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Pore Network Modelling of Low Salinity Water Injection Under Unsteady-state Flow Conditions

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Abstract

In this work, we describe a dynamic pore network model that has been developed to investigate the effects of low salinity (LS) water injection on oil recovery under dynamic flow conditions. For the first time, we introduce a formulation whereby the evolving spatial distribution of brine salinity is explicitly tracked during unsteady-state secondary and tertiary LS floods. Phases are updated in capillary elements according to the relative balance between capillary and viscous forces, the former being correlated to salinity through a functional relationship between effective contact angle (i.e. wettability) and local brine concentration.

We have investigated the impact of several key parameters on secondary and tertiary LS injection, including: injection rate, viscosity ratio, and salinity-induced wettability modifications. We have implemented a stochastic approach throughout in order to assess statistical variability in recovery outcomes. For the particular network architecture studied, simulations have shown a range of results for different induced wettability changes. When the contact angle variation shifted the system from strongly oil-wet to weakly oil-wet, most cases exhibited a small positive secondary LS effect but negligible tertiary benefit. Greater variation in LS outcome was observed when LS brine modified pores to close to neutral-wet conditions – a generally positive secondary LS effect was seen but there were several exceptions dependent upon frontal advance rate and viscosity ratio, where the displacement regime could switch from capillary-dominated flow to viscous fingering. Salinity modification of wettability to a water-wet configuration resulted in positive secondary LS displacement and a positive tertiary LS effect.

The study shows that the impact of LS injection can often be difficult to predict a priori for any given combination of rock/fluid parameters and laboratory protocol, due to the complex way in which the underlying parameters interact. When compared against high salinity (HS) data, both positive and negative LS effects have been observed depending upon the prevailing system properties and the timing of LS initiation. However, by running a series of network modelling simulations, we are able to identify areas of parameter space that are more likely to elicit a positive LS response. In particular, we observe that a change in the dominant flow regime (capillary fingering, viscous fingering, frontal advance) may be induced by the injection of LS brine and this has been found to play an important role in determining LS efficacy.

Keywords: pore network modelling, low salinity, secondary water injection, tertiary water injection, unsteady-state flow, contact angle modification.

1. Introduction

With ever-increasing energy demands across the world, new methods have been developed to maximise recovery from oil reservoirs. Exploiting only natural recovery mechanisms, such as depletion, would leave significant amounts of oil behind, and even secondary recovery processes, such as water injection or gas injection, might not be able to yield the desired recovery profiles (especially for high viscous ratios where viscous fingering can result in poor volumetric sweep). Tertiary recovery methods are often applied at this stage to mobilise some of the oil left behind and to yield additional oil recovery. These techniques are also referred to as Enhanced Oil Recovery processes (EOR) and generally involve the injection of one or multiple fluids to shift the reservoir conditions into a more favourable state that could result in further oil recovery. This could be achieved by decreasing the interfacial tension between oil and water (i.e. surfactant injection), shifting the wettability of the reservoir toward a favourable configuration (i.e. low salinity (LS) water...
injection) or improving the mobility ratio to strengthen the viscous forces of the displacing phase
and switch the flow regime from inefficient viscous fingering toward more favourable frontal
advance (i.e. polymer injection). The current paper focuses on a number of issues affecting low
salinity water injection.

LS water injection has been examined in various works in the literature, and several experimental
studies have reported additional recovery when fresh or LS water is used to displace oil in both
secondary and tertiary modes (Ashraf et al., 2010 [1]; Webb et al., 2005 [2]; Zhang and Morrow
Bernard, 1967 [7]). Today, LS water injection is becoming an increasingly popular EOR technique,
and interest in its applications is growing. Some of the latest works in this area include the
investigation of LS injection in both secondary and tertiary modes using coreflood data and history
matching analysis for different wettability configurations (Xie et al., 2015 [8]). This study showed a
significant increase in oil recovery and decrease in water production in both modes. Contradictory
results have been reported by Zeiniijahromi et al (2015) [9], where negligible incremental oil
recovery (less than 1%) has been achieved based on history data from 7 years of LS water injection in
the Russian Zichebashskoe field. Combining LS water and polymer has been also investigated in
recent years (Zhuoyan et al., 2015 [10]; Shiran and Skauge, 2013 [11]) and a positive synergetic
behaviour has been reported compared to that obtained from polymer applied in HS water
environments.

In a review published in 2011, Morrow and Buckley [12] discussed the major advances in LS
application and presented the various suggested mechanisms for the so-called Low Salinity Effect.
Changing the wettability of the rock (by affecting the adhesion of oil molecules to the rock surface
and/or changing the brine composition) is believed to be a key consequence of LS injection. This
wettability change is associated with a shift in oil-water contact angle that may reduce capillary
forces, mobilise trapped oil ganglia, and/or cause water fingers to swell and thicken. Recent
experimental micromodel work by Song and Kovscek (2015) [13] has shown that LS water flooding
can shift the system wettability towards a more mixed-wet configuration: the adherence of oil to oil-
water clay particles led to increased oil recovery by 14% when these particles were mobilised after
being exposed to LS water. Bartels et al. (2017) [14] have observed a modification of contact angle
towards more water-wet values in response to LS water exposure in single-channel micromodels.
The authors reported that contact angle change was a necessary but not sufficient condition for
obtaining additional recovery in their systems, which they observed when trapped oil ganglia
became reconnected with spanning oil clusters. However, it should be noted that the LS
environment in their single-channelled micromodels could be expected to be rather different from
that expected in the complex heterogeneous structure of many natural porous media – the contact
angle responsiveness reported may, therefore, not be generally applicable. Recent microCT scans of
in-situ oil-water contact angles have also revealed clear indications of a shift from weakly oil-wet
towards weakly water-wet configurations. This has been shown in the work of Khishvand et al.
(2017) [15], who injected low salinity water in miniature core samples where wettability had been
restored to mimic reservoir conditions. The contact angle reduction led to increased oil recovery,
which was explained by the reduction of pressure threshold required to displace oil from small
capillaries.

