HETEROGENEITY STUDY THROUGH REPRESENTATIVE CAPILLARY PRESSURE MEASUREMENTS - IMPACT ON RESERVOIR SIMULATION AND FIELD PREDICTIONS

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ABSTRACT

Capillary pressure, particularly imbibition capillary pressure, is an important petrophysical parameter for the interpretation of core flood displacement experiments such as water flood, and for calibrating appropriate reservoir simulation models. Several techniques are available for its measurement with the semi-dynamic method (patented by IFP) being the only recognized laboratory method to determine both capillary pressure and relative permeability of rock-fluid systems at full reservoir conditions (without using any filter or membrane). The prime objectives were assessment of capillary pressure for different rock types in a mature carbonate reservoir, and evaluation of the impact of capillary pressure in a reservoir simulation model for full field development (FFD).

The novel capillary pressure measurement technique presented in this paper, coupled with in situ saturation monitoring (ISSM), allows determination of the Pc-data at each location where local saturations are measured. This leads to a set of Pc-curves instead of a single curve derived from other existing methods. All those curves are representative of the studied sample and account for the influence of the heterogeneity on the Pc-data. Hence, for heterogeneous samples there is a scatter of the Pc points while for homogeneous plugs, all the Pc-curves reduce down to almost one Pc-curve. The results of such a heterogeneous study are presented in the case of carbonate samples with different levels of heterogeneity.

The simulations, performed with the valid water/oil imbibition capillary pressure data obtained with the new approach, fit well the fluid distribution at equilibrium for different pressure levels. These data are expected to significantly improve the field performance predictions, compared to empirical correlations and non-representative Pc data.

INTRODUCTION

A major step in a SCAL study is the determination of the classical petrophysical parameters: resistivity index (RI), capillary pressure (Pc) and relative permeability (kr). This is the starting point of any process efficiency study. To be representative of reservoir conditions, these measurements generally have to be performed on carefully selected samples and under pressure and temperature.

This paper is focused on the determination of the two parameters kr and Pc, using the semi-dynamic method. This method is the only one which allows both measurements on the same sample, at full reservoir conditions. It was applied on carbonate samples from the Middle East region. Several rock types were investigated and a new approach was developed to study the influence of the sample heterogeneity on the imbibition capillary pressure. For each sample, a set of representative Pc-curves was determined and used in reservoir simulations for field performance predictions.

The principle of the semi-dynamic method is recalled in the first part of the paper. The second part presents the heterogeneous approach of the method, which leads to a set of representative Pc-curves for each sample. The application of the method to different carbonate rock types is then detailed. Thanks to these representative Pc-curves the performance predictions of the investigated field will be highly improved.

SEMI-DYNAMIC METHOD

The semi-dynamic method is the only fully integrated petrophysical tool suitable to determine the whole Pc-cycle, for gas/oil or water/oil fluid systems, at full reservoir conditions. The relative permeability of the displacing phase can be determined analytically during the same experiment, on the same sample. Furthermore, the history matching of the experiment leads to the kr determination for both phases.

Principle and device

The semi-dynamic method was first validated at ambient conditions on sandstone and chalk outcrop samples [1, 2, 3]. The SDM prototype developed for reservoir condition measurements, as well as the first results obtained on a carbonate sample, can be found in Lombard *et al* [4]. Comparison with other techniques and experimental guidelines are also proposed in this reference [4].

The principle is based on the balance between the capillary pressure and the viscous pressure drop. The sample is set in a core holder, without any semi-permeable membrane. During an experiment, one fluid is injected through the sample while the second one washes the outlet face of the core. A separator is used to measure fluid production. Local saturation profiles can be measured with different techniques. The used devices are equipped with X-ray generators and detectors. A steady-state equilibrium is reached if inlet and outlet pressures and saturation profiles are all constant. For each equilibrium, capillary pressure and relative permeability are determined at the entrance of the porous medium. The principle of the design, which can operate up to 130°C and 330bar, is presented in Figure 1.

Interpretation: Local Saturation and Relative Permeability

For each injecting flow rate q, the inlet saturation Si(Pi) and the inlet pressure Pi give a point on the Pc-curve. If local saturations are measured, the Pc-curves can be obtained directly with the collected data, by extrapolation of the measured profile. If not, the inlet saturation has to be calculated analytically. Ramakrishnan and Capiello [5] determined the inlet saturation from the average saturation <S>:

$$\mathrm{Si(Pi)} = \langle \mathrm{S} \rangle + \mathrm{q}.\frac{\mathrm{d}\langle \mathrm{S} \rangle}{\mathrm{dq}} \tag{1}$$

For homogeneous samples, the extrapolated and the calculated inlet saturation values are identical. Figure 2 presents an example of equilibrium saturation profiles and of the derived forced imbibition capillary pressure curve (water/oil), measured on an homogeneous carbonate sample (Rock Type number 4, RRT4 plug properties are given in Table 1, [4]). Both the calculated and the direct saturation values are comparable.

