Imaging of infiltration and water distribution in drainage using X-ray tomography

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Aims and objectives

- Water influx in a giant gas field is important because this can be used to determine reserves.
- Understanding of fluid distribution in these sandstones becomes attractive.
- The sample is laminated sandstone supplied by DEA Deutsche Erdoel AG.

In this study, by using X-ray microtomography (XMT), we are going to:
- Study the distribution of brine and gas as a function of capillary pressure.
- Use the results to interpret, explain and predict effective permeability, relative permeability and resistivity index.
Research interests

1. Using multiphase flow imaging technique to imaging brine distribution at different capillary pressure values using porous plate.

2. Use the brine distribution map from image analysis to simulate resistivity index values at different
Key challenge: sub-resolution micro-porosity

Challenge:
• The brine distribution within the sample is highly dependent on fine lamination layers.
• The size of pores within the lamination layers are below image resolution.

Developing a workflow to visualise and quantify sub-resolution pores becomes important.

- Injecting high concentration KI with differential imaging.
Solution for the challenge: sub-resolution micro-porosity

(a) The original dry scan.
(b) The KI saturated scan at 30 wt% and the dry scan.
(c) The difference image after filtering.
(d) Three-phase segmentation showing grains (blue), sub-resolution pores (green) and macro pores (red).

The porosity within the sub-resolution region can be estimated.

The total porosity for all three phases can match Helium (He) measurement.
The benefits of resolving sub-resolution pores by injecting 30 wt% KI:

- Avoid the misidentification of low density minerals as sub-resolution pores.
- Accurate porosity estimation:
  - Total porosity from imaging:
    - Macro pores: 0.078
    - Sub-resolution pores: 0.111
    - Total porosity: 0.189
  - Helium (He) Porosity: 0.195 ± 0.006

Solution for the challenge: sub-resolution micro-porosity.
Solution for the challenge: sub-resolution micro-porosity

- Without considering sub-resolution pores, 53.6% of the macro pores are connected.
- 99.9% of macro pores are connected through sub-resolution pores.

It is expected that the value should be close to 100% since brine can access both macro pore and sub-resolution pore regions in our flow-based experiments – We can see the region becomes bright!
Solution for the challenge: sub-resolution micro-porosity

Publication:


Applications:

• The existing single phase and multi-phase model can be updated to consider sub-resolution pores to have better prediction of rock properties:
  ➢ e.g. permeability.

• Most of the experimental methodology can be incorporated with this new technique, to visualise and extract extra information:
  ➢ e.g. brine distribution and saturation during drainage process with full range of capillary pressures (100% at atm to irreducible saturation).
Experimental apparatus - Flow loop
Experimental apparatus

- Flow cell
- Core holder
- X-ray source
- Rotation stage
Brine distribution at different capillary pressures

Voxel size: 5 µm
S12: Porosity within sub-resolution pores

(a) The original dry scan.
(b) The KI saturated scan at 30 wt% and the dry scan.
(c) The difference image after filtering.
(d) Three-phase segmentation showing grains (blue), sub-resolution pores (green) and macro pores (red).

Total porosity
Imaging: 0.166
Helium: 0.170
S16B: Porosity within sub-resolution pores

(a) The original dry scan.
(b) The KI saturated scan at 30 wt% and the dry scan.
(c) The difference image after filtering.
(d) Three-phase segmentation showing grains (blue), sub-resolution pores (green) and macro pores (red).

Total porosity

Imaging: 0.148
Helium: 0.153
Norway: Porosity within sub-resolution pores

(a) The original dry scan.
(b) The KI saturated scan at 30 wt% and the dry scan.
(c) The difference image after filtering.
(d) Three-phase segmentation showing grains (blue), sub-resolution pores (green) and macro pores (red).

Total porosity
Imaging: 0.206
Helium: 0.215
Brine saturation at different capillary pressures includes:

- Brine in the macro pores.
- Brine in the sub-resolution pores.

Brine saturation within sub-resolution regions

6.89 kPa
1 psi
Brine saturation at different capillary pressures includes:

- Brine in the macro pores.
- Brine in the sub-resolution pores.

At high capillary pressure, brine only exists in sub-resolution pores.

Image calibration needed
Brine saturation: calibration (reference values)
Brine saturation within sub-resolution pores

6.89 kPa 1 psi

**Blue:** 0% brine (grains + pores with N$_2$)
**Green:** x% brine within sub-resolution pores
**Red:** 100% brine in macro pores

### Brine saturation

<table>
<thead>
<tr>
<th>Voxel counts</th>
<th>Grey-scale value (CT number)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0% brine</td>
<td>7000 - 8000</td>
</tr>
<tr>
<td>x% brine</td>
<td>8000 - 9000</td>
</tr>
<tr>
<td>100% brine</td>
<td>9000 - 12000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Vol%</th>
<th>Brine%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Macro pore (red)</td>
<td>0.259</td>
<td>1</td>
</tr>
<tr>
<td>Sub-res pore (green)</td>
<td>0.065</td>
<td>0.294</td>
</tr>
<tr>
<td><strong>Brine saturation</strong></td>
<td><strong>0.845</strong></td>
<td></td>
</tr>
</tbody>
</table>
S12: Brine saturation at different capillary pressures
Non-linear relationship in log-log axis

Sw ~ 100% -> Rt = Ro

DEA’s assumption of parallel electrical current

Air displacing water
Non-linear relationship in log-log axis

Sw until ~20 - 30% -> Rt increases nearly linear with reduction of Sw

DEA’s assumption of parallel electrical current

Air displacing water
Non-linear relationship in log-log axis

Sw <20 % -> Rt ‘does not see’ the further reduction of Sw

Micro to nano pore system has higher water saturated and masks progressing drainage of formation water in the meso to macro pore system.