Other reports of possible LS mechanisms include:
• Fines migration (Tang and Morrow, 1999 [16]): clay components could detach from the rock surface when the water salinity is low. This might trigger partial mobilisation of residual oil attached to clay.

• Microscopic diversion (Spildo et al., 2012 [17]): detached clay components could block small throats resulting in increased pressure gradients in other regions of the network.

• Chemistry-related phenomena, such as pH variation, multi-component ionic exchange and double layer expansion (Xie et al., 2015 [8]).

In light of the wide variety of studies reported to date, it is highly likely that the LS effect is a manifestation of several mechanisms acting synergistically (and goes some way towards explaining the contradictory results in some cases reported in the literature regarding additional recovery yielded by LS water injection). The design of robust experimental protocols consequently becomes difficult to achieve and laboratory results may exhibit large uncertainty. Network modelling can provide an alternative cheap approach to investigate the effect of several key flow parameters on LS waterflooding.

2. Modelling Approach

2.1 Pore Space Description

In general, the pore network modelling approach seeks to approximate a given porous medium by means of a network of interconnected capillary elements, partitioned into nodes (pore bodies) and bonds (pore throats), with the nodes being linked by the bonds (Figure 3). To each network element (a node or bond) a range of geometric attributes can be attached (inscribed radius, length, volume, shape factor) that enables us to consider a number of different network modelling philosophies. At its most simplistic, we can use the framework to model the pore space as a simple scaffold of interconnected cylindrical bonds; an approach that is useful for obtaining rapid, qualitative results, as fewer pore-scale entities need to be considered. At the other extreme, we can also use the methodology to model multi-phase flow through networks that are topologically and geometrically complex, where the pore space is comprised of irregular pore elements with distributed connectivity. We will adopt the former approach here for simplicity (and restrict our study to 2D for the present) but note that more detailed geometries can be considered without adding a great deal of additional complexity to the modelling (See Boujelben, 2017 [18]).

Regular networks are assigned pre-determined dimensions $N_x \times N_y \times N_z$, where $N_x, N_y, N_z$ are the number of nodes in the $x$, $y$ and $z$ directions, and capillary entry radii can be assigned randomly to the constitutive elements from a realistic pore size distribution in order to approximate the porous medium under investigation. A more physical network can be generated through the use of a series of image processing operations conducted on 3D images taken from real rock samples (Silin et al., 2003 [19]). A topologically equivalent network of capillary elements can then be built and loaded into our software with properties extracted from the original Micro-CT data (e.g. radius, volume, shape factor). Investigations using these more complex systems – including explicit film-flow transport – is on-going and will be the subject of a future paper.

2.2 Unsteady-state Flow Model

The first flowing pore network model used to examine low salinity flooding was reported by Watson et al., 2017 [20], who developed a novel, steady-state approach in which LS brine was injected into a 3D network following breakthrough of high-salinity brine. Their results highlighted two principal
effects of dynamic contact angle modification at the pore-scale: a “pore sequence” effect, characterised by an alteration to the distribution of displaced pore sizes; and a “sweep efficiency” effect, demonstrated by a change in the overall fraction of pores invaded. The assumptions made regarding contact angle modification in [15] built upon those presented previously in the pore-scale theory of Sorbie and Collins (2010) [14] and their study was an important foundation to the steady-state work. The inclusion by Watson et al of explicit fluid transport within the pore network was able to identify phenomena that would have been difficult to predict using the percolation theory approach in [14]. Moreover, no viscous forces or transient behaviours were considered in these previous models – important aspects of the process that will be addressed by the unsteady-state model developed here, which builds upon the earlier formulation of Regaieg et al [18], who investigated waterflooding in heavy oil systems. Details of the unsteady-state model are presented in the Appendix whilst excellent discussions of a wide range of pore network modelling approaches (both steady- and unsteady-state) can be found in the review articles of Blunt (2001) [21], Joekar-Niasar and Hassanizadeh (2012) [22] and Blunt (2017) [23]. By modelling the effects of wettability alteration upon the evolving pressure field during injection, we are able to simulate different LS protocols and to quantify the resulting oil recovery at different stages of the water flooding. We note that the study presented here is limited to networks anchored to relatively homogeneous rocks (i.e. Berea sandstones) – LS transport in carbonates is under investigation but is far more complex due to wide variations in pore size and the presence of nano-porosity in many instances.

The LS model developed in this work forms part of a more general pore network EOR simulator that has been implemented using the C++ programming language and Qt framework (Figure 1). This simulator package – numSCAL (numerical Special Core Analysis Laboratory) – includes several flow models that cover a wide range of pore-scale processes, including:

- Quasi-steady state two-phase and three-phase flow
- Three-phase pressure depletion
- Unsteady-state waterflood
- Unsteady-state ganglion migration
- Unsteady-state EOR floods (low salinity brine, surfactant, polymer)

A basic open source version of numSCAL is available online and can be downloaded from the public GitHub repository: https://github.com/ahboujelben/numSCAL_basic.
2.3. Tracer Dynamics

As discussed above, the LS model presented in this work builds upon the earlier steady-state approach described in Watson et al., 2017 [20]. In the current study, when modelling the flow of LS water in the network, the following conditions are considered:

- LS water is injected into an initially oil-wet system.
- LS water and HS water are miscible and mix instantly in a capillary element.
- No meniscus is considered between LS water and HS water.
- LS water cannot mix with oil or flow through the oleic phase.
- Fines migration during LS injection is not considered.

To capture the effect of LS water at the pore-scale, we adopt a highly pragmatic methodology whereby we model the central manifestations of the LS mechanism instead of tracking the complex chemistry underlying the interaction between LS water molecules with the rock surface. We therefore assume that LS water primarily affects the oil/water contact angles and mathematical relationships are used to couple local salinity to the degree of contact angle modification. Of course, this cannot hope to capture all of the intricate LS mechanisms proposed to date, but we consider this a useful foundation for the development of a more comprehensive modelling framework. Moreover, from a physical standpoint, our assumption of effective contact angle modification appears reasonable, since wettability alteration is a phenomenon commonly believed to accompany LS flooding in a variety of reported coreflooding studies.

