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Mathematical Models for Multi-phase Fluids Underground Filtration: Manifestation of Capillary Effects and Flow Instability.

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The problems of multi-phase fluids filtration in homogeneous and inhomogeneous porous media are scientifically relevant to many practical issues. Developing new models is necessary for description of liquid non-aqueous phase contaminants underground migration, their entrapment in the zones of inhomogenity, and forecasting the results of remediatory activities in the vicinities of waste storages and contaminated sites.

The models for fluids displacement from porous matrixes are applicable for enhancing oil recovery in frontal displacement of oil by water or solutions from underground reservoirs. Entrapment of residual fluid by the displacing one lowers down the displacement quality leaving most of residual viscous fluid in porous matrix.

Another important application of the obtained results is the problem of delivering water to the roots of plants in irrigated zones.

The goal of the present lecture is to give a broad coverage for experimental and theoretical investigations of the capillary driven filtration in porous media with homogeneous and inhomogeneous porosity and permeability under normal and strongly reduced gravity conditions. The lecture would provide the results illustrating the sensitivity of capillary forces to variations of porous media characteristics. The experimental results obtained for fluid imbibition into unsaturated artificial and natural porous media would be compared. Theoretical and experimental results on determination of mixing fluxes in two-phase filtration would be discussed.

In frontal displacement of a more dense and viscous fluid by a less dense and viscous one the Rayleigh-Taylor or Saffman-Taylor instability of the interface could bring to formation and growth of “fingers” of gas penetrating the bulk fluid. The growth of fingers and their further coalescence could not be described by the linear analysis. Growth of fingers causes irregularity of the mixing zone. The tangential velocity difference on the interface separating fluids of different density and viscosity could bring to a Kelvin-Helmholtz instability resulting in “diffusion of fingers” partial regularization of the displacement mixing zone. Thus combination of the two effects would govern the flow in the displacement process.

The goal of our study was, as well, to investigate analytically, numerically and experimentally the instability of the displacement of viscous fluid by a less viscous one in a homogeneous and inhomogeneous porous media, and to determine characteristic size of entrapment zones. Both miscible and immiscible displacement was investigated. The main accent in the investigations was placed on non-linear effects being of major importance for the quantitative evaluation of the process. Extensive direct numerical simulations allowed to investigate the sensitivity of the displacement process to variation of values of the main governing parameters.

Numerical simulations for the problem of viscous fluid displacement from saturated porous medium by a less viscous one were carried out. Validation of the code was performed by comparing the results of model problems simulations with experimental data and with existing solutions published in literature.

Taking into account non-linear effects in fluids displacement allowed to explain new experimental results on the pear-shape of fingers and periodical separation of their tip elements from the main body of displacing fluid. Those separated blobs of less viscous fluid move much faster then the mean flow of the displaced viscous fluid.

Thus the developed new mathematical models for multi-phase filtration incorporating non-linear terms into the partial differential equations allowed to perform numerical simulation of subterranean flows of immiscible and miscible fluids. The results of numerical simulations processed on the basis of dimensions analysis allow to introduce criteria characterizing the arising instability and quality of displacement.