THE EFFECTS OF WETTABILITY ON THREE-PHASE FLOW IN POROUS MEDIA: BASIC THEORY AND NETWORK MODELLING RESULTS

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SUMMARY

Pore-scale network models are usually employed to derive capillary pressure-saturation and relative permeability-saturation relationships from pore-scale physical principles. These models are particularly useful for three-phase flow processes, such as water-alternating-gas injection (WAG), as the three-phase relationships are very difficult to obtain experimentally. Furthermore, network models are used directly alongside micromodel experiments (Sohrabi *et al*, 2000) to identify the important pore-scale displacement mechanisms.

Existing three-phase network models focus mainly on strongly water-wet or oil-wet systems (Mani and Mohanty, 1998; Fenwick and Blunt 1998; Pereira, 1999). Here, we describe the development of a network simulator for capillary-dominated three-phase flow in media where the wettability varies from pore to pore. Reduction of phase continuity in weakly wetted pores has required incorporation of double and multiple displacements for mobilisation of disconnected phase clusters. We have also implemented outlet boundary conditions that are consistent with intra-system pressure changes. A WAG injection cycle is simulated for which the saturation path is recorded along with the statistics of the corresponding phase pore occupancies and displacement mechanisms. Results show the importance of multiple displacements in weakly wetted systems. By definition, network models apply to lengthscales much smaller than reservoirs, hence simulated saturation trajectories, residual saturation levels and hysteresis relate to the local physics in this capillary-dominated limit.

DESCRIPTION OF THE 3D, THREE-PHASE NETWORK MODEL

The network is built on a rectangular 3D grid with capillary tubes (pores) of randomly distributed sizes and has variable co-ordination number z. The degree of oil-water wettability is specified by the cosine of the oil-water contact angle $\cos\theta_{ow}$, which in turn determines the gas-oil and gas-water contact angles in relation to the interfacial tensions σ_{ij}, $ij = ow, go, gw$ (van Dijke *et al*, 2001). The value of $\cos\theta_{ow}$ also determines the presence of a wetting film (Morrow and McCaffrey, 1978) of water for $\cos\theta_{ow}$ close to 1 and of oil for $\cos\theta_{ow}$ close to –1. Gas-filled pores may have a spreading oil film. Flow is assumed to be capillary dominated and capillary entry pressures for each pore are given by $P_{c,ij} = \eta \frac{\sigma_{ij} \cos\theta_{ow}}{r}$, with $\eta = 1$ for snap-off and $\eta = 2$ for piston-wise displacements.

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MULTIPLE DISPLACEMENTS

When wetting films are absent, clusters of each phase may be disconnected from the inlet or outlet but are not necessarily trapped and such clusters can only move by double or even multiple displacements, i.e. injection of the invading phase triggers a chain of interface displacements throughout the network involving a series of phase clusters from inlet to outlet. To determine the most likely displacement, we must first find the pore with lowest capillary entry pressure for each cluster-cluster interface. Then, for each possible chain of clusters, the target pressure difference P_{ij}^{target} between the invading phase i and the pressure of one of the remaining phases j at the outlet is found as

$$P_{ij}^{target} = P_{c,ik}^{eff} + P_{kj}^{out} \tag{1}$$

where $P_{c,ik}^{eff}$ represents the sum of the capillary entry pressures for the involved clusters. P_{kj}^{out} denotes the difference between the pressure in the outlet connected cluster in the chain, with phase k and the chosen outlet pressure ($i, j, k = o, w, g$ and $i \neq j$). For example, for gas injection we may have gas (at the inlet) displacing water from pore $r_{gw,1}$, then water displacing oil from r_{wo}, then oil displacing gas from r_{go} and then gas displacing water from $r_{gw,2}$ through the outlet, where oil is the reference phase at the outlet. Hence, the target is P_{go}^{target}, where $P_{c,gw}^{eff} = P_{c,gw}(r_{gw,1}) - P_{c,ow}(r_{wo}) - P_{c,go}(r_{og}) + P_{c,gw}(r_{gw,2})$, with P_{wo}^{out} at the outlet. Of all possible displacements the one with minimum P_{ij}^{target} is carried out and this requires a "shortest-path" tree-search algorithm. Furthermore, as not all pores in the displacement chain have the same size, multiple displacements lead to fractionally filling of pores, which has been incorporated in the model to obtain accurate saturation calculations.

