Training on CCA and SCAL Experiments

1. Overview

This document presents an example of the training provided by CYDAREX on special core analysis (SCAL) experiments.

The training can cover the following topics:

- Gas permeability/porosity
- Formation factor
- Liquid Permeability Experiments
- Tracer Test Experiments
- P_c/RI Experiments
- Two-Phase Flow Experiments in steady state
- Two-Phase Flow Experiments in unsteady state

All experiments are done under laboratory conditions, with pressure below 5 bars.

2. Porosity measurement

Porosity is defined as:

$$\phi = \frac{Vp}{Vt} \tag{1}$$

Where Vp is the volume of pores and Vt the total volume. Porosity can also been calculated using the volume of solid Vs since Vt=Vp+Vs

$$\phi = \frac{Vt - Vs}{Vt} \tag{2}$$

For cylindrical plugs, the total volume is derived from the length L and diameter D:

$$Vt = \pi \, L \, D^2 / 4 \tag{3}$$

And the volume of solid using the grain density d and the dry mass Mdry

$$Vs = Mdry / d \tag{4}$$

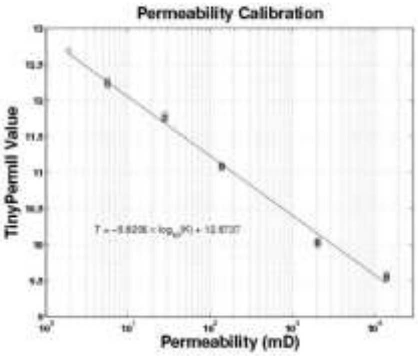
Mass is determined with a balance (accuracy 0.01 g) and dimensions with a caliper (accuracy 0.01 mm)

3. Gas Permeability Experiments

Gas permeability is measured with a TinyPerm commercialized by Vindum Engineering.

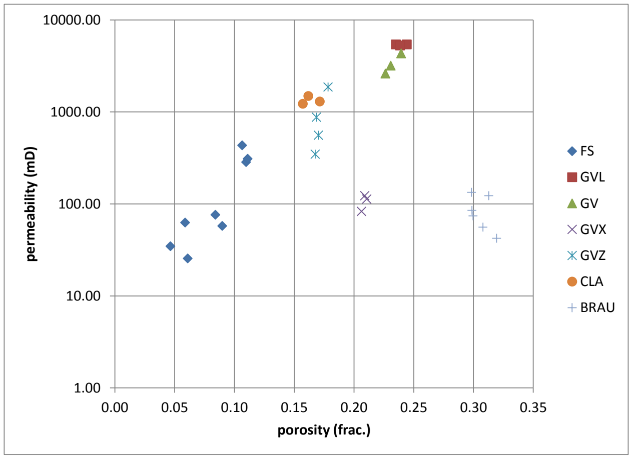
TinyPerm is a portable handheld air permeameter used for measurement of rock matrix permeability on outcrops and at the core scale.

The measurement is based on the transient decay of the pressure inside the cylinder when the valve is open. The apparatus deliver a number converted into permeability with a chart.



4. Rock typing

For the various samples, permeability is plotted as function of porosity in semi-log scale. The trends correspond to the different types of rocks, sandstones, carbonates, double porosity…

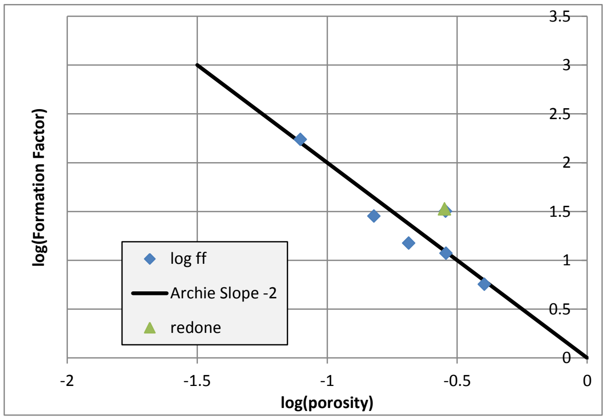


5. Formation factor

The plugs are provided 100% saturated with brine, NaCl 35 g/l (density ρ =1.024 g/cc). The dry mass before saturation is known.

1) Pore volume is determined from the difference of mass $\mathrm{Pv} = (\mathrm{Msaturated} - \mathrm{Mdry}) / \rho$
2) Porosity is determined using Pv and geometrical total volume Vt: $\phi = \mathrm{Vp} / \mathrm{Vt}$

Formation factor is derived from the measurement of electrical resistivity ρ of the plug. Resistance is given from voltage and intensity (1000 Hz generator, 1Volt maximum voltage) $\mathrm{R} = \mathrm{V} / \mathrm{I}$ and resistivity by: $\mathrm{R} = \rho \mathrm{L} / \mathrm{S}$, where L is length and S surface area. Intensity is obtained my measuring the tension over a calibrated resistance (200 ohms).



