Available online at www.sciencedirect.com
ScienceDirect
Journal of Hydrodynamics
2016,28(6):937-946
DOI: 10.1016/S1001-6058(16)60695-9
www.sciencedirect.com/
science/journal/l0016058

Modern methods of underground hydromechanics with applications to reservoir engineering*

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(Received June 22, 2016, Revised October 27, 2016)

Abstract: In the report the basic principles of new approach to the study of transport processes in porous medium are represented. The “percolation” approach has arisen as an attempt to overcome the traditional phenomenological approach in the underground hydromechanics, based on the assumption of continuity of saturated porous media, which does not allow to explain and to model a number of effects arising from the fluids flow in porous media. The results obtained are very interesting not only from the scientific point of view but as the scientific basis for a number of enhanced oil recovery technologies.

Key words: fluid flow in porous media, percolation theory, relative phase permeability, oil field development, low salinity waterflooding

Introduction

The new approach aims to take into account for the description of fluid flow in porous media such details as structure of the pore space and the interaction of the fluids with the mineral surfaces. The mathematical foundation of this approach is the theory of percolation.

This approach has arisen as an attempt to overcome the traditional phenomenological approach in the underground hydromechanics based on the assumption of continuity of saturated porous media. The traditional approach does not allow to model, to describe and explain a number of effects arising from the fluids flow in porous media.

The new approach aims to take into account the description of fluid flow in porous media, especially the structure of the pore space and the interaction of the fluid with the surface of minerals. The mathematical foundation of this approach is the theory of percolation. The possibilities of the mathematical apparatus developed are illustrated in the examples of the study of the fluid flow characteristics in reservoirs.

Transportation or conductive properties of porous media are determined primarily by the presence of conductive pore channels. The most simple and convenient model which allows describe the interaction of these channels and, as a result, to obtain the permeability of the porous medium as a macroscopic object–3-D lattice of conductive capillaries. It is natural to assume that the capillary radii in such lattice are distributed according to the actual porometrical curve–distribution density function of pore channel’s radii $f(r)$. Given the distribution density function of the structure elements, the percolation modeling which allows to describe the conductivity of a heterogeneous medium, have been developed by the author[1,2].

1. General principles of the modern approach in the underground fluid mechanics

The approach based on a generalization of the Shklovsky-de Gennes model for an infinite cluster (IC) structure (Fig.1) in the case of the lattice containing conductive elements with the randomly distribution of their intrinsic value. Based on the representations of the IC structure, we have the problem of determining the conductivity of its skeleton which responsible for

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the transport properties of IC and thus a porous medium as a whole.

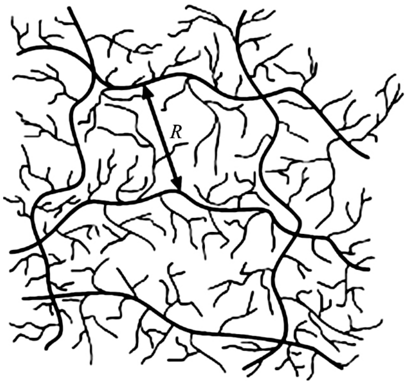

Fig.1 Schematic representation of the IC structure in the Shklovsky-de Gennes model without taking into account a tortuosity (fractality) of its components

Conducting channels for the fluid flow are chains of hydraulically interconnected pore channels (capillaries) (Fig.2) of different radii r (conductivity $\sigma \sim r^{\lambda}$, where exponent λ is determined by nature of the transport process). The conductivity of the chain σ will be determined by the thinnest capillary, so it is natural to assume that this radius is the main characteristic of such a chain. Using it, we introduce the concept of "r - chain"-so we called the chain of capillaries, where the minimum radius of its capillaries is in the range $r / r + \mathrm{d}r$.

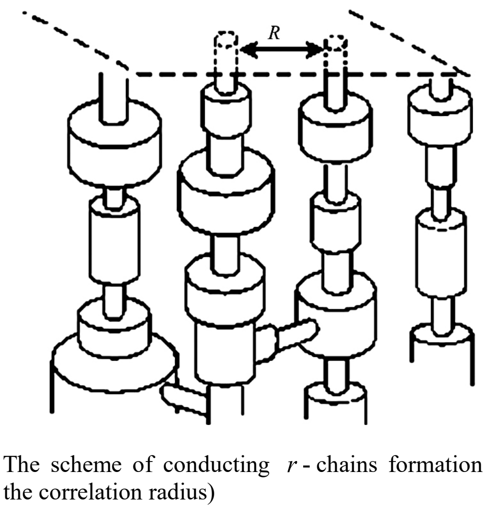

Fig.2 The scheme of conducting r - chains formation (R is the correlation radius)

IC skeleton will be formed by r - chains within entire range of the function $f(r)$ and the number for each r will have its own which is unknown in advance. Therefore it is necessary to construct an algorithm for determining the amount of the resulting r - chains, their conductivity and subsequent summation in order to find the total conductivity of the IC. That is, the algorithm is the main element of the percolation model.

The presented approach is based on the introduction of a specific systematization or hierarchy of r - chains, which allows implement the above scheme of summation.

It can be shown that the concentration $n(\sigma_1)$ of conducting chains per unit cross-section area perpendicular to the selected direction composed of capillaries with $\sigma \geq \sigma_1$

$$n(\sigma_1) = l^{(1-D)} \left[\omega \int_{\sigma_1}^{\sigma_c} f_0(\sigma) \mathrm{d}\sigma \right]^{\nu(D-1)} \tag{1}$$

where critical conductivity σ_c is determined by percolation threshold P_c^b

$$\int_{\sigma_c}^{\infty} f_0(\sigma) \mathrm{d}\sigma = P_c^b$$

Accordingly, the distribution function for conducting chains by σ_1 is related to the value n in the ratio $F(\sigma_1) = -\mathrm{d}n / \mathrm{d}\sigma_1$, since n increases with decreasing σ_1

$$F(\sigma_1) = \nu(D-1) l^{(1-D)} \left[\int_{\sigma_1}^{\sigma_c} f_0(\sigma) \mathrm{d}\sigma \right]^{\nu(D-1)-1} f(\sigma_1) \tag{2}$$

Now determine $k(\sigma_1)$ is the average conductivity of the unit of the length of σ_1 is the chain composed of series-connected links with $\sigma \geq \sigma_1$ (Fig.2). At this stage it is necessary to take into account the difference between 2-D and 3-D grids. In 2-D case r - chains are smooth lines, so

$$k(\sigma_1) = \left[\int_{\sigma_1}^{\infty} f_0(\sigma) \frac{\mathrm{d}\sigma}{\sigma} \right]^{-1} \left[\int_{\sigma_1}^{\infty} f_0(\sigma) \mathrm{d}\sigma \right] \tag{3}$$

However in 3-D grids significant tortuosity (fractality) of IC skeleton takes place. It can be shown that the actual length of the r - chain in more than

$$\left[\int_{\sigma_1}^{\sigma_c} f_0(\sigma) \mathrm{d}\sigma \right]^{\nu-\zeta}$$

times that normal linear distance between its ends.

Consequently the final expression for the average conductivity per unit length for the 3-D porous space is