The workflow of the unsteady-state LS model is shown in Figure 2. The effective contact angles (affecting directly the capillary pressure in pore elements) are correlated with LS brine concentrations. The unsteady state model is then called to solve the pressure field in the network and to update the phase saturations in all capillary elements. Finally, the concentrations of LS water...
are updated according to mass conservation laws, and the next time step is taken until a user-defined number of pore volumes have been injected.

Figure 2: LS model workflow

LS water is modelled as a tracer with dimensionless concentration ranging from zero to one. It can flow from the inlet pores either immediately the simulation starts (secondary mode) or after some period of HS water injection (tertiary mode). In both cases, we use a mass conservation law to update tracer concentrations according to the pressure field in the network. Note that the term “tracer concentration” or “LS concentration” refers to the concentration of LS water and is equivalent to (1-salinity).

Considering the configuration shown by Figure 3, and denoting the LS water concentration in each pore $i$ by $C_{LS,i}$, the flow $Q_i$ in each pore $i$ is determined after solving the flow equations in the network, and the new volumetric water fractions $F_{W,new}$ are updated accordingly in all pores. Next, a new tracer concentration $C_{LS,new}$ in pore 1, after a timestep $\Delta t$ is computed after updating elementary water fractions in the network, and we calculate it as follows:

\[ C_{LS,new} = \frac{F_{W,old}}{F_{W,new}} C_{LS,old} + \left( \frac{Q_1}{Q_{int,1}} I_{LS, into, node} - I_{LS, out, from 1} \right) \left( \frac{\Delta t}{F_{W,new} \times V_1} \right) \]  

where $V_1$ is the volume of pore 1 and $Q_{int,1}$ corresponds to the total volumetric flow into node 1.

$I_{LS, into, node}$ refers to the mass flux of LS water entering the node and is calculated as:

\[ I_{LS, into, node} = Q_3 C_{LS, old} + Q_4 C_{LS, old} \]  

We assume that the LS water is partitioned among the downstream pores in proportion to their individual flows. Thus the mass flux of tracer entering pore 1 is given by \( \frac{Q_1}{Q_{int,1}} I_{LS, into, node} \). The mass flux of tracer leaving pore 1 is calculated as:

\[ I_{LS, out, from 1} = Q_1 C_{LS, old} \]
2.4. Coupling the LS Effect to Tracer Concentration

Although the precise cause of any LS effect may be related to a wide variety of pore-scale phenomena, we assume in this work that wettability alteration is the main consequence of the underlying chemistry and hence of any LS effect. This occurs when the initial contact angle attributed to a capillary element changes when it comes into direct contact with LS water. If the contact angle change shifts the network wettability towards a less oil-wet configuration, a reduction of the resisting capillary forces is expected, which could affect recovery.

When an oil-filled pore is being invaded with LS water (or is adjacent to LS water-filled pores), we assume that its initial oil-water contact angle can change according to its salinity (or the average salinity corresponding to adjacent water-filled pores). The new contact angle is calculated as:

\[
\theta_{\text{new},i} = \theta_{\text{initial},i} + \Delta \theta \times \Psi(C_{\text{LS}})
\]

(4)

where \(\Delta \theta\) is a parameter that corresponds to the maximum contact angle change when the concentration of LS water is equal to one and \(\Psi\) is a Hill function (Atkins, 1973) [24] given by:

\[
\Psi(C_{\text{LS}}) = \frac{C_{\text{LS}}^{\Gamma_1}(1 - \Gamma^n)}{C_{\text{LS}}^{\Gamma_1}(1 - 2\Gamma^n) + \Gamma^n}
\]

(5)

\(\Gamma\) refers to the concentration at which half of \(\Delta \theta\) is reached, whilst \(n\) is the Hill function exponent that determines the rate of change. In this model, we set \(n\) equal to 30 and \(\Gamma\) equal to 0.88 (Figure 4), meaning that the local salinity must be relatively low for a significant contact change to occur.

This results in a naturally delayed wettability alteration on a timescale of tens of minutes (as the salinity gradually reduces as the LS brine permeates the system). The timescale associated with wettability alteration has been a topic of some interest in the past and LS waterflooding has encouraged renewed research in this area. Whilst some studies have observed very rapid wettability...

Figure 3  Phase configuration for four connected pores in a 2D network (left) at the start of a timestep (right) at the end of the timestep.
modification (Al-Anssari et al., 2015 [25]), others have described contradictory behaviour – for example, Mahani et al. (2015) [26] have recently reported a time constant of hours to days for some wettability changes to occur for a specific glass/clay/fluid system (although data exhibited a wide degree of scatter). Whilst an additional delay term could be readily included in (4) for any rock/fluid system of interest, the timescale for wettability alteration is affected by a wide range of physico-chemical properties – including brine composition, clay type, clay orientation, pH, and oil composition – hence, we choose to exclude this refinement at this stage. Furthermore, under certain flow conditions and viscosity ratios, delayed wettability modification could also result in the premature termination of LS floods caused by topological limitations of our 2D system: the absence of the third dimension means that a network could reach residual oil saturation before any contact angle modification had had time to occur (whilst in 3D there would be cases where some oil remained connected to the system outlet following water breakthrough). Note that this issue could also have important implications for LS micromodel experiments characterised by long wettability modification timescales – the 2D nature of such experiments means that any LS effect could be underestimated as far as displacement of bulk oil is concerned.

![Figure 4: Hill Function is used to relate the tracer concentration to LS effect.](image)

3. Results and Discussion

3.1 Simulation Protocol

In order to study the effect of LS water on oil recovery, we have run a large number of simulations covering a wide variation of injection protocols. Note that all simulations reported here are 2D in nature and only bulk oil displacement has been considered (the impact of layer flow and 3D implementation of the model in realistic rock architectures will be reported in a forthcoming paper).

