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Lattice Boltzmann modeling of pore-scale fluid flow during wettability alteration-based enhanced oil recovery in marine porous carbonate reservoirs

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The Middle East has become the largest overseas oil production base of China, where marine porous carbonate reservoirs are widely-distributed. Large recoverable reserves are still unexploited, implying a great potential to obtain higher oil production. Influenced by pore type, multi-modal pore structure, initially oil-wet or mixed-wet condition, the microscopic displacement efficiency is relatively low, only 40%~60%. Using ion-matched surfactant flooding to carry out wettability control from initially oil-wet or mixed-wet to water-wet, oil recovery ratio of marine carbonate reservoirs can be remarkably increased. Ion-matched surfactant flooding has been regarded as an attractive technique to greatly improve oil recovery after waterflooding in marine carbonate reservoirs. However, pore-scale mathematical models of wettability control by ion-matched surfactant flooding have not been reported in the literature. It is unclear about the pore-scale fluid flow mechanism during wettability control.

To tackle these issues, core samples from a typical carbonate reservoir in the Middle East were selected. Multi-modal pore structure image data were acquired by micro-focus X-ray CT scans. The study employed the U-Net fully convolutional neural network deep learning semantic segmentation algorithm. With a limited amount of image data, it accurately identified and constructed a digitized core model of the multi-modal pore structure. A pore-scale fluid flow mathematical model for LSW-S system infiltration control and lattice Boltzmann simulation method were then established by describing major physical-chemical processes such as oil/water two-phase flow, wettability alteration, solute convection-diffusion, surfactant adsorption/desorption and reducing oil/water interfacial tension. By comparing with classical equation analytical solutions, the accuracy of the simulation results was verified. The study investigated the impact of factors on pore-scale fluid flow characteristics of enhanced oil recovery through infiltration control, including displacement system, ion-concentration, capillary number, and wettability .

The research results indicated that due to local adsorption-desorption imbalance, both LSW drive and LSW-S drive caused dynamic changes in rock wettability, effectively detaching oil film but without altering the flow path of the displacing medium. In porous carbonate rocks, the sequence of pore-scale oil displacement efficiency was: LSW-S > LSW > HSW. A lower concentration of ion-matched water facilitated the detachment of oil films and droplets from small pores. A lower concentration of ion-matched water was more conducive to detaching oil films and droplets from small pores. Ion concentration mainly affected the relative permeability of the oil phase and had a minor impact on the relative permeability of the water phase. The capillary number had a significant impact on oil displacement efficiency and fluid microscopic distribution. As the capillary number increased, the force of fluid driving increased, leading to a significant increase in both oil and water relative permeabilities. With rock wettability transitioning from oil-wet to neutral wetting, the oil phase's relative permeability increased, while the water phase's relative permeability decreased. Under neutral wetting conditions, ion-matched water exhibited pronounced effects on infiltration control, substantially increasing the relative permeability of the oil phase and mobilizing microscopic residual oil.

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