Radial effect and sample heterogeneity effect on centrifuge capillary pressure curves.

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Abstract

The purpose of this work is to highlight two important potential sources of errors in the centrifuge technique: i) the problem of neglecting the radial nature of the centrifugal field and ii) the problem of interpreting data from centimeter scale heterogeneous cores.

To demonstrate experimentally the radial effect and its correction, homogeneous sandstone and carbonate outcrop samples were centrifuged at a large and then at a small radius of rotation to generate low or high radial effect. Between large and small radius experiments, a shift as large as 10 saturation units was observed. When radial effects are accounted for in the interpretation technique, a unique centrifuge capillary pressure curve is found which is also in agreement with the curve obtained by porous plate measurements. The radial correction is simple to implement, can be performed independently of existing interpretation techniques and increases accuracy of capillary pressure functions from the centrifuge method. In particular for high speed centrifuges, the correction is necessary.

To study the effect of heterogeneity, two sandstone and carbonate outcrop samples were centrifuged with the most porous side either placed at the smallest or the largest radius of rotation, yielding two capillary pressure curves for each sample. Visual examination and porosity profiles of the samples indicate centimeter-scale heterogeneities. Depending on the orientation of the sample, significant saturation and pressure shifts were observed on the capillary pressure curves. The results indicate that:

(i) the effect of centimeter-scale heterogeneities can be similar to micron-scale heterogeneities ("double porosity"),

(ii) a unique curve consistent with the centrifuge measurements cannot be found in certain cases. In contrast to porous plate or mercury injection technique that are not sensitive to the orientation of the sample, the centrifuge technique can detect heterogeneous sample in terms of capillary pressure .

For reservoir samples suspected to be heterogeneous (porosity is not a good indicator of such heterogeneity), it is necessary to perform centrifuge experiments in both orientations. If only one experiment can be performed, the sample should be placed with the most porous face farthest from the centrifuge axis of rotation.

Introduction

A considerable amount of work has been devoted to the centrifuge technique, both on the experimental aspects and the data interpretation, providing a growing confidence in the centrifuge technique. However, an important aspect has so far been neglected: the centrifugal pressure field during the experiments has a radial symmetry and thus, the pressure gradient is not strictly parallel to the axis of the sample tested. Also, homogeneity is assumed in the calculation and it is not known if this assumption is critical and if strongly heterogeneous samples can be analysed using the centrifuge technique. The aim of this work is to provide experimental evidence of those two potential measurement artefacts.

The importance of the radial effect for certain geometries has been pointed out by several authors (Christiansen, 1992, Ayappa et al. 1994, Forbes et al., 1994a and b) but never demonstrated experimentally. The radial effect can be characterised by a single number N introduced by Christiansen (1992). When the radial effect correction is applied in addition to the usual data interpretation, the predicted saturation shift (to higher values) is of the order of N saturation units. Depending on the type of centrifuge and the size of the sample, N ranges from 0.06 to 0.02 (see section Data Interpretation) and thus, the correction can be significant. For the case of the data of Ajufo et al. (1993), which have been recently re-analysed (Forbes et al. 1994), an agreement has been found between the centrifuge and the porous plate methods when the radial effect is taken into account. However, discrepancies between the two methods should not be systematically interpreted as an evidence of radial effects. Furthermore, when the centrifuge data interpretation is properly performed, the "average" capillary pressure curve (inlet capillary pressure versus average saturation) is recalculated from the Pc curve and should fit the experimental data points. This test is necessary but the result can be wrong because radial effects are not included in the model.

The centrifuge technique is also sensitive to the orientation of the sample in the core holder when heterogeneous cores are considered. In principle, due to the non uniform pressure gradient, the same average saturation will not be reached at a given speed of rotation whether the most permeable or porous side of the sample is located the closest or the farthest from the axis of rotation. Thus, two centrifuge experiments with a different orientation performed on the same sample at the same average radius of rotation will yield different experimental data. Furthermore, it is not known if those data can in practice be interpreted using techniques that assume homogeneity.

