Does Structural Heterogeneity Overshadow the Effects of Wettability Heterogeneity on Fluid Flow at Pore-scale?

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Abstract

Wettability plays a pivotal role in multiphase flow in porous media.[1–3] Unlike homogeneous wettability, where the whole rock surface has a uniform molecular affinity to the fluids in contact, heterogeneously wetted porous media present a variation in affinities for the fluids at different regions.[3] Most rocks naturally display heterogeneous wettability due to their non-uniform surface chemistry.

Limited pore-scale experimental studies (e.g. micromodel testing) have shown the impact of wettability heterogeneity at pore scale on residual saturations and fluid displacement.[1] Pore-scale numerical simulation provides invaluable insights into multiphase flow in porous media. However, 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 structures.

We have previously studied the effect of homogeneous and heterogeneity wettability on two-phase flow in a homogenous porous structure via a quasi-3D pore-scale numerical model. [4] We observed that heterogenous wettability plays a substantial role in front evolution, breakthrough time, saturation distribution and phase trapping. We reported different wettability distributions result in different front instability and phase trapping patterns and that residual saturations in heterogeneous models were higher than that of homogenous wettability models studied. Moreover, some wettability distributions parallel to the flow direction triggered front instability and the creation of viscous fingers. We concluded that a porous medium with equal surface areas of different wetting properties or contact angles does not simply behave similarly to a medium with its average contact angle. In other words, intermediate or neutrally wet porous media which is

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usually represented by a contact angle of 90° is not a true representative of porous media with heterogeneously distributed surfaces with similar average wetting conditions. [4]

Porous media show a great deal of structural heterogeneities from pore- to Darcy-scale. As in our previous work, we only studied homogenous structures, in the current study, we investigate whether the structural heterogeneity of a porous media overshadows the effect of wettability heterogeneities at pore-scale. Direct numerical simulations (DNS) studies were conducted using the Phase Field (PF) method and commercial computational fluid dynamics (CFD) software (COMSOL Multiphysics). [5] The PF method is a reliable technique for capturing the interface between immiscible fluids. The interface transports with the flow while the total energy of the system is minimized which ensures that there is a solution to flow in complex geometries without any required simplification. As wettability is classically defined using the concept of contact angle, we have used the latter parameter to define different wettability conditions in the simulation models. Two-phase flow displacements are performed at certain capillary numbers and compared at different uniform and non-uniform contact angle distributions for homogenous and heterogeneous porous structures. We employed several porous structures with different levels of heterogeneity to better understand the significance of wettability heterogeneities on fluid flow in presence of structural heterogeneity.

We observed that at the flow conditions of our study, the effects of wettability distribution do not vanish as structural heterogeneity of the porous medium increases and both structural and wettability heterogeneities have 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. The results of this study are of interest to different subsurface processes including CO₂ storage.

*Keywords:* wettability & structural heterogeneity, flow instability, trapping, CO₂ storage

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