PETROPHYSICAL PARAMETER MEASUREMENTS: COMPARISON OF SEMI-DYNAMIC AND CENTRIFUGE METHODS FOR WATER-WET AND OIL-WET LIMESTONE SAMPLES

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ABSTRACT

Reservoir simulations require relative permeability and capillary pressure curves as representative as possible of the studied case, especially in terms of reservoir conditions. Several methods can be used to determine these parameters and each one has its own advantages but also its own limitations, whatever the experimental conditions, ambient or reservoir. Within a SCAL study, the selection of the most appropriate method is thus very difficult for the reservoir engineer.

The main objective of this paper is to compare two methods for capillary pressure measurement: the centrifuge technique, which is widely used under ambient conditions, and the semi-dynamic method (SDM), first presented in 1993, which can operate under reservoir conditions.

The principle of the experimental and interpretation methods is recalled in the first part of the paper (Forbes' interpretation method for the centrifuge technique and a recently patented interpretation method for the semi-dynamic technique that allows determining the impact of the small scale sample heterogeneity on the petrophysical parameters).

The second part is dedicated to the acquisition of experimental data. Although some results are available in the literature, the comparison is difficult since the experiments were performed on sister plugs and not exactly on the same sample. A new experimental data set was collected with the two methods, applied on the same sample, a homogeneous Lavoux limestone. In the first set of experiments, first drainage was performed with each method on the water-wet sample, at ambient conditions. Both methods lead to comparable results for this homogeneous sample. The sample was then rendered oil-wet and the forced imbibition was studied with both techniques. In that case, due to a non-uniform initial Swi-profile, the sample behaved as a heterogeneous one: the SDM and centrifuge Pc-curves derived from the homogeneous approach are not superimposed and the bandwidth delimited by the local SDM Pc-curves is wide.

The interpretation of this apparent disagreement is given in the third part of the paper, based on the numerical experiment of forced centrifuge imbibition on the La6 sample at non-uniform Swi conditions. The "homogeneous" interpretation of this numerical forced imbibition provides a Pc-curve very close to the Pc-curve derived from the real centrifuge experiment. This demonstrates the importance of the sub-plug size heterogeneities in the determination of the Pc-curve with the centrifuge method, while its interpretation is based

on strong homogeneity assumptions. When these assumptions hold, centrifuge and SDM Pc-curves are in good agreement. However for heterogeneous samples, if centrifuge experiments can be performed on a large number of samples for screening purposes, only the semi-dynamic method and the heterogeneous approach can provide a variability interval of capillary pressure for one sample and at reservoir conditions.

INTRODUCTION

Rock typing and reservoir simulations require relative permeability and capillary pressure curves as representative as possible of the studied case, especially in terms of reservoir conditions [1, 2]. Several methods can be applied to determine these parameters and each one has its own advantages but also its own limitations, whatever the experimental conditions, ambient or reservoir. Within a SCAL study, the selection of the most appropriate method is thus very difficult for the reservoir engineer. This is particularly noticeable for heterogeneous rocks [3, 4, 5 and 6].

One of the most commonly used techniques to determine capillary pressure curves is the centrifuge method [7, 8, 9 and 10]. This method, which allows measuring quickly forced imbibition and drainage Pc-curves, is nevertheless generally applied at ambient conditions and is based on a homogeneous interpretation [10]. The validity of the results obtained on samples which present heterogeneities in terms of structure and wettability is often discussed [6]. The objective of the paper is to compare this technique to the semi-dynamic method (SDM), which can operate at reservoir conditions and which can tackle heterogeneity issues [6, 11, 12, 13 and 14]. Such a comparison was already tempted [6], but the capillary pressure was measured with the two techniques on sister plugs and the conclusion was not obvious. As main observation, the centrifuge Pc-curves were found to be located within the set of SDM local Pc-curves, for homogeneous and heterogeneous rock samples. In order to get a definitive answer, it was thus decided to acquire a new experimental data set with centrifuge and SDM techniques applied on exactly the same sample.

The principle of the two techniques is recalled in the first part of the paper. The second part is dedicated to the experiments performed on the selected Lavoux limestone sample: first drainage on a homogeneous water-wet and forced imbibition performed on the same sample rendered oil-wet. The results obtained with both techniques are presented and discussed. Finally, a simulation work is detailed, which is useful to better understand the information provided by both methods.

PRINCIPLE OF THE METHODS

Table 1gathers the main characteristics of centrifuge and SDM methods. Their principle is summarized here below.

Centrifuge Method

The classical centrifuge technique was first introduced by Hassler and Brunner in 1945 [7]. The principle is based on the rotation of a core at various angular velocities. The studied core is saturated with the two fluids for which the capillary pressure has to be determined. For each velocity, at the equilibrium, the average production is measured. The capillary pressure curve can then be deduced from these experimental data if the related inversion integral problem can be solved. From experimental and interpretation points of views, many advances have been made during the past decades. Sophisticated devices allow now the automatic measurement of production [see for example 8]. Models exist in the literature to extrapolate the production at infinite time [9] and the interpretation of the data in term of Pc-curves is generally done using Forbes' method [10].