Radial Effect Experiments

The radial effect can be demonstrated by performing centrifuge experiments on the same sample at different radii of rotation. These experiments were performed using a large radius low speed centrifuge. Core holders can handle samples of length and diameter of 7 and 4 cm respectively. The maximum radius of rotation is 15.9 cm and the maximum speed of rotation is 3500 rpm. Hence, using our equipment, the radial effect could be tested by using samples of small length (about 2 cm) and large diameter (4 cm), and located at radii of rotation varying from 7.55 up to 15.9 cm. The smallest of these values is representative of the geometry in Beckmann centrifuges commonly used for capillary pressure measurements. Production is read manually while spinning using a stroboscope with a precision of ±0.1 cc. Thus the error on the saturation is about ±1.5 % (pore volume of about 6 cc, table 1), which we consider as the maximum value admissible.

The outcrop samples used were a Vosges sandstone and a Estaillade limestone (table 1). Homogeneity was checked by measuring porosity profiles (CT scan). The two samples were first centrifuged under oil (drainage, experiment 1) at the smallest radius of rotation possible, i.e. the inlet face near the top of the core holder (table 1). Then, they were cleaned and re-saturated with brine. Finally, they were centrifuged a second time (experiment 2) under oil at the largest radius of rotation possible, i.e. the outlet face at the bottom of the core holder (table 1). The parameter N listed in table 1 ranges from 0.064 up to 0.114 and thus both experiments have theoretically a significant radial effect that should be corrected. For a given sample, N varies by a factor of two (table 1). The fluids used were brine (10 g/l NaCl, 1.005 g/l) and Soltrol 130 (0.750 g/l). Porous plate data using the same fluids are available for the sandstone sample S1.

Capillary equilibrium was checked by frequent readings of production. For experiment 2, the speed steps were increased in order to reach similar capillary pressure values as in experiment 1 (at higher radius). Also, for a given capillary pressure, the duration of the speed steps were kept identical between experiment 1 and 2.

Sample	S1	S2	S3	S4
Type	sandstone	limestone	sandstone	limestone
Porosity	23.0	30.2	20.2	12.9
Diameter (cm)	3.97	3.96	3.93	4.0
Length (cm)	2.02	2.07	4.0	4.0
R1 exp. 1 (cm)	7.55	7.55	Less porous face at 12.55	Less porous face at 14.6
R1 exp. 2 (cm)	13.79	13.83	Most porous face at 12.55	Most porous face at 14.6
N exp. 1	0.114	0.110	0.030	0.030
N exp. 2	0.066	0.064	0.030	0.030

Table 1: characteristics of the samples used in the radial effect experiments (exp. 1 and 2) and in the heterogeneity effect experiments. R1 is the radius of the face closest to the axis of rotation (Fig. 2) and N is a parameter characterising the radial effect. Porosity profiles for samples S3 and S4 are shown in Fig. 4.

Data interpretation

Experimental data (average saturation versus speed of rotation) were converted into capillary pressure curves using the method of Forbes (Forbes, 1991). The additional correction to account for radial effect was performed as a pre-process of the data, i.e. a new set of experimental values is calculated before computing the Pc curve. The procedures can be summarised as follows:

• *Non-Radial Procedure*

$$\{\overline{S}, \omega\} \dashrightarrow \{\overline{S}, Pc_l\} \Rightarrow \left\{ \begin{array}{l} \text{Non Radial Analysis} \\ \text{Technique (Forbes 1991)} \end{array} \right\} \Rightarrow (S, Pc)$$

• *Radial Procedure*

$$\{\overline{S}, \omega\} \dashrightarrow \{\overline{S}, Pc_l\} \dashrightarrow \{\overline{S}^\circ, \frac{Pc_l\,(1+N)}{b}\} \Rightarrow \left\{ \begin{array}{l} \text{Non Radial Analysis} \\ \text{Technique (Forbes 1991)} \end{array} \right\} \Rightarrow (S, Pc)$$

where

$$N = \frac{R^2}{R_3^2 - R_1^2}$$

$$\overline{S}^\circ = \overline{S} + a\,[\,\overline{S}(aPc_l) - \overline{S}\,]$$