The relative permeability (Lenormand *et al* [4]) of the injected fluid is given at the inlet of the sample by equation 2:

$$\mathrm{kr} = \frac{\mathrm{L}.\mu}{\mathrm{K.A}} \frac{\mathrm{dq}}{\mathrm{dPi}} \tag{2}$$

In equation 2, K is assumed to be uniform over the sample, as for other SCAL techniques.

Figure 3 shows the imbibition krw-curve (water is the displacing fluid) and the drainage kro-curve (oil is the displacing fluid) obtained for the homogeneous RRT4 carbonate sample. The history matching of the equilibrium pressures and saturation profiles were also performed to determine the kr-curve of both phases [4].

With only equilibrium measurements, it is thus possible to determine both capillary pressure and relative permeability using the SDM technique.

HETEROGENEOUS APPROACH

In heterogeneous samples, the semi-dynamic method leads to capillary pressure curves which are different if they are determined by extrapolation of the saturation profiles or if they are calculated by the analytical method. Figures 4 and 5 show the examples of forced imbibition experiments performed in two heterogeneous carbonate samples (RRT1 and RRT2 plugs, properties given in Table 1). Due to the heterogeneity of the samples, the extrapolation of saturation profiles gives inlet saturation values different from the "average" analytical values. Which capillary pressure curve is the most representative of the studied sample, of the investigated rock type? To answer this question and to study the variability in Pc-curves due to local heterogeneity, a new "heterogeneous approach" is proposed. With this new interpretation of the semi-dynamic experiment, it is possible to evaluate the capillary pressure curve at each location where local saturation is measured. Such approach is often used in reservoir simulation.

Principle

The principle is based on the fact that the local variations of pressure field in an heterogeneous medium are much smaller than saturation variations (Guérillot *et al* [6], Egermann *et al* [7]). The pressure is a “long range” field that averages the local fluctuations.

- In a first step, the SDM Pc and krw curves are determined analytically at the inlet of the plug by the Ramakrisnan method [5], with equations 1 and 2.
- In a second step, the average pressure field is solved using the SDM Pc-curve and the SDM krw-curve. The simulation is performed with ATHOS, the in house IFP simulator.
- Then, in a last step, this average pressure field is combined with the local saturation profiles to determine the local capillary pressures and observe an eventual scattering of the Pc-data due to heterogeneity.

Example

This methodology was followed for the interpretation of the forced imbibition in the heterogeneous RRT1 sample:

1. Step 1: Pc and kr-data (Figure 6):

- Pc-curve: the forced imbibition Pc-curve was obtained with the SDM method (equation. 1).
- The krw-curve was determined with the SDM method (equation 2),
- The kro-curve can not be determined analytically (displaced phase). A Corey representation with a Corey exponent of 3 was adopted. With such a coefficient, the kinetics of the experiment is not reproduced but it has no influence on the equilibrium pressure profiles which are necessary for the heterogeneous approach.

Step 2. Pressure profiles (Figure 7)

With these Pc- and kr-curves, the pressure profiles were calculated at each step.

Step 3. Pc(Sw) data at several locations (Figure 8)

With the calculated pressure profiles and the measured saturation profiles all the Pc(Sw) data were determined. For each point of the sample where local saturation was measured, the capillary pressure at the equilibrium was estimated from the water pressure profile (oil pressure profile is uniform during the SDM forced imbibition). The different sets of Pc-curves obtained for the heterogeneous RRT1 plug with this approach are plotted in Figure 8. A large variability of the Pc-curve due to heterogeneity can be noticed.

This methodology allows thus to observe the influence of heterogeneity on the capillary pressure curve. For one sample of a considered rock type, the SDM experiment, performed at reservoir conditions, provides a full set of Pc-curves representative of the Pc-curve dispersion within a rock type, instead of a single curve derived from other existing methods.

APPLICATION WITHIN A SCAL STUDY

The semi-dynamic method was used within a general SCAL work program to determine representative Pc-curves of the different rock types of a carbonate reservoir, and to study the influence of heterogeneity on these Pc-curves.

Plug selection

It is well known that heterogeneities in core plugs generally disturb and influence fluid flow and consequently the measured petrophysical parameters like capillary pressure or relative permeability [7, 8, 9, 10]. This is particularly observed in the case of large scale heterogeneity like in fracture, laminae or cross bedding systems. In this study, such heterogeneities were discarded thanks to CT-scan observations. Six carbonate rock types with only small scale local heterogeneities were considered. The heterogeneity level and the absolute permeability value decrease with the rock type number. After analysis (CT-scan images, HPMI pore throat size distribution, NMR pore body size distribution, permeability, porosity, thin section), one plug per rock type was selected. The main properties of these samples are gathered in Table 1.