Two different injection scenarios are reported here:

- **LS-sec**: This refers to the injection of LS brine in secondary mode – injection of the tracer occurs at the very beginning of the waterflood.
- **LS-ter**: This refers to the injection of LS brine in tertiary mode. Once a spanning HS water cluster forms following a period of HS water injection, a drop in pressure is observed at the system outlet, and no further significant recovery is usually observed. It is at this point that we start the injection of LS brine.
To simulate the LS effect on contact angle, we consider three scenarios. As described earlier, we correlate the LS concentration to the contact angle change assigned to capillaries in direct contact with the LS brine. Initially, all the capillary elements are considered oil-wet and assigned a contact angle equal to 140°. As the concentration of LS water starts to build up in a capillary element, the associated contact angle starts to decrease until it reaches a minimum value corresponding to a tracer concentration equal to one (i.e. a salinity of zero). The three scenarios studied here are as follows:

- **OWOW**: This corresponds to a change from a strongly oil-wet configuration to a weakly oil-wet configuration. The contact angle change is $\Delta \theta = 30°$ and a maximum shift from 140° to 110° is allowed in the contact angles of the capillaries in direct contact with low salinity brine.
- **OWNW**: This corresponds to a change from a strongly oil-wet configuration to a neutral-wet configuration. The contact angle change is $\Delta \theta = 45°$ and a maximum shift from 140° to 95° is allowed in the contact angles of the capillaries in direct contact with low salinity brine.
- **OWWW**: This corresponds to a change from a strongly oil-wet configuration to a weakly water-wet configuration. The contact angle change is $\Delta \theta = 60°$ and a maximum shift from 140° to 80° is allowed in the contact angles of the capillaries in direct contact with low salinity brine.

The additional oil displaced by LS processes can be greatly affected by the flow rate and the initial viscous ratio. We have therefore considered three different values for each, enabling us to investigate a vast range of experimental parameter combinations.

- Viscosity ratio $M=1, 10, 100$: the HS and LS water viscosity are fixed at 1cP and oil viscosity is varied according to the value of $M$ of interest (for $M=100$, oil viscosity is equal to 100cP).
- Frontal advance rates of $V=1\text{m/day} \ (Ca=3.85^{-7})$, $5\text{m/day} \ (Ca=1.93^{-6})$ and $10\text{m/day} \ (Ca=3.85^{-6})$ ($\mu_{\text{water}}=1\text{cP}$, $\mu_{\text{oil}}=10\text{cP}$). Here, we have defined the macroscopic capillary number $(Ca)$ as $Ca = \frac{\mu_{\text{injected}}V}{\sigma}$ (Blunt, 2017 [23]) where $\mu$ and $\sigma$ are the viscosity of the injected fluid and the oil-water surface tension, respectively.

### 3.2. Base Case Parameters

For the simulations carried out in this work, 200x100 statistically generated networks are used to examine the LS effect – this corresponds to a physical sample size of (2cm x 1cm). We consider the networks to be initially oil-wet with contact angles equal to 140°. The initial viscosity ratio is equal to 10 ($\mu_{\text{water}}=1\text{cP}$, $\mu_{\text{oil}}=10\text{cP}$), and water is injected at a rate that is consistent with an average frontal velocity $V$ equal to 5m/day (see Appendix for more details about water injection at constant flow rate). LS brine gradually shifts the contact angles from 140° to 95° (OWNW). The initial water saturation is set to 0 for the simulations undertaken here – this allows us to examine the impact of contact angle modification on displacement efficacy without introducing the additional confounding factor of LS brine mixing with HS S_w (although this is an important issue to address in future work, as it could introduce an additional delay in wettability alteration and any LS effect).
For ease of interpretation, we restrict our simulations to relatively simple geometric networks that have an average connectivity and range of pore sizes that are consistent with a generic sandstone. The inscribed radii are sampled from a Truncated Normal distribution (Figure 6) and the networks are distorted to generate a range of pore lengths. We reiterate that irregular network topologies obtained from image data pertaining to real rocks can be accommodated by the model and these will form the focus of a future publication.

The geometrical properties of the statistically generated networks are given by Table 1. These parameters result in network porosities and permeabilities of $\phi = 7.56\%$ and $\kappa = 208 mD$ respectively.

<table>
<thead>
<tr>
<th>Geometrical Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coordination number</td>
<td>3.65</td>
</tr>
<tr>
<td>Average Pore Length</td>
<td>100 $\mu m$</td>
</tr>
<tr>
<td>Maximum Inscribed Radius</td>
<td>30 $\mu m$</td>
</tr>
<tr>
<td>Minimum Inscribed Radius</td>
<td>1 $\mu m$</td>
</tr>
<tr>
<td>Pore Size Distribution</td>
<td>Truncated Normal ($\mu=9$, $\sigma=6$)</td>
</tr>
</tbody>
</table>

Figure 5  Right: Network description. Left: corresponding steady-state mercury injection capillary pressure curves (primary drainage and spontaneous imbibition)

Figure 6: Pore size distribution of the statistically generated networks used in the thesis: Truncated Normal ($\mu=9$, $\sigma=6$)
3.3 Stochastic Variability

The 2D statistically generated networks used in this study are distorted and pore radii are sampled from a predefined pore size distribution. During the sampling operation, it is important to be able to reconstruct exactly the same network in order to make valid comparisons between different simulations when certain rock/fluid properties and injection protocols are varied. We therefore use a unique random number seed when we generate a given network – this can be seen as a parameter that ensures that every time we sample a sequence of numbers from a random distribution, we always end up with the same sequence. Therefore, two networks generated with the same seed would share identical microscopic and macroscopic properties. Two statistically generated networks built from two different seeds, however, would share the same macroscopic properties (i.e. average coordination number, pore size distribution) but they would have completely different spatial distributions of pores: although the radii of both networks are sampled from the same distribution, they evolve different phase structures due to their different seed numbers.

