Summary

Two dimensional laboratory experiments has been performed in order to study the segregation of gas and water, and foam. The observed gas/water segregation was in good agreement with segregation theory, whereas foam segregation appears to be slower than predicted from theory, indicating an improved sweep efficiency by injection of foam. The latter observation is not conclusive, however, as all aspects of the foam experiments are not presently understood.

Introduction

When gas and water are injected simultaneously into a reservoir, the phases will separate due to the density difference of the fluids. In addition to a water/gas zone, one gas- and one water flooded zone are formed as illustrated in Figure 1. According to Stone and Jenkins, the extensions of the different zones depend on the viscous to gravity ratio, VGR, defined by:

\[
VGR = \frac{Q_{fot}}{g \Delta p k_v a \left( \frac{k_m^{nw}}{\mu_w} + \frac{k_m^{rg}}{\mu_g} \right)}
\]

VGR can be interpreted as the segregation length-to-reservoir length ratio for a linear geometry. It depends on the phase mobility functions, which are normally measured in 1D coreflood experiments.

Compared to normal, non-lamellar fluids, foam may improve the value of VGR and hence the sweep, by reducing phase mobilities. In addition, the lamellar nature of foam may introduce (additional) permeability anisotropy to the porous medium. If the foam lamellae are on average more oriented parallel to the main flow direction of the gas, they will increase the resistance to phase segregation more than the resistance to flow along the reservoir. The net effect of this may be that foam segregates slower than that predicted from 1D coreflood data, and the sweep efficiency of injected gas may increase. The aim of the present study was to clarify if foam segregation can be modelled with mobility data obtained in 1D coreflood experiments, or if lamellar anisotropy effects may improve the sweep of gas.

Experimental

Segregation of normal fluids was studied using both the air-water system, and a low-IFT (1 mN/m) model fluid system where gas was simulated by an oil phase. The model fluid system was composed of water, CaCl₂, isopropanol and isooctane. For the foam experiments, a 0.25 wt% aqueous solution of the fluorinated surfactant FC-751 from 3M was used together with air, giving an IFT of 16 mN/m.
Different glass beads were used in the normal fluid and foam experiments. Bead size, pore volumes, permeability and porosity obtained in the different packings are summarised in Table 1.

For measurements of phase mobility functions, the glass beads were packed in a 0.5 m long, 2.2 cm diameter tube. The tube was fitted into a standard flooding rig for measurement of relative permeabilities by the steady state technique. The phase saturations were determined from the mass or level of the separator, or the mass of the beadpack.

A sketch of the 2D flow apparatus is shown in Figure 2. In the 2D flow model, the porous medium was kept between two 67 cm long and 47 cm high glass plates. The injection profile was controlled by using 16 individually fed injection ports. The complete set up is described in detail in Reference 3.

Results and discussion

Gas/water injection experiments

Figure 3 illustrates the result of a co-injection experiment where the low-IFT model gas and water was injected in a volumetric ratio of one, at a design VGR of 0.46. The predicted zone boundaries, based on Stone-Jenkins segregation theory and 1D measured relative permeabilities, are in good agreement with the observed boundaries. This conclusion was supported by 12 additional experiments involving both co-injection and alternating injection. The observed flow profiles showed that theory overestimated the segregation lengths by 0-20%, however. The results indicate that relative permeabilities determined in 1D flow experiments involving co-current flow can be used to describe phase segregation involving counter-current flow.

In normal gas-water segregation experiments, poor agreement with the Stone-Jenkins theory was observed. Seven experiments with design VGRs between 0.4 and 1.7 exhibited equal flow patterns, all with almost equal segregation lengths, as illustrated in Figure 4. It appears that the non-ideal flow pattern obtained during the gas/water injection experiments was the result of the dominance of capillary forces.

Scaling of experiments

The balance between capillary and gravity forces, on the scale of the flow unit, may be quantified by the capillary to gravity force ratio (CGR), which can be defined as

\[
CGR = \frac{2\gamma}{\Delta \rho gh \frac{k}{\phi}}
\]  

(2)

The value for CGR in a gas injection process in a 30 m high high-permeable sandstone reservoir would typically be 0.01. Correspondingly, the values for the 2D flow experiments with the model fluid system and gas-water system were found to be 0.05 and 0.77, respectively. Thus, while the flow was dominated by gravity forces in the low IFT fluid system, as it would be in a reservoir, capillary forces dominated fluid flow in the gas-water injection experiment. This explains the deviations between the observed flow pattern in gas-water injection and the Stone-Jenkins theory, which assumes zero capillary pressure.

