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STUDYING THE FEATURES OF SIMULATING FLUID MOVEMENT IN POROUS MEDIA

Abstract

The study of fluid flow in porous media, differing from traditional pipe flow is crucial for developing efficient methods in oil extraction and minerals, considering the challenges associated with ambiguous flows and diverse porous structures. This paper addresses the complexity of investigating fluid flow in porous media, a phenomenon significantly distinct from fluid movement in pipes. Emphasis is placed on the absence of clearly defined flow tubes in porous media, complicating measurements, and analysis. The study introduces a new approach incorporating both analytical and numerical methods, applied to various porous media. The research proposes a mathematical model based on laws and correlations to describe systems, including concepts such as permeability, flow velocity potential, characteristics of single-phase and multiphase systems, and fluid compressibility. Special attention is given to the characteristics of oil reservoirs, determined based on fluid properties in the reservoir, including porosity and saturation, as assessed by engineers. Numerical results represent fluid displacement in a flat channel and a one-dimensional problem in a porous medium, performed using finite-difference approximation of equations with an explicit scheme. The numerical results of this model were implemented in the Matlab software.

Key words: mathematical modeling, porous media, filtration, Darcy's law, permeability, fluid flow.

Introduction

Studying fluid flow in porous media is a complex phenomenon that cannot be described as simply as the movement of fluid in pipes. Unlike the ease of measuring the length and diameter of a pipe to determine its conductivity based on pressure, the flow in porous media has its peculiarities. A distinctive feature is the absence of clearly defined flow tubes with measurable cross-sections.

Research on fluid movement in porous media has evolved in two directions: analytical and experimental [1–5]. In works [6–8], the behavior of fluids in porous media ranging from sand to crushed glass was analyzed, and based on these studies, laws, and correlational dependencies were developed for the analytical description of such systems. The study presented in [9] explores the flow of liquid in heterogeneous porous media, which holds fundamental significance for the operation of many systems and applications. Such environments typically exhibit heterogeneity in the form, size, connectivity, and surface structure of pores on small scales, as well as spatial changes in porosity, permeability, and elastic moduli on larger scales.

The research emphasizes that any attempt to model flow in porous media requires the ability to handle large volumes of data used to calculate the spatial distribution of pressure, fluid velocity, etc., throughout the pore space. The development of efficient prediction algorithms has always been an active area of research. In the study described in [10], the effects of stress-dependent deformation of pores on the properties of multiphase flow in porous media are discussed. Key parameters characterizing multiphase liquid flow in porous media for various natural and industrial applications are relative permeability and capillary pressure.

Literature review

The study shows that while the influence of porous media deformation on single-phase liquid flow is well-studied, the dependence of flow on stress in multiphase systems is not fully explored. Concepts such as permeability, flow velocity potential, characteristics of single-phase and multiphase systems, and fluid compressibility are used to describe flow characteristics in porous media [11-13]. Characteristics of oil reservoirs are determined based on fluid properties in the reservoir, with assessments of reservoir porosity and saturation conducted by engineers.

Fundamental principles

One of the key tasks is to determine the rock's ability to conduct fluid, that is, to assess its permeability. Permeability is a petrophysical constant determined by Darcy's law [14-16].

$$V_s = -\frac{k}{\mu v}\left(v\frac{\partial p}{\partial s} + \frac{\partial z}{\partial s}\right) \quad (1)$$

where (V_s) is the mass flow rate and permeability for a homogeneous fluid, (μ) is a dynamic viscosity, (p) is a pressure, (z) is a vertical coordinate, (v) is a specific volume, and (ρ) fluid density – all these parameters play a crucial role in characterizing the process. Permeability in porous media can be determined using equation (1), and the sum $\left(v\frac{\partial p}{\partial s} + \frac{\partial z}{\partial s}\right)$ characterizes the fluid filtration velocity potential. Then equation (1) can be expressed in the following form:

$$V_s = -\frac{k}{\mu v}\cdot\frac{\partial \Phi}{\partial s} \quad (2)$$

During studies conducted by Darcy [17-19], fundamental assumptions were established, delimiting the application domain of his renowned law. Firstly, it assumes that the fluid is a homogeneous substance existing in a single phase. This significantly simplifies the modeling process by excluding the need to account for more complex characteristics of multiphase fluids. Furthermore, it assumes the absence of chemical interaction between the fluid and its surrounding environment, implying their chemical inertness. It is also asserted that the permeability of the medium is a constant, unaffected by the properties of the liquid, such as its type, temperature, pressure, or spatial distribution, simplifying computational operations. It is essential to note that in the Darcy model, flow is considered laminar, excluding more complex turbulent flows from consideration. Additionally, the electrokinetic effect arising from potential differences during fluid movement under pressure through a porous capillary structure is not considered [18-21]. Finally, the Klinkenberg effect, describing permeability changes induced by the presence of gas phases in porous materials, is ignored within this model. These assumptions establish conditions under which Darcy's law provides the most accurate description of fluid behavior in porous media. However, it is important to consider that adapting or supplementing the Darcy model may be necessary for a more precise description of changing physical conditions [22].

