distributed almost evenly. A significant pressure drop is observed in the narrow part of the channel connecting adjacent "pores". Analysis of the velocity distribution allows us to conclude that the maximum speed is observed in the narrow part of the channel. In this case, the flow is observed in the Central part of the channel. Inside the channel, as the distance from the axis of the liquid increases, velocity decreases to almost zero.

![Figure 2](image)

**Figure 2.** The field of allocation of pressure (a) and velocity (b) in the capillary channel plane.

To understand the nature of the pulsating fluid flow, the time characteristics of the velocity were checked. It is a pulsating motion with the frequency of the inlet pressure pulsation. However, a deeper analysis allows us to conclude that the velocity pulsations are imposed on some stationary flow...
(averaged value). The numerical value is ten times lower than the amplitude of the pulsation, however, it is comparable with the values of the velocity of the filtration fluid flow.

![Figure 3. The field of allocation of pressure (a) and velocity (b) in the carbonate reservoir model.](image)

To understand the nature of the pulsating fluid flow, the time characteristics of the velocity were checked. It is a pulsating motion with the frequency of the inlet pressure pulsation. However, a deeper analysis allows us to conclude that the velocity pulsations are imposed on some stationary flow (averaged value). The numerical value is ten times lower than the amplitude of the pulsation, however, it is comparable with the values of the velocity of the filtration fluid flow.

Processing and analysis of the results of the numerical experiment allowed us to determine the dependence of the average speed on the amplitude of oscillations and frequency. Fig. 4 presents the dependences of the averaged velocity value on the axis in the narrow part of the channel on the amplitude and frequency of oscillations.

![Figure 4. The dependence of the averaged values of the flow velocity in a narrow channel on the frequency f and the amplitude of the velocity fluctuations \( U_0 \).](image)

(1 – \( U_0 = 10 \) mm/s, 2 – 1 mm/s, 3 – 0.1 mm/s, 4 – 0.01 mm/s).

To establish the functional dependence of the averaged flow rate on the determining factors, dimensionless parameters were introduced:

\[
\frac{\bar{\mu}}{f \sqrt{\mu}} \quad \text{and} \quad \frac{U_0}{f \sqrt{\mu}}
\]

(3)

where \( \rho \) is the density of the liquid, kg/m\(^3\); \( c \) is the speed of sound in the liquid, m/s; \( \mu \) is permeability, m\(^2\).
Figure 5 shows the interdependence of these dimensionless parameters, which is approximated by the power function.

![Figure 5. The interdependence of the dimensionless parameters.](image)

From this power function, the averaged velocity is determined by the following expression:

\[
\overline{u} = 1.78 \cdot U_0^{1.22} \cdot f^{-0.22} \cdot \mu^{-0.11}
\] (4)

The calculated data averaged over an integer number of oscillation periods showed that when velocity oscillations are imposed in the absence of a stationary flow, a fluid flow directed from the radiation source is formed. The velocity distribution over the channel cross section is similar to the stationary flow at equivalent pressure drop.

4. Conclusion
The results of numerical studies have shown that the imposition of velocity fluctuations leads to an increase in the average velocity of the liquid in a porous medium. It is established that the increase in speed depends on the amplitude and frequency of the imposed oscillations, and its functional dependence is obtained. The obtained results open a new direction of research in the field of pressure fluctuations effect on the fluid flow in the channels of complex shape and its practical application in the filtration in porous medium. These results can be used to improve the methods of wave action on the productive layers.

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