SDM Method

The principle is based on the balance between the capillary pressure and the viscous pressure drop. Details can be found in the literature [6, 11, 12, 13 and 14]. The sample is set in a core holder, without any semi-permeable membrane. During an experiment, one fluid is injected at a given flow rate through the sample, while the second one circulates on the outlet face of the core. For each equilibrium, i.e. flow rate, the saturation and the capillary pressure are measured at the entrance of the sample.

Saturation at the inlet of the sample [15]:
When local saturations are measured, the Pc-curve can be obtained directly with the collected data: the saturation is determined by extrapolation of the measured saturation profiles at the inlet of the sample. If not, the inlet saturation has to be calculated analytically from the average saturation <S> with equation 1:

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

For homogeneous samples, extrapolated and analytical saturations are identical but they can differ in heterogeneous cases [6].

Relative permeability [13]:
The relative permeability of the injected fluid is given at the inlet of the sample by equation 2

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

The relative permeability of both fluids can be also determined by history matching the SDM experiment [6, 14, 16 and 17]. With only equilibrium measurements, it is thus possible to determine both capillary pressure and relative permeability using the SDM technique.

Heterogeneous approach:

When local saturation measurements are available, a new interpretation of the semi-dynamic experiment can be used to study the influence of heterogeneity on Pc-curves. It allows evaluating the capillary pressure curve at each location where local saturation is measured [6, 16 and 17].

The principle is based on the fact that the local variations of pressure field in an heterogeneous medium are much smaller than saturation variations [18].

- In a first step, the SDM Pc and krw curves are determined at the inlet of the plug 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 the in house IFP simulator FIRST^{RS}.
- 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.

The first application of this method on carbonate samples is presented in reference [6]. This method was also extended to the study of the variability of kr-curves with heterogeneity [17]. In the next session, Figures 4 to 7 show the application of this method for the first drainage of a Lavoux limestone.

EXPERIMENTS AND RESULTS

Operating Conditions

Porous medium: La6

The whole study was conducted on a Lavoux limestone sample (98% of calcite; d=3.8cm, L=6.0cm, ϕ=0.25, Kw=4.9mD). NMR analyses and mercury injection (Figure 1) show that such a rock is homogeneous from a petrophysical point of view. The shape of the mercury capillary pressure curve is simple and classical, indicating a homogeneous throat size distribution. The estimated average pore throat radius is about 1 micron. The homogeneity of this sample is also observed on the NMR T2 distribution (related to the pore body size distribution) which is also classical, with a T2 mean value of 62ms. The CT scan analyses of the studied sample La6 (Figure 2) confirm its homogeneity.

Fluids:

The experiments were performed at ambient conditions (22°C) with a 20g/l NaCl brine doped with KI (μ_w=0.97cP, ρ_w=1.04g/cm^3) and with dodecane (μ_o=1.44cP, ρ_o=0.75g/cm^3). Dead oil was used for the aging of the sample.

Devices:

A modified Jouan KR 4-22 centrifuge was used for both drainage and imbibition. The SDM experiments were performed under CT-scan to acquire local saturation data.

First Drainage of the Water-wet La6 Sample

The first experimental data set was acquired on the cleaned water-wet La6 sample. The first water/oil drainage of La6 was performed first by centrifuge, and then, after cleaning and re-saturation, by the SDM method (Table 2).

Figure 3 shows the Pc-curves obtained with the two techniques. For the SDM method, the extrapolation of the equilibrium saturation profiles at the entrance of the samples leads to results (notation "Pc SDM extrapolation" in the Figures) comparable to the results calculated analytically (notation "Pc SDM analytical" in the Figures), as expected for a homogeneous uniformly water-wet sample. Furthermore, these two SDM curves are very similar to the centrifuge Pc-curve. For homogeneous samples there is no theoretical reason that the two methods lead to different results. The measured Pc-curves are also comparable to the Pc-curves derived from the mercury Pc-curves of an end-cut (La6) and of a sister plug (La5) of the studied La6 sample (Figure 3).
The heterogeneous approach was applied for the SDM experiment (oil injection):
Figure 4 shows the Pc and kr-curves used for the simulation of the first drainage.
The equilibrium pressure profiles calculated for each flow rate are given in Figure 5.
From these calculated pressure profiles and from the measured equilibrium saturation profiles (Figure 6), a capillary pressure curve was determined at each location along the sample where saturation had been measured.
The full set of Pc-curves is presented in Figure 7. The bandwidth defined by the local Pc-curves is very narrow and includes both the initial SDM and centrifuge curves. This result confirms that both methods lead to comparable results in the case of homogeneous, uniformly water-wet samples. This has to be checked for heterogeneous samples.
Remark: the area located below the first drainage Pc-curves is large. This shows the water-wet character of the investigated sample. The spontaneous imbibition of brine (SDM experiment) observed after the first drainage, and the sharp shape of the forced imbibition curve confirm this behaviour (Figure 8).

