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Spontaneous Imbibition in Small Cores

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Abstract

This paper presents experimental data for co-current spontaneous imbibition in cores having bulk volumes from 0.1 to 12 cm³. Simple experiments of brine imbibition into air-filled cores were carried out. Homogeneous sandstone cores (Berea and Bentheimer) and a carbonate core (Mt. Gaboro) were used in the experiments. The experimental data were scaled using the scaling laws reported in the literature.

The results demonstrate that reliable experimental data of spontaneous imbibition can be obtained for the small cores of homogeneous porous media. Such data are of immense interest for validating the predictive models of core-scale processes based on micro-CT images of rock fragments with bulk volumes from 0.1 to 12 cm³. The data for cores of different sizes were successfully scaled using five different methods. The recovery models proposed by Ma et al. and others produced an excellent match for the normalized imbibition recovery data. The results obtained in this study can be used to validate the predictive models of spontaneous imbibition.

1. Introduction

Accurate prediction of spontaneous imbibition is crucial in optimization of oil and gas recovery processes, e.g., improving water injection performance by design of oil fields and diminishing residual gas saturation in gas fields. Network models based on micro-CT images promise great potential to better understand and more accurately predict the dynamics of imbibition processes. Advances in extracting representative networks from micro-CT images of porous materials have improved the predictive capabilities of the network models. The networks extracted from the images are used in models to predict multiphase flow properties such as relative permeability, capillary pressure, and spontaneous imbibition processes. All these predictions need to be validated using laboratory data in order to test the predictive value of the models. The imbibed rock fragments are small compared to conventional cores having bulk volumes of the order of 0.1 cm³.

A number of attempts have been made to compare limited laboratory measurements with network model predictions. Although the results of those comparisons are encouraging, the networks used were derived using computer-generated process-based reconstructions of the porous medium which have significantly different properties than those used in the actual experiments. Moreover, the experimental data used were obtained on conventional cores having bulk volumes of at least 10 cm³, which are several orders of magnitude smaller than those of the rock fragments used to produce the micro-CT images.

Scaling of spontaneous imbibition has long been used as a predictive tool for estimating the field performance of waterfloods. The recovery models presented in this study were successfully scaled using five different methods to produce data for cores of different sizes. The imbibition recovery data were successfully scaled using five different methods. The recovery models proposed by Ma et al. and others produced an excellent match for the normalized imbibition recovery data. The results obtained in this study can be used to validate the predictive models of spontaneous imbibition.

2. Scaling of Spontaneous Imbibition

Spontaneous imbibition of water into a matrix block is a very complex process and depends on many factors such as permeability, tortuosity, shape, and size of the matrix, boundary conditions, and interfacial tension and viscosity of the fluid system. Detailed reviews of hydrocarbon recovery by spontaneous imbibition have been reported.

Spontaneous imbibition of water into gas-saturated porous rock can be considered to be a piston-like displacement with the imbibed mass given by the Handy equation,

\[ m_w = \frac{2 \pi i_{w} x_{i} \mu_{w}}{\mu_{w} - \mu_{o} + \mu_{m}} \]

where \( m_w \) is the mass of the water imbibed, \( p_i \) is the capillary pressure, \( x_i \) is the water permeability, \( \phi \) is the porosity, \( \mu_w \) is the water viscosity, \( \mu_o \) is the oil viscosity and \( \mu_m \) is the mixing viscosity of the water and oil phases. The imbibition role of the capillary pressure increases with the decrease in the dimensionless imbibition index, \( I_o \). The scaling of spontaneous imbibition in this approach is based on the following equation:

\[ \frac{t_o}{t_{c}} = \left( \frac{L_o}{L_{c}} \right)^{n} \]

where \( t_o \) is the time that the imbibition front moves from inlet to the outer boundary. The use of the dimensionless time \( t_o \) for spontaneous imbibition in oil-saturated sandstone and carbonate cores has been reported. The results show that the scaling of the spontaneous imbibition time is valid for different rock types at the same permeability condition.

Based on the scaling laws reported by Pasyuk and Leu, the dimensionless imbibition recovery is given by:

\[ \frac{R_{w}}{R_{w,max}} = \frac{L_o}{L_{c}} \]

where \( R_{w} \) is the imbibition recovery at time \( t \), and \( R_{w,max} \) is the maximum imbibition recovery.