$$a = 3/4\ \frac{1+\sqrt{1-B}}{2}\left(\frac{N}{1+N}\right)$$

$$b = 1 + 0.23\left(\frac{N}{1+N}\right)$$

$$Pc_l = \Delta\rho\,\omega^2(R_3^2 - R_1^2)/2$$

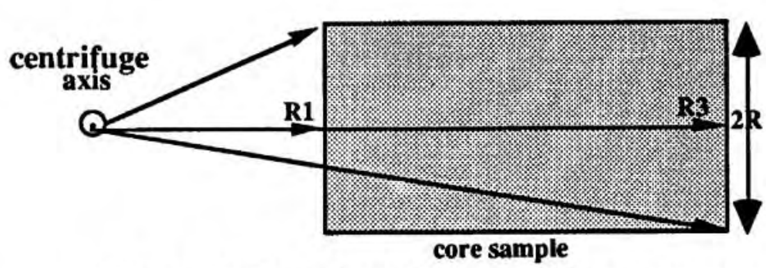

Figure 1 : Top view of the centrifuge geometry.

The mathematical derivation of the formulae above are described in Forbes et al. (1994b). An experimental data set $\{\overline{S}, Pc_l\}$ is thus shifted to higher saturation $\overline{S}^{\circ}$ and to higher pressure $Pc_l(1+N)/b$ when the radial correction is applied. When calculating $\overline{S}^{\circ}$, the value of $\overline{S}$ at the pressure aPc_l must be determined. This is done by interpolating the measured values $\{\overline{S}, Pc_l\}$ at the desired pressures (the parameter a is small and thus, $\overline{S}(aPc_l)$ are usually interpolated near the entry pressure).

When the radial correction is applied as a post-process, the radial correction can be applied to the calculated set (S, Pc). The saturation shift can be estimated roughly at moderate pressure (1 Bar) by taking $a \approx N$ and $S(aPc_l) = 1$. From the equations above, the saturation shift will be approximately N(1-S). N values for typical geometries vary from 0.02 to 0.053 (table 2). For low speed centrifuges, the radial correction is of the order of the interpretation errors. However, for high speed centrifuges, the radial correction becomes significant (table 2).

Centrifuge	High speed D = 2.5 cm	High speed D = 4 cm	Low speed D = 4 cm	Low speed D = 4 cm
R_1 , R_3 (cm)	5 , 7.5	5 , 10	10 , 15	15 , 20
N	0.050	0.053	0.032	0.023

Table 2: N values for typical centrifuge geometries. D is the diameter of the sample. N is approximately the saturation shift when the radial correction is taken into account.

To test the computed Pc curve, the $\{\overline{S}, Pc_l\}$ curve is always recalculated and compared to the experimental data points. If the shape of the Pc curve is not satisfactory according to the knowledge on the core, the solution can be modified (smoothed) manually. Also during that operation, the $\{\overline{S}, Pc_l\}$ curve is always recalculated to fit as closely as possible the experimental data points. Although these modifications are rather suggestive, the calculated Pc curves do not differ by more than 1 saturation unit when performed by different persons.