This is clearly apparent in Figure 7, where HS water injection is simulated on two networks generated from two different seeds. Although both networks share the same properties and the same flow parameters have been used, the final water distributions are spatially rather different (even though the same flow regime is evident in this case).

![Image of water distributions in two 2D networks](image)

Figure 7  HS water distribution in two 2D networks after 4PVs. Base case network properties and flow parameters are used to build and simulate the networks but using two different seeds. Water is coloured in white, oil in black.

The sensitivity to the seed might present some issues when trying to quantify a LS effect on additional oil recovery. As the oil produced can sometimes be affected by the available pathways and the random topology of the underlying networks, it is possible to observe two different EOR outcomes when we simulate the same experiment on two similar networks generated with two different seeds. To illustrate this point, we simulated HS water injection and secondary LS water injection (LS-sec) on two networks with two different seeds. This particular case lies at the crossover between capillary-dominated flow and modest viscous fingering. Figure 8 shows a small positive LS effect for the first network whilst a negative effect is observed for the second.
Figure 8: Oil recovery during HS and LS-sec injection for two different seeds. Although a positive LS effect was observed for the first seed (left), a negative effect was seen in the second case (right).

These results highlight the fact that deploying one single simulation using one seed (or one single experiment) should not be considered as a reliable approach to quantify the effect of the underlying EOR process. To address this, we run multiple simulations for each scenario on several networks generated with multiple different seeds. In this work for instance, every single scenario has been carried out on ten different networks which share the same average properties but which are built with different random structures. The results are presented as statistical distributions rather than single curves. If we consider again the HS water injection versus secondary LS water injection, case shown in Figure 8, the range of final recoveries after injecting four pore volumes for different network realisations is illustrated in Figure 9.

Figure 9: Simulated final oil recovery after 4 PVs for HS and LS-sec processes using ten seed values. A statistical dispersion is used to quantify the LS effect instead of referring to a single simulation values.

Using this approach it is apparent that, for this particular parameter set, secondary LS injection yields, on average, a slightly negative effect on recovery compared to HS injection. When looking at the simulated results individually, however, a positive LS effect might be observed for some cases.
The average shift in recovery can best be determined by looking at the Interquartile Range (IQR) (depicted by the grey area in Figure 9), which shows the middle 50% of the simulated final recoveries. Of course, using ever larger networks should help reduce the observed variance in results but some degree of scatter will always be present.

In the following section three wettability scenarios, three viscous ratios and three flow rates will be considered for three injection protocols. For each case, ten networks were constructed with different seeds and the final oil recovery after four pore volumes of injected water were measured. This sums to a total of 210 simulations carried out in this study.

3.4 LS Water Effect

3.4.1 Base Case

We will begin by considering the 2D network and flow parameters described in Table 1. Both secondary and tertiary LS water injection are simulated, and final oil recovery is compared to the recovery obtained via HS water injection alone (Figure 10). The contact angles of the pores in direct contact with LS water are allowed to change from 140° to 95° (OWNW case).

Simulated Oil Recovery for HS, LS-sec and LS-ter processes
200x100 2D network, OWNW, V=5m/day, M=10

![Figure 10: Final oil recovery after 4 PVs for: HS, LS-sec and LS-ter processes. Ten seeds are considered for each case.](image)

Results show that LS water injection in secondary mode yields, on average, a slightly poorer recovery when compared to recovery due to HS water injection. Whilst this might appear counter-intuitive (the capillary pressures are expected to be reduced at the entry of pores due to the shift of contact angles towards a neutral-wet value and so to the reduction of \( \cos \theta \)), this effect can be explained by examining the final water distribution for each case (Figure 11).
Figure 11: Final water distribution after 4PVs of HS water injection (left) LS water injected in secondary mode (middle) and LS water injected in tertiary mode (right). Wettability configuration: OWNW. HS water is coloured in white, LS water in light blue and oil in black.

Whilst the water invaded the network following a capillary fingering pattern during HS water injection, viscous fingers emerged during LS injection in secondary mode. The contact angle modification has changed the ratio of viscous to capillary forces and shifted the flow regime from capillary fingering to viscous fingering (which resulted in thin fingers breaking through the network). Although smaller oil-filled pores might be available at this stage to the invading water, the change of flow regime (and thus the elongation of the water clusters) has had a detrimental effect on the final oil recovery.

Tertiary LS water injection has no positive effect on oil recovery for the base case parameter set. This can be explained by the drop in pressure gradient observed after water breakthrough. Indeed, although the capillary entry pressures have been reduced due to LS-induced contact angle modification, the pressure gradient across the network and at the tips of water clusters are not high enough to displace any additional oil and the LS brine simply flows through the well-established HS backbone.

3.4.2 Effect of Wettability Modification

The effect of each wettability modification scenario is now studied. We now include both OWOW and OWWW cases alongside the OWNW scenario, where the contact angles of the capillary elements in direct contact with LS water shift from 140° to 110° and 80° respectively. Final recovery results are presented in Figure 12.
Simulated Oil Recovery for HS, LS-sec and LS-ter processes and for 3 wettability modification scenarios; \( V = 5 \) m/day, \( M = 10 \)

For the OWOW configuration, the effect of LS water is positive but relatively small for secondary mode. In addition, no LS effect is observed when LS water is injected in tertiary mode. The reduction of contact angle from 140° to 110° corresponds to a drop of the capillary pressures by a factor of 2 which is not sufficient to trigger significant additional oil displacements for this particular pore size distribution. In contrast, when the wettability of the network is shifted toward a more water-wet state (OWWW), a marked increase in oil recovery is observed for both secondary and tertiary modes. For instance, approximately 33% of the original oil in place (OOIP) is recovered for the LS-sec scenario compared to an average of 27% after HS water injection.

Figure 12: Final oil recovery after 4 PVs for: HS, LS-sec and LS-ter processes. Three wettability configurations are considered: OWOW, OWWW and OWWW. Ten seeds are considered for each case.