OUTLET BOUNDARY CONDITIONS

In three-phase flow, two outlet pressure differences P_{kj}^{out} must be specified, particularly if separate clusters of the invading phase are present at the outlet. These pressures may be kept constant during a flood, i.e. external pressures are applied, when the network is considered to represent an entire micromodel or core. On the other hand, the outlet pressure differences may vary with the movements of interfaces within the network. This condition reflects the view that the network represents only a small local region, on which fluxes are imposed rather than pressures. Specifically, when a disconnected cluster reconnects to the outlet, the pressure of the reconnecting cluster is taken as the new outlet pressure for that phase. Hence, the latter pressure is consistent with the latest chain of displacements. For a reconnecting cluster with phase l, which is part of a displacement chain, we have a pressure difference with the reference outlet phase of

$$P_{lj}^{rec} = P_{c,lk}^{eff} + P_{kj}^{out} \tag{2}$$

If in the displacement example above, the oil cluster reconnects to an oil cluster that was already connected to the outlet, then $P_{oo}^{rec} = -P_{c,go}(r_{og}) + P_{c,gw}(r_{gw,2}) + P_{wo}^{out}$. Hence, the outlet oil-water pressure difference becomes $P_{wo}^{out,new} = P_{oo}^{rec} - P_{wo}^{out}$ and the gas-oil pressure difference is $P_{go}^{out,new} = P_{go}^{out} - P_{oo}^{rec}$. A slightly different reconnection would have taken place if the second gas cluster reached the outlet directly but equation (2) is also adequate for this event, simply with $P_{go}^{rec} = P_{c,gw}(r_{gw,2}) + P_{wo}^{out}$.

When the outlet pressures are allowed to vary, variations may be non-monotonic as a result of pore accessibility. However, analogous to imposing a monotonically increasing target capillary pressure, we may choose to increase the outlet conditions only, i.e. by taking the maximum over the course of the process (Fenwick and Blunt, 1998; Lerdahl *et al*, 2000).

SIMULATIONS

Three-phase simulations have been carried out in a mixed-wet network with 15×10×10 pores (15 in flow direction) and $z = 4$. Radii (r) are uniformly distributed between 5 and 25 μm. Pores with $r < 15$ μm are water-wet ($\cos\theta_{ow} = 1$); the rest are oil-wet ($\cos\theta_{ow} = -1$). With $\sigma_{gw} = 48$ mN/m, $\sigma_{ow} = 32$ mN/m and $\sigma_{go} = 24$ mN/m, oil is non-spreading and gas is wetting relative to water in oil-wet pores. For the base case, wetting films are absent, up to 5 multiple displacements are allowed (for computational reasons) and outlet boundary conditions are varied as described above. A WAG cycle is simulated by injecting water into 100% oil until $S_w = 0.20$, then gas is injected until $S_g = 0.40$, then water until $S_w = 0.35$ and eventually gas, until no further displacement chains from inlet to outlet are possible.

The corresponding saturation path is given in Figure 1 showing oil recovery during each flood, although there is very little during the second gas flood. At the end of the last flood, the oil saturation is $S_o = 0.299$. For comparison, the WAG flood is also shown in the same mixed-wet system, but including water wetting films in the water-wet pores and oil wetting films in the oil-wet pores. As a result, the continuity of oil and water is much higher than in the base case and at the end of the last gas flood the residual oil saturation is virtually zero.