Table 1: Selected carbonate plugs

Plug Nb	**RRT**	**d (cm)**	**L (cm)**	**ϕ**	**Kw (mD)**	**Swi**
46	1	4.88	7.87	0.296	451	0.083
322	2	4.87	7.94	0.295	44.9	0.09
59	3	4.84	7.14	0.329	24.6	0.089
95	4	4.86	6.0	0.310	13.0	0.090
176	5	4.91	8.16	0.290	4.02	0.069
613	6	4.90	7.36	0.151	0.14	0.099

Procedure

For each plug the following procedure was adopted:

- Plug preparation: prior to the experiment, the plug was cleaned with the most efficient procedure and fully saturated with reservoir brine.

The irreducible water saturation was then set by the porous plate technique and the sample was aged during four weeks, at reservoir conditions, with live oil. No difference between the X-ray profiles measured before and after aging was observed.

- Pc-cycle: positive and negative imbibition displacements were then performed at reservoir conditions, followed by negative and positive drainage displacements. The applied flow rates were adjusted for each plug, according to permeability and length. For each injecting flow rate, the transient and stabilized pressures and saturation profiles (Nwo) were measured.

- Calibration profiles: at the end of the experiment, the sample was cleaned by miscible displacements (toluene, methanol…). The calibration profiles of the plug fully saturated with brine (Nw) and fully saturated with live oil (No), were then measured. Finally, the saturation profiles were calculated at each step with the profiles Nwo, Nw and No.
- Determination of the Pc-curves: the SDM experiments were then interpreted in terms of Pc-curves, and for the negative (forced) imbibition in terms of krw-curves.
- Heterogeneity study: for the forced imbibition experiments, the heterogeneous approach was applied and one set of representative Pc-curves was determined per plug and rock type.

Results

Figures 9 to 14 show the sets of Pc-curves obtained for each plug. For RRT1, RRT2 and RRT3, the set of representative Pc-curves is wide, due to the heterogeneity of the samples. For the plugs with a lower permeability (RRT4, RRT5 and RRT6), the Pc-points are close to the analytical Pc-curve. This confirms the homogeneity of these plugs that had been observed on CT-scan images.

For the RRT6 plug, it is to be noticed that all the local Pc-points are located in the high water saturation region. For this rock type a high entry pore pressure was measured. The observed plateau is mainly due to the homogeneity of the sample (like for the RRT5 case). Its permeability being very small, the pressure was very high at the minimum flow rate (Qw=1cc/hr) and, consequently, a saturation gap was observed between the Swi state (entry pressure) and the first step (Qw=1cc/hr). The given Pc-data on the plateau of the analytical curve (Swi<Sw<0.6) were derived from the HPMI Pc-curve performed on a end cut.

Comparison with centrifuge results

The previous results have shown one of the main advantages of the semi-dynamic Pc-measurements. The method allows to study the variability of Pc-curves with local heterogeneity, at reservoir conditions.

Parallel to these experiments, several centrifuge Pc-measurements were performed. For RRT1 and RRT5, sister plugs of the SDM plugs were used. Their properties are gathered in Table 2.

Table 2: Centrifuge plugs

Plug Nb	**RRT**	**d (cm)**	**L (cm)**	**ϕ**	**Kw (mD)**	**Swi**
409	1	3.9	5.56	0.298	1010	0.10
176b	5	3.96	7.21	0.290	3.7	0.08

The centrifuge experiments were interpreted with the Forbes method [12], based on a homogeneous model approach. For each RRT, one Pc-curve was determined at the entrance of the sample.

For the comparison with the reservoir condition SDM Pc-data, these centrifuge Pc-data were corrected by the Leverett J-function, that is by permeability, porosity and interfacial tension data. The comparison between both Pc-curves is presented in Figure 15 for the RRT1 plug, and in Figure 16 for the RRT5 sample. For both RRTs, the centrifuge Pc-curve is well in the area defined by the local SDM Pc-points. It is representative of the rock type and can be used for reservoir simulations, but with caution. Only the SDM method with the interpretation proposed here can give the upper and lower Pc-curve limits.

Pc-curves and Rock Types

Within the same SCAL study, waterflood experiments were performed at reservoir conditions, on composite samples from each rock type. The displacements were interpreted by history matching the oil production, the in-situ saturation profiles and the evolution of the differential pressure. ATHOS software was used for the simulations. For each rock type, the best capillary pressure was selected in the area delimited by the local SDM Pc-points (Figures 9 to 14). All the selected Pc-curves are gathered in Figure 17. They are plotted in adimensional form, using the J-function. There is a clear ordering as a function of the RRT number. The bending of the Pc-curves increases when the RRT number decreases (when K increases). It may be explained by the pore size distribution, which tends to be wider for the low RRT number. For the low permeability RRT6 sample, the end point is very different from the other RRTs but the bending is comparable to the bending of the RRT5 Pc-curve.