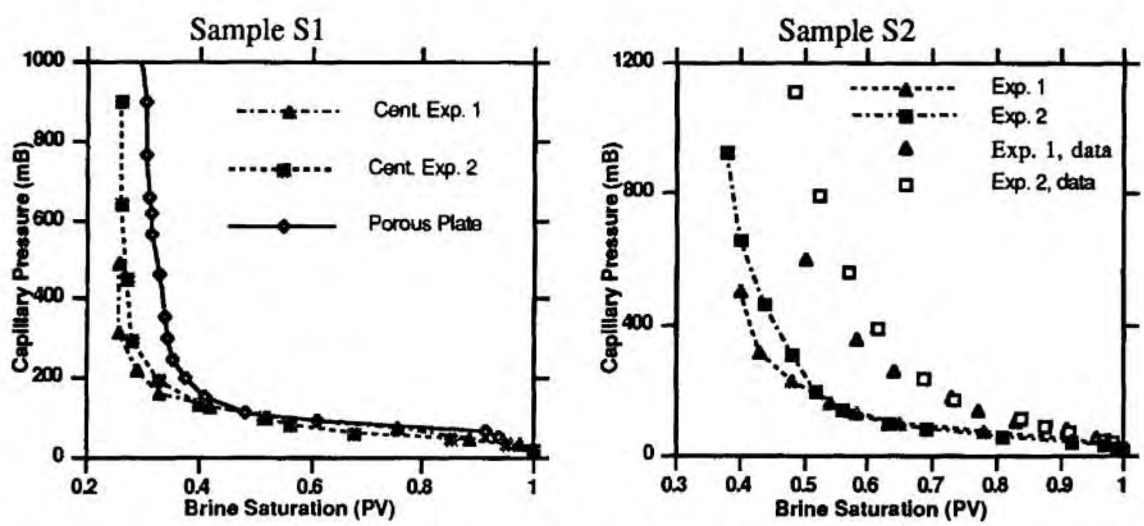

Figure 2: Calculated Pc curves **without correction** for radial effect. Exp. 1 and 2: centrifuge experiments at a small and large radius respectively (table 1). Left (sample S1): the two centrifuge experiments yield different Pc curves, both different from the Porous Plate curve. Right: different Pc curves are found as a result of different data $\{\overline{S}, Pc_l\}$.

Results: radial effect

The experimental data were first analysed without taking into account the radial effect. For the sandstone sample S1 (Fig. 2), 2 different capillary pressure curves are found and they are also both different from the curve obtained by the porous plate technique. Differences can mainly be observed near the irreducible water saturation and not in the high saturation range (Fig. 2). Relative to the porous plate curve, there is a shift to lower saturation and this shift is more important for the experiment in which the sample was at the smallest radius of rotation (experiment 1). At a pressure of about 460 mB, the saturations calculated from experiment 1 and 2 are respectively 0.255 and 0.270, whereas the porous plate measurement yields a saturation of 0.33. These differences are significant: when the production is recalculated, the average curve $\{\overline{S}, Pc_I\}$ obtained from experiment 1 does not fit the experimental data from experiment 2, and vice-versa.

For the limestone samples S2, similar results were found when the radial effect is not taken into account. The Pc curve calculated from the experiment in which the sample is at the smallest radius (N large) is always shifted to a lower saturation (Fig. 2). When the experimental data points are plotted (Fig. 2), average saturation versus capillary pressure at inlet face, significant differences can also be observed and thus it is obvious that a unique curve cannot be calculated from the data.

When the radial effect is taken into account, the calculated curves are shifted to higher saturation (Fig. 3). For the sandstone sample S1, this shift yields an agreement with the porous plate measurements near Swi. Near 500 mB, the correction yields a shift of 4 % for experiment 2 (from 0.27 to 0.31, N=0.066) and 6.5 % for experiment 1 (from 0.255 to 0.32, N=0.114). From both centrifuge experiments 1 and 2, a unique curve can be calculated, within experimental errors. In the saturation range [0.5 1], the observed discrepancies in pressure are due to experimental errors (they are also not of practical interest).