The scaling laws reported by Pasyuk and Leu for spontaneous imbibition in oil-saturated sandstone and carbonate cores have been used to validate the models of spontaneous imbibition. The models proposed by Ma et al. and others produced an excellent match for the normalized imbibition recovery data. The results obtained in this study can be used to validate the predictive models of spontaneous imbibition.

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where \( a \) is the characteristic mobility and \( M^* \) is the characteristic mobility. The use of the dimensionless time \( t_o \) for spontaneous imbibition in oil-saturated sandstone and carbonate cores has been reported. The results show that the scaling of the spontaneous imbibition time is valid for different rock types at the same permeability condition.
the water saturation at the infiltration front, $S_w$ is the initial water saturation, $p_{wi}$ is the water saturation at the infiltration front, and $A$ and $b$ are constants associated with capillary and gravity forces, respectively, $A$ is the density difference between water and gas in the gravitational constant. Eq. 9 is derived from the Darcy’s equation for a plane-parallel displacement. It is not straightforward to determine $S_w$ and $p_{wi}$, and Horn1 and Horn2 suggested that care be taken using constants $a$ and $b$, which need to be determined from a plot of inhibition rate versus the reciprocal of gas recovery:

$$Q = \frac{dh}{dt} = \frac{a}{R} - b$$

where $Q$ is the volumetric rate of water inhibition, $R_w$ is the cumulative volume of water imbedbed, and $R$ is the gas recovery in terms of pore volume. The authors reported that Eq. 9 scales the spontaneous inhibition of water into different porous media (Berea, chalk, and Graywacke cores) with different initial water saturations. One of the features of Eq. 9 is that almost all the factors involved in core spontaneous inhibition include porosity, permeability, pore structure, matrix size, fluid viscosity, initial water saturation, wettability, interfacial tension, capillary pressure, relative permeability, and gravity, are considered. The shortcoming of the scaling law, as reported by the authors, is the difficulty in correlating the entire inhibition process for different rock types.

Another way to scale spontaneous inhibition is the use of the normalized hydrocarbons recovery. Anstoy and others19 reported a mathematical equation which takes into account the normalized oil recovery ($R_o$) to time by an exponential function:

$$R_o = \frac{1}{1 + \epsilon^2 R - R}$$

where $\epsilon$ is a rate constant. $R_o$ is defined by

$$R_o = \frac{V}{V_0}$$

$R$ is the recovery at time $t$, and $R_0$ is the ultimate recovery.

Ma and others20 modified the Anstoy and others19 correlation by taking into account for directional differences and viscosity effects:

$$R_o = \frac{1}{1 + \epsilon^2 R - R}$$

where $\epsilon$ is the non-wetting phase production decline constant, $V$ is the volume for all-water systems in sandstones, alabund, and aluminum silicate core21.

Vinkad and others22 proposed another empirical equation for oil recovery from strongly water-wet porous media with zero initial water saturation, which is given by

$$S_o = 1 - \frac{1}{1 + (1 + 0.014 t)^{1/3}}$$

They showed that Eq. 17 represented all their experimental data for oil-water systems with zero initial water saturation in sandstones and chalk core samples.

Li and Horn23 presented a different type of normalized recovery for gas-water system inhibition, using 50% Methanol and 50% Toluene and then dined at an oven at 90°C until there was no change in weight before the next stage of the experiment. The reproducibility of the experimental procedure was tested for all the experiments by performing the same experiment twice. Figs. 4 and 5 show examples of the reproducibility tests for the largest and smallest Berea core.

Menthes Jump Correction. At the first contact between the first brine in the container and the second brine in the tank, there is always an increase in weight because of the liquid surface energy and capillary suction. This sudden jump in weight measurements is known as the menthes contact effect and the data is corrected for that24. The correction was done by subtracting the first reading on the balance from the recorded weight increase data.

Apparatus Accuracy Check. The experimental apparatus was validated by measuring spontaneous imbibition of silicone oil into glass capillaries and spontaneous imbibition of millipore water into a nonporous Vycor glass rod.