Formation factor F is defined as the ratio of the plug resistivity by the brine resistivity given by a diagram (from Schlumberger). The results are in good agreement with Archie's law: $\mathrm{F} = \phi^{-2}$

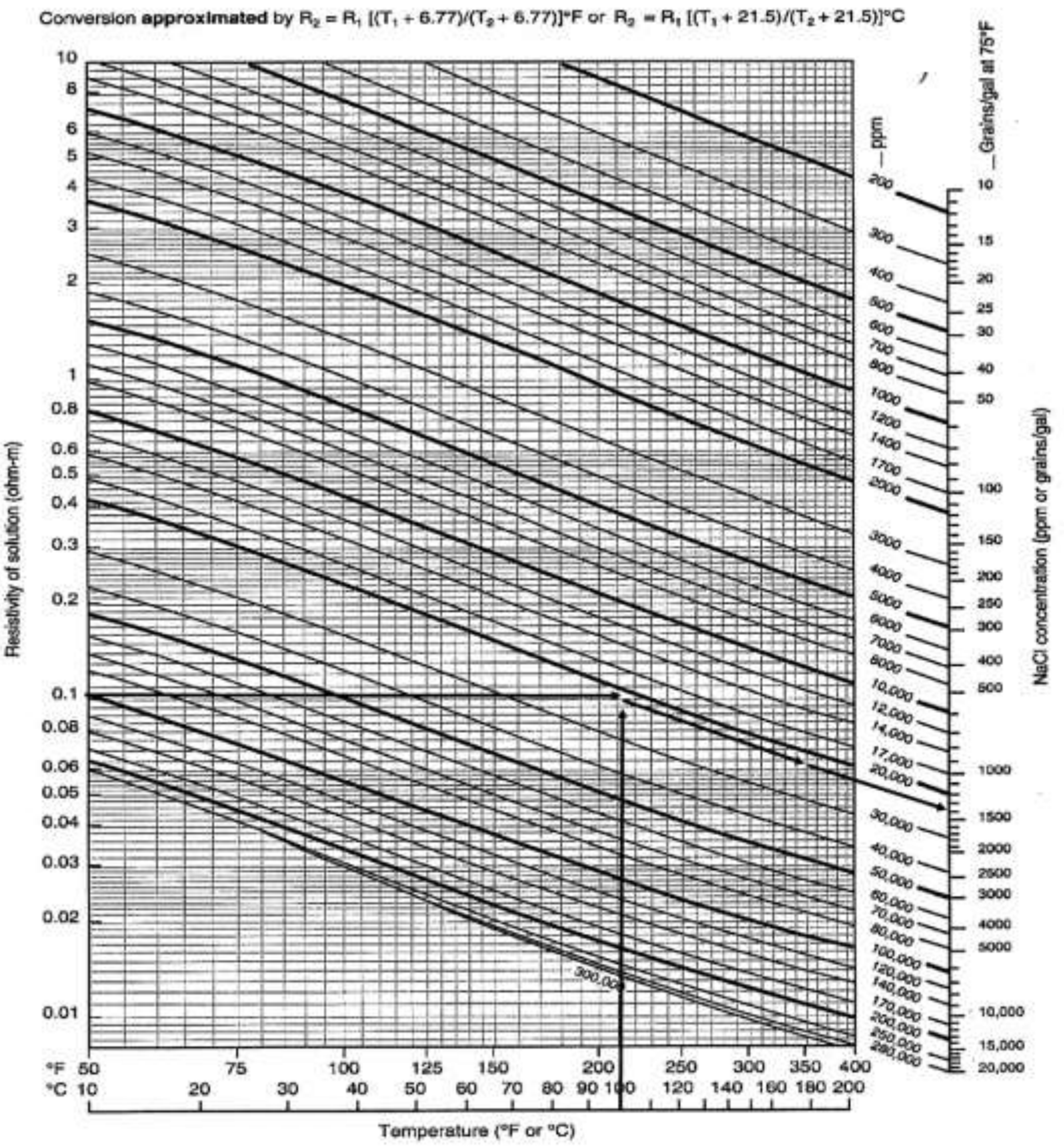
6. Liquid Permeability Experiments

Objective

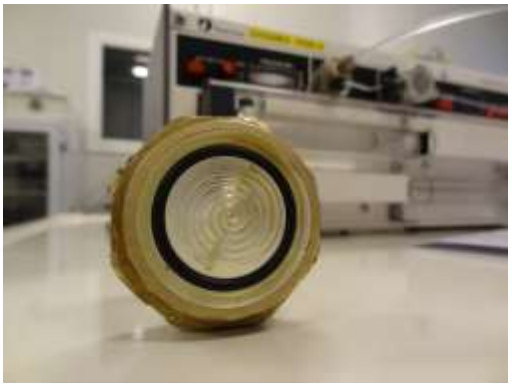
Measuring the variation of pressure as a function of flow rate to measure the absolute permeability.

Experimental Design

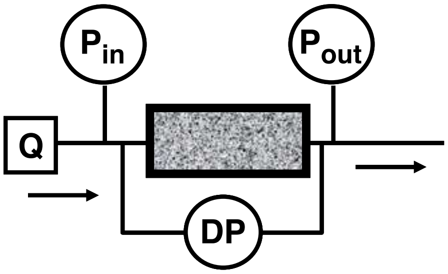
Core holder: Rock samples are typically 25 mm in diameter and 40 mm in length.