This trend with the RRT number has to be considered carefully as it is based on the assumption that the J function is applicable, which is not obvious for carbonates samples. Besides, the actual selected Pc-curves were representative of the investigated rock types and this SCAL study example shows how useful the SDM sets of Pc-curves are.

Influence on reservoir simulations

The subject reservoir of the above described SCAL study is a heterogeneous carbonate formation in a giant field, comprising a higher permeability upper zone and a lower permeability lower zone, with comparable initial oil in place. The reservoir is currently under peripheral water injection. Because of a high contrast in permeability, the injected water has advanced in the upper zone much faster, resulting in some watered out wells in this zone. The water movement in the lower zone is by water slumping from the upper zone, hence, significantly influenced by the capillary pressure characteristics of the formation and by gravity. Ignoring the capillary forces, and consequently the wettability of the reservoir, would lead to large uncertainties and to erroneous prediction in the field development. This is illustrated in the literature [13]. The inclusion of the measured representative capillary pressure data in the full field simulation model significantly enhances the representation of the water hold-up mechanism. Consequently, a better match between model and observed behavior could be obtained for water slumping and horizontal well performance, when compared to the results based on empirical correlations and non-representative capillary pressure data.

CONCLUSION

Within a general SCAL study, the semi-dynamic method was used to determine the most representative Pc-curves of six different rock types of a carbonate reservoir. The experiments, performed at reservoir conditions, led to an "average" Pc-curve per rock type. In addition, a new method was developed to propose, for each rock type, a set of representative Pc-curves. These Pc-curves were obtained for each location where local saturation was measured. For homogeneous samples, all these Pc-curves reduce down to almost one Pc-curve, while for heterogeneous samples, there is a scattering of the Pc-points.

This new interpretation method of the semi-dynamic experiments allows thus to study the influence of heterogeneity on Pc-curves and to estimate the variability of the Pc-curves within the investigated rock types. Use of representative Pc-data obtained with this methodology in reservoir simulations will improve the prediction of field performance.

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NOMENCLATURE

A	cross-section area of the sample
K	single-phase permeability
kr	relative permeability
L	length of the sample
N	X-ray profile (photons/s)
Pc	capillary pressure
Pi	inlet pressure
q	volume flow rate
S	saturation
<S>	average saturation
Swi	irreducible water saturation
ϕ	porosity
μ	viscosity
ΔP	differential pressure
indices o,w:	oil, water
indice i:	inlet

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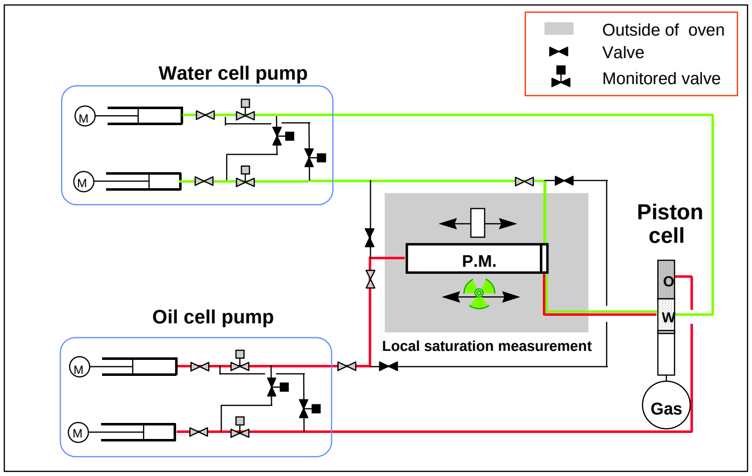

Figure 1: Principle of the semi-dynamic equipment

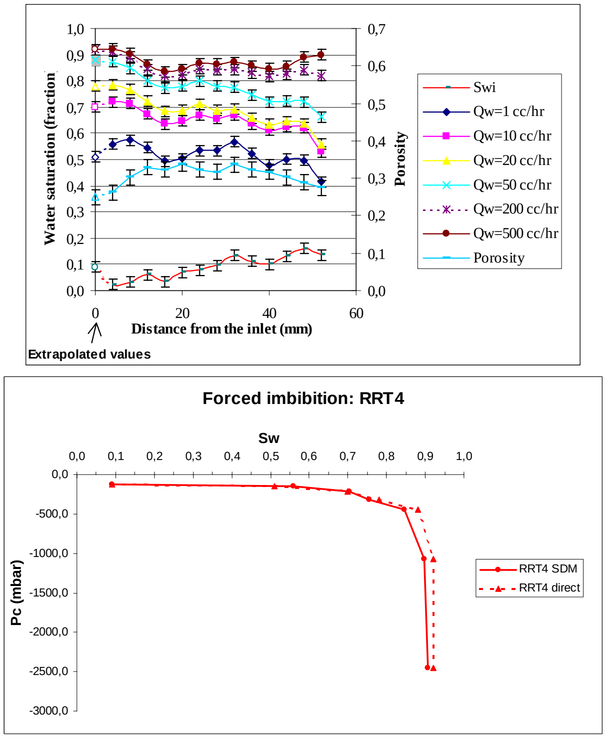

Figure 2: Forced imbibition in an homogeneous carbonate sample
Extrapolated (direct) and calculated (analytical) inlet saturation