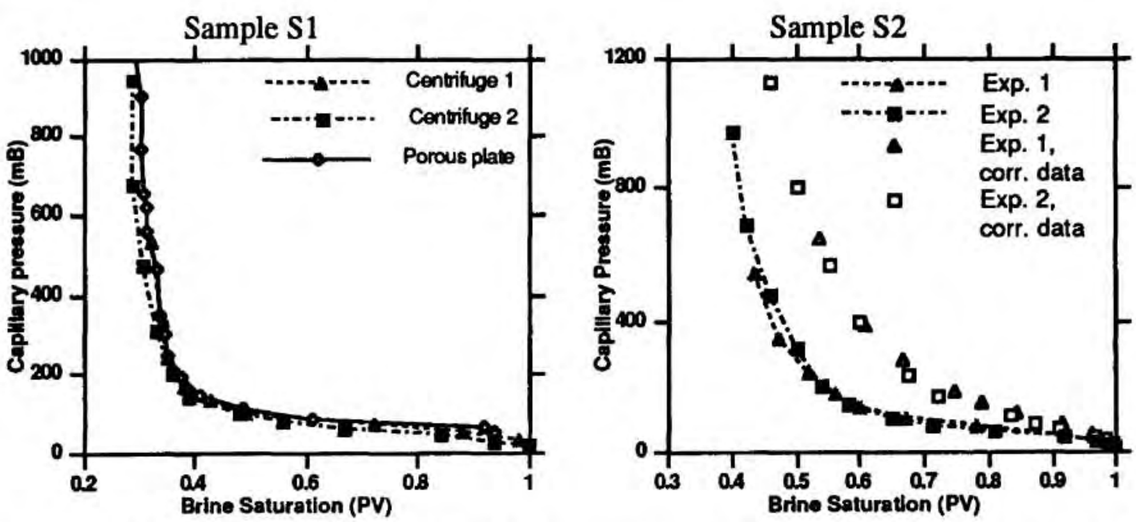

Figure 3: Calculated Pc curves **with correction** for radial effect. Exp. 1 and 2: centrifuge experiments at a small and large radius respectively (table 1). Left (sample S1): the two centrifuge experiments agree with the Porous Plate measurements. Right: the same Pc curves are found and the corrected experimental data are identical.

For the limestone sample S2, a unique Pc curve can also be calculated from both experiments (Fig. 3). When the experimental data are pre-processed, the data from both experiments 1 and 2 for each sample can be described by one experimental curve (Fig. 3) and thus, the resulting Pc curve is unique.

Heterogeneity Effect Experiments

Two samples were selected in which heterogeneities are described by visual examination and by CT scan. For the Fontainebleau sandstone S3, there is a variation of 8% in the porosity profile (fig. 4), with an average of 20.2%. This sample has also a large permeability (about 1000 mD). The smooth change in the porosity profile is due to the presence of a lamination tilted at about 45° from the axis of the sample (direction of acceleration). For the St Maximin limestone S4, porosity changes are more abrupt (fig. 4) but less important (3.5%). Permeability is of the order of 1 mD. In this case, the sample appears to be more or less composed of two parts; this case correspond to a lamination perpendicular to the axis of the sample. From other studies (mercury porosimetry and microscopic observations), we have identified double porosity with this type of limestone.

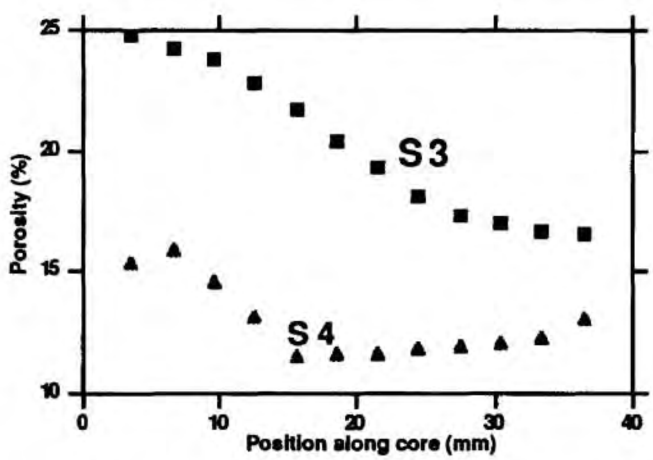

Figure 4: porosity profile for the Fontainebleau sandstone (S3) and the St Maximin limestone (S4) samples. S3 and S4 have a lamination nearly parallel and perpendicular to the centrifuge acceleration, respectively.

Two centrifuge drainage experiments were performed on each sample (without sleeves). In experiment 1, the less porous face was placed at the smallest radius of rotation and in experiment 2, the orientation of the sample is reversed after cleaning with the most porous face at the smallest radius of rotation (table 1). For the sample S3, an oil-brine drainage was performed (brine at 20g/l NaCl and dodecane) whereas for sample S4, an air-brine drainage was performed. The duration of the 12 speed steps is 4 hr on average and equilibrium is checked by frequent readings of production. An air-brine porous plate drainage experiment was also performed on S4.

Results: heterogeneity effect

For the Fontainebleau sandstone sample S3, only small differences were observed between the two centrifuge experiments in which the orientation of the sample was changed. When the most porous face is either placed at the largest or the smallest radius of rotation, the entry pressure (the minimum pressure at which a production is observed) did not vary significantly (about 10 mB), despite the large variation in porosity (fig. 4). This observation is consistent with the presence of a lamination in the sample nearly parallel to acceleration: porosity is different from one face to the other but large pores exist at both faces. For both experiments, the data have been analysed without difficulty (fig. 5): the experimental data can be fitted within ±0.7% PV, uncertainties that are within the experimental errors. When the capillary pressure curves from experiment 1 and 2 are compared (fig. 6), differences are close to the uncertainties due to the interpretation technique.