The unit of permeability is called a Darcy (D), and its dimension can be defined as follows:

$$V_s = -\frac{k}{\mu v}\cdot\frac{\partial \Phi}{\partial s} \quad (3)$$

If we express the parameters of the Darcy equation in terms of mass M, length L, and time T:

$$V_s = \frac{L}{T};\ \rho = \frac{M}{L^3};\ \frac{\partial p}{\partial s} = \frac{M}{L^2T^2};\ \mu = \frac{M}{LT};\ g = \frac{L}{T^2} \quad (4)$$

Let's $\frac{k}{LT}$ correspond to $\frac{L}{T}$, then $k = L^2$

$$\frac{k}{LT}=\frac{L^2}{LT}=\frac{L}{T} \tag{5}$$

Therefore, the permeability unit is equivalent to the square of the length dimension.

In fluid dynamics, two distinct types of processes can be identified: fast and slow. This division is based on the speed at which changes occur in the fluid state. Fast processes are characterized by short-term, intense changes, such as instantaneous flows or surges. Slow processes occur more smoothly and persistently, such as the gradual movement of a mass of liquid or constant circulation flows. By separating these processes, it is possible to simplify the study of fluid dynamics, especially in complex systems. Applying such a division allows for the derivation of the averaged motion equation, which represents an averaged model of fluid dynamics, excluding short-term fluctuations and focusing on larger and more constant flows. Such divisions are due to the fact that the characteristic hydrodynamic times for fast and slow processes differ significantly (6). The characteristic hydrodynamic time is the time scale over which significant changes in fluid flow occur. Fast processes have short characteristic times, whereas slow processes occupy significantly longer periods. This difference allows for the analytical separation of fast oscillations from slower, systematic changes in fluid motion.

$$\omega >> \frac{\nu}{L^2} \tag{6}$$

To describe the dynamic processes of fluid in porous media at the microscale, linear Stokes equations are applied, intended for a fluid that is incompressible and possesses zero viscosity. Since the filtration process is very slow and in dimensionless variables, the reduced viscosity is of the order ε_0^2, where ε_0 is the average dimensionless pore diameter, and when averaging the obtained microscopic model, the reduced viscosity together with the average pore size tends to zero. Dissolving soil with an active admixture induces flow into the pore space. For the chosen system of dynamic equations, such a boundary condition is natural. However, for the Stokes equations of viscous incompressible fluid, this boundary condition leads to practically insurmountable mathematical and computational difficulties.

Materials and methods

The motion of two distinct viscous liquids, which do not mix and have different constant densities, inside a capillary occurs under the influence of external pressure: $\Omega=\{\mathbf{x}\in \mathrm{R}^2 : -1<x<1, -h<y<h\}$. The moving boundary separates the zones and is filled with various liquids. Next, the flow patterns can be described by the following equations: Stokes (7), continuity (8), and state (9):

$$\alpha_\rho \frac{\partial \vec{u}}{\partial t} = div\mathbf{P} + \rho\vec{e}, \tag{7}$$

$$\frac{1}{\alpha_p}\frac{\partial p}{\partial t} + div\vec{u} = 0, \tag{8}$$

$$\mathbf{P} = \alpha_\mu D(x,\vec{u}) - pE\,. \tag{9}$$

As for the boundary conditions they are defined as:

$$S^{\pm} : \mathrm{P}\vec{n} = -p_0\vec{n}\,,\ S^0 : \vec{u} = 0 \tag{10}$$

At the boundaries of «inlet» and «outlet», boundary conditions are specified ($S^- = \{\mathbf{x}\in R^2 : x_1=-1, -h<x_2<h\}\subset S$, $S^+ = \{\mathbf{x}\in R^2 : x_1=1, -h<x_2<h\}\subset S$ respectively):

$$\mathrm{P}(\mathbf{u},p)\cdot\mathbf{n} = -p^0\mathbf{n},\ \mathbf{x}\in S^{\pm}. \tag{11}$$

here $\mathsf{P}(\mathbf{u}, p) = 2\mu\mathsf{D}(\mathbf{u}) - pI$, $\mathsf{D}(\mathbf{u}) = \frac{1}{2}(\nabla\mathbf{u} + (\nabla\mathbf{u})^*)$,

where I is the unit tensor, $p^0(\mathbf{x})$ is a given linear function, $\mathbf{n} = (1,0)$ is the unit vector normal to $S^\pm$.

