Impact of Wettability Evolution on Dynamic Capillary Pressure

Abay M. Kassa, Uni Research, Sarah E. Gasda, Uni Research
Kundan Kumar, University of Bergen, Florin A. Radu, University of Bergen

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1 Introduction

The wetting property of a given fluid-solid system is determined from surface chemistry and forces acting at the molecular scale at fluid-solid interface. At larger scales, these molecular forces directly control capillary effects. Recent experimental data reveal that P_c-S curves are not static when wettability alteration occurs, despite the fact that experiments are performed under "equilibrium" conditions. The dynamics due to wettability alteration like those observed in [1] are fundamentally different from receding-advancing contact angle hysteresis and the non-equilibrium condition effects.

A few studies attempted to capture wettability alteration within P_c-S curves ([2], [3]). In these works, empirical models for wettability alteration derived from laboratory data are incorporated into the equilibrium capillary pressure function via the residual saturation. However, the extent of wettability change is dependent on the exposure time to a wettability-altering fluid. Since pores drain differentially, exposure time will vary from pore to pore, leading to a highly heterogeneous distribution of contact angles in space and time. Thus, the process is complex, and a simple scaling that lacks information about pore-scale alteration is insufficient.

A reliable mathematical characterization of the dynamic part in P_c-S curves introduced by wettability alteration has not been previously addressed. Here, wettability evolution in time is introduced at the pore-scale using two hypothetical, but physically-based models. The pore-scale is represented by a cylindrical bundle-of-tubes (BoT) model. Even thought this approach is simplistic, it is sufficient to implement dynamic wettability and develop time-dependent correlated expressions. Based on the capillary pressure data derived from the pore-scale simulation, we extend the Brooks-Corey model to capture the effect of the dynamic wettability evolution.

2 Approach

The extended relationship for P_c introduces a dynamic component that captures the deviation of the dynamic capillary pressure from the equilibrium capillary pressure. This relationship can be described as follows,

$$P_c - P_c^{\mathrm{eq.}} = f^{\mathrm{dyn.}}(t, S_{\mathrm{nw}}...) \tag{1}$$

In equation (1), P_c^{eq} represents the capillary pressure under a static wettability. The new dynamic term is a undetermined function $f^{\mathrm{dyn.}}$. In order to quantify f^{dyn}, we introduce two pore-scale wettability models that are dependent on the history of invading fluid saturation, velocity and exposure time which can be given as:

$$\theta_k(\cdot) = \theta_{k,\mathrm{in}} + \big(\theta_{k,\mathrm{max}} - \theta_{k,\mathrm{in}}\big)\Lambda(\cdot) \tag{2}$$

where $\theta_{k,\mathrm{max}}$ and $\theta_{k,\mathrm{in}}$ are the ultimate and initial contact angles. Here, we suggest two possible models for Λ:

$$\Lambda(\chi_k) = \begin{cases} \frac{\chi_k}{(c_1+\chi_k)} \cdots \text{(model L)} \\ \frac{\exp(c_2\chi_k)-1}{\exp(c_2\chi_k)+1} \cdots \text{(model H), where } \chi_k = \big(\frac{1}{L}\int_0^\infty |q_k| dt\big)\int_0^\infty t S_{\mathrm{nw}} dt \end{cases} \tag{3}$$

where c_1, and c_2 are non-dimensional fitting parameters. We incorporate the proposed wettability alteration models into a BoT model and applied a volume averaging approach to quantify up-scaled fluid properties.

3 Numerical experiments and Simulation Results

In this Sec., the effect of wettability alteration on capillarity is studied then compared to the corresponding result using a static contact angle.

3.1 Drainage Displacement Processes

A quasi-static drainage numerical experiment is performed to investigate the effect of wettability alteration on P_c-S curve. Here, the fluids in the larger pores are assumed to be able to affect the smaller pores wettability over time. The effect of wettability interface velocity, and capillarity are depicted in Figure 1. In Figure 1 (second column), we observe that the interface velocity for the altered pores are faster than the velocity breakthrough into unaltered pores. This indicates that the displacing fluid can accesses small pores by altering the fluid-fluid interface property. In the third column of Figure 1, it is observed that the dynamic capillary pressures shift from the $P_c^{eq.}$ curve for the same water content. Magnitude of capillary shift from $P_c^{\mathrm{eq.}}$ against exposure time is illustrated in the last column of Figure 1. Further, we observe a significant capillary shift for negligible wettability change.