Figure 13: Final water distribution after 4PVs of HS water injection (left) LS water injected in secondary mode (middle) and LS water injected in tertiary mode (right). Wettability configuration: OWWW. HS water is coloured in white, LS water in light blue and oil in black.
The final water distribution for the OWWW case is displayed in Figure 13. For the secondary LS water process, the invasion pattern is similar to a stable displacement. Note that this case corresponds to an imbibition process and although the network appears to be fully saturated with water, most of the large pores remain oil-filled and trapped. For the tertiary LS injection case, the wettability modification removes the capillary pressure barrier at the oil-water interface, which make it possible for fingers to swell transverse to the global pressure gradient.

Note that when the network wettability changes to a water-wet configuration, additional pore filling mechanisms might begin to play a role following exposure to LS brine, such as film swelling, layer flow, and snap-off events. Although a basic film flow mechanism has been included in the current model (mainly to define the trapped fluid clusters), additional mechanisms need to be added in the future to assess the effect of LS water on film and layer behaviour. This is currently being implemented in the model and is discussed in the Conclusions section of the paper.

3.4.3 Effect of Viscosity Ratio M

To study the effect of viscous ratio, we consider three oil viscosities: 1cP, 10cP, and 100cP whilst maintaining the water viscosity equal to 1cP and the frontal advance rate at 5m/day (Ca= 1.93\textsuperscript{-6}). This results in three viscosity ratios: 1, 10 and 100. Both secondary and tertiary LS water processes are considered alongside HS water injection, and final oil recovery results are presented in Figure 14 and Figure 15.

The viscous ratio is found to have a significant impact on additional oil production following LS injection. Whilst a negative secondary LS water effect has been observed for M=10 (base case), both M=1 and M=100 yield a positive LS effect in secondary mode compared to HS injection. This incremental recovery is higher for M=1 (42% total recovery compared to 34% for the HS case), as the viscous forces in the aqueous phase are close to those in the oleic phase. Thus higher pressure values are expected to be maintained in the network and more oil displacements are expected when the capillary pressures are reduced for this viscosity ratio. This also explains the small positive tertiary LS effect, with oil recovery increasing by an average of 2%. Note also that at this viscous ratio, no change of the flow regime is expected (in contrast to the M=10 case), and the growth pattern is expected to remain similar to capillary fingering.
Simulated Oil Recovery for HS, LS-sec and LS-ter processes and for 3 viscous ratios OWNW, V=5m/day

Figure 14: Final oil recovery after 4 PVs for: HS, LS-sec and LS-ter processes. Three viscous ratios are considered: 1, 10 and 100. Ten seeds are considered for each case.

Figure 15: Final water distribution after 4 PVs of HS water injection and LS water injected in secondary mode for different values of viscous ratio. Wettability configuration: OWNW. HS water is coloured in white, LS water in light blue and oil in black.

For M=100, the regime is expected to revert to viscous fingering, and secondary LS water injection results in additional recovery (an average of 15% compared to 12% for HS water injection) due to the reduction of capillary entry pressures. No tertiary LS injection effect is observed, however, due to the weak viscous forces in the aqueous phase (which make it difficult to displace more oil after the reduction in contact angles, especially after the decrease in global pressure following breakthrough).

3.4.4 Effect of Flow Rate

We finally study the effect of LS water injection in both secondary and tertiary modes for three frontal advance rates: 1m/day, 5m/day and 10m/day. An OWNW system is used for all three cases.
and the viscosity ratio is fixed at $M=10$. Simulated final recovery results are presented in Figure 16 and Figure 17. These results show that the flow rate also plays a key role in determining the efficacy of LS injection in secondary mode. As discussed earlier, the change of regime from a capillary growth pattern to viscous fingering results in a negative LS effect for $V=5\text{m/day (Ca}=1.93 \times 10^{-6})$ (base case). This behaviour is magnified for $V=10\text{m/day (Ca}=3.85 \times 10^{-6})$ where the fingers are expected to be thinner, and thus the final oil displacement is, on average, 5% less than the that achieved during HS water injection. In contrast, when the flow rate is low enough to prevent any regime change – as is the case for $V=1\text{m/day (Ca}=3.85 \times 10^{-7})$ – a positive LS effect is observed (an increase of approximately 4% compared to the HS case). No tertiary LS effect was obtained for the three cases studied.

Simulated Oil Recovery for HS, LS-sec and LS-ter processes and for 3 flow rates OWNW, $M=10$

Figure 16: Final oil recovery after 4 PVs for: HS, LS-sec and LS-ter processes. Three frontal advance rates are considered: 1m/s, 5m/s and 10m/s. Ten seeds are considered for each case.

Figure 17: Final water distribution after 4PVs of HS water injection and LS water injected in secondary mode for different values of flow velocity. Wettability configuration: OWNW. HS water is coloured in white, LS water in light blue and oil in black.
Note that all of the results reported so far relate to one particular network architecture and one particular pore size distribution. It is highly likely that rock structure and variance in pore size will both play important roles in determining the outcome of a LS flood – these issues will be presented in forthcoming papers.

4. Conclusions

In this paper, we have introduced for the first time a new formulation to study the effect of low salinity brine injection using an unsteady-state pore network model. LS injection has been considered by adopting a simplified, pragmatic approach, whereby the manifestations of the underlying complex chemistry have been implemented through various modifications to effective contact angle (i.e. wettability alteration). A statistical approach has been introduced where, instead of relying on a single simulation for each parameter combination, a range of statistically similar networks have been used and the full distribution of results presented. This has necessitated the running of a large number of simulations (in excess of 200) in order to study the effect of LS brine injection on oil production from 2D networks in secondary and tertiary modes. For brevity, not all results have been shown here but the full range of simulations can be found in Boujelben (2017).

The study shows that impact of LS brine on oil displacement can be affected by several key parameters, including – but not restricted to – viscosity ratio, injection rate, and the extent of LS-induced wettability modification. It is consequently extremely difficult to predict a priori any outcome without running a range of suitably-anchored network modelling simulations. Both positive and negative secondary LS effects have been observed and a change in the flow regime has been found to be a key mechanism by which LS injection can affect additional oil recovery. Results show that tertiary effects are less significant but are more likely to occur for low viscous ratios and wettability changes that shift the network to a water-wet configuration.

