Capillary Trapping Capacity of Rocks and Sandpacks
Stefan Iglauer¹, Wolfgang Wülling², Christopher H Pentland¹, Saleh K Al Mansoori¹ and Martin J Blunt¹, SPE,
¹Imperial College London, ²Basler Versicherungen

Abstract
We quantify the influence of the initial non-wetting phase saturation and porosity on the residual non-wetting phase saturation based on data in the literature and our own experimental results from sandpacks and consolidated rocks. The principal application of this work is for carbon capture and storage (CCS) where capillary trapping is a rapid and effective way to render the injected CO₂ immobile, guaranteeing safe storage.

We introduce the concept of capillary trapping capacity \(C_{\text{trap}}\) which is the product of residual saturation and porosity that represents the fraction of the rock volume that can be occupied by a trapped non-wetting phase. We propose empirical fits to the data to correlate trapping capacity and residual saturation to porosity and initial saturation. We show that trapping capacity reaches a maximum of approximately 7% for rock porosities of 20%, which suggests an optimal porosity for CO₂ storage.

Introduction

Capillary trapping has been measured in oil-water, gas-water and three-phase gas-water-oil systems; Figures 1 and 2 show a compilation of two-phase data in the literature (Agarwal 1967, Aissaoui 1983, Al-Mansoori et al. 2008, Chierici et al. 1963, Crowell et al. 1966, Declaud 1991, Firoozabadi et al. 1987, Flett et al. 2004, Geffen et al. 1952; Gittins et al. 2009, Irle and Bryant 2005, Jerauld 1997, Kantzas et al. 2001, Kleppe et al. 1997, Kralik et al. 2000, Land 1968a+b, 1971, Ma and Youngren 1994, McKay 1974, Mulyadi et al. 2000, Naar and Henderson 1961, Pentland et al. 2008, Plug 2007, Spiteri et al. 2005, Suekane et al. 2008a,b). In Figure 1, the influence of the initial non-wetting phase saturation \(S_{\text{nw,i}}\) on the residual non-wetting phase saturation \(S_{\text{nw,r}}\) is plotted, while Figure 2 plots \(S_{\text{nw,r}}\) as a function of porosity \(\phi\). The scatter in Figures 1 and 2 is caused by variation in interfacial tension (IFT) (the authors used different fluid systems), pore morphology, displacement mechanism (some authors used a displacement sequence representative of flow in geological porous media, whereas others used evaporation and/or spontaneous imbibition which is not necessarily representative of reservoir processes), and wettability (most cores were water-wet, but also mixed-wet and oil-wet samples were investigated).
Several empirical trapping models which describe $S_{(nw)r}$ as a function of $S_{(nw)i}$ have been proposed (Land 1968a+b, 1971, Geffen 1952, Naar and Henderson 1961, Agarwal 1967, Jerauld 1997, Ma and Youngren 1994, Kleppe et al. 1997, Aissaioui 1983, Spiteri et al. 2005). The Land model is the most commonly used correlation in the petroleum industry, which is generally used to predict the trapped gas saturation:

\[
S'_{gr} = \frac{S_{gr}^{*}}{1 + C S_{gr}^{*}}
\]  

where

\[
C = \frac{1}{S_{gr}^{max}} - 1
\]

and $S'$ is the effective saturation: $S' = S/(1-S_{nr})$ where $S_{nr}$ is the connate or irreducible water saturation.

Recent work at Imperial College London (Pentland et al. 2008, Al-Mansoori et al. 2008 and Gittins et al. 2009) has shown that the best match to experimental data from unconsolidated sand packs is given by Aissaioui’s law. This was the same conclusion reached by Suzanne et al. (2003) after an extensive series of tests. The correlation, which can be applied to gas (as here) or oil is as follows:

\[
\text{If } S_{gr} < S_{gr}^{max} \text{ then } S_{gr} = \frac{S_{gr}^{max}}{S_{gr}^{max}} - S_{gr}^{max}, \text{ else } S_{gr} = S_{gr}^{max}
\]
Capillary trapping experiments
The Appendix describes the details of a series of experiments we performed to measure the trapping capacity of sandpacks and sandstones. We statistically analyzed our oil-brine and air-brine laboratory data for LV60 sand ($\phi = 0.37$) to find a functional relationship between $S_{or}$ and $S_{oi}$ and $S_{or}$ and $S_{oi}$ in unconsolidated systems. In a least square approach bi-linear relationships were derived (Breiman 1992, Lawson and Hanson 1995). For the oil-brine data we found:

$$S_{or} = 0.2535 \cdot S_{oi} \quad \text{if } S_{oi} \leq 0.403$$
$$0.0891 + 0.0324 \cdot S_{oi} \quad \text{if } S_{oi} > 0.403 \quad (4)$$