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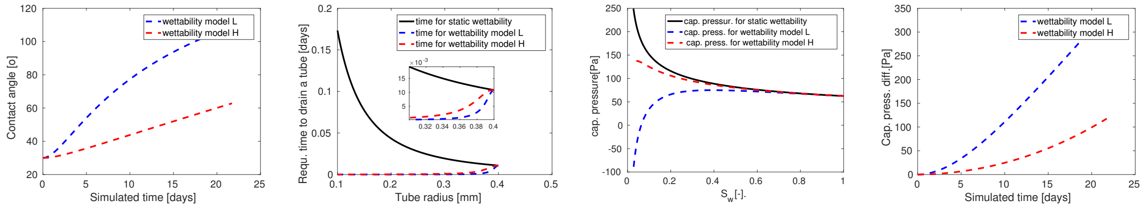


Figure 1: Effect of wettability alteration on macro-scale fluid properties

3.2 Drainage-imbibition Cycle and Wettability Hysteresis

We assume that wettability change starts after the altering fluid is in contact with the rock surface. That means, the larger pores are highly exposed for wettability change during drainage-imbibition cycle. However, the contact angle corresponding to pores that are reoccupied by water are not altered further. Figure 2 shows the resulting P_c-S curves from repeated drainage-imbibition cycles. Here, the wettabilitiy alteration mechanism is simulated based on model L in (2). The water phase reoccupies small pores with very low displacement pressure gradients at the imbibition cycle. From Figure 2(right), we observe that medium sized pores in the distribution are less altered than the larger pores, but large pressure gradient is needed to reoccupy these pores.

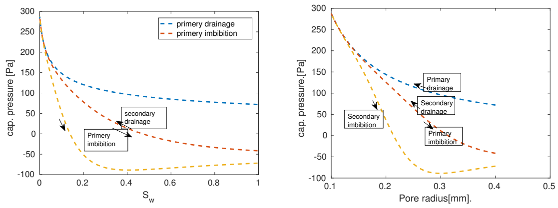
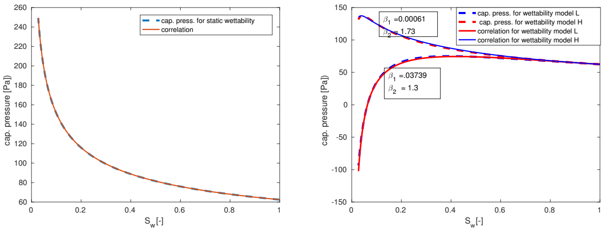


Figure 2: Capillary hysteresis motivated by wettability alteration during imbibition-drainage cycles

4 Physical Based Correlation

The $P_c^{\text{eq.}}$-S relations are correlated well by the Brooks-Corey model in Figure 3(a). From the numerical results, we suggest that the dynamic part in (1) should be governed by a power law and has a form: $P_c = P_c^{\text{eq.}} - \beta_1 \widetilde{\chi}^{\beta_2}$, where $\widetilde{\chi}$ is volume averaged version of the pores-scale variable χ_k. This model is used to correlate the dynamic capillary pressure numerical data. The correlation result is depicted in Figure 3(b). In Figure 3(b), we can see that the proposed dynamic model correlates the time-dependent capillary pressures very well.



(a) *(b)*

Figure 3: Correlation for equilibrium capillary pressure (left) and exposure time dependent capillary pressure (right)

5 Conclusion

We have studied the effect of wettability alteration on constitutive relations in two-phase porous media flow. We have developed a Darcy-scale dynamic capillary pressure model that captures the effect of altering fluid exposure time. The model should be tuned with laboratory experiment to improve its applicability and reliability.

References

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