Finally, the initial conditions are described as:

$$\vec{u}\big|_{t=0} = u^*,\ p\big|_{t=0} = p^*$$

At the initial stage of the time interval, when, the considered density is represented as a function with piecewise-constant values. This assumption is based on the representation of density by two separate positive quantities, each corresponding to different phases of the flow:

$$\rho(\mathbf{x},0) = \rho_0(\mathbf{x}) = \begin{cases} \rho^+, & \mathbf{x} \in \Omega^+(0), \\ \rho^-, & \mathbf{x} \in \Omega^-(0), \end{cases} \rho^\pm = \text{const}, \rho^- > \rho^+ > 0 \tag{12}$$

In this case, the initial conditions for density can be represented as a surface $\Gamma(0) = \Gamma_0$, separating two regions $\Omega^\pm(0)$, initially filled with different liquids. For simplicity, let's assume that $\Gamma_0 = \{\mathbf{x} \in \mathsf{R}^2 : x_1 = 0, -h < x_2 < h\}$. The task is to determine $\mathbf{u}$, p and $\rho(\mathbf{x},t)$ densities according to equations (7) - (9), which correspond to the initial and boundary conditions. The problem has a nonlinear nature since equation (9) includes an additional term $\mathbf{u} \cdot \nabla\rho$. To facilitate the analysis, we will switch to uniform boundary conditions by introducing a new parameter $p \to p - p^0(\mathbf{x})$:

$$\mu\Delta\mathbf{u} - \nabla p = \mathbf{f} \equiv \nabla p^0 - g\rho\mathbf{e}, \tag{13}$$

$$\mathsf{P}(\mathbf{u}, p) \cdot \mathbf{n} = 0, \mathbf{x} \in S^\pm. \tag{14}$$

The motion defined by these equations supports the continuous coexistence of two distinct zones $\Omega^\pm(t)$, where each zone includes one of the specified liquids. These zones are always separated by an unchanging dynamic boundary. Therefore, the considered process reduces to determining the parameters $\mathbf{u}$, p and their influence on the displacement of this boundary $\Gamma(t)$.

Results and Discussion

Numerical calculations were performed to simulate the displacement of one liquid by another in a flat channel, and a detailed study and formulation of a one-dimensional problem in a porous medium were conducted. A Finite-difference approximation of the equations using an explicit scheme was implemented, allowing for an accurate modeling of the physical processes in the given environment. Calculations for the one-dimensional problem were carried out using the Matlab software environment, ensuring the required precision and clarity of results. One of the key findings is presented below, showing the dynamic change in the free boundary in a unitary capillary (Figure 1, p. 67). This boundary represents the difference between the liquids inside the channel or pore, significantly influenced by the physicochemical characteristics of the considered liquids in the porous medium.

Throughout the study, we conducted a comprehensive analysis of fluid flow in porous media, relying on both analytical and numerical methods. Modeling flow in porous media, especially in the context of oil reservoirs, requires consideration of numerous variables and intricate interdependencies. The results confirm that traditional approaches based on Darcy's law may be insufficient to describe all aspects of such complex systems, particularly in the presence of multiphase flows and changes in fluid properties under the influence of pressure and temperature. The proposed mathematical model incorporates concepts such as permeability, flow velocity potential, characteristics of single-phase and multiphase systems, as well as fluid compressibility. These elements were integrated within the developed numerical scheme implemented in the Matlab software environment. It is essential to note that our findings underscore the need for further research in this field. Specifically, issues related to pore deformation, and the impact of stress on multiphase systems remain open and require deeper analysis. The search for more efficient computational methods and algorithms for the analysis and modeling of flows in porous media, especially under conditions of high heterogeneity and structural complexity, remains a pertinent aspect.

