Understanding the combined effect of structural and wettability heterogeneity on two-phase flow in porous media

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The individual and combined impact of pore size disorder and wettability on the fluid distribution in different applications including hydrocarbons recovery, underground storage and soil remediation has been widely studied.[1,2] However, the combined effect of heterogeneities in both pore structure and wettability is not fully understood. Wettability plays an important role in multiphase flow which is generally classified as homogeneous and heterogeneous (also known as fractional and mixed).[3,4,5] Unlike homogeneous wettability, where the whole rock surface has a uniform molecular affinity to the fluids in contact, for heterogeneously wetted porous media there is a variation in affinities for the fluids at different regions.[5] Moreover, most rocks naturally have a propensity to display heterogeneous wettability due to their formation diagenesis.

Limited pore-scale experimental studies (e.g. micromodel testing) have been performed on microscale wettability heterogeneity mainly due to fabrication challenges.[3,6] Significant impact on fluid displacement and level of residual saturation have been observed in porous media with non-uniform wettability.[3] Fabricating a large number of porous media replicas with different spatial configurations for wettability heterogeneities may not be feasible, and therefore, using pore-scale numerical simulation can provide insights into multiphase flow and trapping for different scenarios and optimize further experimental investigation. However, to the best of our knowledge, most of the published numerical simulation studies have investigated the effect of different homogenous wettability on fluid flow dynamics in either homogenous or heterogeneous pore structure.

In this work, we have used direct numerical simulations (DNS) to investigate wettability and structural heterogeneity at pore-scale. DNS studies were conducted using the Phase Field method and commercial computational fluid dynamics (CFD) software (COMSOL Multiphysics).[7] We have built Quasi-3D pore-scale models and simulated two-phase flow in porous media. Two-phase flow displacements are compared at different uniform and non-uniform contact angle distributions for homogenous and heterogeneous porous structures. We systematically change the pore structure heterogeneity in the pattern to better understand the combined effects of wettability and structural heterogeneities.

We observed that non-uniform wettability distribution is as important as structural heterogeneity and their combined effect has a significant impact on the evolution of fluid interface, displacement efficiency and trapped saturation. Simulations showed that trapped saturations can be either continuous or discontinuous based on the imposed spatial configuration of wettability on the heterogeneous media. Certain wettability configurations, e.g. being parallel to the flow direction, promote flow instability for the same pore-scale geometry, while others, such as being perpendicular to the flow direction, may assist the front stability and result in less trapping. The results of these DNS studies are of interest to different subsurface processes involving reactive transport and wettability alteration.

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