Scaling of characteristic forces was required also for the foam experiments (described below). Some reduction of CGR, from the value encountered in the gas-water experiments, was obtained by addition of surfactant to water. The IFT was reduced from 73 down to approximately 16 mN/m. In addition, the bead size in the model had to be increased to further reduce the capillary forces. Then, a CGR of 0.06 was obtained, close to the value obtained during the experiments with the model gas/water system.
Another important dimensionless group for a foam system is the ratio between capillary pressure and disjoining pressure of the foam films. In the present experiment a foam system with a disjoining pressure much larger than the capillary pressure height of the model was employed.

**Foam injection experiments**

Foam injection experiments were run at two different flow rates. The conditions for the experiments are summarised in Table 2. The measured 1D relative permeabilities used in the prediction of VGR are shown in Figure 5.

Figures 6 and 7 presents the results for the two experiments. Predictions for the zone boundaries, based on injected fluid fractions and measured 1D relative permeabilities, are shown with dashed lines. The gas flooded zone, as observed in the experiments, is shaded, while the water zone is white. For Experiment 1, the VGR value deduced from the observed segregation length is 0.51. In Experiment 2, the entire model was flooded by foam, showing that VGR was larger than one. Table 3 shows that the segregation lengths observed in the two experiments are at least 60% larger than that predicted from 1D coreflood mobility data. The increased segregation lengths observed in both experiments can be explained by reductions in the vertical gas permeabilities to approximately 55% of the value predicted from 1D coreflood data.

In the analysis above it is tacitly assumed that foam properties are equal in the 1D and 2D flooding experiments. One measure of the foam properties is the gas saturation in the foam. In the 2D model, foam bank saturations could be appraised from injected volumes and foam bank area, both early in the injection process, when the displacement process was piston-like, as well as at the end of Experiment 2, when the entire model was flooded with foam. These data are compared to the design saturation expected from the 1D core flood in Figure 8. In the early stage of foam injection, observed gas saturations were lower than predicted from 1D coreflood data, suggesting that the foam in the 2D model was weaker, possibly due to short ageing time. At the end of Experiment 2, the saturation in the 2D model (94%) approached the 1D core flood result (95.5%), but was still somewhat lower. This means that the segregation length enhancement observed in the 2D tests was not due to the foam in the 2D model being stronger than in the coreflood. On the contrary, the somewhat weaker foam observed in the 2D model should have segregated even faster than the 1D prediction. The VGR value expected from the observed final saturations, and the measured water relative permeability curve, was 0.33, a factor two lower than the design VGR, as shown in Table 3. This analysis suggest that the foam anisotropy may give an segregation length enhancement by at least a factor three.

It is interesting to note that foam was formed at all for the extremely low flow velocities (1-2 cm/d) employed in the 2D experiments (Table 2).

**Injection pressures**

In addition to the gas saturation, the injection pressure should be an independent measure of the foam strength in the 2D experiments. If \( Q_{in} \) in Equation 1 is expressed using Darcy's law for flow of gas and water in the foam bank, neglecting segregation within in the foam zone, the following expression is obtained for a linear geometry:

\[
VGR = \frac{k_h}{k_v} \frac{h}{l} \frac{1}{\Delta \rho g} \nabla p
\]

Equation 3 shows that the sweep can improved for any injection fluid by increasing the injection pressure. This may be obtained by increasing the rate as well as using less mobile fluids. Equation 3 suggests that foam may offer VGR improvement without increased injection pressure, if the presence of foam leads to an increased \( k_h/k_v \)-ratio. For a radial flow geometry, foam may give an additional improvement compared to normal fluids, due to the shear thinning properties of foam.
Moreover, it appears that the measured pressure gradient should be a direct test for the presence of vertical anisotropy for foams, without reference to 1D foam properties. Equation 3 shows that the injection pressure for a given VGR value should be sensitive only to the anisotropy. The injection pressure data have been difficult to interpret, however. The measured differential pressure across the 2D model in the foam experiments are shown in Figure 9, together with calculated steady state differential pressures across the model. Both the absolute value, and the noise in the experimental data, are much larger than the expected steady state differential pressures. It also appears that the observed differential pressures do not correlate with the development of the foam flooded zone, with no marked signature of gas breakthrough in the pressure data. It appears that the measured differential pressures are strongly influenced by experimental factors, such as hydraulic heads and capillary pressures, that are presently not understood. Before the observed differential pressures are understood, it can not be definitively concluded that the increased segregation length observed with foam is due to foam anisotropy.