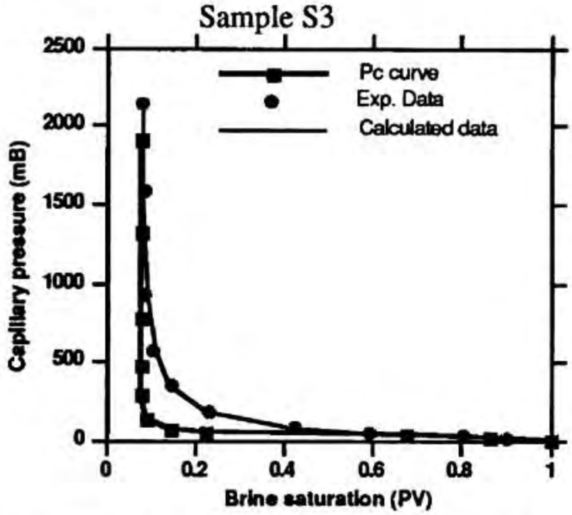

Figure 5: Calculated Pc curve for the Fontainebleau sandstone in experiment 1 (the most porous face at the largest radius of rotation).

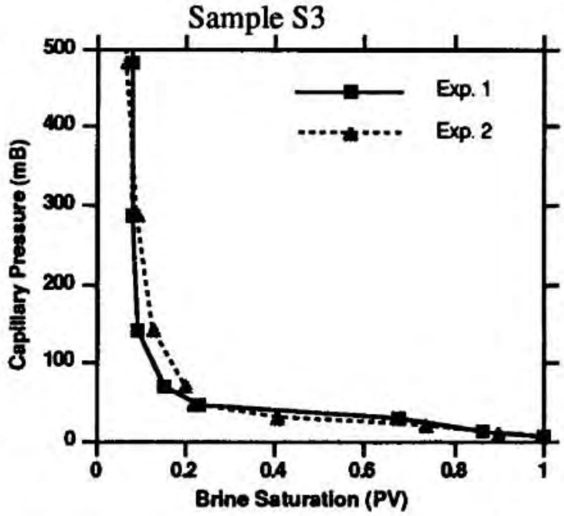

Figure 6: comparison between Pc curves from the experiment 1 and 2. Case of a lamination nearly parallel to acceleration.

For the St Maximin sample S4, we were also able to interpret the data as if the sample were homogeneous. A good fit can be obtained between experimental and recalculated data (fig. 7), indicating that the interpretation is consistent. The calculated capillary pressure curves present several "bumps" (fig. 7) that are not due to errors of measurements but necessary to reproduce the experimental data. The bump at about 5 Bar and 0.5 PV is due to the desaturation of the microporosity and was expected for this type of limestone. However, such features are not expected at high saturation and at least one bump is an artefact generated by the centrifuge technique as described below.

Strong differences were observed when centrifuging the sample in two different orientations (fig. 8). First, the estimated entry pressure varied from 100 mB to 250 mB (fig. 8) for experiment 1 and 2 respectively. For experiment 1, the less porous face was the closest to the axis of rotation where the pressure gradient is the largest. Second, there is an important saturation shift between the two curves. This is a direct consequence of the non uniform pressure gradient. Third, the bump at the highest saturation is attenuated for experiment 2 which is a strong indication of heterogeneity. The available porous plate measurements (fig. 8) are closer to the Pc curve from experiment 1 and do not show irregularities observed on centrifuge curve below 3 Bar.

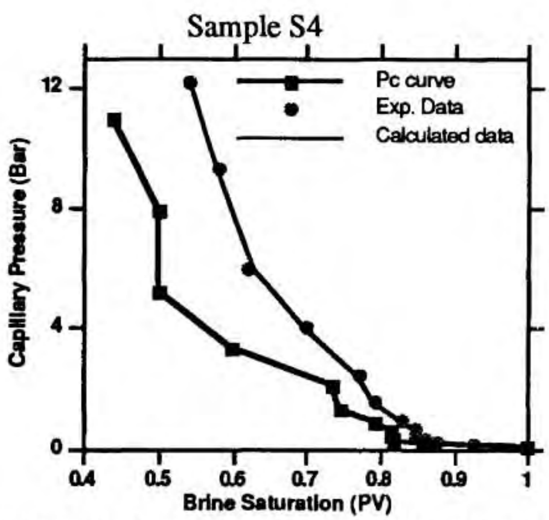

Figure 7: Calculated Pc curve for the St Maximin limestone in experiment 2 (the less porous face at the largest radius of rotation).