Conversion **approximated** by $R_2 = R_1\,[(T_1 + 6.77)/(T_2 + 6.77)]$°F or $R_2 = R_1\,[(T_1 + 21.5)/(T_2 + 21.5)]$°C



Experimental Setup:



Experimental Protocol:

Injection of 20 g/L NaCl brine at different flow rate Q. Measurements of P_{in}; P_{out} is atmospheric pressure.

5 steps in Q: 0, 100, 200, 300, 400, 499 cc/h. Measure ΔP at plateau. Measurements done with increasing and decreasing flow rate for quality control.

Here, sample GVI-4, 25 mm in diameter, 40 mm in length.

Results

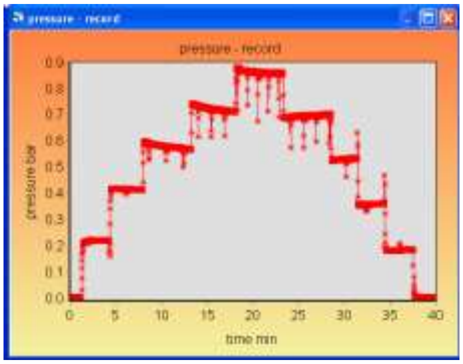


Figure 1: Data acquisition showing pressure as a function of time.

Q (cc/h)	ΔP (bar) at plateau
0	0.0074
100	0.223
200	0.417
300	0.575
400	0.714
499	0.856
400	0.700
300	0.533
200	0.361
100	0.185

Table 1: Pressure at plateau.

Interpretation

Interpretation using module Permeability in CYDAR, option Steady-State liquid.

Fill in “Information”, “Sample”, “Fluid”, and “Data Points”.
Then “Calculate Permeability”. Results can be seen in “View” menu.

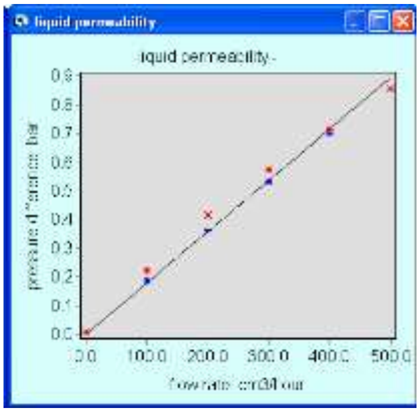


Figure 2: permeability measurement analyzed in CYDAR.

Final calculation: k = 124 mDarcy.

Troubleshooting

Potential problems and corrections:

- Inertial effects if Reynold's number > 1.
- Klinkenberg effects for gas if density is low.
- Clay within the sample could make it hard to reach a steady pressure.
- Air within the sample.

7. Tracer Test Experiment

Objective

A Tracer Test gives a measure of the homogeneity of the sample. If the sample is heterogeneous, it should not be used for measurements of relative permeability.

Experiment Design

A sample is loaded with 20 g/L NaCl brine. During injection of a 50g/L NaCl brine, the electrical conductivity of the solution at output is measured. The changed of conductivity as a function of time will give information on the pore size distribution.

Results

Raw Data: Measurements done on GP4.

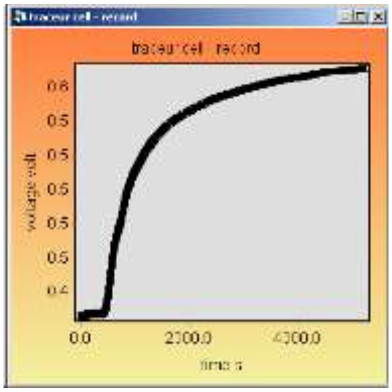


Figure 3: 50 g/L replacing 20 g/L.

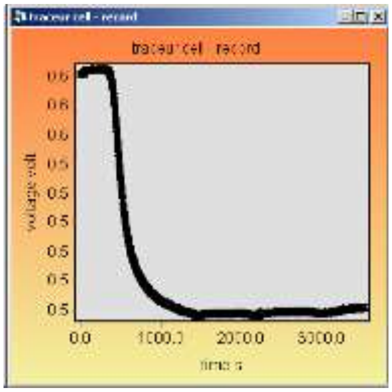


Figure 4: 20 g/L replacing 50 g/L.

Interpretation

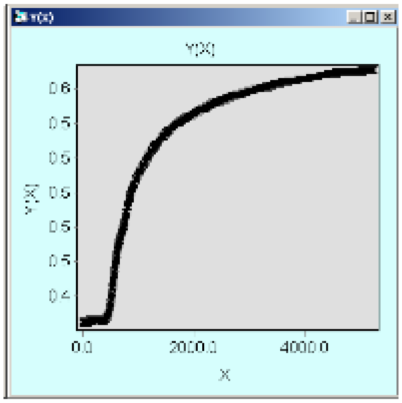


Figure 5: Voltage as a function of time.

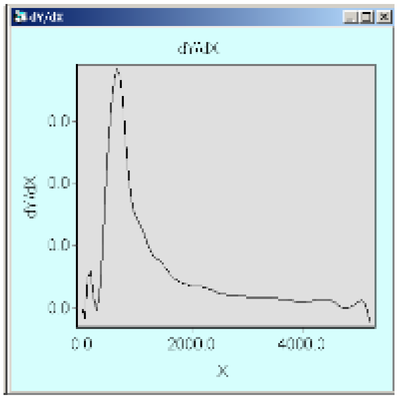


Figure 6: First derivative using Cydar.