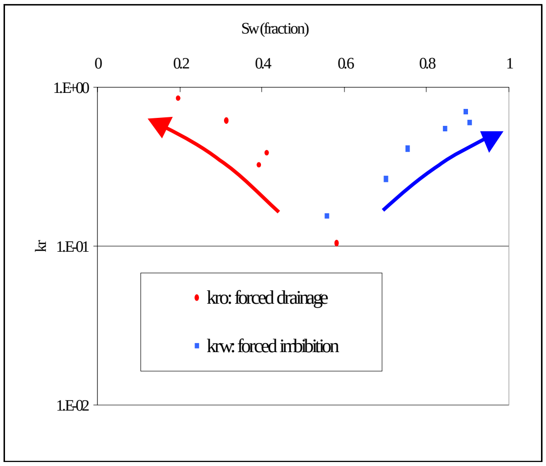

Figure 3: Analytical kr of the injecting phases - Homogeneous carbonate sample

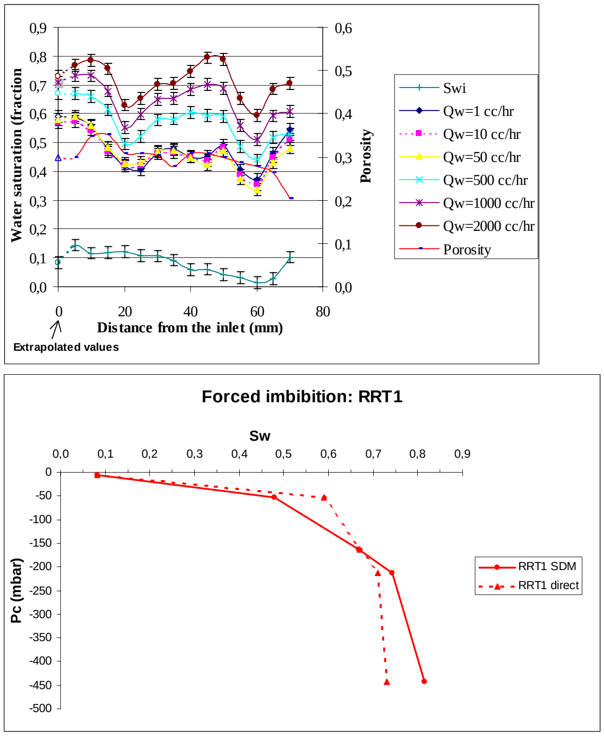

Figure 4: Forced imbibition in an heterogeneous carbonate sample - RRT1
Extrapolated (direct) and calculated (analytical) inlet saturation

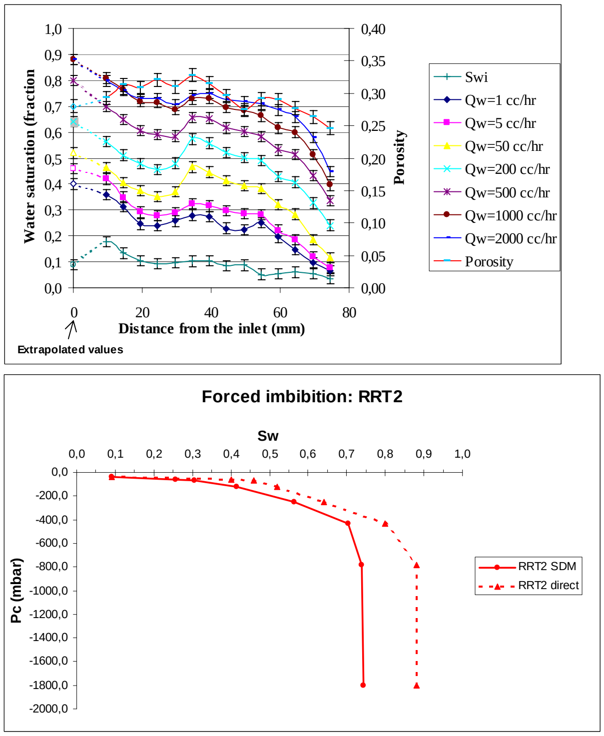

Figure 5: Forced imbibition in an heterogeneous carbonate sample - RRT2
Extrapolated (direct) and calculated (analytical) inlet saturation

