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Pore-Scale Investigation of Two-Phase Flows in Three-Dimensional Digital Models of Natural Sandstones

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Abstract—The results of numerical simulation of the processes of two-phase flow through a porous medium in three-dimensional digital models of the porous space of three natural sandstone samples are given. The calculations are carried out using the lattice Boltzmann equations and the digital field gradient model over a wide range of the capillary numbers and the viscosity ratios of injected and displaced fluids. The conditions of flow through a porous medium with capillary fingering, viscous fingering and with stable displacement front are revealed.

Key words: mathematical simulation, X-ray CT, heterogeneity of porous space, two-phase flows, capillary number, fingering, drainage.

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The problems of two-phase fluid flows through porous media are topical in many branches of science and technics; among them we can note hydrogeology, pedology and soil sciences, underground water dynamics, and oil- and gas-field developments. Together with the gravity, the viscous, capillary, and inertia forces control two-phase fluid flow dynamics in the porous space. The paper by Lenormand et al. [1] is one of the first widely known experimental studies on the investigation of two-phase fluid flows in the pore-scale using artificially constructed two-dimensional models of porous media. In that investigation it was demonstrated that in the process of draining the distribution of two fluids in pores is controlled by two dimensionless parameters. These are the capillary number Ca defined as the ratio of the viscous and capillary forces and the viscosity ratio of non-wetting (injected) and wetting (displaced) phases M: $\mathrm{Ca} = \mu_{nw} u_{nw}/(\sigma \cos\theta)$ and $\mathrm{M} = \mu_{nw}/\mu_w$, where μ_w and μ_{nw} are the dynamic viscosities of the wetting and non-wetting phases, respectively, u_{nw} is the injection velocity of the non-wetting fluid, σ is the surface tension, and θ is the interfacial angle (wetting contact angle). In view of low velocities of flow through the porous medium and, respectively, low Reynolds numbers, the inertia forces are insignificant in the problems of this type.

In subsequent years, the authors of [2–7] identified three types of flows with reference to two-dimensional homogeneous and heterogeneous models, namely, these are flows with capillary fingering, viscous fingering, and with stable displacement front. The ranges of the parameters Ca and M were determined for each of the types of flow and the model of porous medium. The distinguishing features of the flow types were revealed on the basis of visual analysis of dynamics of the fluid distributions and it was also found that for intermediate values of Ca and M numbers both capillary and viscous fingerings are simultaneously formed in the sample (crossover zone [8]). The results of all these investigations contain the fundamental bases of two-dimensional flows on the pore scales; nevertheless, the structure of the porous space in these models is not natural. At present, it was carried out a few similar tests on the real three-dimensional samples, in particular, on the carbonate fractured types of porous media and the available results are given only in several studies of recent years [9–12].

The difficulty of the investigation of multiphase flow in 3D space consists in specifics of visualization and methods of nondestructive testing of the displacement of phase interface. One of the ways of "in

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