Forced Imbibition of the Oil-wet La6 Sample

The objective of the second set of experiments was to compare the methods for the forced imbibition of an oil-wet sample. The same plug La6 was used for both SDM and centrifuge experiments (Table 2). Prior to each experiment the sample was cleaned, set to Swi by centrifuge (Swi=0.18 - Ko(Swi)=4.4mD) and aged at 80°C in dead oil during four weeks. The sample was then flooded by cyclohexane to prevent any asphaltene deposit, and finally by dodecane.
The Pc-curves determined on this oil-wet sample are presented in Figure 9. The agreement between the two methods is not as good as in the drainage case. Furthermore, the SDM extrapolation and analytic results are not superimposed. This sample behavior is representative of a heterogeneous one [6] and for such a sample, the Pc-curves provided by the SDM and centrifuge methods are different. The slight heterogeneity observed on the porosity profile at the outlet of the porous medium and, more probably, the non-uniform initial saturation profile (end effects due to the centrifuge Swi-setting) are at the origin of this phenomenon (Figure 10). Due to this non-uniform Swi profile, the wettability of the sample was not restored uniformly. At the outlet of the sample, the initial water saturation being higher, the oil wetness was less pronounced than at the inlet.
During the SDM imbibition experiment, the shape of the measured equilibrium profiles (Figure 11) tends to follow the Swi-profile one at low flow rates and becomes more

uniform at high flow rates. The application of the heterogeneous approach for this experiment leads to the set of Pc-curves plotted in Figure 12. As for heterogeneous samples [6], the bandwidth delimited by these local curves is wide compared to the corresponding curves for drainage (Figure 7). The initial conditions have thus led to a non uniform wettability sample that behaves like a heterogeneous plug.
The centrifuge and SDM experiments provide different information on the imbibition Pc-curves. Whereas the SDM method allows investigating the influence of heterogeneity, including in the present case the non uniform wettability, on Pc-data, the centrifuge technique leads to a single curve on the assumption of general homogeneity. To know if such a curve is representative of the heterogeneous sample the following centrifuge experiment simulation was considered.

SIMULATION - DISCUSSION

The “heterogeneous” sample La6 was considered as 5 homogeneous plugs set in series, each plug having its own Swi-value and its own Pc-curve (Figure 13). The Swi-value assigned to each region of the sample is the average value measured by CT-scan after the centrifuge Swi-setting. The Pc-curve assigned to each part of the sample corresponds to the local SDM Pc-curve determined by the heterogeneous approach in the middle of the considered region (Figure 14).
The centrifuge imbibition experiment was then simulated with these parameters and with Corey-type kr-curves (Corey exponents for oil and brine equal to 2). Figure 15 shows the calculated oil production for each velocity. As these Corey type kr-curves used for the simulation are not representative in terms of wettability, the kinetics of the imbibition can not be investigated. Only equilibrium production data are thus considered. These equilibrium production data represent the equilibrium production data obtained during the theoretical centrifuge imbibition of the “heterogeneous” (or non-uniformly oil-wet) La6 sample. Considering this numerical centrifuge experiment and the corresponding calculated production, Forbes’ method was used to deduce the “equivalent homogeneous” centrifuge Pc-curve (Figure 16). This equivalent Pc-curve (black bold line) obtained considering the sample homogeneous is different from all the regional Pc-curves. Figure 17 shows that this equivalent curve (bold line) is very close to the experimentally obtained centrifuge Pc-curve (triangles). The measured centrifuge Pc-curve is thus consistent and represents well the "heterogeneous" La6 plug.
A sensitivity study should be performed on the number of homogeneous plugs to be set in series to represent La6 sample, but it is expected that increasing this number would lead to a final calculated centrifuge Pc-curve closer and closer to the experimental one.
Regarding theses results, for heterogeneous samples, the homogeneous interpretation of a centrifuge experiment (and also of a SDM displacement) provides an average Pc-curve which is not always in the range of the local Pc-curves. The centrifuge technique, which is sensitive to heterogeneity [19], could be used to study the variability of Pc-curves with heterogeneity, but only qualitatively due to the homogeneity hypothesis of the interpretation, and it would require a screening on a large number of samples. The SDM method, applied with local saturation (or pressure) measurements, presents the advantage

to provide a full set of representative local Pc-curves, for one sample. This method is time consuming compared to a centrifuge experiment but gives highly detailed and useful information on heterogeneous samples and can be operated at reservoir conditions.

CONCLUSIONS

Centrifuge technique and SDM method present their own advantages and limitations. For homogeneous samples (structure and wettability) both methods lead to the same results. This was observed in the case of a first drainage performed at ambient conditions on a Lavoux limestone. The local SDM Pc-curves obtained by the heterogeneous approach delimit a very narrow bandwidth, as already observed in the literature for such a sample. The SDM and centrifuge Pc-curves derived from the homogeneous interpretation are located in this bandwidth. In the case of a homogeneous sample, if no wettability issue has to be considered (reservoir conditions not necessary), the centrifuge method which is less time consuming than the SDM method can be used.