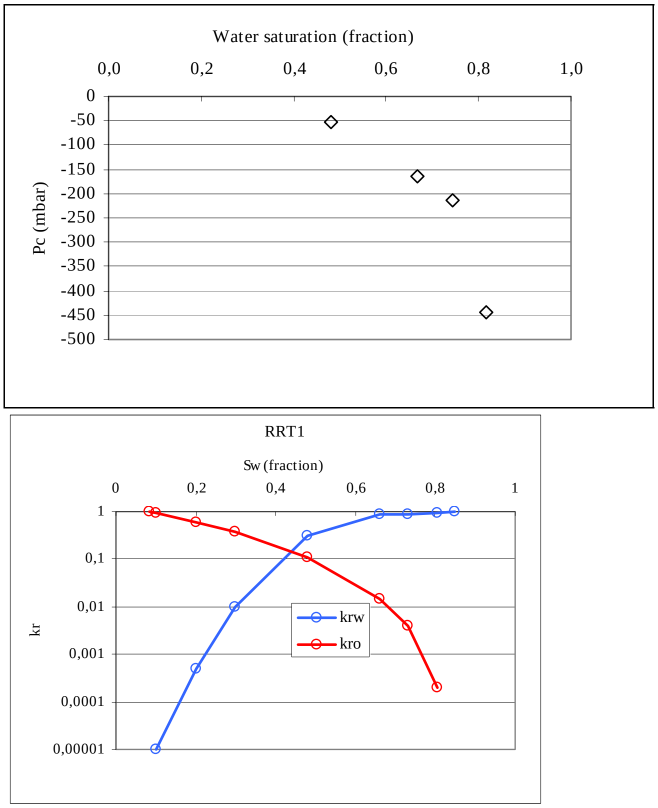

Figure 6: Step 1. Pc-SDM (equation 1) and krw-SDM (krw with equation 2, kro with Corey exponent of 3) - Forced imbibition in a RRT1 heterogeneous plug

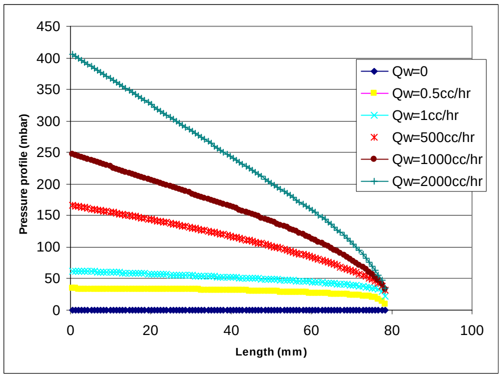

Figure 7: Step 2. Determination of the pressure profile (ATHOS) - Forced imbibition in a RRT1 heterogeneous plug

