Contribution ID: **939** Type: **Oral 20 Minutes**

Detailed numerical simulation of capillary pressure curve hysteresis

Thursday, 17 May 2018 15:32 (15 minutes)

We present a detailed analysis of a "full physics"simulated drainage-imbibition capillary pressure hysteresis on a packed sphere test case, with particular focus on the fluid displacement mechanisms. The chosen LBM-based flow simulator includes a surface-element boundary scheme to ensure accurate surface treatment and robust handling of arbitrary geometries even in low grid resolution scenarios. This simulator also allows specification of the wetting condition, which is essential for multi-phase flow.

During primary drainage, oil (non-wetting fluid) is pushed into a strongly water-wet porous media displacing water. The oil pressure is slowly increased and resulting water saturation values are measured. The entry pressure of the simulated drainage capillary pressure curve is compared to a theoretically derived reference solution based on the Young-Laplace law and geometric considerations. It is shown that the entry pressure is consistent with the inscribed radius of the critical pore throat, and it is further demonstrated that the entire drainage capillary pressure curve depends primarily on the geometry of the porous medium.

The final state of the primary drainage simulation is used as the initial condition of the main imbibition simulation. The oil pressure is slowly reduced to allow water to imbibe the pore space. By plotting the resulting primary drainage and main imbibition capillary pressure curves together, it is seen that for a given water saturation value, the pressure at which water displaces oil (imbibition) is different compared to the pressure at which oil displaced water (drainage), demonstrating capillary hysteresis.

Detailed analysis reveals that the imbibition curve depends strongly on both the curvature of the fluid-fluid interface and the solid geometry. Therefore, accurate prediction of capillary pressure curve hysteresis requires direct simulation of both fluid phases and correctly capturing the detailed interface topology at each pressure condition. This in turn implies that geometry and surface wetting condition are important –geometry simplification and unrealistic contact angle distribution will likely lead to significant inaccuracies.

Another aspect of the presented analysis is the displacement time-scale. During the drainage process, as pressure is slowly ramped up, the change of water saturation is small until the entry pressure has been overcome. Oil then quickly streams into the now accessible pore space. This phenomenon, known as a Haines jump, can also be observed during the imbibition process.

Finally, the simulation method is used to predict the drainage-imbibition capillary pressure cycle on a real sandstone rock sample. It is shown that the same basic mechanisms observed for packed spheres are also present for complex pore spaces.

References

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Session Classification: Parallel 11-F

Track Classification: MS 1.23: Challenges in porous media characterization and modelling of multiphase flow with capillarity