Glass Capillaries. Both high- and weight-time experiments were simultaneously carried out. Glass capillaries of 0.5, 0.45, and 1.85 mm in radi radius and 50mm in length were used. The silicone oil used in the experiments (purchased from Dow Corning) had a surface tension of 21.1 mN/m, density of 0.965 kg/l and viscosity of 0.5 cp. Before measurements, the capillaries were cleaned by full immersion in chronic acid for 30 minutes, followed by 20 minutes in a mixture of concentrated hydrochloric acid (50%) and distilled water (50%). The capillaries were then thoroughly rinsed with distilled water and dried at an oven at 110°C for 2 hours. Measurements were carried out at room temperature (22±2°C).

The high-time measurements were made using still video images. The results of the height were converted to those of weight using the density of the silicone oil and the cross-sectional area of the capillary tube.

The water flow rate of the system of Terasaki analytical equation as presented by Li and Horn20:

$$\begin{align*}
    \frac{d\theta}{dt} &= \frac{\rho g}{k} \left( \frac{h_1 - h_2}{h_1 h_2} \right) \\
    \text{where} h_1 &\text{is the static height and } h_2 \text{ is the height at the rising front.}
\end{align*}$$

Vycor Glass Rod. A weight-time measurement was made using a Vycor glass rod which had a density of 2.48 oz/ cu. in (0.137 g/cm3) and a length of 1.25 cm of nylon. A millipore water was used ($\mu$ = 0.935 cp) as the infusing fluid. Prior to the experiment, the Vycor samples were cleaned in a mixture of concentrated sulfuric acid (35%) and hydrogen peroxide solution (70%) followed by rinsing in millipore water and drying in vacuum at 90°C. The mean pore diameter at re- ported for both glass and Vycor are 40 and 28%, respectively. The present data is in good agreement with the results of other measurements reported by Huber20 and others in Fig. 6.
5. Conclusions

Co-current spontaneous inhibition experiments were performed on two outboard diaphragm steam generators.

The following conclusions are made:

- High-accuracy, simple, binary displacement air spontaneous inhibition experiments have been presented. The results demonstrate that reliable experimental data for spontaneous inhibition can be obtained for the cores of homogeneous pebble bed reactors having a bulk volume of 0.3 m³.
- The measured data can be used for validating the predictive value of network models which employ micro-CT-based realistic networks where sample sizes are small.
- All the existing scaling laws, considered in this study, for spontaneous inhibition scale the experimental data for the same rock type satisfactorily, but with different values for the dimensionless time.
- The normalized gas recovery was calculated using three different models reported. The models proposed by Møl og Vinkum et al. show best agreement with measured data. The data of the largest and smallest cores were successfully scaled for all three types of rocks.

6. Acknowledgement

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References

Table 1: Bulk volumes of the cores used in a number of spontaneous imbibition experiments reported.

<table>
<thead>
<tr>
<th>Author</th>
<th>Smallest (cm³)</th>
<th>Largest (cm³)</th>
<th>Rock Type/Fluid System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Morey &amp; Kyser</td>
<td>14.2</td>
<td>56.0</td>
<td>Aluminum, sandstone/Oil-brine</td>
</tr>
<tr>
<td>Hanson &amp; Vidal</td>
<td>444.6</td>
<td>3965.0</td>
<td>Aluminum silicate coral/Oil-water</td>
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<tr>
<td>Conic et al.</td>
<td>56.7</td>
<td>226.9</td>
<td>Oyster chalk/Oil-brine</td>
</tr>
<tr>
<td>Zhang et al.</td>
<td>13.3</td>
<td>116.8</td>
<td>Bone/Oil-brine</td>
</tr>
<tr>
<td>Tie et al.</td>
<td>59.1</td>
<td>91.0</td>
<td>Bone, Mt. Gambier carbonate/Oil-brine</td>
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<tr>
<td>Li &amp; Horn</td>
<td>38.0</td>
<td>874.7</td>
<td>Bone, chalk, greywacke/Water-air</td>
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<tr>
<td>This Study</td>
<td>0.1</td>
<td>12.3</td>
<td>Bone, Benbowite, Mt. Gambier/Oil-air</td>
</tr>
</tbody>
</table>

Fig. 1: Procedure of downsampling the core samples.

Fig. 4: Reproducibility test for the smallest Benbowite core.

Fig. 7: Water imbibed versus square root of time for all Bone sandstone cores.

Fig. 2: Schematic of the spontaneous imbibition apparatus.

Fig. 5: Spontaneous inhibition of silicone oil into glass capillaries.

