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Impact Of Time-Dependent Wettability Alteration On Dynamic Capillary Pressure

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Summary

In many applications, the wettability of the rock surface is assumed to be constant in time and uniform in space. However, many fluids are capable to alter the wettability of rock surfaces permanently and dynamically in time. We simulate the dynamic system using a bundle-of-tubes (BoT) approach, where an empirical model for contact angle change is introduced at the pore scale. The resulting capillary pressure curves are then used to correlate the time-dependent term to the upscaled version of the wettability model. This study shows the importance of time-dependent wettability for determining capillary pressure over timescales of weeks and months. The impact of wettability has implications for experimental methodology as well as macroscale simulation of wettability-altering fluids.

Introduction

Wettability plays an important role in many industrial applications, in particular subsurface porous media applications such as enhanced oil recovery (EOR) and CO2 storage [1, 4]. The wetting property of a given multiphase system is defined by the contact angle, which describes the affinity of one fluid for the surface of the medium over another. The contact angle is determined from surface chemistry and associated forces acting at the molecular scale along the fluid-solid interface [1]. In porous media applications, these molecular forces have significant implications for the strength of capillarity across a range of scales.

Wettability is recognized as a critical factor in geological CO2 sequestration which exerts an important role on caprock performance, [4, 5, 7]. WA can influence the ability to prevent CO2 leakage from the reservoir by altering the capillary forces that act to trap CO2 as buoyant phase beneath a low-permeability caprock. This process is highly dependent on CO2 being a strongly non-wetting fluid, and WA may lead to conditions that allow for CO2 leakage [2]. In addition, WA can affect residual saturation results an impact on trapping efficiency of injected CO2 [3]. Therefore, reliable quantification of wettability is key to understand the macroscale processes in these applications.

Despite the fact that WA is known to impact macroscale capillarity and relative permeability bahavior, few detailed measurements are available to characterize the alteration of the constitutive function themselves. Recent experiments measured capillary pressure curves for a silicate sample using a fluid pairing of scCO2 and brine [9]. Repeated drainage-imbibition cycles were performed over a period of 6 months, and a clear reduction in capillary pressure was recorded for each subsequent drainage cycle. The authors attributed these deviations from the usual capillary curve to a change in wettability of the rock sample over time due to scCO2 exposure, i.e. aging. This hypothesis was confirmed through observations of a wetting angle increase from 0° to 75° after 6-months exposure. It is also reported similar Pc-S instability and deviation in dolomite/carbonate [8], and quartz [6, 8] sands for scCo2-brine system. More literature on WA and PC-S measurements can be found in [7].

To our knowledge, a rigorous mathematical characterization of dynamics in p_c-S functions introduced by exposure to a WA agent has not been previously performed. In this paper, we develop a new correlation and scaling for dynamic capillary pressure that is derived using numerically simulated p_c-S curves from a pore-scale model. Here, WA in time is introduced at the pore-scale using hypothetical model. The pore-scale is represented by a cylindrical bundle-of-tubes (BoT) model. Even thought this approach is simplistic, it is sufficient to implement the impact of WA on macro-scale relations.

Approach

We approximate the fluid movement across the length of a given tube by the Washburn flow model:

$$q_k = \frac{r_k^2(\Delta P - P_c^{\text{mic}})}{8(\mu_{\text{nw}} x_k^i + \mu_{\text{w}}(L - x_k^i))}, \tag{1}$$

where q_k is interface velocity, x_k^i is the position of the menisci in tube k, r_k is the k-th tube radius, whereas μ_{nw} and μ_{w} are non-wetting and wetting fluid viscosities respectively. In equation (1), P_c^{mic} is the Young-Laplace entry pressure and is defined as:

$$P_c^{\text{mic}}(r_k, \theta_k) = \frac{2\sigma_{ow}\cos(\theta_k)}{r_k}, \; k = 1, 2, \cdots, N, \tag{2}$$

where σ_{ow} is fluid-fluid inter-facial tension, θ_k is fluid-fluid contact angle. In this paper, we assumed that the contact angle is altered from water-wet to intermediate-wet system in time. This phenomena is designed at pore-scale as

$$\theta_k(\cdot) = \theta_{k,\text{in}} + \left(\theta_{k,\max} - \theta_{k,\text{in}}\right)\chi_k/(K + \chi_k) \cdots (\text{model S}), \tag{3}$$

where K is non-dimensional parameter that controls the speed and extent of WA from water-wet to intermediate-wet or hydrophobic system. The non-linear variable, χ_k, is a measure of exposure time which defined as:

$$\chi_k(t, S_{nw_k}) = \frac{1}{T_c}\int_0^{t_f} S_{nw_k} dt, \tag{4}$$

where T is the characteristic time. The change in θ_k leads to a change for entry pressure in equation (2).