More specifically, for the particular network configuration studied (pore size distribution, average connectivity), the following was observed for each LS-induced wettability change:

(i) Oil-Wet pores becoming less Oil-Wet (OWOW): almost all cases studied exhibited a positive secondary LS effect, but no significant tertiary LS effect was observed;

(ii) Oil-Wet pores becoming close to Neutral-Wet (OWNW): this scenario showed greater variation in LS outcome (a generally positive secondary LS effect was seen but there were several exceptions. One parameter combination (M=1, V=10m/day) also showed a positive tertiary LS effect;

(iii) Oil-Wet pores becoming Water-Wet (OWWW): all cases gave a positive secondary LS effect and a smaller positive tertiary LS effect (the latter supplemented by clear-out of capillary end effects).

At fluid-fluid interfaces, the relative drop in viscous pressure gradients versus capillary entry pressures plays a central role in determining the potential for additional displacement via LS flooding and this balance is controlled through synergies amongst various system parameters (Figure 18). It is therefore not surprising that some floods could switch flow regime under LS conditions.

Of course, the results presented here correspond to a single pore size distribution (and other network properties associated with a generic sandstone) and changing such parameters could be expected to yield different outcomes from those shown in this work – both in direction and magnitude. Furthermore, note that we have chosen to neglect explicit models for corner and layer flow at this stage of the modelling and these could be important complementary displacement
mechanisms. Corner flow could be important as a transport mechanism for the injected LS brine, for example, and there is also potential drainage of oil layers from oil-wet pores in response to local changes in brine salinity. Considering an angular pore in which HS water and oil layers remain in the corners following HS flooding, the extent of the oil layer will depend on the local capillary pressure – subsequent LS invasion could then produce additional oil as menisci push further into the pore corners and corner water swells to maintain consistency with the modified capillary pressure. Depending upon the precise pore geometry and fluid properties of the system, the contribution of such oil drainage to the overall recovery could be important. Additional mechanisms could also be added to improve the modelling of LS transport: for example, diffusion could be implemented in future work and this might be relevant at very low flow rates.

It should be highlighted that the simulations carried out in this work used 2D networks and, although these networks provide valuable insights into the impact of the mechanisms studied, we stress that the third dimension is also an important factor that should be examined. The trapping characteristics, for example, differ between 2D and 3D systems, as water clusters have more space to swell in 3D space and oil clusters have more escape routes to the system outlet. Furthermore, the presence of an initial high salinity (HS) water saturation could also be important and so 3D simulations at non-zero initial water saturations are needed to consolidate the conclusions reported here (this work is currently on-going).

It should also be noted that the scale of the simulations could affect the degree of additional recovery due to LS water injection. The work of Regaieg et al. (2013) [27] has previously demonstrated the impact of network length on the thickening of viscous fingers after breakthrough (due to its impact on the balance between the final pressure gradient across the network and the capillary forces across oil-water interfaces), and so it is reasonable to conclude that the size of the system undergoing LS water injection could be an important determinant of LS efficacy.

Although the simplified approach presented here does not yet include a number of complementary mechanisms, our results nevertheless emphasise the complexity of phenomena occurring at the pore-scale (even in the absence of explicit chemical modelling and layer flow). Pore network modelling is a valuable tool with which to examine scenarios that can be challenging to realise experimentally. Indeed, by running a series of network LS simulations, we are able to identify key areas of parameter space that are more likely to elicit a positive LS response than others.
Figure 18: Schematic showing how various system parameters could interact to affect the local balance between viscous and capillary forces during a LS waterflood.

Conflicts of interest
None.

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References


Appendix: Unsteady-State Model Description

The unsteady-state flow model developed in this work is based upon an earlier model by Regaieg et al., 2013. [27] Like any other pore network model, a number of underlying assumptions are made when implementing the basic unsteady-state drainage model.

- The flow inside the capillary elements is considered to be laminar – the meniscus between two fluids is assumed to be always perpendicular to the axis of the pore.
- The fluids inside the capillaries are incompressible and immiscible.
- Film flow is not modelled explicitly at this stage (although it is taken into account in the context of phase trapping).
- Counter-current imbibition is not considered.
- Ganglia mobilisation is neglected.
- Gravity forces are not considered significant.

To simplify the model description, we will consider a waterflooding simulation where water displaces oil in an oil-wet network. The workflow of the model is described by Figure 19. At each timestep, (1) the network is explored to look for trapped clusters; (2) a capillary pressure term is calculated in each capillary element containing an oil-water meniscus; (3) a pressure gradient is coupled to the chosen flow rate; (4) mass conservation is applied at every node, the pressure field in the network is calculated, and elementary flows in each capillary element are derived; (5) pores exhibiting counter-current imbibition behaviour are temporarily frozen, and the pressure solution is iterated (step 3), until a consistent pressure field with no counter-current imbibition flow is attained; (6) phase saturations are updated according to mass conservation. This sequence is repeated until a desired number of pore volumes has been injected.

Figure 19: Unsteady-state model workflow

1. Capillary Force Calculation

Inlet and outlet pores are assigned, and the network is filled with oil. Every pore is assigned two fluid flags at the end of its two extremities. These flags signal the existence of either oil or water at each end of the capillary element and determines whether a capillary pressure term should be included in the pressure solution. The simulation begins with water flowing into the inlet pores – the fluid flags on the upstream extremities of these pores are consequently instantaneously switched to “water” (Figure 20).

At every timestep during the simulation, the network is explored to look for menisci in capillary elements. A meniscus is taken into consideration when water is displacing oil from an oil-filled pore. This is reflected in the corresponding code by the presence of two different fluid flags. If the pore being considered is untrapped, we calculate the capillary pressure term corresponding to the meniscus separating the two fluids.
In the case of a cylindrical bond, the capillary pressure \( P_c \) is given by the Young-Laplace equation:

\[
P_c = \frac{2\sigma \cos \theta}{r}
\]  

where \( \sigma \) is the interfacial tension, \( r \) is the pore radius and \( \theta \) is the oil/water contact angle.