Fig. 8: Water imbibed versus square root of time for all Mt. Gambier carbonate cores.

Fig. 3: Reproducibility test for the largest Benbowite core.

Fig. 6: Spontaneous inhibition of millipore water into Vycor glass rod.

Fig. 9: Water imbibed versus square root of time for all Mt. Gambier carbonate cores.

Table 2: Physical properties and dimensions of the cores used and constants "c" values for Li and Horn model.

<table>
<thead>
<tr>
<th>Samples</th>
<th>Properties</th>
<th>Bone</th>
<th>Benbowite</th>
<th>Mt. Gambier</th>
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<tbody>
<tr>
<td>A</td>
<td>L (cm)</td>
<td>2.40</td>
<td>2.56</td>
<td>2.59</td>
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<tr>
<td></td>
<td>D (cm)</td>
<td>2.52</td>
<td>2.56</td>
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<td></td>
<td>c</td>
<td>1.17</td>
<td>1.11</td>
<td>0.96</td>
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<tr>
<td>B</td>
<td>L (cm)</td>
<td>2.40</td>
<td>2.56</td>
<td>2.59</td>
</tr>
<tr>
<td></td>
<td>D (cm)</td>
<td>1.52</td>
<td>1.49</td>
<td>1.48</td>
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<tr>
<td></td>
<td>c</td>
<td>1.17</td>
<td>0.96</td>
<td>0.70</td>
</tr>
<tr>
<td>C</td>
<td>L (cm)</td>
<td>2.40</td>
<td>2.56</td>
<td>2.59</td>
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<td>D (cm)</td>
<td>0.32</td>
<td>0.53</td>
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<td></td>
<td>c</td>
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<td>0.71</td>
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<tr>
<td>D</td>
<td>L (cm)</td>
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<td>1.54</td>
<td>1.50</td>
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<tr>
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<td>D (cm)</td>
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<td>0.55</td>
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<td></td>
<td>c</td>
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<td>1.65</td>
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<tr>
<td>E</td>
<td>L (cm)</td>
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<td>0.52</td>
<td>0.51</td>
</tr>
<tr>
<td></td>
<td>D (cm)</td>
<td>0.52</td>
<td>0.53</td>
<td>0.55</td>
</tr>
<tr>
<td></td>
<td>c</td>
<td>1.36</td>
<td>1.35</td>
<td>1.36</td>
</tr>
</tbody>
</table>

Table 3: Petrophysical properties of the literature data used in this study.

<table>
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<tr>
<th>Author</th>
<th>Rock</th>
<th>q</th>
<th>k (D/cm²)</th>
<th>l (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li &amp; Horn</td>
<td>Chalk</td>
<td>0.045</td>
<td>0.0006</td>
<td>2.5</td>
</tr>
<tr>
<td>Schmitz et al.</td>
<td>Greywacke</td>
<td>0.045</td>
<td>0.0006</td>
<td>2.52</td>
</tr>
<tr>
<td>Li &amp; Horn</td>
<td>Benbowite</td>
<td>0.15</td>
<td>0.5</td>
<td>11.0</td>
</tr>
<tr>
<td>Li &amp; Horn</td>
<td>Benbowite</td>
<td>0.28</td>
<td>0.5</td>
<td>4.95</td>
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<tr>
<td>Harbaugh et al.</td>
<td>Benbowite</td>
<td>0.245</td>
<td>1.2</td>
<td>43.6</td>
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<tr>
<td>Harbaugh et al.</td>
<td>Benbowite</td>
<td>0.21</td>
<td>0.5</td>
<td>6.0</td>
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</tbody>
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Fig. 10: Various scaling laws for spontaneous imbibition of water into air-saturated Berea cores.

Fig. 11: Comparison of various scaling laws for spontaneous imbibition into Berea core A.

Fig. 12: Water imbibed versus dimensionless time for all Bentheimer sandstone cores.

Fig. 13: Water imbibed versus dimensionless time for all Mt. Gambier carbonate cores.

Fig. 14: A comparison of normalized recoveries using Eqs. 16 and 17 (Ma et al. and Viklund et al. models, respectively).

Fig. 15: Normalized recovery using Eq. 18 (Li and Horne model).

Fig. 16: Comparison of the experimental data (Core A only), scaled using the Viklund et al. recovery model, with those reported for spontaneous imbibition of water into air-saturated Berea cores.