However generally, the studied samples present local heterogeneities. These heterogeneities can be structural (carbonate case for instance) or can come from a non-uniform wettability. In the case investigated in this paper the imbibition was performed on a homogeneous sample which wettability was not uniform due to a non-uniform initial Swi-profile. This sample behaved as a heterogeneous one. The centrifuge Pc-curve (Forbes' method) is different from the SDM Pc-curve (Ramakrishnan method) and both are different from the local SDM Pc-curves derived from the heterogeneous approach. A theoretical centrifuge imbibition of the La6 sample (with an initial non uniform Swi-profile and with local Pc-curves) was simulated. The homogeneous interpretation of this theoretical experiment led to a Pc-curve close to the experimental one showing its representativity of the whole sample. Nevertheless, if this Pc-curve is representative of the sample it can not reflect its heterogeneous character.

Therefore the centrifuge Pc-curve on a heterogeneous sample could not be extrapolated to other samples, even from the same rock-type. When sub-plug size heterogeneities exist it is recommended to use the centrifuge technique only for screening purposes on a large number of samples. Thus, the semi-dynamic method should be considered. Performed with local saturation measurements, this method with the appropriate interpretation provides a full set of representative Pc-curves for a given sample, at ambient or reservoir conditions (important for water/oil fluid systems). Wettability and heterogeneity effects can be thus investigated through this method.

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NOMENCLATURE

A	cross-section area of the sample
K	single-phase permeability
kr	relative permeability
L	length of the sample
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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Table 1: Centrifuge and SDM methods main characteristics (* standard equipment)

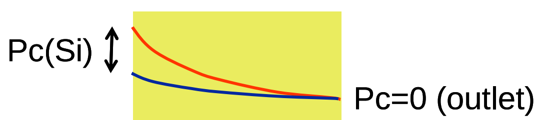
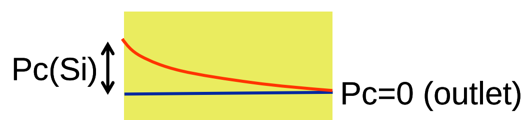
Centrifuge Method	**Semi-Dynamic Method**
Reduced temperature	Reservoir temperature
Ambient pore pressure	Reservoir pore pressure
No confining stress *	Reservoir confining stress
Fluids: brine, gas, dead oil	Reservoir fluids
No In-Situ Saturation Monitoring (no ISSM)	ISSM (X-ray device or CT-scanner)
Limited Pc	High Pc possible
Static measurement at equilibrium(both fluids at rest)	Semi-dynamic displacement (1 fluid is flowing)
Range of Pc based on density difference and body forces	Range of Pc based on K and on viscous forces
Pressure profile: 	Pressure profile: 
Disconnected phase can be produced	Representative trapping
No spontaneous imbibition *	Forced and spontaneous displacements
Homogeneous interpretation (Forbes' method)	Homogeneous interpretation (Ramakrishnan method)
No heterogeneity investigation	Heterogeneity investigation through ISSM (whole set of Pc-curves)
Fast	Time consuming (duration ~ L^2/K)
Standard	SCAL

Table 2: Rotation speeds and flow rates for centrifuge and SDM experiments

Centrifuge first drainage (r1=12cm - r2=18cm)															
Speed (tr/min)	800	1050	1100	1200	1320	1450	1600	1750	1940	2130	2370	2800	3400	4100	4900
Centrifuge forced imbibition (r1=19cm - r2=25cm)															
Speed (tr/min)	800	1000	1100	1280	1490	2790	3639	5042							
SDM first drainage - Oil flow rate qo (cc/hr)						2	5	10	50	75	100	150	185		
SDM forced imbibition - Water flow rate qw (cc/hr)						1	2	5	10	25	50	100	200		