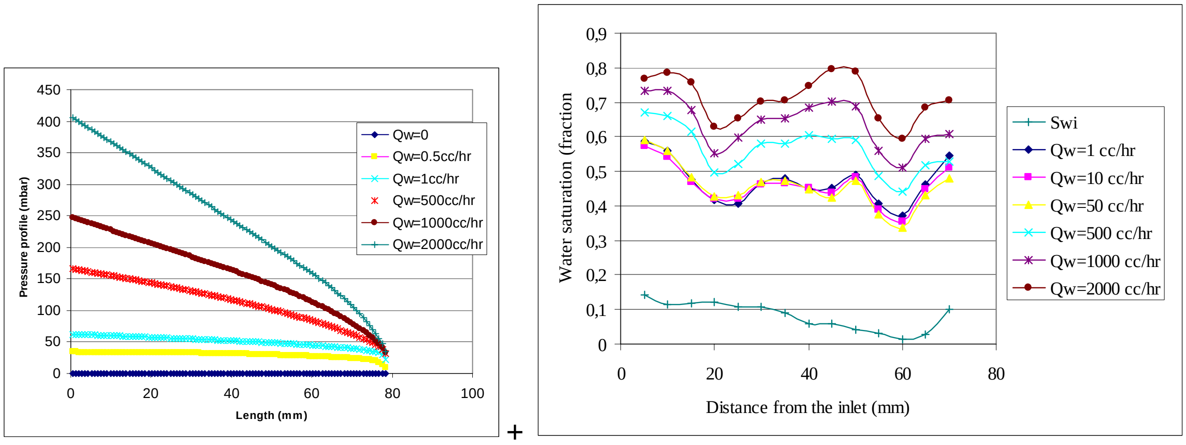

Figure 8a: Pressure profiles

Figure 8b: Saturation profiles

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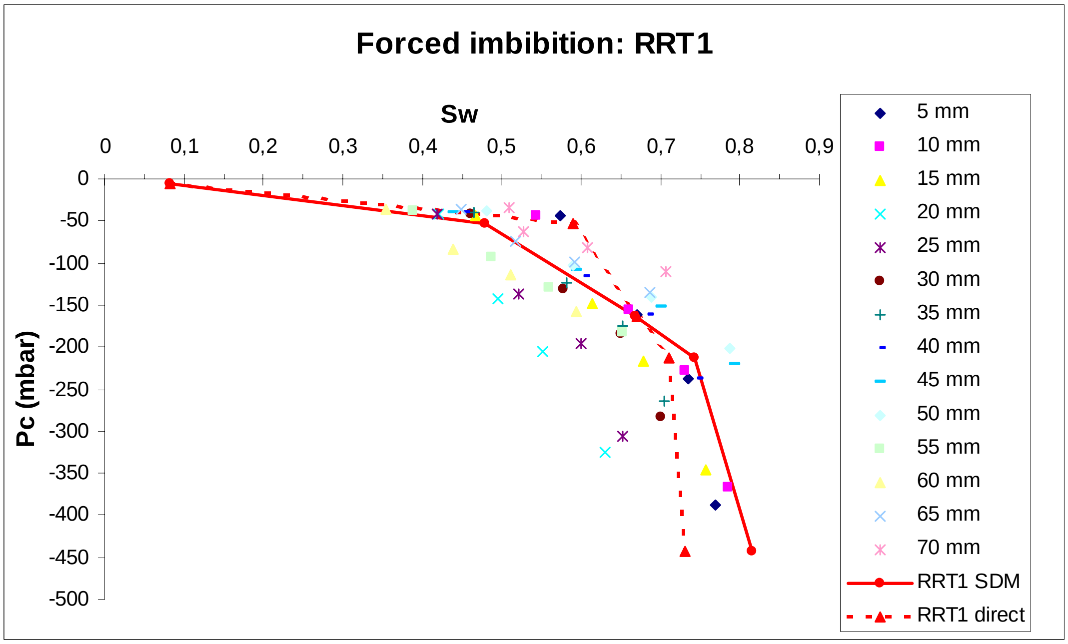

Figure 8c: Pc at different locations

Figure 8: Step 3. Determination of Pc(Sw) at each location where saturation is measured - Forced imbibition in a RRT1 heterogeneous plug