The dynamic capillary change from the equilibrium carve is measured by,

$$P_c - P_c^{\text{eq,in}} = f^{\text{dyn.}}(t, S_{\text{nw}} \dots), \tag{5}$$

where $P_c^{\text{eq,in}}$ is the initial wetting-state capillary pressure. The dynamic term in Equation (5) can be scaled by the difference between initial-and final wetting-state capillary pressures to give,

$$\omega(\cdot) = \frac{f^{\text{dyn.}}}{P_c^{\text{eq,fi}} - P_c^{\text{eq,in}}}, \tag{6}$$

where $P_c^{\text{eq,fi}}$ is the final wetting-state capillary pressure. We incorporate the proposed time-dependent WA model (3) into the BoT model (1) and execute drainage-imbibition displacement numerically to quantify and model the dynamic deviation quantity, ω.

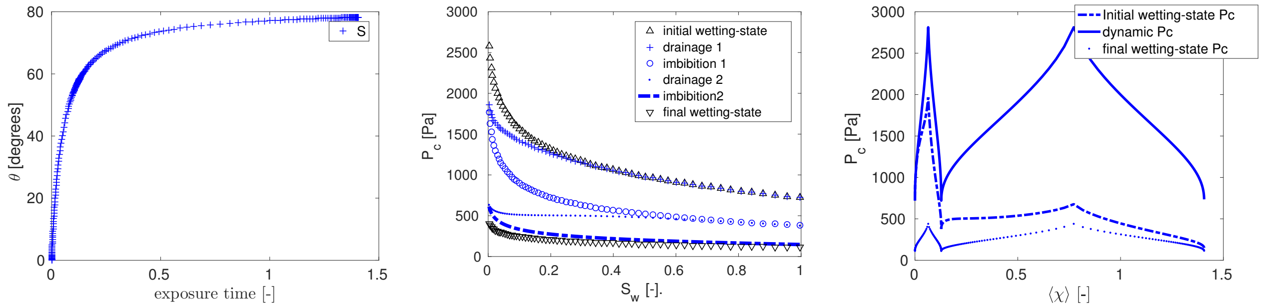
Simulation Results and Correlation

In this Sec., the effect of WA on capillarity is studied and quantified. Here, the fluids in the larger pores are assumed to be able to affect the smaller pores wettability over time and vice-versa.

Drainage-imbibition Displacement Processes

In this Sec., the time to drain-out pores and WA agent contained in the drained pores are used to update the wettability of all tubes in the bundle based on a WA model S. Thus, the contact angle evolution is measured in terms of time-dependent variable $\langle \chi \rangle = \frac{1}{T}\int_0^t S_{nw} d\tau$ for all pores uniformly regardless of either the WA agent is in contact with the pore surface or not.

Based on the above argument, quasi-static drainage-imbibition displacement simulations are executed to investigate the effect of WA on P_c-S curve. The simulated results are obtained for contact angle evolution and P_c-S curves as depicted in Figure 1. In Figure 1a, we observe that the water-wet porous

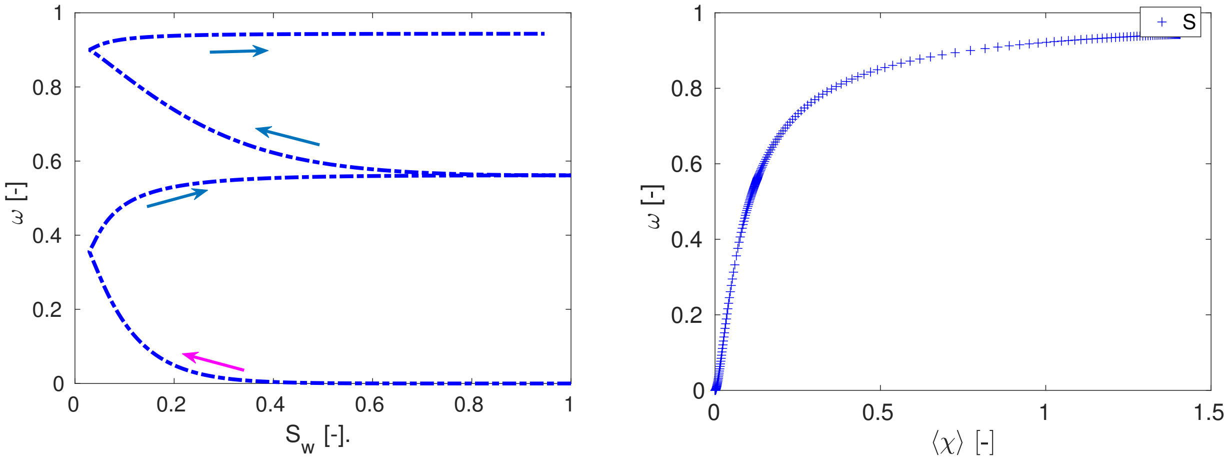


(a) (b) (c)