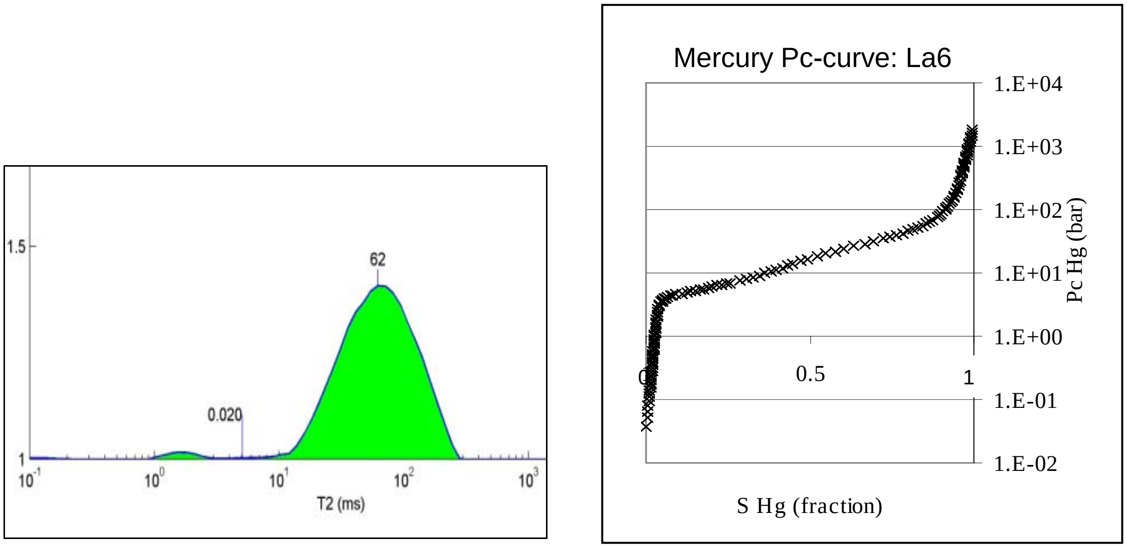


Figure 1. NMR T2 distribution and mercury Pc-curve of La6 plug

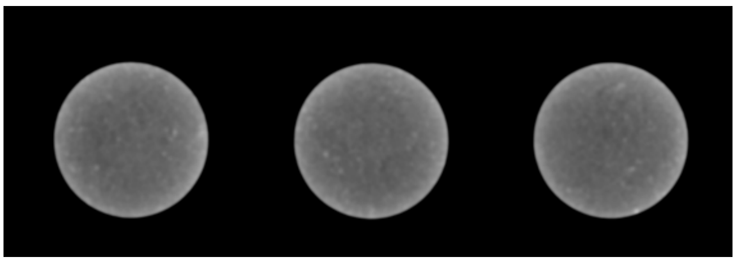


Figure 2. CT-scan cross sections of La6 plug

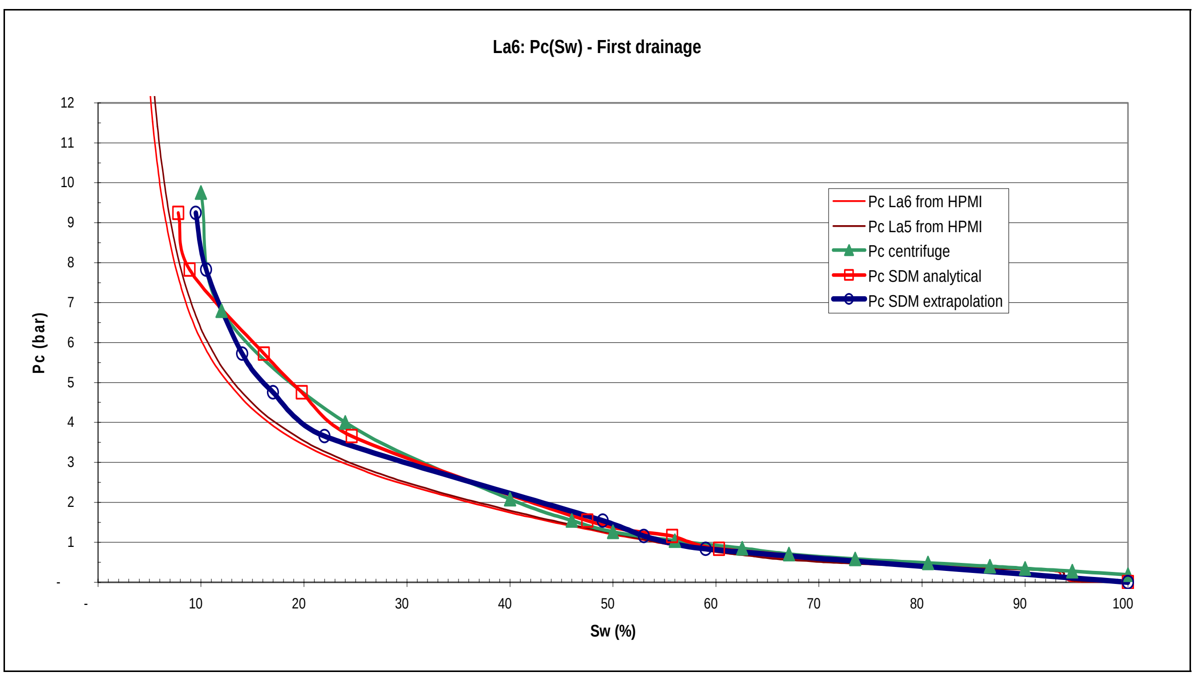


Figure 3. Pc-curves determined by HPMI, centrifuge and SDM methods – La6 first drainage (triangles for centrifuge, squares and circles for SDM, lines for HPMI)