CYDAR curve fitting tool is used to fit the experimental data with a spline function, and calculate the first derivative. Time can be normalized as the time needed to inject one pore volume. Voltage (or density) can be normalized between 0 and 1.

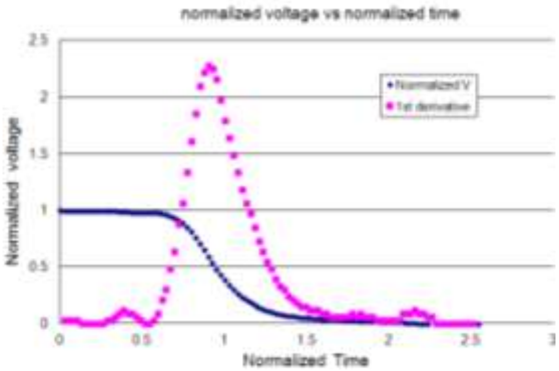


Figure 7: normalized voltage vs. time and first derivative.

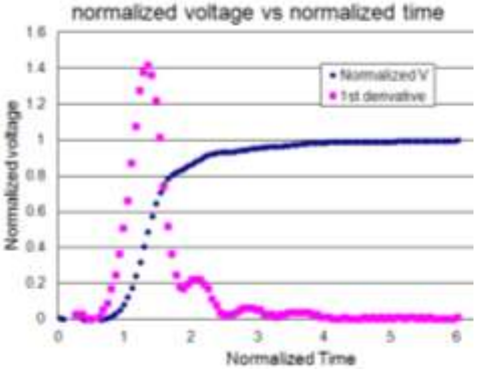
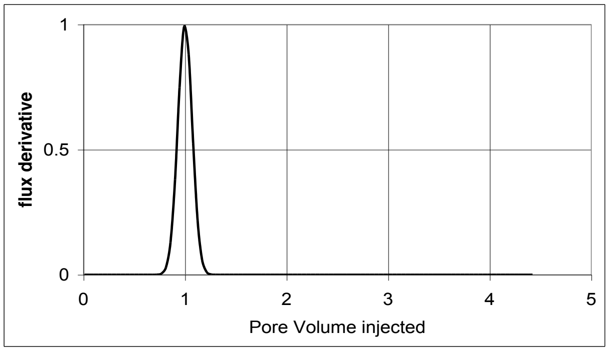
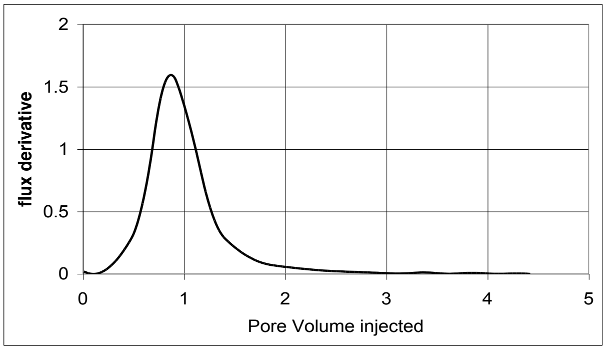


Figure 8: normalized voltage vs. time and first derivative.

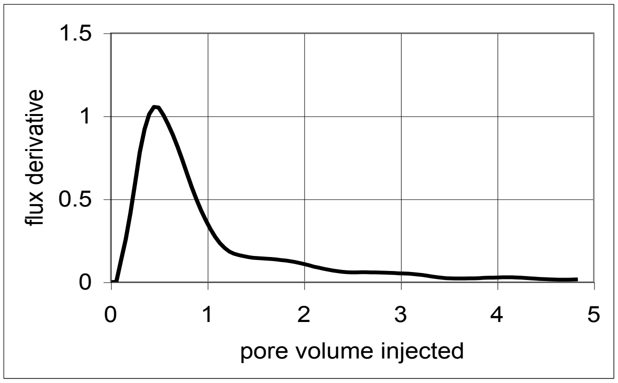
Interpretation:



Homogeneous sample (theoretical): spreading << 1 pore volume.



Symmetrical curve: highly heterogeneous but no preferential paths.



Dissymmetrical curve: highly heterogeneous with preferential paths.

Troubleshooting

If the sample is heterogeneous, it should not be used for measurements of relative permeability.

8. P_c/RI Experiments

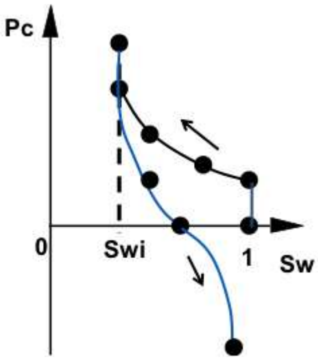
Objective

To obtain the capillary curve (P_c) curve as a function of water saturation, and water saturation as a function of Resistivity Index (RI).