For the air-brine data we found:

$$S_{or} = 0.7165 \cdot S_{gi} \quad \text{if } S_{oi} \leq 0.194$$
$$0.1384 + 0.0011 \cdot S_{gi} \quad \text{if } S_{oi} > 0.194 \quad (5)$$

Figure 2: Maximum residual non-wetting phase saturation as a function of porosity. The colored symbols indicate measurements performed for this work, while the black symbols show data compiled by Jerauld (1997).

Capillary trapping capacity
In the context of CCS the capillary trapping capacity $C_{\text{trap}}$ is of great importance since it states how much CO$_2$ can be stored securely per unit rock volume:

$$C_{\text{trap}} = \phi S_{or} \quad (6)$$

Figure 3 presents the same dataset shown in Figure 1, but this time the ordinate is $C_{\text{trap}}$. We can then find a correlation similar to Eqs. (4) and (5) for our oil/brine data:
\[ C_{\text{trap}} = 0.0938 \cdot S_{\text{(nw)i}} \text{ if } S_{\text{(nw)i}} \leq 0.403 \]
\[ = 0.03296 + 0.0120 \cdot S_{\text{(nw)i}} \text{ if } S_{\text{(nw)i}} > 0.403 \]  

and for our air/brine data:

\[ C_{\text{trap}} = 0.2651 \cdot S_{\text{(nw)i}} \text{ if } S_{\text{(nw)i}} \leq 0.194 \]
\[ = 0.05135 + 0.000411 \cdot S_{\text{(nw)i}} \text{ if } S_{\text{(nw)i}} > 0.194 \]

Figure 3: Capillary trapping capacity as a function of initial non-wetting phase saturation. The colored symbols indicate our own experimental data on sand packs.

Residual saturation as a function of porosity

We then analyzed the relationship between \( S_{\text{(nw)r}} \) and \( \phi \). We first considered only our own data and then studied the complete dataset shown in Figure 2. A statistical analysis was used, plotting least square fits through the datasets. Results are shown in Figures 4 and 5 and Tables 1 and 2. An important point to recognize is that these are endpoint saturations, i.e. \( S_{\text{(nw)r}} \) is equal to \( S_{\text{(nw)r}}^\text{max} \) in these correlations, where \( S_{\text{(nw)r}}^\text{max} \) is the maximum residual saturation possible for a given system (the initial saturation is 1 - \( S_w \)).

The correlations \( S_{\text{(nw)r}} \) vs. \( \phi \) are excellent for our data and good for the dataset containing our data plus the literature data. The quadratic fit is the best for our data, while a logarithmic fit is best for the entire dataset. In terms of the entire dataset, above a \( \phi \) of circa 35%, the quadratic fit turns unstable and over predicts \( S_{\text{(nw)r}} \).

Figures 6 and 7 replot the data as trapping capacity as a function of porosity which displays a non-monotonic behavior. By performing the parameter transformation the Pearson coefficient reduces, especially for the entire dataset fits (cp. Tables 3 and 4). \( C_{\text{trap}} \) has a maximum of around 7% at a porosity of approximately 20%.

Conclusions

Key findings from this study include:

1. The capillary trapping capacity (\( C_{\text{trap}} \)) – the product of residual saturation and porosity – depends on the initial non-wetting phase saturation and porosity. There is also considerable scatter in the data which reflects the dependence on rock structure, interfacial tension and wettability.
2. \( C_{\text{trap}} \) has a maximum of approximately 7% at 20% porosity which indicates optimal conditions for CO2 storage.
3. We have proposed empirical correlations, fit to experimental data, to predict trapped saturation as a function of initial saturation, and maximum trapped saturation as a function of porosity.
Curve fit  $S_o$ vs. $\phi$ fit