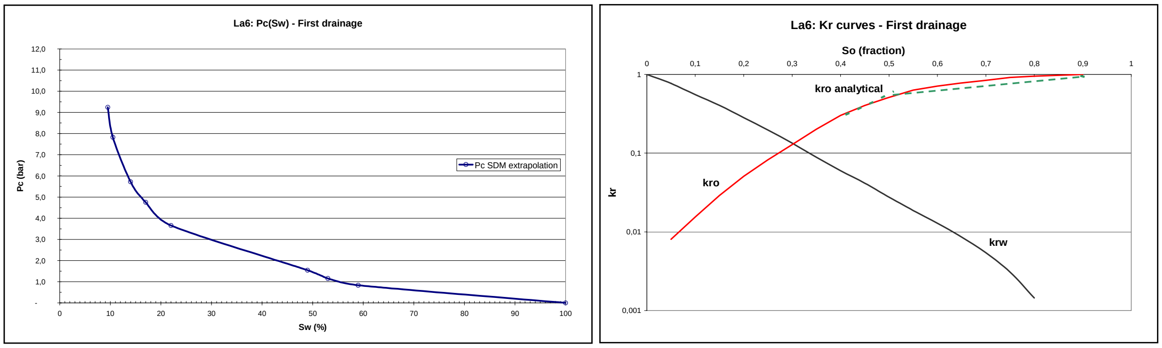


Figure 4. Pc and Kr-curves used for the heterogeneous approach – La6 first drainage