Conclusions

Experiments with a gas/water model system show that observed phase segregation, involving counter-current flow, is in good agreement with predictions from Stone-Jenkins segregation theory, using 1D relative permeabilities measured in co-current flow.

Foam segregation experiments resulted in larger segregation lengths than predicted from segregation theory. This can be explained by introduction of permeability anisotropy for gas due to the presence of foam, resulting in reduced vertical gas permeability. This explanation is not conclusive, as all aspects of the experiments are not presently understood.

References


Symbol list

\[ a = \] horizontal area between wells, \( m^2 \)

\[ \text{CGR} = \] capillary to gravity force ratio

\[ g = \] acceleration of gravity, \( m/s^2 \)

\[ h = \] height of reservoir, \( m \)

\[ \text{IFT} = \] interfacial tension

\[ k_{h or v} = \] horizontal or vertical absolute permeability, \( m^2 \)

\[ k_r^m = \] relative permeability of phase \( i \) in the mixed flow zone

\[ l = \] model length or inter-well distance, \( m \)

\[ \Delta p = \] pressure gradient, \( \text{kg/m}^2\text{s}^2 \)

\[ Q_{\text{tot}} = \] total injected rate, \( m^3/s \)

\[ \text{VGR} = \] viscous to gravity force ratio

\[ \phi = \] porosity

\[ \gamma = \] interfacial tension, \( \text{mN/m} \)

\[ \mu_i = \] viscosity of phase \( i \), \( \text{kg/ms} \)

\[ \Delta \rho = \] density difference, \( \text{kg/m}^3 \)
Table 1: Description of porous media used in 1D and 2D experiments.

<table>
<thead>
<tr>
<th>Model</th>
<th>1D</th>
<th>2D</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Normal fluids:</strong></td>
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<tr>
<td>Bead size (µm)</td>
<td>70-110</td>
<td>70-110</td>
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<tr>
<td>Pore vol. (ml)</td>
<td>55</td>
<td>1130</td>
</tr>
<tr>
<td>Porosity (%)</td>
<td>28</td>
<td>38</td>
</tr>
<tr>
<td>Perm. (D)</td>
<td>3.4</td>
<td>4.0</td>
</tr>
<tr>
<td><strong>Foam:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bead size (µm)</td>
<td>200-300</td>
<td>200-300</td>
</tr>
<tr>
<td>Pore vol. (ml)</td>
<td>56</td>
<td>1300</td>
</tr>
<tr>
<td>Porosity</td>
<td>29</td>
<td>38</td>
</tr>
<tr>
<td>Perm. (D)</td>
<td>41</td>
<td>60</td>
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Table 2: Experimental conditions for foam segregation experiments.

<table>
<thead>
<tr>
<th></th>
<th>Exp. 1</th>
<th>Exp. 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design VGR</td>
<td>0.31</td>
<td>0.63</td>
</tr>
<tr>
<td>Gas rate (ml/h)</td>
<td>1.9</td>
<td>3.75</td>
</tr>
<tr>
<td>Water rate (ml/h)</td>
<td>0.3</td>
<td>0.66</td>
</tr>
<tr>
<td>Darcy velocity (m/d)</td>
<td>0.01</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Table 3: Predicted and observed VGR values for foam injection experiments.

<table>
<thead>
<tr>
<th>VGR from</th>
<th>Exp. 1</th>
<th>Exp. 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1D mobilities</td>
<td>0.31</td>
<td>0.63</td>
</tr>
<tr>
<td>final saturations</td>
<td>-</td>
<td>0.33</td>
</tr>
<tr>
<td>segregation length</td>
<td>0.51</td>
<td>&gt;1</td>
</tr>
</tbody>
</table>

Figure 1: Flow zones for gas (g), water (w) and mixed flow of gas and water (mix).

Figure 2: 2D flow apparatus.

Figure 3: Predicted and measured flow zones during co-injection using the model gas/water system.
Figure 4 Typical flow profile for 2D gas/water injection experiments.

Figure 7 Predicted (dotted lines) and observed flow zones at steady state for Experiment 2.

Figure 5 Relative permeabilities for surfactant solution and gas in the presence of and without foam.

Figure 8 Gas saturation in foam flooded region early in the experiments.

Figure 6 Predicted (dotted lines) and observed flow zones at steady state for Experiment 1. Grey area is flooded by foam and gas.

Figure 9 Measured differential pressures across 2D model during foam injection experiments and predicted steady state differential pressures.