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The Effects of Surface Roughness on Fluid Displacement Mechanisms and Residual Residual Trapping - A Pore Scale Investigation

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Immiscible fluid displacement and the trapping of residual oil and gas phases in the pore spaces of reservoir rocks is critical to geological operations such as carbon geo-sequestration and enhanced oil recovery. In carbon geo-sequestration, residual trapping is advantageous because it ensures long-term storage security of carbon dioxide (CO_2). In contrast, residual trapping can pose significant challenges during waterflooding in oil recovery operations where large volumes of oil may remain trapped in the interstitial spaces of the porous reservoir rock and cannot be extracted, thereby reducing the efficiency of the recovery process. In such operations, residual trapping is strongly influenced by the inherent surface roughness of the solid rock matrix amongst many factors. Surface roughness occurs in natural reservoir rocks as a result of geological processes that physically, chemically or biologically convert sediments into sedimentary rock (known as diagenesis) and weathering.

The effects of surface roughness on immiscible two-phase flow are currently not well understood. Previous investigations into residual trapping in porous media have mainly focused on the influence of factors such as pore geometry, wettability, fluids interfacial tension, mobility ratio and injection scenarios. Although some of these studies acknowledge the potential effect of surface roughness, there is still a lack of quantitative characterization and understanding of the influence of surface roughness on immiscible two-phase displacements in porous media.

In this study, the impacts of surface roughness on immiscible two-phase displacement are quantified. Immiscible two-phase displacement of air by water was conducted in a custom laser-manufactured glass microfluidic chip (micromodel). The glass chip comprised a 2.5D micro-structure analogous to the pore network pattern (micro-structure) of a natural reservoir rock, Oolitic limestone. The pore network pattern consisted of cylindrical pillars 400 μm in diameter arranged in a rhombohedra type of packing, generated on to a glass substrate using an ultrafast, pulsed picosecond laser. Surface roughness is an innate characteristic of laser machined surfaces and as a result, small variations in depth of the porous micro-structure were observed (50 ± 8 μm). The average surface roughness (S_a) of the laser-machined structure was measured to be 1.2 μm.

Experimental results for the rough micromodel exhibit high repeatability of fluid displacement patterns (preferential flow pathways) demonstrating that surface roughness has a strong influence on fluid invasion patterns and sweep efficiency and its effects must not be ignored. To ascertain the effects of surface roughness on the fluid displacement process, a direct numerical simulation (DNS) of the fluid displacement process was performed in OpenFoam using the Volume of Fluid (VOF) method assuming zero surface roughness. Comparing the experimental results with the numerical simulations, we show that surface roughness can significantly enhance residual trapping in porous media by up to 49.2%.