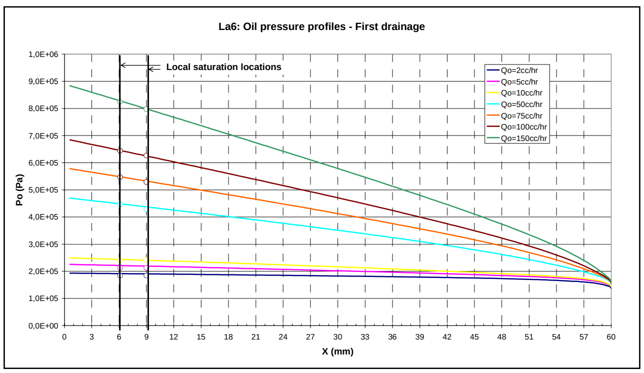


Figure 5. Calculated equilibrium pressure profiles – La6 first drainage

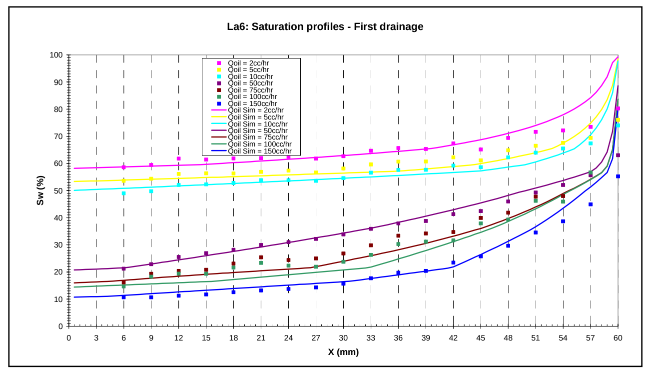


Figure 6. Measured equilibrium saturation profiles – La6 first drainage

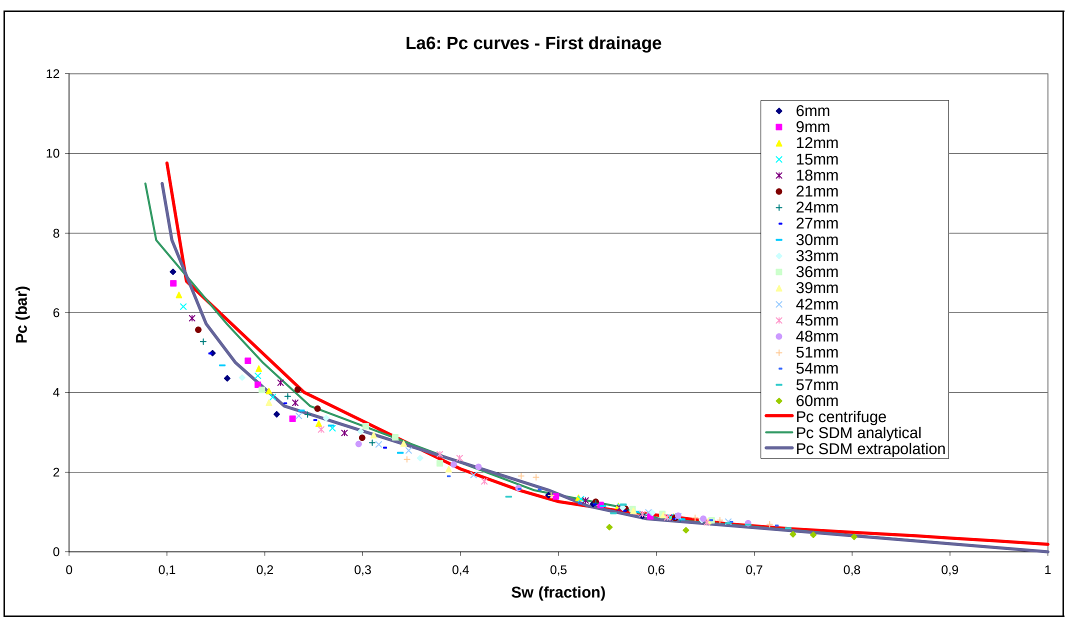


Figure 7. Local SDM Pc-curves – La6 first drainage

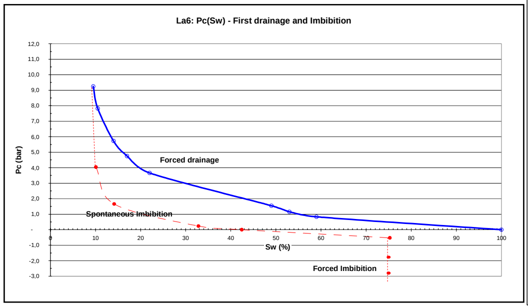


Figure 8. La 6 (WW) - First drainage and imbibition SDM Pc-curves

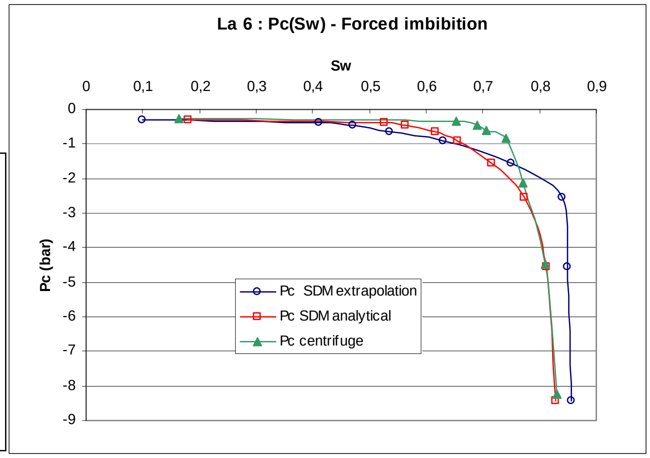


Figure 9. Pc-curves determined by centrifuge and SDM methods – La6 (OW) imbibition