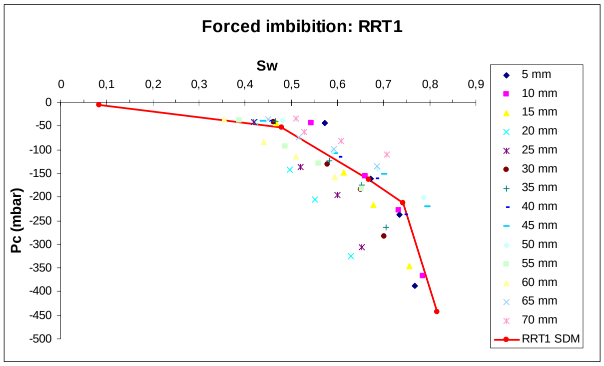

Figure 9: Forced imbibition Pc-curves - Heterogeneous RRT1 sample

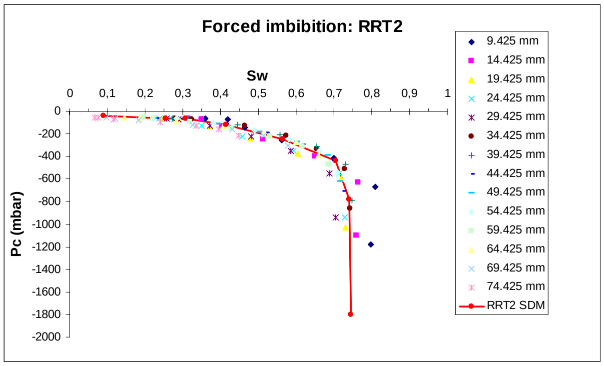

Figure 10: Forced imbibition Pc-curves - Heterogeneous RRT2 sample

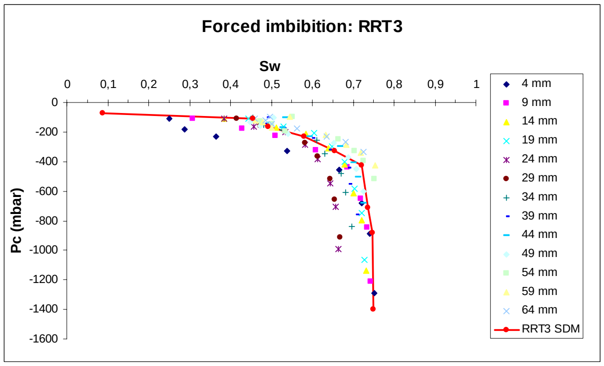

Figure 11: Forced imbibition Pc-curves - Heterogeneous RRT3 sample

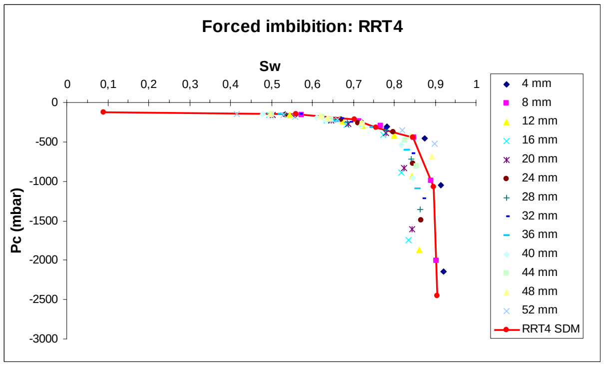

Figure 12: Forced imbibition Pc-curves - Homogeneous RRT4 sample

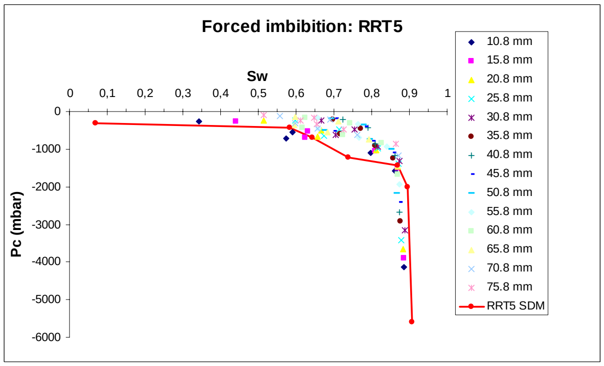

Figure 13: Forced imbibition Pc-curves - Homogeneous RRT5 sample

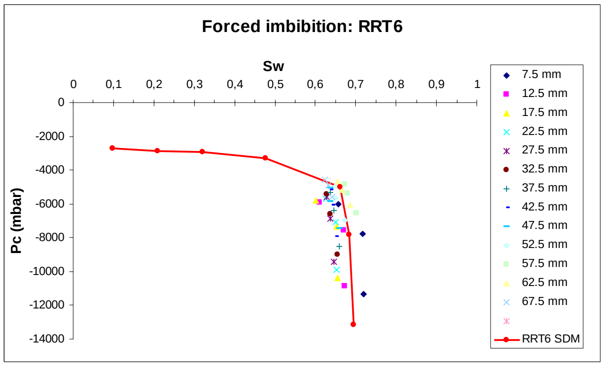

Figure 14: Forced imbibition Pc-curves - Homogeneous RRT6 sample

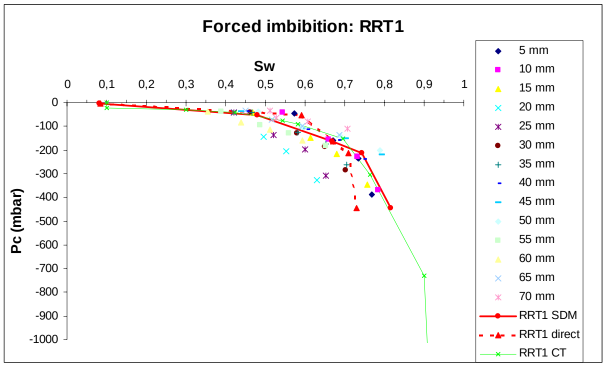

Figure 15: Heterogeneous RRT1 plugs - Centrifuge and SDM Pc-curves

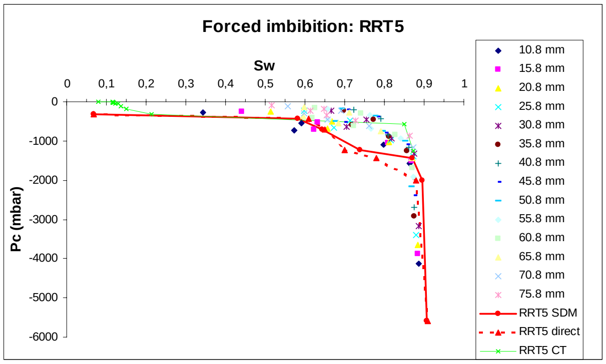

Figure 16: Homogeneous RRT5 plugs - Centrifuge and SDM Pc-curves

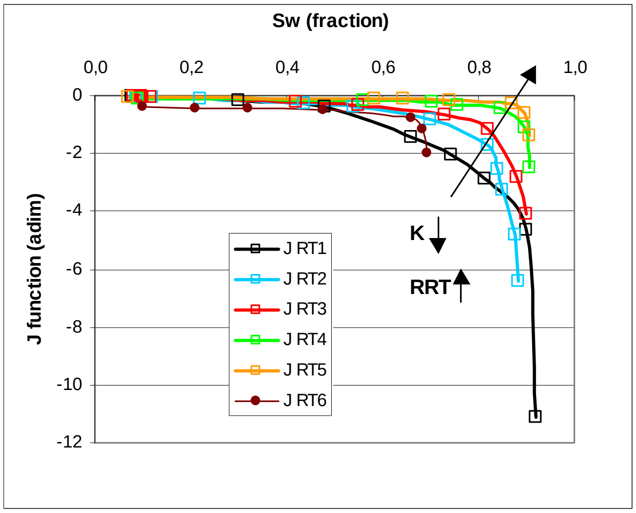

Figure 17: Representative Pc-curves used for the history matching of waterfloods