<table>
<thead>
<tr>
<th>Fit Type</th>
<th>Equation</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>data from this study -</td>
<td>$S_o = 0.9043 - 3.7628 \phi + 4.3837 \phi^2$</td>
<td>0.9876</td>
</tr>
<tr>
<td>quadratic fit</td>
<td></td>
<td></td>
</tr>
<tr>
<td>data from this study -</td>
<td>$S_o = -0.2293 - 0.3464 \ln(\phi)$</td>
<td>0.9736</td>
</tr>
<tr>
<td>logarithmic fit</td>
<td></td>
<td></td>
</tr>
<tr>
<td>data from this study -</td>
<td>$S_o = 1.025\exp(-5.8996 \phi)$</td>
<td>0.9407</td>
</tr>
<tr>
<td>exponential fit</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Statistical data; $R$ is the Pearson correlation coefficient.

Curve fit  $S_o$ vs. $\phi$ fit

<table>
<thead>
<tr>
<th>Fit Type</th>
<th>Equation</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>all data –</td>
<td>$S_o = 5.6526 \phi^2 - 4.171 \phi + 0.9577$</td>
<td>0.8689</td>
</tr>
<tr>
<td>quadratic fit</td>
<td></td>
<td></td>
</tr>
<tr>
<td>all data –</td>
<td>$S_o = -0.3025 \ln(\phi) - 0.1365$</td>
<td>0.8888</td>
</tr>
<tr>
<td>logarithmic fit</td>
<td></td>
<td></td>
</tr>
<tr>
<td>all data –</td>
<td>$S_o = 0.926\exp(-4.8219 \phi)$</td>
<td>0.8307</td>
</tr>
<tr>
<td>exponential fit</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Statistical data; $R$ is the Pearson correlation coefficient.
Curve fit          $C_{\text{trap}}$ vs. $\phi$ fit

$C_{\text{trap}} = R^2$

data from this study - based on quadratic fit in Table 1

$0.9043 \phi - 3.7628 \phi^2 + 4.3837 \phi^3$

$R^2 = 0.8525$

data from this study - based on logarithmic fit in Table 1

$-0.2293 \phi - 0.3464 \phi \ln(\phi)$

$R^2 = 0.5286$

data from this study - based on exponential fit in Table 1

$1.025 \phi \exp(-5.8996 \phi)$

$R^2 = 0.7102$

Figure 6: Capillary trapping capacity $C_{\text{trap}}$ as a function of $\phi$, our data (only oil/brine data).

Curve fit          $S_{\text{or}}$ vs. $\phi$ fit

$S_{\text{or}} = R^2$

all data - based on quadratic fit in Table 2

$5.6526 \phi^3 - 4.171 \phi^2 + 0.9577 \phi$

$R^2 = 0.2686$

all data - based on logarithmic fit in Table 2

$\phi (-0.3025 \ln(\phi) - 0.1365)$

$R^2 = 0.4432$

all data - based on exponential fit in Table 2

$0.926 \exp(-4.8219 \phi)$

$R^2 = 0.4103$

Table 3: Statistical data; R is the Pearson correlation coefficient.

Table 4: Statistical data; R is the Pearson correlation coefficient.

Nomenclature

$C_{\text{trap}}$: capillary trapping capacity
$S_{\text{gr}}$: residual gas saturation
$S_{\text{gr}}^{\text{max}}$: maximum residual gas saturation
$S_{\text{gc}}$: critical gas saturation
$S^*$: effective saturation
$S_{\text{gi}}^*$: effective initial gas saturation
$S_{\text{gr}}^*_{\text{max}}$: maximum effective residual gas saturation
$S_{\text{or}}$: residual oil saturation
$S_{\text{nwi}}$: residual non-wetting phase saturation
$S_{\text{gi}}$: initial gas saturation
$S_{\text{oi}}$: initial oil saturation
$S_{\text{nwi}}$: initial non-wetting phase saturation
$\phi$: porosity
$S_{\text{wc}}$: connate water saturation

where; $S^*=S/(1-S_{\text{or}})$

where; $S_{\text{gi}}^*=S_{\text{gr}}/(1-S_{\text{or}})$

where; $S_{\text{gi}}^*=S_{\text{gi}}/(1-S_{\text{or}})$

where; $S_{\text{gr}}^*_{\text{max}}=S_{\text{gr}}^{\text{max}}/(1-S_{\text{or}})$
Acknowledgments

We would like to acknowledge the following funding: Shell under the Grand Challenge on Clean Fossil Fuels; Qatar Petroleum, Shell and the Qatar Science and Technology Park under the Qatar Carbonates and Carbon Storage Research Centre; the EPSRC (grant number EP/C536754/1); NERC (grant number NE/C516401/1); and ADNOC (Abu Dhabi, UAE).