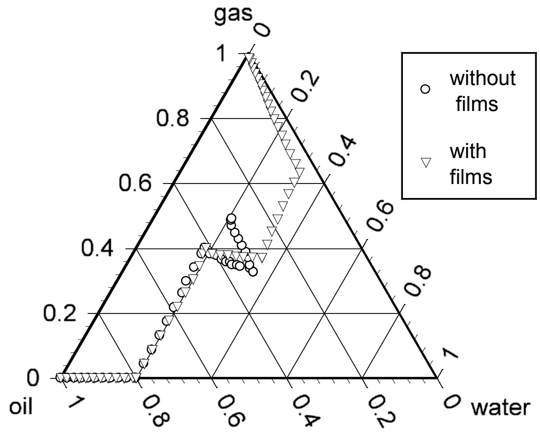
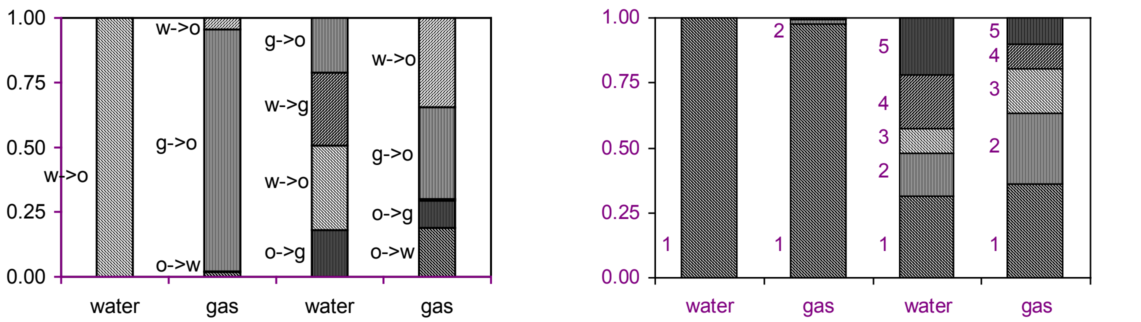


Figure 1 – Saturation paths for WAG cycles in a mixed-wet system without wetting films (base case) and with wetting films for both water and oil.

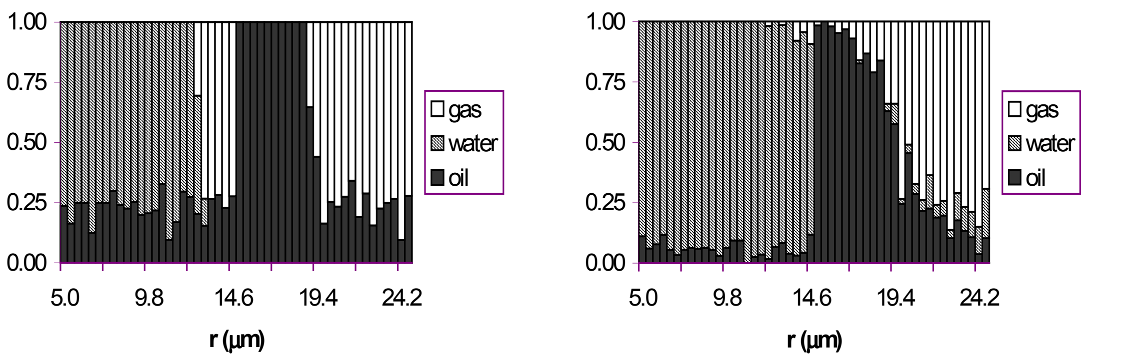
The displacement statistics for each flood are presented in Figure 2. In each displacement chain, one pore is allowed to fill exactly and the nature of this displacement is recorded in Figure 2a. In Figure 2b the numbers of clusters involved in a displacement chain are given. Figure 2b shows that multiple displacements (> 2) are important only in the second water and gas floods.



a. **b.**

Figure 2 – Displacement statistics for consecutive floods in WAG cycle, a. type of displacements (e.g. g->o indicates gas displacing oil), b. number of displacements per chain: single (1), double (2) etc.

