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Dynamic effects in P^c-S relationship for two-phase flow in 3D heterogeneous porous media: experiment and modeling

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To characterize multi-phase flow in porous media, a correct determination of various fluid and porous media properties and, the constitutive relationships among capillary pressure (P^c), fluid phase saturation (S) and relative permeability (K_r) are necessary. However, the P^c-S-K_r relationships are not unique and depend on the flow dynamics due to applied boundary condition (BC), i.e., steady state or dynamic, among other factors. It has been shown that existing empirical models which describe dynamic two-phase flow processes in porous media using steady-state equations (multiphase version of Darcy equation) may be inadequate to account fully for the physics of flow in dynamic conditions. This is particularly prominent when P^cdepends strongly on saturation and saturation changes with time. To address this lacuna, new P^c-S relationships have been proposed which include an additional term to account for the dependence of P^c on saturation and time derivative of saturation $(\partial S/\partial t)$.This additional tem contains a parameter called capillary damping coefficient, also known as dynamic coefficient (τ), which establishes the speed at which flow equilibrium is reached. The dependence of P^c-S relationships on $\partial S/\partial t$ is called *dynamic effects*.

In obtaining P^c-S-K_r relationship, one may assume that the porous medium is homogeneous; however, micro-scale heterogeneities occur at length scales below those of core scale measurement devices and affect the P^c-S-K_r relationships significantly. These issues have been studied individually but the combination of dynamic effects and micro-scale heterogeneities on the P^c-S relationships has not been quantified accurately, particularly in 3D domains. Consequently, there are significant uncertainties on the reported values of τ in the literature.

In this paper, we report on our experimental and numerical study to establish drainage dynamic and quasi-static P^c-S curves for various homogeneous and heterogeneous 3D domains. Then, we analyze the effects of applied BC and variations in intensity and distribution of the micro-heterogeneities on dynamic two-phase flow in a cylindrical porous domain. Binary combinations of fine sand imbedded in coarse sand are used to display the micro-scale heterogeneities. Intensity of heterogeneity is defined by the volume proportion of fine sand bodies in the coarse background sand.

The results obtained in our study give further evidence that there is unique P^c-S curve and varies depending on different factors arising from both fluid and media properties. We show in this study that dynamic effects and micro-heterogeneities cause non-uniqueness in different ways. For example, we show that although presence of micro-scale heterogeneities in the domain causes non-uniqueness but this depends strongly on the intensity and distribution of heterogeneities apart from other factors, e.g., boundary conditions. We find that, in general, dynamic coefficient as a measure of dynamic effect is a non-linear function of saturation. Further, with the increase in the intensity of heterogeneity, dynamic coefficient increases. However, this dependence is not a linear function and depends on a complex interplay of various factors. We discuss the role of boundary conditions on the shape P^c-S curves whenever necessary.