References


Intergovernmental Panel on Climate Change, Carbon Dioxide Capture and Storage; Cambridge: Cambridge University Press, 2005.


SPE 120960

Appendix

Unconsolidated porous media

The work we conducted on unconsolidated sandpacks is described elsewhere (Pentland et al. 2008, Al-Mansoori et al. 2008, Gittins et al. 2009).

Consolidated porous media

We selected common geological porous media (sandstones) which covered a range of different porosities and pore morphologies. Observed petrophysical parameters are presented in Table A. The exact test procedures are described below.
Our corefloods were conducted with n-octane (Aldrich, ACS grade) as the non-wetting phase and brine (1 wt% NaCl and 5 wt% KCl, both ACS grade, in de-ionized water) as the wetting phase. The tests were performed at ambient conditions: pressure = 0.103 MPa and temperature = 293.15 K.

<table>
<thead>
<tr>
<th>core name</th>
<th>St. Bees</th>
<th>Lough Allen</th>
<th>Berea (grey)</th>
<th>Clashach</th>
</tr>
</thead>
<tbody>
<tr>
<td>effective $\phi$ [%]</td>
<td>18.72</td>
<td>17.80</td>
<td>22.23</td>
<td>10.96</td>
</tr>
<tr>
<td>absolute $\phi$ [%]</td>
<td>20.44</td>
<td>20.10</td>
<td>23.90</td>
<td>12.68</td>
</tr>
<tr>
<td>BV [mL]</td>
<td>78.96</td>
<td>46.53</td>
<td>60.28</td>
<td>92.04</td>
</tr>
<tr>
<td>effective PV [mL]</td>
<td>14.78</td>
<td>8.28</td>
<td>13.40</td>
<td>10.09</td>
</tr>
<tr>
<td>$k_{air}$ [mD]</td>
<td>288</td>
<td>1480</td>
<td>1297</td>
<td>31.96</td>
</tr>
<tr>
<td>$S_{wc}$ [%]</td>
<td>50.98</td>
<td>44.34</td>
<td>48.84</td>
<td>33.81</td>
</tr>
<tr>
<td>$S_{or}$ [%]</td>
<td>37.27</td>
<td>36.27</td>
<td>31.28</td>
<td>53.13</td>
</tr>
<tr>
<td>$C_{trap}$</td>
<td>6.99</td>
<td>6.456</td>
<td>6.950</td>
<td>5.823</td>
</tr>
</tbody>
</table>

Table A: Basic petrophysical and coreflood data for selected consolidated sandstone cores. $k_{air}$ = air permeability.

Air permeabilities were measured in a standard Hassler cell under a confining pressure of 1.4 MPa. Effective porosities were measured with a Helium porosimeter and absolute porosities were determined via mass balance assuming that the rock matrix has a density equal to quartz, i.e. 2650 kg/m$^3$ (Hollemann and Wiberg 1985). The bulk volume was calculated by measuring the lengths and diameters of the cylindrical samples with an electronic vernier caliper.

Coreflood experiments

First, the cores were cleaned by boiling them in a 50 wt% toluene/50wt% methanol mixture for 48 hours in a Soxhlet extractor. Then gaseous CO$_2$ was injected into the dry core for 15-30 minutes at an overpressure of 0.2 MPa in order to displace air which would otherwise be trapped due to capillary forces. Then 8 PV (pore volumes) of de-aired brine were injected followed by an injection of an additional 2 PV with an applied backpressure of 0.2 MPa. Saturation was checked by mass balance. After brine saturation, 10 PV of de-aired n-octane were injected under ambient conditions in a primary drainage displacement process. The oil was injected at a flow rate of 1 mL/min, which corresponded to a capillary number of $1.5 \times 10^{-7}$. The remaining water saturation in the core was then determined by mass balance.

To reach residual saturation the core was waterflooded. We injected 10 PV of de-aired brine into the core at a flow rate of 1 mL/min which corresponded to a capillary number of $3.2 \times 10^{-7}$. Shortly after the injection of 1 PV no additional oil production was observed visually. $S_{or}$ was measured by mass balance.