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Effects of flow history on residual saturation during two-phase flow in porous media

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During the process of immiscible displacement of a receding fluid by an invading fluid in porous media one or more pores may be bypassed by the invading fluid as it advances through the medium. This process creates disconnected fluid clusters which are left behind, trapped in the porous structure. Enhanced knowledge of the parameters affecting the morphology and distribution of the trapped fluid in porous media is required for exploitation in various applications such as soil remediation or the enhanced oil recovery. In the present study, we investigated the effects of flooding history on the amount of the trapped fluid at different capillary numbers (defined as the ratio of viscous to capillary forces) ranging from 10^{-6} to 10^{-3}. In total 43 rounds of imbibition experiments through spherical and crushed glass beads with particle sizes ranging from 0.5 to 1 mm packed in a quasi-two-dimensional transparent Hele-Shaw cell (100mm x 100mm x 4mm) were conducted. The dynamics and patterns of fluid phase distributions were visualized using a high resolution CCD camera connected to a computer. Dyed water as wetting and displacing fluid was injected into the glass cell initially saturated with the nonwetting phase which was either Soltrol 220 or PCE with the dynamics viscosity of 4.12 and 0.89 cP respectively. The injection of the displacing fluid was continued until steady state was reached and no change in the phase distribution was observed. At that point, the flow rate of the invading fluid was increased and flooding was continued until reaching a new steady-state condition. This procedure was repeated till reaching the maximum designed capillary number. Our findings have two major contributions: (a) in a fairly homogenous quasi-two dimensional model, not only the size and shape of the trapped oil clusters depend on the history of flooding but also the residual oil saturation strongly depends on the history of flooding rather than the ultimate flow rate. For example, remarkably less oil entrapment was observed when the injection rate started from a low capillary number gradually increased to the ultimate (high) capillary number compared to the case when the injection was performed with the ultimate (high) capillary number; (b) a non-monotonic relation between the capillary number and residual saturation was observed which has been rarely reported in the literature as in most cases monotonic capillary desaturation curves are presented. This observation may be due to homogeneous distribution of pore sizes over the model causing a fairly homogeneous distribution of capillary forces at the invading front. Consequently, as flow rate increases, instability at the interface due to inverse viscosity ratio may increase the chance of trapping. However, after a certain capillary number, further increase of the injection rate will create enough drag force to mobilize the trapped zones resulting in reduction of the residual oil saturation. This non-monotonic observation is consistent over the examined viscosity ratio of 4.12 and 0.88 in both spherical and crushed glass beads.