Experiment Design

Definitions:

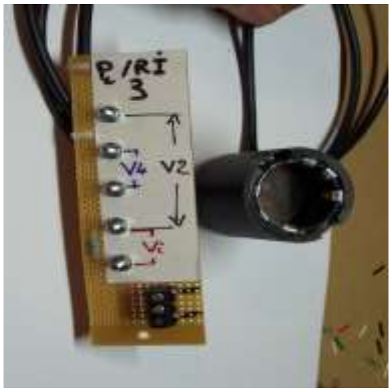
- Drainage: experiment where water is pushed with oil. Starts at $S_w \sim 1$.
- Imbibition: experiment where oil is pushed with water.
- Capillary Pressure: $P_c = P_{oil} - P_{water}$



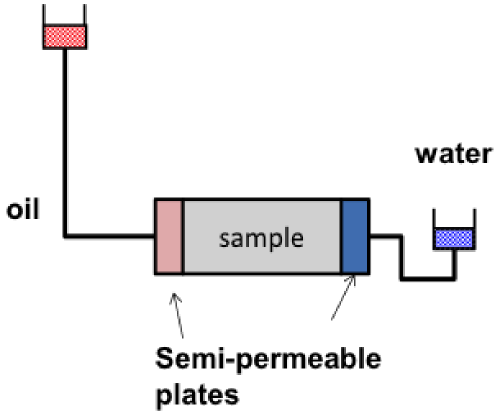
- Resistivity Index: $RI = R(S_w)/R(S_w{=}1) = S_w^{-n}$
- Formation Factor: quantify effect of rock on electric conductivity
  $f_R = R_{rock} / R_{brine} = \sigma_{brine}/\sigma_{rock}$
  Archie's law used for log calibration: $f_R = \phi^{-m}$

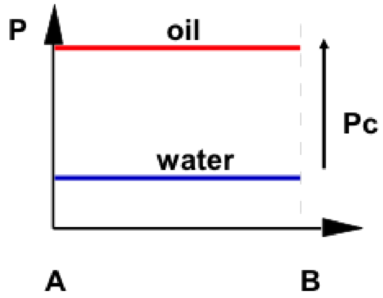
With ϕ the porosity; m, Archie's law exponent or cementation exponent. For a clean formation, m = 2, m < 2 with clays

Experimental cell:



Experimental Set-Up:





Measurements of Resistivity:

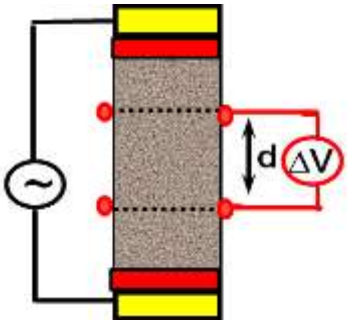


Figure 9: measurement with 4 electrodes.

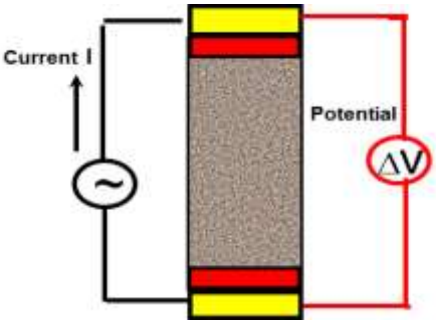
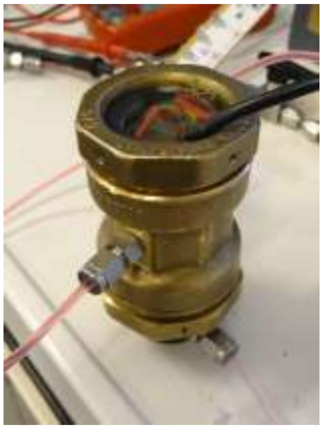


Figure 10: measurement with 2 electrodes.

To avoid contact resistance due to oil on the electrodes, a technique with 4 electrodes is preferred.

Actual Set-Up:



The pressure is imposed with the air tank on the oil surrounding the sample. A porous plate allows the water to exit the sample but not the oil. For each pressure step, the volume of water produced and the resistivity are measured as a function of time.

Experimental Simulation using CYDAR

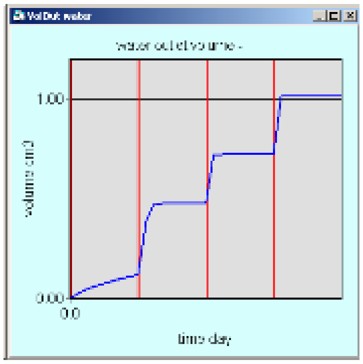
Determining the optimum oil pressure steps using CYDAR:

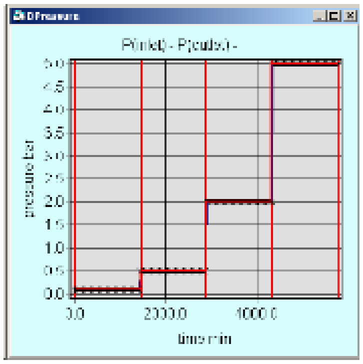
Two-Phase Flow experiments, Porous plate Experiment,

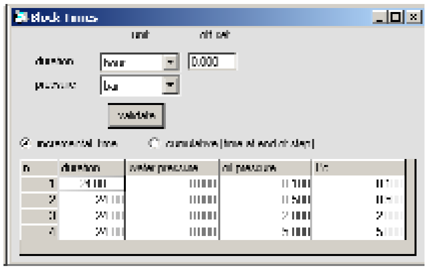
- Sample size, sample characteristics, fluid characteristics,
- one porous plate in outlet,
- block times, starts with 1 day per step and 5 pressure steps,
- K_r is entered as a Corey function,

- P_c input is usually obtained from mercury measurements, and is copy/paste.