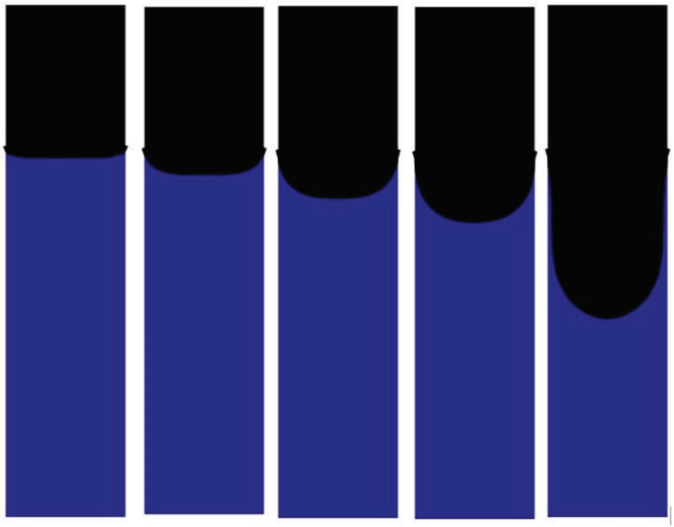

Figure 1 – Dynamics of a free boundary in a single capillary

Conclusion

This work proposes an approach that involves understanding the fundamental processes occurring in porous media, serving as a foundation for the development of specific new approaches to oil extraction and the modeling of processes such as mineral leaching. However, it emphasizes the importance of ongoing research in this field to enhance existing technologies and develop new ones.

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КЕУЕКТІ ОРТАДА СҰЙЫҚ ҚОЗҒАЛЫСЫН МОДЕЛЬДЕУ ЕРЕКШЕЛІКТЕРІН ЗЕРТТЕУ

Аңдатпа

Құбырлардағы дәстүрлі ағыннан ерекшеленетін кеуекті ортадағы сұйықтық ағынын зерттеу дұрыс анықталмаған ағындармен және кеуекті құрылымдардың әртүрлілігімен байланысты қиындықтарды ескере отырып, мұнайды және басқа да пайдалы қазбалар өндірудің тиімді әдістерін әзірлеудің кілті. Бұл жұмыста кеуекті ортадағы сұйықтық ағынын зерттеудің күрделілігі қарастырылады, бұл құбылыс құбырлардағы сұйықтық ағынынан айтарлықтай ерекшеленеді. Өлшеу мен талдауды қиындататын кеуекті ортада нақты анықталған ағын түтіктерінің болмауына назар аударылды. Зерттеу әртүрлі кеуекті орталарға қолданылатын аналитикалық және сандық әдістерді қамтитын жаңа тәсілді ұсынады. Зерттеу өткізгіштік, ағынның жылдамдығы потенциалы, бір фазалы және көп фазалы жүйелердің сипаттамалары мен сұйықтықтың сығылғыштығы ұғымдарын қамтитын жүйелерді сипаттау үшін заңдар мен корреляцияға негізделген математикалық модельді ұсынады. Инженерлер бағалаған қабаттағы сұйықтықтардың қасиеттеріне, оның ішінде кеуектілігі мен қанықтылығына қарай анықталатын мұнай қабаттарының сипаттамаларына ерекше назар аударылады. Сандық нәтижелер тегіс арнадағы сұйықтықтың орын ауыстыруын және кеуекті ортадағы бір өлшемді есепті ұсынады, ол айқын схеманы пайдалана отырып, теңдеулердің соңғы айырмашылығын жақындату арқылы орындалады. Бұл модельдің сандық нәтижелері Matlab бағдарламалық ортасында жүзеге асырылды.

Тірек сөздер: математикалық модельдеу, кеуекті орта, сүзгілеу, Дарси заңы, сұйықтық ағыны.

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ИССЛЕДОВАНИЕ ОСОБЕННОСТЕЙ МОДЕЛИРОВАНИЯ ДВИЖЕНИЯ ЖИДКОСТИ В ПОРИСТЫХ СРЕДАХ

Аннотация

Исследование потока жидкости в пористых средах, отличающегося от традиционных потоков в трубах, имеет ключевое значение для разработки эффективных методов добычи нефти и других полезных ископаемых, учитывая сложности, связанные с нечетко определенными течениями и разнообразием пористых структур. В данной работе рассматривается сложность изучения потока жидкости в пористых средах, явление, которое значительно отличается от движения жидкости в трубах. Акцентируется внимание на отсутствии четко определенных трубок тока в пористой среде, что усложняет измерения и анализ. Исследование представляет собой новый подход, включающий как аналитические, так и численные методы, с применением к разнообразным пористым средам. В рамках исследования предложена математическая модель, основанная на законах и корреляциях для описания систем, включающих в себя концепции проницаемости, потенциала скорости течения, характеристик однофазных и многофазных систем, а также сжимаемости жидкости. Особое внимание уделяется характеристикам нефтяных пластов, определяемым на основе свойств жидкостей в пласте, включая пористость и насыщенность, оцениваемые инженерами. Численные результаты представляют вытеснения жидкости в плоском канале и одномерной задаче в пористой среде, выполненные с применением конечно-разностной аппроксимации уравнений по явной схеме. Численные результаты данной модели были реализованы в программной среде Matlab.

Ключевые слова: математическое моделирование, пористая среда, фильтрация, закон Дарси, поток жидкости.

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