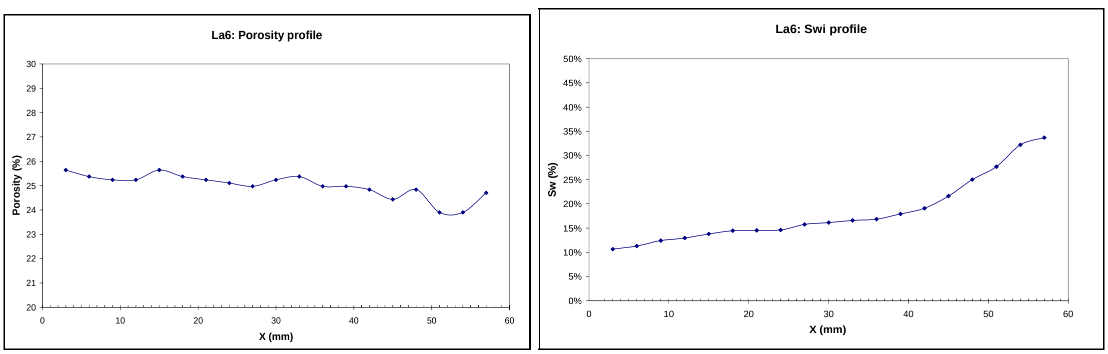


Figure 10. La6 porosity and Swi profiles

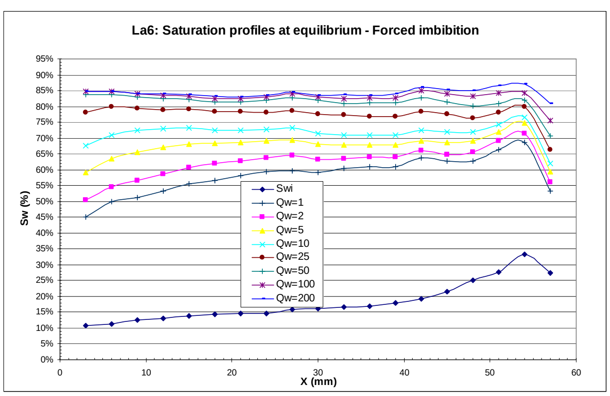


Figure 11. Equilibrium saturation profiles – La6 imbibition

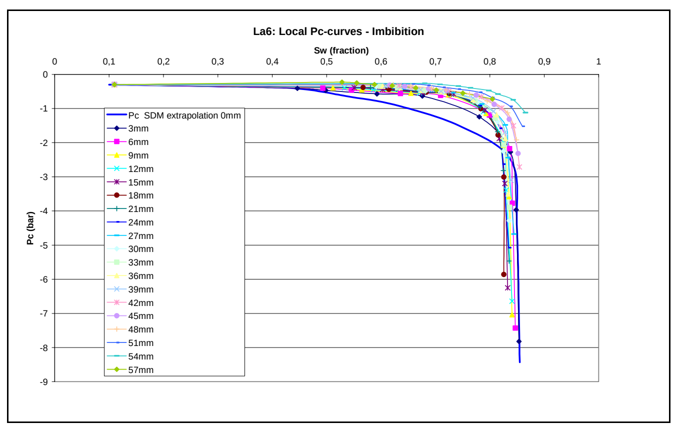


Figure 12. Local SDM Pc-curves – La6 imbibition

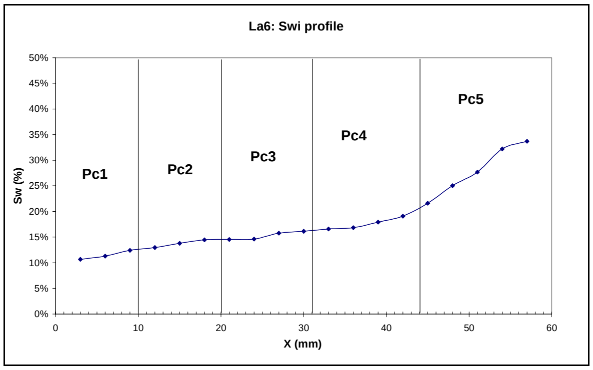


Figure 13. La6 Swi profile – Discretisation of La6 for the numerical centrifuge imbibition

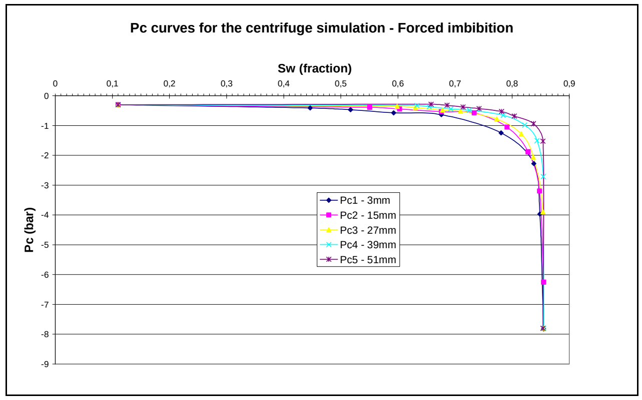


Figure 14. Selection of 5 Pc-curves for the La6 centrifuge numerical imbibition

Centrifuge radius	Velocity (tr/min)
r1=19cm	1000
r2=25cm	1100
	1280
	1490
	2790
	3639
	5042

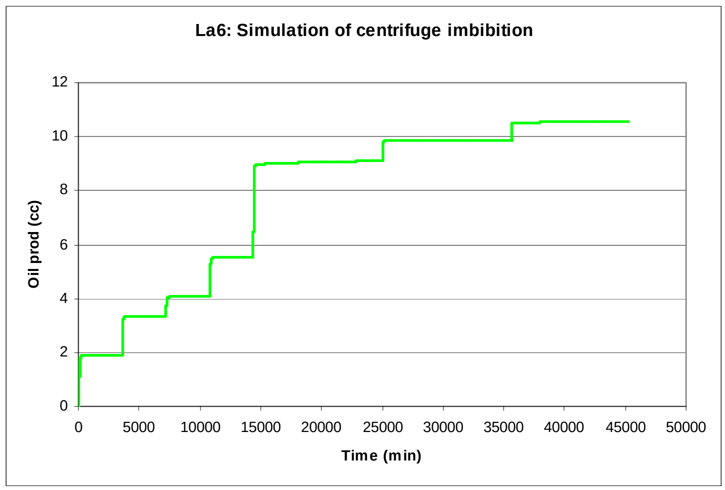


Figure 15. Simulation of La6 centrifuge imbibition - Oil production

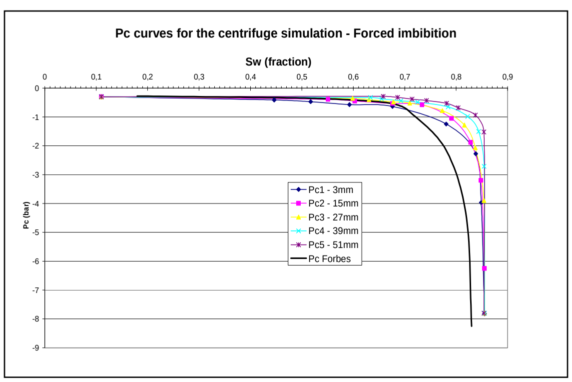


Figure 16. Simulated equivalent homogeneous centrifuge Pc-curve (Forbes) and selected local Pc-curves

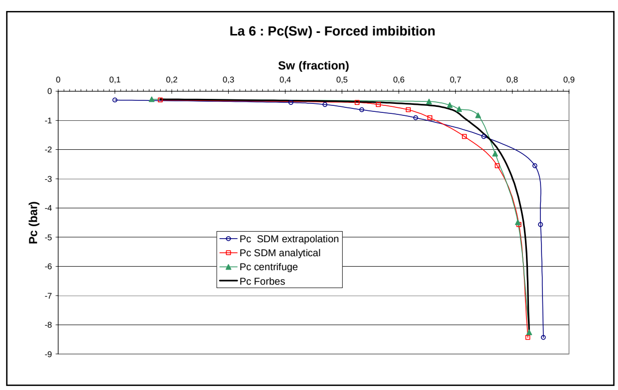


Figure 17. Simulated equivalent homogeneous centrifuge Pc-curve and experimental centrifuge and SDM Pc-curves