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**Figure 20**: Fluid flags at the extremities of pores. Inlet pores are assigned a water flag at their inlet extremities to trigger the creation of a meniscus and a capillary pressure (a). Water starts to invade the network from the inlet pores (b).

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2. Computing the Pressure Field Across the Network

Computing the nodal pressure field throughout the simulation is an essential component of the simulation process and is used to update the network state at each time step. In this section, we describe the methodology used to determine the pressure field in the network under consideration.

We set a fixed injection rate for the flood (although constant pressure drop simulations can also be readily considered), which is effectively used as a boundary condition to determine the nodal pressure distribution and elementary flows within the system at each time step. We assume that for a single element of shape factor \( \gamma \), length \( l \) and cross section \( A \), the flow is given by a Poiseuille-type law:

\[
Q = g \Delta P \gamma = \frac{A^2 G}{\mu} \Delta P
\]  

where \( g \) is the element conductance, \( \mu \) is the fluid viscosity in the element and \( \Delta P \) the pressure difference acting across the element.

By applying a pressure gradient across the network (we choose to set a zero pressure at the inlet and a negative pressure at the outlet to ensure we have a phase flow towards outlet), the pressure field inside the network can be obtained by applying the mass conservation law at each node \( i \):

\[
\sum Q_{ij} = 0
\]  

where \( Q_{ij} \) is the flow between node \( i \) and node \( j \). When a capillary pressure is present across the curved interface between oil and water in a pore, a capillary pressure term should be included in the set of equations to obtain a consistent pressure solution. To do so, whenever a fluid-fluid interface is present in a capillary element, the elementary flow equation becomes:

\[
Q_{ij} = g(P_i - P_j \pm P_c)
\]  

The sign of \( P_c \) is determined based on the direction of flow from \( i \) to \( j \). As we are treating a drainage case, the capillary pressure would always be resisting the advancing water flow. For instance if the water is flowing from \( i \) to \( j \) (\( P_i > P_j \)), the sign of \( P_c \) would be the opposite of \( P_i - P_j \), and vice versa.
Applying the mass conservation law at for every node yields a system of linear equations where the nodal pressures constitute the unknowns. The system can be written schematically as:

\[ G \times P = Q + C \]  

(10)

where \( G \) is the conductivity matrix, \( P \) is the vector of unknown nodal pressures, \( Q \) is the vector describing the flow at the boundaries, and \( C \) is the vector capturing the capillary forces. The boundary conditions are provided by the pressure values in the inlet and the outlet pores.

We solve this system using Cholesky factorisation when dealing with 2D networks. This method can become considerably slow for 3D networks, and the simulator switches automatically to the bi-conjugate gradient method.

3. Coupling the Pressure Gradient Across the Network to the Flow Rate

To compute a consistent pressure field corresponding to the target flow rate, we need to apply the appropriate pressure gradient between inlet and outlet pores. To solve this problem, we begin by assigning a null pressure at the inlet, and an initial approximation to the outlet pressure resulting in an initial pressure gradient equal to \( \Delta P_0 \). We then compute the pressure field corresponding to \( \Delta P_0 \), which then allows us to calculate the elementary flows. By summing flows from the outlet pores, we obtain the total outlet flow \( Q(\Delta P_0) \) corresponding to the initial approximation \( \Delta P_0 \). We then apply an iterative Secant Method to find a \( \Delta P \) value satisfying the desired target flow. The computed pressure gradient at the \( (k + 1)^{th} \) iteration is given by:

\[ \Delta P_{k+1} = \Delta P_k - \frac{Q(\Delta P_k) - Q_{\text{target}}}{Q(\Delta P_k) - Q(\Delta P_{k-1})} \Delta P_k \]  

(11)

Once the Secant method has converged, we apply the resulting pressure gradient to the network, finalise the pressure value at each node, and go on to determine the new flow in each capillary element.

4. Closing Pores with Counter-current Flow

If we consider the configuration described by Figure 21, it is possible to conceive a scenario where the calculated elementary flow is directed from node 2 to node 0. This case would correspond to an imbibition process where oil displaces water in our oil-wet network. The model does not allow this in order to conserve the mass of the aqueous phase (although it will be modelled in the ganglion module described later), and thus, all the pores where an imbibition process is taking place become “closed” temporarily (this is achieved by assigning them a null conductivity). The pressure field is computed again until we reach a configuration where no imbibition flow is occurring (Figure 21, right). The pressure field is then consistent with all the elementary flows and mass is conserved when updating the phase fractions.

5. Multiple Pore Filling Algorithm

Once the elementary flows are known for all the capillary elements, we loop over all the untrapped pores where the water flow is positive, and we update the water fractions \( F_{\text{water},i} \) in all of these pores according to:
where $V_i$ is the pore volume, $Q_i$ is the pore elementary flow, and $\Delta t$ is the time step used in the current iteration.

The time step is calculated at each iteration to ensure mass conservation when updating phase fractions. Thus, the timestep chosen corresponds to the shortest time required to fill entirely an oil-filled pore hosting an oil/water meniscus. $\Delta t$ is therefore calculated as follows:

$$\Delta t = \min_{i \in \mathcal{K}} \frac{V_i}{Q_i} F_{\text{water},i}$$  \hspace{1cm} (13)$$

where $\mathcal{K}$ is the set of untrapped pores with an oil/water interface.
Highlights

• A new pore network model is proposed to simulate low salinity water flooding, where tracer dynamics are coupled with the degree of wettability alteration.

• A stochastic approach is adopted to assess statistical variability in recovery outcomes.

• A change in the dominant flow regime (capillary fingering, viscous fingering, frontal advance) is found to play a major role in determining LS efficacy.

• LS effect is shown to interact non-linearly with the prevailing system properties (i.e. flow rate, viscous ratio).