CYDAR is used to simulate the time to reach equilibrium, and the total volume of water produced.







The constraints are to have a measurable production of water at each step, and a maximum pressure below 5 bars. Here, for instance, we see that the first pressure step doesn't quite reach equilibrium and should be longer.

Results and Interpretation

Production of water as a function of time is recorded. And for each measurement, the tension V_I, V_2, and V_4 are measured.

The initial water saturation S_W was 1; measuring the water produced gives S_W as a function of time, imposed P_c, and RI.

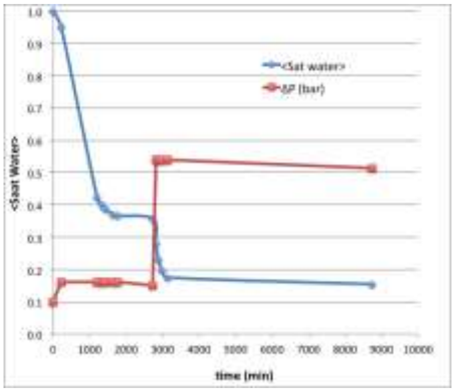


Figure 11: Imposed pressure (red) and water saturation (blue) as a function of time.

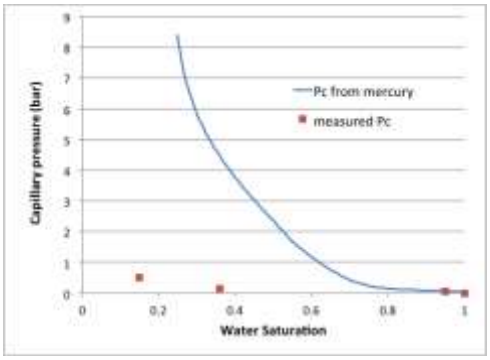


Figure 12: Measured Pc (red) compared to Mercury Pc (blue).

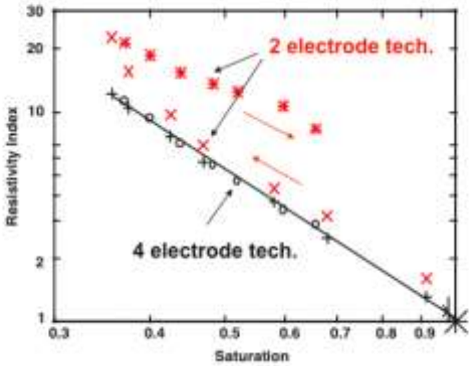


Figure 13: Log RI as a function of Log of water saturation measured with 2 (blue) and 4 (red) electrodes.

The experiment presented here shows a much smaller P_c (Figure 12) compared to what expected. The sample seems to have produced too much water for the applied pressure.

Troubleshooting

- Risk of breaking the porous plate when closing the cell.
- Risk of imposing an initial pressure that is too high and emptying the sample in one step. Need for simulation.
- Make sure to lock the cell with screws to avoid loss of pressure over time.

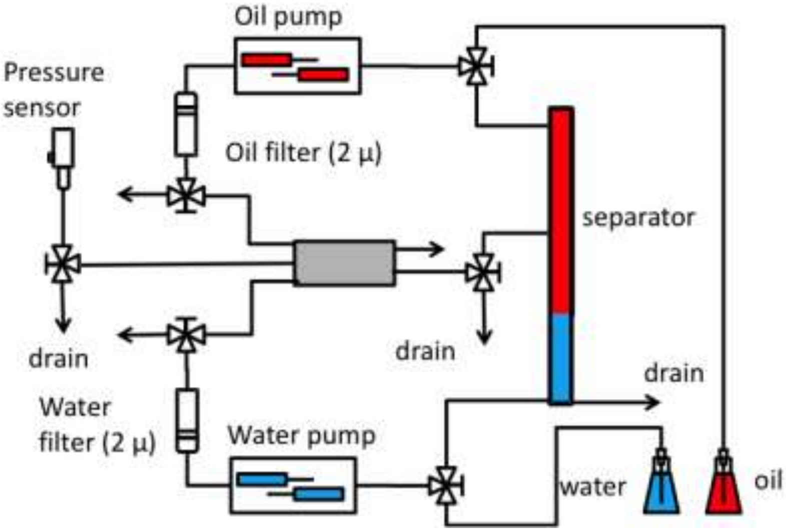
9. Two-Phase Flow Experiments – steady state

Objective

Determining the relative permeabilities Kr_{oil} and Kr_{water} **injecting two fluids**. Once the absolute permeability is determined (with a Perm experiment), ΔP and V_{water} produced are used to determined Kr.

Evaluating the volume of water produced is easier since the system is at equilibrium, so the ratio of water to oil in dead volume can be measured.