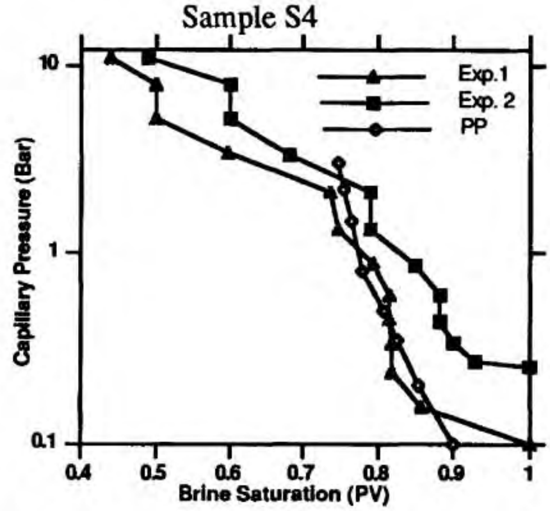

Figure 8: Pc curves (air-brine) from centrifuge experiment 1, 2 and porous plate (PP). Case of a lamination perpendicular to acceleration.

Interpretation of heterogeneity effect

Using simulated centrifuge data, we show in this section that the presence of bumps (e.g. fig. 7 and 8) on capillary pressure curves can be due to heterogeneity of the core and depends on its orientation during the experiment. The sample is assumed to be equally composed of two media having two different capillary pressure curves (fig. 9). This situation corresponds to a lamination perpendicular to acceleration. Note that the two media have the same irreducible water saturation and differ only by the entry pressure. To generate the centrifuge data, we took a typical sequence of 10 speed steps that would be realised experimentally to determine the Pc curve. For each speed of rotation, the saturation profile in the sample is calculated using the capillary pressure from figure 9 and L = 5 cm, R_1 = 10 cm, $\Delta\rho$ = 0.2. After averaging, we obtain a simulated data set $\{\overline{S}, Pc_i\}$ which was analysed using the technique of Forbes (1991). Two simulations were performed: in case 1, the medium 1 (first half of the sample) is located the closest to the axis of rotation followed by the medium 2 and in case 2, the orientation is reversed.

Depending on the orientation, the calculated Pc curves present a bump when the medium with the smallest entry pressure is located the closest to the axis of rotation (case 2, fig. 9). In case 1, the calculated Pc curve is closer to an "average" curve deduced from medium 1 and 2. The Swi value of 0.2 which is the same for both medium, is reached in case 1 and not in case 2 where the saturation is shifted to higher values. It is also interesting to note that the interpretation technique is able to reproduce properly the simulated experimental data (checking procedure described in the section Data Interpretation), in particular for case 2 (fig. 10). Errors induced by the interpretation technique and by the limited amount of information (10 data points) is of the same order of magnitude as errors of measurements.

These simulations aid in understanding the features observed on the St Maximin limestone sample S4. On that sample, the entry pressure is very different depending whether the most porous side is placed the closest or the farthest from the axis of rotation. Although there might not be a direct relation between porosity and capillary pressure, this situation could correspond approximately to the simulation presented above. We also verified using simulation that in the case of a lamination parallel to the axis of the sample and 2 media with different capillary properties (as shown in figure 9), the calculated Pc curve does not trend in an abnormal manner. The case of the Fontainebleau sandstone S3 is close to this situation (a lamination tilted at 45° from the axis of rotation) and thus, the results are not sensitive to the orientation of the sample.