Figure 1 *WA over time (a) and capillary pressure curves againast water saturation (b) and* $\langle \chi \rangle$.

medium is altered to intermediate-wet system. As a result a dynamic capillary pressure shift from the $P_c^{\text{eq,in}}$ curve is observed. These capillary deviations are caused by only time-dependent WA apart from reservoir complexity and uncertainty. The difference between the equilibrium and WA induced capillary pressure is increasing with respect to the averaged quantity $\langle\chi\rangle$. This may cause CO2 mobility within low permeable caprocks. On the other hand, the imbibition displacements require a higher pressure drop to breakthrough the altered and CO2 occupied pores. For high trapping number the effect of this WA may not be significant.

Following the approach in Sec., we applied equation (6) to calculate the scaled WA induced P_c-S deviation and is depicted as in Figure 2 The simulated WA induced deviation for drainage-imbibition displacements are well behaved with respect $\langle\chi\rangle = \frac{1}{T}\int_o^t S_{nw} d\tau$ within the alteration from water-wet to intermediate-wet system. However, the WA induced dynamic capillary deviation is related with wetting-phase saturation non-uniquely, but still increasing for drainage as well as imbibition displacements. This shows that reservoir system may take long time to reach at equilibrium and even may not reach at equilibrium if the two fluids in contact compete to alter the wettability of the rock surface.



(a)

(b)

Figure 2 The scaled dynamic deviation terms vs water saturation (a) and $\langle\chi\rangle$ (b).

Physical Based Correlation

From the simulation result in Figure 2b, it is observed that the dynamic component in (6) follows the Langmuir type model and can be recalled as:

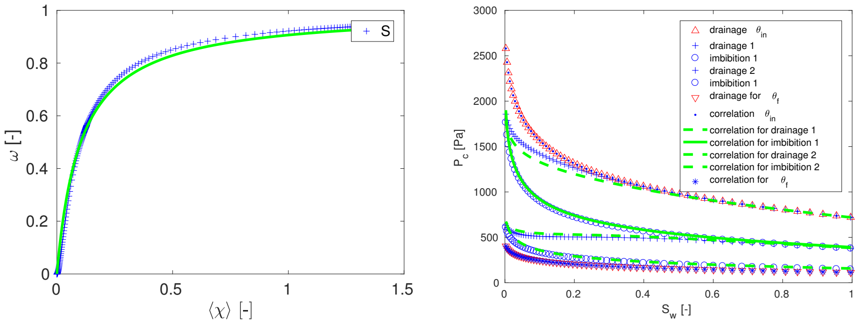
$$\omega(\cdot) = \langle\chi\rangle/(c+\langle\chi\rangle), \tag{7}$$

where c is fitting parameter. This model is used to correlate the scaled dynamic capillary deviation. The proposed correlation model is a one value parameter model that able to correlate the capillary deviation for a possible number of drainage-imbibition displacements. Moreover, the model is the upscaled version of the WA model.

The correlation result is depicted in Figure 3(b) and the fitting parameter is estimated to be $c = 0.1033$ In Figure 3, we can see that the proposed dynamic model agrees with the simulated time-dependent capillary pressures. The microscopic wetting variability of the REV over time is handled by a very straight simple interpolation of equilibrium final and initial wetting-state capillary pressure models. Here, the initial and final wetting-state capillary pressure curves are correlated with the Brooks-Corey constitutive model. The model captures the pore-scale time-dependent WA alteration processes.

Conclusion

We have studied the effect of wettability alteration on capillarity in two-phase porous media flow. We proposed a Darcy-scale dynamic capillary pressure model that captures the effect of altering fluid ex-



(a) (b)

Figure 3 *The correlation for the scaled dynamic capillary pressure deviation.*

posure time. Simple correlation is successful in modelling time-dependent WA induced dynamics for pores that are altered from water-wet to intermediate-wet system.

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