Experiment Design

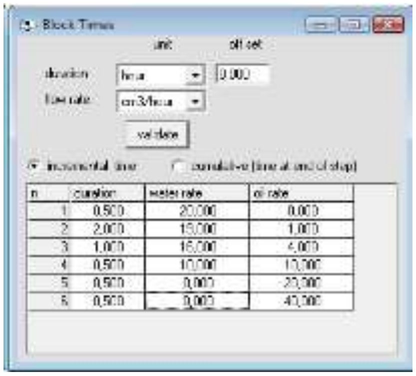


(Oil and water filters are now 15 µm).

Experimental Simulation using CYDAR

Numerical simulation in CYDAR is used to determine the oil and water flow rates, the duration to reach equilibrium, and the corresponding water and oil productions and pressure.

For sample GVI-3, with an absolute permeability of 168 mD and a porosity of 24%:



unit off set

duration hour 0,000

flow rate cm3/hour

● incremental time ○ cumulative (time at end of step)

n	duration	water rate	oil rate
1	0,500	20,000	0,000
2	2,000	19,000	1,000
3	1,000	16,000	4,000
4	0,500	10,000	10,000
5	0,500	0,000	20,000
6	0,500	0,000	40,000

Figure 14: block times and Q_W and W_O.

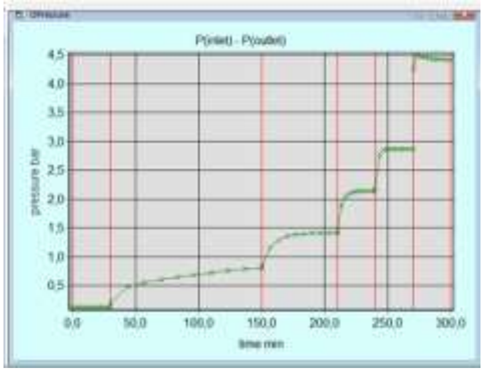


Figure 15: pressure for each block time.

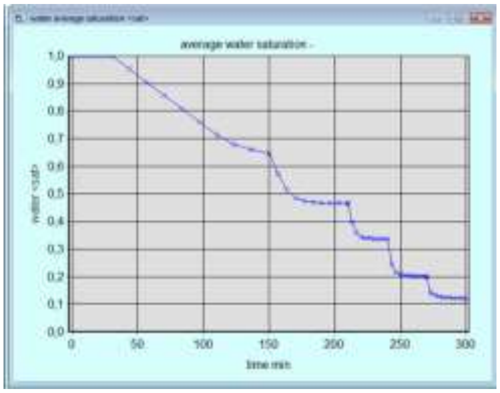


Figure 16: average water saturation for each block time.

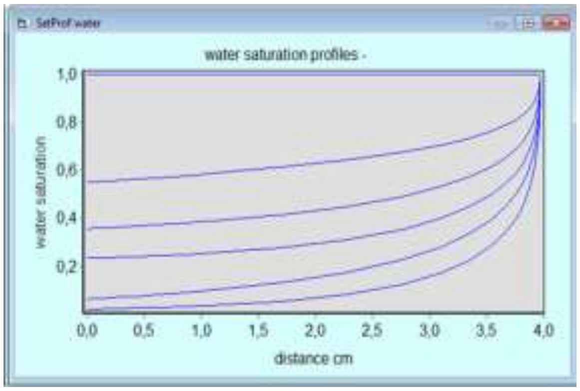


Figure 17: water saturation profile for each block time.

Note: At the end of measurements, possibility to make bumps (increase Q_O with $Q_W = 0$) to have information on P_c because the profile saturation is linked to the capillary pressure.

Results and Interpretation

Water production and pressure measurements are used in history matching to determine the optimal Kr.

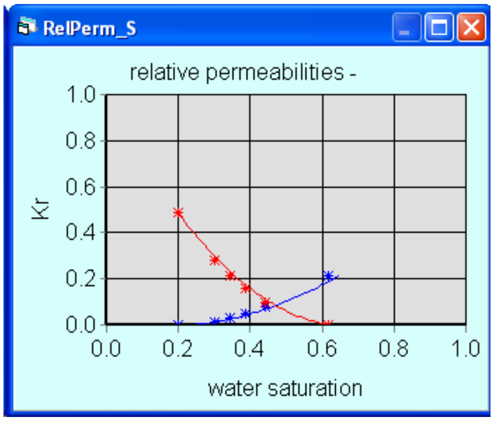


Figure 18: Relative permeabilities after optimization.

Troubleshooting

- In SCAL experiments, numerical simulations are required by major companies (Shell, Total, Chevron …).
- More accurate since they can take into account the real physics: capillary pressure, gas compressibility, heterogeneities, non-constant injection conditions…
- As quality control, comparison between raw data (pressure, effluents, profiles…) and simulated results.
- Difference for the final saturation:
  - with analytical calculation (Figure 19, symbols) Sw(final) = 0.68
  - with numerical simulation (Figure 19, solid line) Sw(final) = 0.80
  - The analytical calculation does not take into account the capillary end effect and uses the average saturation derived from the effluent balance

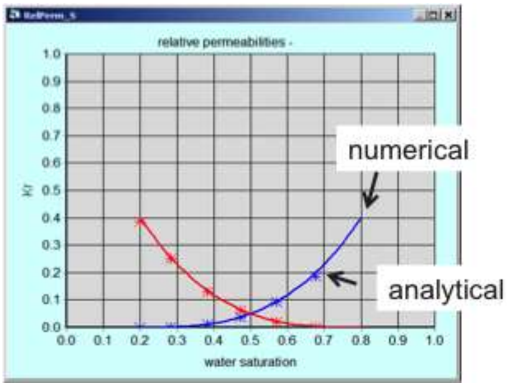


Figure 19: Difference between analytical and numerical results.