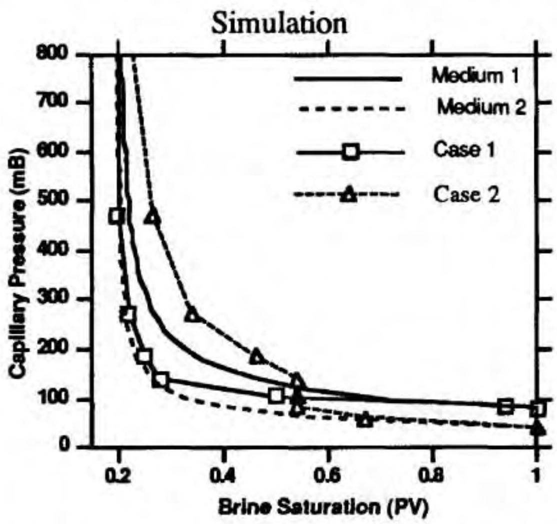

Figure 9: Interpretation of simulated centrifuge data with a heterogeneous sample. In case 1, the medium 1 is the closest to the axis of rotation.

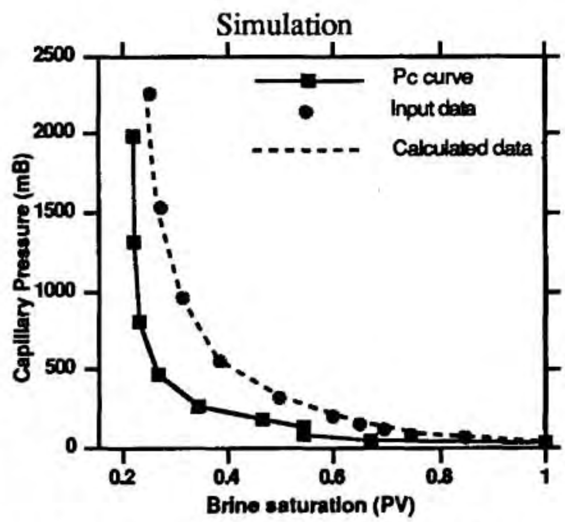

Figure 10: Calculated Pc curve from simulated centrifuge data, case 2 (medium 2 closest to the axis of rotation).

Conclusion

Centrifuge experiments performed on a sample at a small and a large radius of rotation demonstrated clearly the radial effect. Conventional interpretation technique, even those of high accuracy, can lead to different results because the same capillary pressure curve is not found when interpreting data from the two experiments. Capillary pressure curves from the small radius experiments are shifted to lower saturation compared to the large radius experiments and these differences are larger than the experimental errors. For the sandstone sample, the calculated Pc curves from both experiments are shifted to lower saturation compared to the porous plate measurements. The proposed correction for radial effect, validated on synthetic data (Forbes et al. 1994) is now validated by the experimental results. The correction was performed as a pre-process of experimental data and yielded consistent capillary pressure curves between small and large radius experiments for the 2 samples studied. In addition, a good agreement is found with the porous plate measurements. When the parameter N is larger than 0.02, it is highly recommended to apply the radial effect correction because errors of data processing become significantly higher than experimental errors.

When centimeter scale heterogeneous samples are centrifuged, we showed that the collected data are useful and can still be interpreted using a technique that assumes homogeneity. However, the calculated Pc curve depends on the orientation of the sample in the core holder when centimeter scale laminations are perpendicular to acceleration. In this case, the calculated Pc curve presents bumps similar to those observed when analysing double porosity samples (that are heterogeneous at micron scales). If only one experiment can be performed when heterogeneity is suspected, the most porous side (if any) of the sample should be placed the farthest from the axis of rotation of the centrifuge (during drainage) to obtain the largest desaturation and to attenuate interpretation artefacts.

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Nomenclature

a, b	parameter defined in text (section Data Interpretation)
B	geometric factor, $B = 1 - (\frac{R_3}{R_1})^2$
L	core plug length, cm
N	geometric factor defined in text (section Data Interpretation)
P_c, P_{c_1}	capillary pressure, capillary pressure at R_1
R	the radius of core cylinder plug, cm
R_1,R_3	rotation radius of the inlet and outlet face, cm
S, $\overline{S}$	brine saturation and average brine saturation
$\overline{S}^o$	mean brine saturation corrected for radial effect
$\Delta\rho$	density difference of fluid pairs
ω	angular speed of rotation

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