Figure 3 shows examples of pore occupancy statistics. After the first gas flood, quite sharp divisions between gas, oil and water occupancies are seen, indicating good continuity of all three phases, although some 20% of pores of all sizes contain disconnected or trapped oil. Gas has also simultaneously filled both water-wet and oil-wet pores. After the second water flood, gas and oil have become more and more disconnected, as water has not been able to fill the oil-wet pores from the largest onwards, which is expected as gas is wetting to water. However, water has been able to displace additional oil from the water-wet pores, but at least part of this has ended up in the larger oil-wet pores via multiple displacements.



a. **b.**

Figure 3 – Occupancy statistics, i.e. fraction of pores filled with a certain phase as a function of pore size, a. at end of first gas flood, b. at end of second water flood.

In a second simulation, chains of up to only 2 displacements were allowed and the second water flood was already finished at $S_w = 0.320$, as no single or double displacements were found. The pore occupancy showed more oil remaining in the water-wet pores compared to the base case. At the end of the last flood, $S_o = 0.318$.

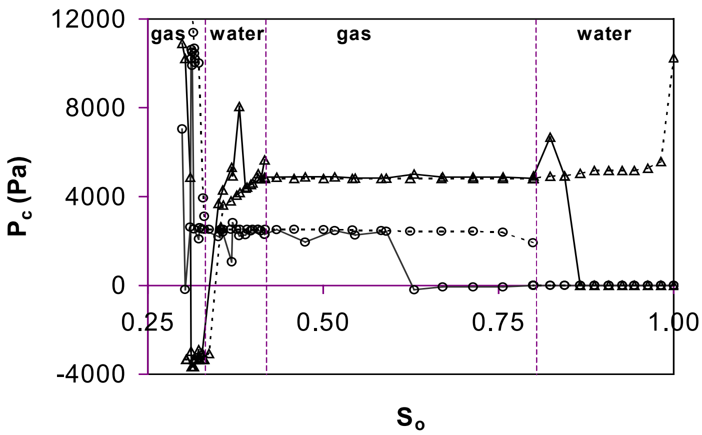


Figure 4 – Oil-water (triangles) and gas-oil (circles) pressure differences during WAG cycle with variable (solid lines) and "constant" (dashed lines) boundary conditions. Floods progress in direction of decreasing oil saturation during injection of water, gas, water and gas as indicated.

A third simulation was performed with "constant" boundary conditions i.e. during a water flood P_{go}^{out} and during a gas flood P_{ow}^{out} is kept constant. The remaining pressure differences vary monotonically, equal to the target pressure differences. Figure 4 compares the outlet pressure differences for this simulation and the base case. Only during the later floods, with low phase continuity and hence many multiple displacements and possible reconnections, large variations occur. During the second water flood, the base case P_{ow}^{out} is significantly higher, causing a different oil saturation at the end of this flood, $S_o = 0.324$ (base case) vs. $S_o = 0.330$. However, the final $S_o = 0.305$ is not vastly different from the base case.

DISCUSSION AND CONCLUSIONS

The presented three-phase network simulations show the importance of the presence or absence of wetting films as a result of (weak) wettability. In the absence of films, chains of multiple displacements become common in higher order floods, when the continuity of the phases decreases. They enhance the internal movement of disconnected phases throughout the network, which is vital for the efficiency of WAG injection. Furthermore, multiple displacements may cause changes in outlet pressure differences, when disconnected clusters become reconnected to the outlet, which yields additional deviations of saturation paths. Since different disconnected clusters of one phase in the network have different pressures, the question arises which (outlet) pressure differences represent the "true" capillary pressures of the network (Mani and Mohanty, 1998). This in turn is important not only for the three-phase capillary pressure-saturation, but also for the relative permeability-saturation relationships.

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