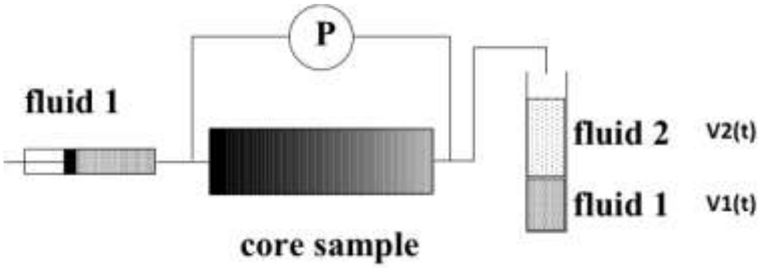
10. Two-Phase Flow Experiments – unsteady state

Objective

Determining the relative permeabilities Kr_{oil} and Kr_{water} **injecting one fluid**, and using the shape of the transient ΔP and water production V_{water}.

Either one step (not used anymore) or multi-steps.

Experiment Design



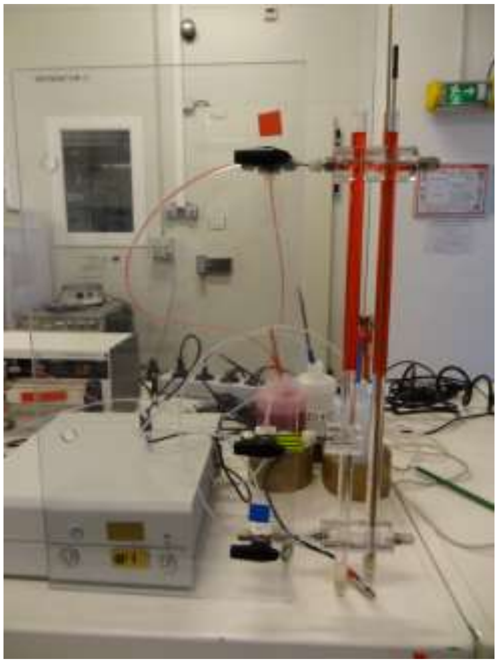


Figure 20: actual set-up. A double separator with a capacitance is used to record the variation of water level with time.

Results

Interpretation

JBN interpretation

"Welge" method or JBN for analytical interpretation in mono-step or multi-steps. Assumes $P_c = 0$. Analyze data after breakthrough.

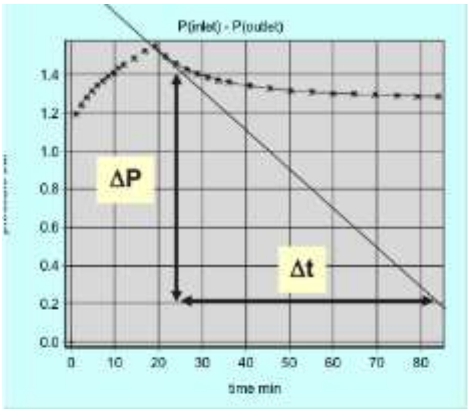
$$P_w^* = \frac{LQ\mu_w}{AK} \quad ; \quad P_o^* = \frac{LQ\mu_o}{AK} \quad V_w + V_o = Qt \quad ; \quad V_w^{'} + V_o^{'} = Q$$

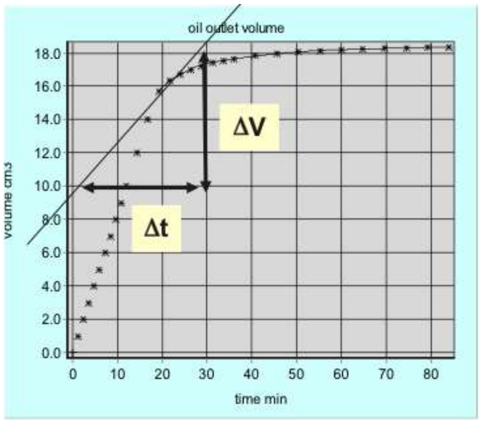
$$S_w = Si_w + (V_o - tV_o^{'}) / V_P$$

$$Kr_w = (1 - \frac{V_o^{'}}{Q}) \frac{P_w^*}{P - t\,P'} \quad ; \quad Kr_o = \frac{V_o^{'}}{Q} \frac{P_o^*}{P - t\,P'}$$

V'=dV/dt.

Example of one step; here breakthrough is at maximum pressure (but not always).


P(inlet) - P(outlet)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
ΔP
Δt
0
10
20
30
40
50
60
70
80
time min


oil outlet volume
volume cm3
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
ΔV
Δt
0
10
20
30
40
50
60
70
80
time min