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Pore-Scale Modeling of Oil-Water Two-phase Flow in Tight Sandstones

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With the advancement of multistage hydraulic fracturing technology, hydrocarbon production from tight reservoirs has exploded recently. Owing to its widespread nanopore, the permeability of tight sandstones are typically ~4 orders of magnitude smaller than conventional formations, thus leading to the breakdown of Darcy's law within the complex nanoporous matrix. However, most of the existing research only concentrates on the single-phase flow in tight sandstones, whereas the transport of oil and water remains essentially not understood. Taking into account the tremendous effect of two-phase flow behavior on the accurate modeling of fracturing fluid flowback and production performance prediction, we studied oil-water two-phase flow in tight sandstones using pore network model.
Recent experimental studies suggested that because of the greater fluid-solid interactions, there exists a boundary layer (also termed immobile layer) near the pore walls, which decreases the pore radius and restricts fluid flow. We first developed a mathematical model, on the basis of previous experimental data, to describe the variation of boundary layer thickness in a circular micro/nano-tube. In comparison to previous models, which only accounted for the effect of pressure gradient, our model included more influencing factors, e.g., pore size, fluid types, temperature-dependent viscosity, etc., and showed excellent fit to the experiment measurements. Then we incorporated this formulation into a pore network model constructed for tight sandstone to simulate the single-phase water flow. The nonlinear correlation between flow rate and pressure gradient agreed well with the physical experiments on tight rock samples, which confirmed the validation of our model. As the pressure gradient increases, the apparent permeability of tight sandstone increases asymptotically and tends to approach a constant value corresponding to that without boundary layer effect.
We further proposed a pseudo-static pore network model to account for the effect of boundary layer on oil-water two-phase flow in tight sandstones. Because the thickness of boundary layer and estimation of hydraulic conductance are dependent on the pressure gradient, the nonlinear continuum equation was solved using an iteration algorithm to obtain the pressure distribution. We simulated the imbibition of water into the matrix of tight reservoirs. Our simulation results show that two-phase flow regions in the relative permeability curves of tight sandstones are always very narrow; that is, a tight rock sample has higher bound water saturation and residual oil saturation, which makes it more difficult to be exploited. We probed the effects of other properties, e.g., pressure gradient, pore/throat size distribution, coordination number, fluid viscosity, etc., on the two-phase flow behavior in tight sandstones. We suggested that the impact of boundary layer on fluid transport in tight sandstones should not be ignored. Our pore network model, which takes into account the effect of boundary layer on both single-phase and two-phase flows, have implications for tight oil but more generally for mass transfer through nanoporous media.

References

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