DEA’s assumption of parallel electrical current

Air displacing water
Simulation of resistivity index (single phase)

Formation factor:

\[ F_0 = \frac{R_0}{R_w} \]

where

- \( R_0 \): The bulk resistivity of the rock when saturated 100% with brine (\( \Omega \text{m} \))
- \( R_w \): The resistivity of the brine (\( \Omega \text{m} \))

Effective formation factor at different capillary pressure (different \( S_w \)):

\[ F_i = \frac{R_i}{R_w} \]

where

- \( i \): Capillary pressure
- \( R_i \): The bulk resistivity of the rock when after drainage with different saturation under different capillary pressure (\( \Omega \text{m} \))
- \( R_w \): The resistivity of the brine (\( \Omega \text{m} \))
Simulation of resistivity index (single phase)

Resistivity index at different capillary pressures (different $S_w$):

$$I_i = \frac{R_0}{R_i}$$

where

- $R_0$: The bulk resistivity of the rock when saturated 100% with brine expressed in $\Omega m$
- $R_i$: The bulk resistivity of the rock when after drainage with different saturation under different capillary pressure ($\Omega m$)

$$I_i = \frac{R_i}{R_0} = \frac{F_i}{F_0}$$
Simulation of resistivity index (single phase)

Simulating formation factor is available via different platforms:

• Imperial college

• Avizo/PerGeos from FEI (www.fei.com)
Resistivity index simulation using PerGeos (S12)

100% saturated

After drainage (103.42 kPa/15 psi)

\[ F_0 = 9.80 \]

\[ F_{15} = 105.89 \]

Resistivity index = 10.8
Assumption of the resistivity index simulation

Assuming sub-resolution regions with brine as 100% brine:

- The overall formation factors of the core ($F_i$, including $F_0$) at different capillary pressure are all underestimated. $F_0$ for the 35 mm core is 32.10)

- Resistivity index at each capillary pressure is defined as: $I_i = F_0 / F_i$.

- As both $F_i$ and $F_0$ are underestimated, the resistivity index, which is the ratio, maybe still close to the real situation.
S12: Resistivity index at different brine saturation
Non-linear relationship in log-log axis

- At high brine saturation, the brine in the macro pores dominates the resistivity index value. There is a good match between image and SCAL measurements.

- The resistivity curve (SCAL) becomes non-linear when the capillary pressure is higher than 103.42 kPa (15 psi). At this capillary pressure:
  - Almost all the brine in the macro pores has been displaced by N₂.
  - The average brine saturation within sub-resolution pores becomes very low.

- The main reason causing non-linear relationship in the log-log axis is the brine in the sub-resolution pores.
  - More likely to be laminations.
Uncertainties of resistivity index simulation

- At low brine saturation, the connectivity of the brine phase can significantly affect the simulation.
  - This is due to the image resolution and the strength of the brine signal within the sub-resolution regions.

- At low brine saturation with high capillary pressure, the majority of the brine in both macro pores and sub-resolution regions has been displaced by N₂. However, there was still brine left in the small corners of all the pores, as well as the thin films/layers around the grain surface, which still can give some resistivity values if we can physically measure the resistivity.

- Those kinds of brine left in corners and existed as forms of thin films/layers were way below image resolution.

- However, due to the limit size of the sample in this flow experiment (5 mm in diameter), there is only one fine lamination layer. However, the size of the sample for SCAL measurement is about 35 mm. There are more than one fine lamination layers, and the overall resistivity for the whole sample at same brine saturation is lower (due to parallel brine paths).
Non-linear relationship in log-log axis

Dry scan

Differential images

- There are more sub-resolution pores in the laminated region.
- At high capillary pressure, the majority of the brine within the laminate region is also gradually displaced by gas.
- Some of the brine stayed within the rock grains which can also give resistivity measurements.
Future work

- A new model needs to be built for more accurate resistivity simulation which considers brine in sub-resolution pores and corners, as well as brine in forms of thin films/layers.
Conclusions

• A standard workflow using differential imaging technique to quantify sub-resolution pores has been established using carbonates with Imperial.

• The technique has been further extended to quantify brine saturation at different capillary pressures during drainage, with porous plate (S12).

➢ The average brine saturation values at different capillary pressures of the 5 mm micro core have a good agreement with the 35 mm core plug.

• The resistivity index values for the 5 mm core (S12) at different capillary pressures were also simulated. The simulation results shows that below the capillary pressure of 103.42 kPa (15 psi), there is a clear linear match in log-log axis.

• Although there is large uncertainties at high capillary pressures with low brine saturation, the non-linear relationship was observed.
Acknowledgements

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